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PREFACE

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This issue contains the information published during June 2012. The arrangement of the contents is alphabetical wise starting from A-Z. The Full text of the article which is either subscribed by the University or available in the web has been provided in this Bulletin.

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An Efficient Adaptive Encryption Algorithm for Digital Images

Shashank Shekhar, Harshita Srivastava, and Malay Kishore Dutta

***Abstract*—This paper proposes an efficient method for encryption of digital images using an adaptive algorithm. According to the proposed algorithm the image used was segregated into significant and non significant blocks. For making the level of security different for different blocks, total and partial encryption has been utilized for the significant and non significant blocks respectively. Spatial as well as transform domain for the significant and non significant blocks respectively are used in this proposed method. The final encrypted image reflects the efficacy of the proposed algorithm. A comparative study between the conventional approaches of spatial and transform domain for the encryption of the image with the proposed encryption algorithm reveals the superior performance of the proposed algorithm. The experimental results suggest that the decrypted image is of excellent quality and signal to noise ratio is maintained well within the limit. The computational time utilized is very less as compared to the conventional approach, which suggests the enhanced overall performance and makes it suitable for high speed online applications.**

***Index Terms*—Arnold catmap, image encryption, logistic map, spatial and transform domain.**

I. INTRODUCTION

Security of Security of digital images is a seriously challenging issue in recent times. With the advent of increase in transmission and distribution of the image, illegal practice has also boomed. To restrict these illegal and piracy operations security of various level is required. The proposed algorithm for the encryption of image turns out to be effective and efficient way of protecting the digital images over the internet. Most of the conventional encryption techniques are based on the spatial and transform domain which gives same level of security to the entire image, and the computational time used is very high. In [1] the Wang et. al. have used image encryption method in transform domain, whereas in [2] spatial domain has been used individually. In both these cases the computational time consumed is large as compared to our proposed algorithm. In the proposed algorithm we have used a combination of the spatial as well as transform domain. Wavelet based partial image encryption [3] is also proposed for digital image security. In [4] the impact of using random coefficient permutation is investigated to provide confidentiality to wavelet based still image compression pipelines. In [5], [6] Arnold cat map and in [7] logistic map has been proposed for encryption of images. Use of chaotic system proposed in [8] for encryption of digital images. In the proposed algorithm image is divided into significant and non significant block. The level of security provided is different for different blocks using different encryption technique. Significant block is encrypted using total encryption technique while the non significant is encrypted using partial encryption technique thereby providing us with reduced computational resources and time. Arnold map employs shearing and wrapping operation to completely scramble a matrix after several iterations and hence the pixels are traversed to new position with each of the iteration. With Arnold cat map we get a distorted matrix of image, it is a preferable method for the image scrambling. Owing to perfect chaotic properties Logistic map has been used as a pseudorandom sequence generator. Both these map have enormous key space thereby making the image far less vulnerable. The paper is organized as follows. Section 2 gives an overview of the segregation of the image. The next section 3 describes the encryption method of the image. Section 4 describes the decryption method. Experimental results are presented in section 5. Finally, Section 6 concludes the paper.

II. SEGREGATION OF THE IMAGE

To make the encryption part more efficient and adaptive, the original image has been segregated into significant and non significant block. Total encryption is applied to the significant block. DWT has been applied in the non-significant block and only the approximate coefficients have been encrypted which saves as lot of computational resources.Following steps describes the various steps for the segregation.

- PREWITT edge detector is used to produce an edge detected output of the original image.
- Next the original image as well as the edge detected image is divided into non- overlapping blocks of size m*m, thereby giving ‘p’ number of blocks, and ‘m’ is user defined.
- Total number of EDP is calculated, denoted by E_{total}
- Now calculate the average number of EDP’s in a block using the formula $E_{average}=E_{total}/p$
- For identifying the significant portion of the image a threshold is defined , as given by Ethreshold=Eaverage*Q
- Similarly total number of EDP’s is calculated for each

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of the block separately.

- Those block which has EDP > $E_{threshold}$ are termed as significant block leaving the rest as non significant block.
- After this step a 1*p row matrix named as Binary significant vector (BSV) was created where each term was given a value either '1' or '0'.A '1' represent that the block is significant and '0' indicates non significant block.

where EDP is edge detected pixels which represent the total number of pixels, whose value is '1'. Q is defined as 1.25

III. Encryption of the Image

The segregated image obtained above is encrypted using spatial domain encryption for the significant block and transform domain encryption for the non significant part.

A. Encryption of Significant Part (Module 1)

For the encryption of significant block, we have used Logistic map as a pseudorandom sequence generator. The Logistic Map has high sensitivity towards initial condition. Hence even with slightly different initial condition, the chaotic output generated by the logistic map is completely different, thereby providing high level of security to the encrypted image in case of any intrusion.A single dimension Logistic map is mathematically represented as $X_{n+1} = r X_n (1-X_n)$, where $0<= X_n <=1$ and r represents "growth rate". Following are the steps describing the Encryption of the significant block.

- The significant block is scrambled using n iterations of the Arnold cat map.
- The Logistic map is iterated using the initial condition t and is used to generate a chaotic matrix of size m*m, where m denotes the block dimension.
- The scrambled block obtained in the first step is summed with the discretise output of the chaotic matrix obtained in the second step to get the modified version of the original significant block.

B. Encryption of the Non-Significant Block (Module 2)

DWT is applied to the non significant block, resulting in separation of approximate coefficients. Further we scramble the approximate coefficient part with the help of Arnold cat map iterations and Logistic map. The various steps for the encryption are described below.

- The insignificant block obtained during the segmentation has to go L-level DWT.
- The approximate co-efficient obtained during the first step is scrambled using Arnold Catmap.
- To generate completely scrambled block, L level IDWT is performed.
- The output obtained is summed with the discretise output of the logstic map.
- Thus we get the encrypted counter part of non significant part as shows in Fig 5.
-

IV. Decryption of Image.

Corresponding to the BSV received through the additional channel significant and non significant block are identified.

C. Decryption of Significant Part.

Following steps are used for the decryption of the significant blocks.

- Iterate the Logistic map with initial condition t to generate random vector which is rearranged into a block of size m*m.
- The descritised output of the random vector is subtracted from the encrypted block.
- The output of the step 2 is descrambled using (y-n) iterations of Arnold cat map to generate the decrypted output. Where, n is the number of iteration used in the encryption process and y is the periodicity of Arnold cat map.

D. Decryption of Non-Significant Part.

Following steps are used for the decryption of the non-significant blocks.

- Iterate the logistic map with initial condition t to generate random vector which is rearranged
  into a block oh m*m.
- The output of the random vector is subtracted from the encrypted block.
- Perform L-level DWT and descramble approximate coefficient using y-n iteration of the Arnold catmap.
- Perform L-level IDWT to retrieve the correct sub-band. Where n is the number of iteration used in the encryption process and y is the periodicity of Arnold catmap.
-

V. Experimental Result

The paper proposed encryption technique for still visual data. In the experiment seven different images of size 256*256 pixels were tested. The sole aim of the paper is basically to make a comparative analysis of the conventional encryption approach with our proposed algorithm. For this purpose we have considered two cases. In the first case the entire image is encrypted with the module developed for significant block. In the second case complete image data is encrypted with the module developed for the non significant block. These two cases denote image encryption in complete spatial and transform domain respectively. Two tests were conducted, one for PSNR and the other for computational time analysis. The result for the Computational time has been shown in Table I. In Table II, we have represented the various EDPs calculated for different blocks. Following graph shows the relative study of PSNR for spatial, transform and proposed algorithm.

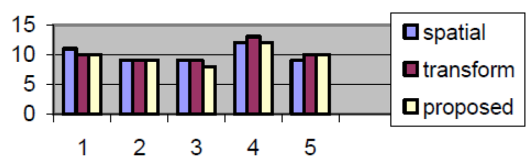

Fig. 1.PSNR (dB) for different images using different Encryption Technique

Formula:PSNR= $[10\log(R^2)]/MSE$ dB

$$MSE = \frac{\sum [I(m,n) - J(m,n)]^2}{M * N}$$

MSE = Men Squared Error
I = Original Image
J = Decrypted Image
M = No. of columns
N = No. of rows

Table I, Gives the comparative analysis of the conventional timing and proposed algorithm. It has been observed that computational time of our proposed algorithm is much less than conventional algorithm. In Table II we have calculated the EDPs for various significant and non significant blocks**.**

TABLE I: TIME TAKEN BY DIFFERENT ENCRYPTION ALGORITHM

	Spatial	Transform	Proposed Encryption
Lena	10.07	8.88	8.25
Mendrill	11.50	9.91	7.87
Cameraman	9.86	8.27	7.98
Barbara	9.87	8.99	7.12
Hut	10.24	9.67	7.93

TABLE II: EDP OF DIFFERENT BLOCKS

Blocks	EDPs	Nature
1	7	Non-significant
2	45	Non-significant
3	36	Non-significant
4	190	Non-significant
5	53	Non-significant
6	232	Significant
7	147	Non-significant
8	119	Non-significant
9	192	Non-significant
10	302	Significant
11	386	Significant
12	292	Significant
13	250	Significant
14	59	Non-significant
15	109	Non-significant
16	109 Total= 2528	Non-significant

$E_{average}$ = 2528/1
Therefore,
$E_{threshold}$ =158*1.25=198

Fig. 2. Original lena

Fig. 3. Edge detected

Fig. 4. Significant block

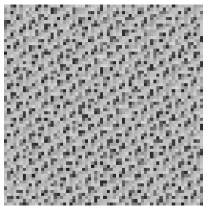

Fig. 5. Scrambled image

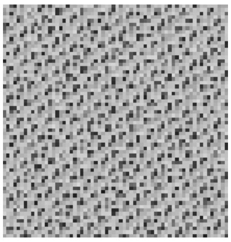

Fig. 6. After sum operation

Fig. 7. Non significant block

Fig. 8. DWT of the non significant part

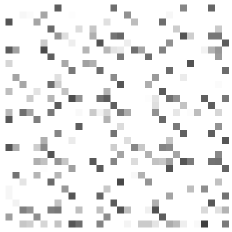

Fig. 9. Scrambled CA

VI. CONCLUSION

A novel prototype of encryption scheme has been proposed in this paper. Different level of encryption is performed depending upon the significant and non significant block, leading to the enhanced overall performance by reducing the computational resources as well as the computational timing. On the basis of comparison between the proposed encryption technique and spatial / transform domain encryption technique it is found that the PSNR of the spatial or transformation domain encryption is same to the proposed encryption technique. This indicates a similar level of incomprehensibility in the encrypted output of these cases.

Apart from the PSNR analysis, the computational time consumed is also observed. It is observed that computational time required for spatial and transform domain is higher than the proposed algorithm. On an average, the proposed algorithm is 18% faster than the transform domain encryption technique where it is 30-35% faster than conventional spatial domain encryption technique.

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Bandwidth and Latency Requirements for Smart Transmission Grid Applications

Prashant Kansal, *Student Member, IEEE*, and Anjan Bose, *Fellow, IEEE*

***Abstract*—The rapid increase of phasor measurements on the high voltage power system has opened opportunities for new applications to enhance the operation of the grid. To take advantage of the high sampling rates of these measurement data, these applications will require a high-bandwidth, networked communication system. The specifications for this next generation communication system that will overlay the continental power grids are under intense discussion at this time by organizations like the North-American Synchro-Phasor Initiative (NASPI). In this paper we present a method to simulate, design and test the adequacy of a communication system for a particular transmission grid. The main difference from typical communication system studies is that we formulate the communication requirements from the power grid application requirements, that is, the communication design, simulation and testing is from the viewpoint of the anticipated power applications. The method is demonstrated on a WECC 225 bus and a Polish 2383 bus transmission system models.**

***Index Terms*—Bandwidth, C37.118, communication protocols, latency, NS2, PMU, smart grid.**

I. Introduction

THE IDEA OF collecting fast measurements that can give us an insight into grid dynamics is fundamental to understanding the grid behavior that is operating near margins and to make it more reliable [1]. With availability of Phasor Measurement Units (PMU), the synchronized measurements can be taken at rates of about 30 to 120 samples per seconds. The smart grid applications [2]–[13] are designed to exploit these real-time measurements. Most of these applications have a strict latency requirement in the range of 100 milliseconds to 5 seconds [11], [12]. To feed these applications we also need a fast communication infrastructure that can handle a huge amount of data movement and can provide near real-time data delivery. These issues become more and more critical when we imagine having phasor measurement units everywhere in the power grid. The latency and bandwidth requirements for smart grid are two very critical issues among these that are addressed in this paper.

Rest of the paper is organized as follows. Section II discusses smart grid applications, as the design of these will determine the communication requirements. Section III discusses various aspects of communication infrastructure needed for the smart grid. Section IV presents the simulation results of possible communication scenarios for two different power systems. We conclude with Section V.

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II. Smart Grid Applications

A. Measurements

The data which we need in real time for successful analysis, operation and control of the grid is its topology and state. The topology defines the interconnection of the grid and is almost constant over time [13]. On the other hand, the state (voltage and angle at all buses) of the power system changes dynamically over time due to changes in loads, generation and switching operations. Without PMUs, state of the grid is derived from voltage magnitude (V), real power (P) and reactive power (Q) measurements using a computer program called State Estimator (SE). Most of the power grid applications based on this set-up are bottlenecked by the latency and accuracy of the estimated state of the system as calculated by state estimator. As these measurements are collected by Supervisory Control and Data Acquisition (SCADA) system by polling over 2–4 seconds, the measurements do not represent a snapshot of the actual system state at one particular time. This set-up seems to work fine for an unstressed grid working in almost steady state conditions. The present operation of the grid is often very close to its security margins and the system ventures into the emergency state more frequently than before. State-estimator cannot capture the changing state of the system and sometimes fails to converge. With PMUs all over the system, the state of the grid (voltage phasors) can be directly measured and moreover can be measured many times per second with time-stamps giving insight into the dynamics of the system.

B. Current Status

A number of smart grid applications have already been developed and some are in the process of development [11]. To understand their communication needs, a brief survey of some of the most important applications in terms of their data requirement and latency is presented in Section II-C and Table I. A communication network designed to handle these basic applications would be able to handle other applications as well.

C. Classification

1) State Estimation: Even though voltage phasors across the grid can be directly measured with PMUs everywhere, state estimation is an essential tool to eliminate effect of bad measurements on the final calculation of the state. Most of the Energy Management System (EMS) applications are fed from state estimated data and are benefited by faster, accurate and synchronized measurements. Also with PMUs, two level state estimators [14] can be designed to run locally within the substation to feed applications like transient stability.

TABLE I
SURVEY OF SMART GRID APPLICATIONS BASED ON LATENCY AND DATA REQUIREMENTS

Main Application	**Applications based on it**	**Origin of Data/Place where we need the data**	**Data**	**Latency requirement**	**Number of PMUs we may need to optimally run the application**	**Data time window**
State Estimation	Contingency analysis, Power flow, AGC, AVC, Energy markets, Dynamic/ Voltage security assessment	All substations/ Control center	P,Q, V, theta, I	1 second	Number of buses in the system	Instant
Transient Stability	Load trip, Generation trip, Islanding	Generating substations/ Application servers	Generator internal angle, df/dt, f	100 milliseconds	Number of generation buses (1/20 buses)	10-50 cycles
Small Signal Stability	Modes, Modes shape, Damping, Online update of PSS, Decreasing tie-line flows	Some key locations/ Application server	V phasor	1 second	1/10 buses	Minutes
Voltage Stability	Capacitor switching, Load shedding, Islanding	Some key location/ Application server	V phasor	1-5 seconds	1/10 buses	Minutes
Postmortem analysis	Model validation, Engineering settings for future	All PMU and DFR data/ Historian. This data base can be distributed to avoid network congestion	All measurements	NA	Number of buses in the system	Instant and Event files from DFRs

2) Transient Stability: Transient stability is a concept related to the speed and internal angles of the generators. A typical system can get transiently instable in approximately 10 cycles. The way to prevent this is to island the system in coherent groups or shed load/generation using Special Protection Schemes (SPS). The wide-area control to do so is still not in place because of latency requirements and it would to be a big challenge to design such a control system even in the future.

3) Small Signal Stability: To solve small signal stability problem, we need signals only at selected key locations where modes are more visible. For any of these modes, if damping happens to change then it changes slowly over time. Moreover, if the damping is negative, even in that case, oscillations take time to build. So small signal instability occurs over a period of time and by observing the mode damping near real time, this can be prevented by resetting the power flows across the lines or by setting Power System Stabilizer (PSS) online.

4) Voltage Stability: Voltage instability spreads over time starting from reactive power (VAR) deficient area and can ultimately cascade and lead to a blackout. The problem can be solved if the voltage in an area can be measured and corrected by balancing VAR in the particular area or by islanding the area.

5) Post-Mortem Analysis: This will be a key application to correct power system models and to update engineering settings for the system. The engineering settings are bound to change as the system changes. This application does not need to run real time and has no latency requirements. This application will require PMU data as well as data from other IEDs (Intelligent Electronic Devices) like DFRs (Digital Fault Recorders).

III. SMART GRID COMMUNICATIONS

A. Infrastructure

We assume smart grid of the future will have PMU data available across the grid. To meet the latency requirements and to handle the huge amounts of data, a real time information infrastructure was proposed [13]. Because of the huge amount of data generated at each substation, not all the data can be sent to one central location. Therefore, there is a need for the application servers to be distributed as shown in Fig. 1. Separating out application servers will also help to tag packets for latency purpose. The middleware system to handle this distributed data base and to provide the latency and other Quality of Service (QoS) is one of the major goals of the NASPI [11], [12] and some research initiatives like Gridstat [15], [16].

B. PMU Data Format (C37.118)

The standard mostly used in practice for PMU data format is C37.118 [17]. Among the four frames that are defined in C37.118, Data Frame is the one that is sent out from substation during normal system operation. Hence, it is important to know the data formats to exactly evaluate how much data is being generated in bytes at each substation. Also, one data frame can carry data from multiple PMUs.

C. Latency

We define data latency as the time between when the state occurred and when it was acted upon by an application. Each application has its own latency requirements depending upon the kind of system response it is dealing with. Among the other delays [18], communication delay also adds to the latency and needs to be minimized. The communication delays on the network are comprised of transmission delays, propagation delays, processing delays, and queuing delays [1]. Each of these delays must be looked into to understand the complete behavior of the communication network for a given network.

D. Communication Within one Control Area

The data from various PMUs from a substation is sent out in C37.118 format Data frame. This data is then received at the location of the application in its respective Phasor Data Concentrator (PDC) usually using proprietary software; the only open source software called Open-PDC is used in this paper.

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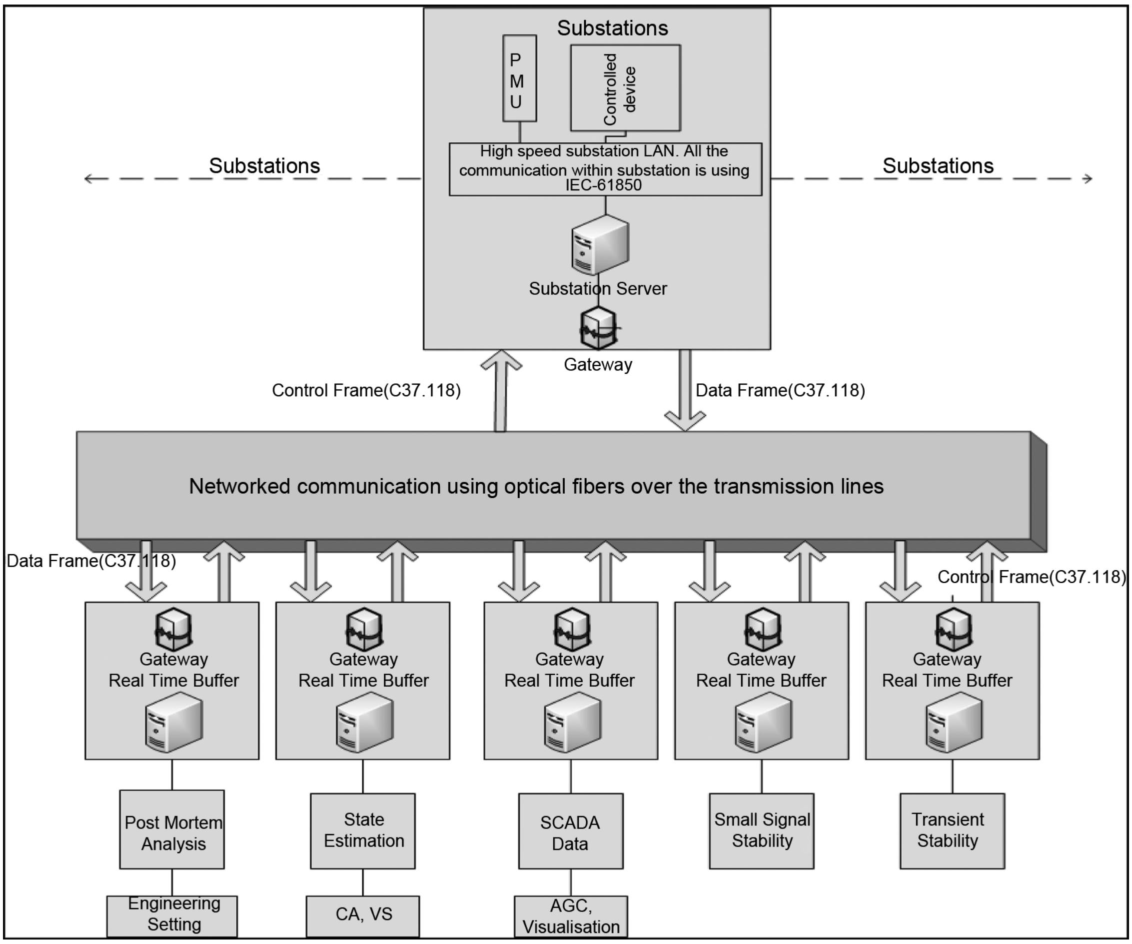

Fig. 1. Communication Architecture.

TABLE II
PROTOCOL LAYERS FOR COMMUNICATION IN ONE CONTROL AREA

Layer	**Protocol**
Application	CBR
Transportation	UDP
Network	IP
Data	Ethernet
Link	Ethernet (Optical fiber)

We know that PMUs are constantly sending out the data frame on the network. For many of the smart grid applications latency is an important consideration in designing a communication infrastructure. Keeping this in mind, User Datagram Protocol (UDP) becomes a preferred protocol at the transportation level over Transportation Control Protocol (TCP). At the application layer, Constant Bit Rate (CBR) is a good choice to carry the continuously generated data frames of PMU. Maximum Transmission Unit (MTU) size of the link layer will play an important role as OpenPDC is designed to receive a complete C37.118 packet and not a broken one. As shown in the simulations, packet size can be around 1500 bytes, i.e., Ethernet communication having MTU size as 1500 bytes is the obvious choice. Given the latency and bandwidth requirements, optical fibers and Broadband over Power Line (BPL) are the promising solutions. For uniformity we assume that optical fiber is present throughout the network. Hence the protocol stack will look like as shown in Table II.

IV. Simulation Results

A. Simulation Setup

Here we present the simulation results for Western Electricity Coordinating Council (WECC) 225 bus system and Poland 2383 bus system [19]. We simulated one of the possible communication scenarios using an event based, open source communication network simulator called NS2 version 2.34 [20], [21]. We further wrote Matlab, Python, Tcl and Awk scripts to do the analysis. We identified the following 7 basic traffics in the network as shown in the simulation snapshot for IEEE 14 bus system in Fig. 2.

1) All the Substation (S/S) to Control Center (CC).
2) Control Center to Control Substation (Generating stations and substation having control units like transformers and reactors).
3) Special Protection Scheme (SPS) substation to SPS.
4) SPS to SPS substation.
5) Generating substation to Generating substation.
6) SPSs to Control Center.
7) Control Center to Control Center.

Here, SPS is used generically to represent any wide-area closed-loop control and/or protection. An SPS may not be located at the control center or at any substation and it needs data only from a few locations and issues commands back to

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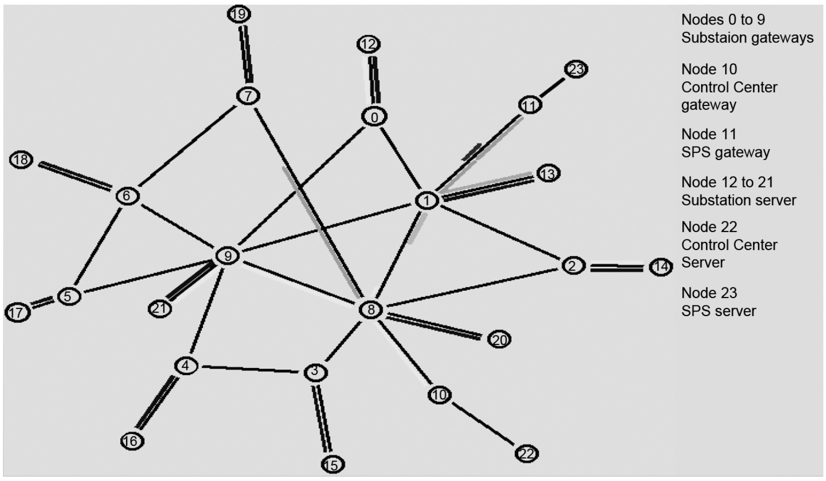

Fig. 2. Snapshot of 14 bus NS2 simulation with 6 traffic types.

few substations only. SPS can be especially useful for transient stability applications where latency is of significant importance.

The key assumptions that we have to make in the simulation are discussed in Section IV-B and Section IV-C. Similar network simulations [22] have been carried out before and some of the assumptions in this paper are similar to [18], [22]–[24]. The main difference in this work is that the assumptions are developed by starting from the power network, substation configurations and anticipated on-line applications (Section IV-B) to determine the data transfer needs. Different scenarios can be studied using different protocols, routing algorithms, data formats, sampling rates, and communication infrastructure. Also, accuracy of the results would depend on the modeling details and some of it may require changing the NS2 source code. This paper focuses on presenting a methodology to simulate a possible communication scenario using power system topology information with design parameters based on smart grid application requirements.

B. Assumptions for Power Systems Data

The information that is required to calculate the amount of data for an actual power system is substation configuration and connected equipment (generators, reactors, and transformers). Location of the application servers (control center and SPS) and location of controls along with their individual data needs then define the amount of data that need to be communicated. For a real power system this information is easily available.

The connection between substations is from the given power system network data and the communication network overlays that. In case of multiple transmission lines between two substations, only one communication link is considered to connect them. Control center (CC) node is connected to the substation node having maximum number of communication links. This will allow distribution of traffic to the CC node through multiple paths. Similarly SPSs are connected to the available substation nodes having maximum connectivity. This completes a communication network graph of network gateways (Gw) for a given power system.

Each gateway is connected to a server. Power system applications and PDCs are running in these servers. As an integrity check and to run communication simulation, we wrote a computer program to verify the connectivity of the network graph obtained after this step.

The second step is to estimate packet sizes in each of these substations, control centers and SPSs. We calculate packet size for data traffic between substation and control center (type-1 traffic) as follows.

1) The configuration for each substation is usually known (in our examples in Sections IV-D and IV-E we assume a breaker and half scheme for all substations). The 3 phase quantities for each section and CB status are measured and communicated.
2) Channels for each PMU are known (assumed to have 9 analog channels and 9 digital channels in examples below).
3) Given the number of PMUs and number of phasors in a substation, the size of C37.118 data frame is calculated.

Type-2 to type-6 traffic have packet sizes smaller than the type-1 traffic because only selected data for control purposes constitute these types.

For the two example power networks used in Sections IV-D and IV-E, we had the power network data but not the substation details. The identification of substation configurations, control substations, control centers and SPSs is first step to determine the data traffic for our simulation studies. We wrote a computer program to do this step. We combine buses that are connected through transformers into one communication node per substation. We then calculated the number of feeders in each of these substations. On top of the substation, we added one control center per zone where we treated each zone as one control area. We then added SPSs assuming that a group of approximately 10 substations will be connected to one SPS.

C. Assumptions for Communication Simulation

After obtaining the network graph and data requirements based on the Sections IV-A and IV-B discussions, the following assumptions are made for communications.

1) As discussed in Section III-D, we used CBR over UDP to simulate the traffic with MTU size as 1500 bytes.
2) As a base case, we assumed duplex links of sufficiently high bandwidth between substations as OC-3 i.e., 155

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TABLE III
WECC STATISTICS AFTER NODE REDUCTION

S.No.	Parameter	Value
1	*Buses*	225
2	*Substations*	161
3	*Control Center*	1
4	*SPS*	16
5	*Generating S/S*	31
6	*Control S/S*	58
7	*SPS S/S*	160

TABLE IV
PACKET SIZE OF TRAFFIC TYPE-1

Maximum (Bytes)	Minimum (Bytes)	Average (Bytes)	Median (Bytes)
1540	148	401	280

TABLE V
LINK BANDWIDTH USAGE

Topology	Max. of used links (Mbps)	Min. of used links (Mbps)	Average of used links (Mbps)	Median of used links (Mbps)	% of unused Gw2Gw links
Min S.T.	58.75	0.10	5.46	0.39	28.6%
1CC links	45.60	0.08	3.34	0.62	11.4%
3CC links	46.80	0.10	2.97	0.51	11.7%
5CC links	44.09	0.08	2.03	0.38	10.8%

Mbps and the receiving link for the CC/SPS as OC-12 i.e., 622 Mbps.

3) To observe larger queuing delays and to avoid packet drops, based on few simulation runs, we assumed the queue size as 5000 packets.
4) To simulate large network such that every packet reaches its destination node without being dropped, based on few simulations run, we set the Time-To-Live (TTL) value to 64 hops.
5) Number of CC and SPSs are chosen based on the size of the network.
6) Data set out from the substation/SPS/Control center server is in C37.118 format (fixed 16-bit).
7) The routing used by NS2 is the shortest route (number of hops) and is kept default as static.
8) We assumed that the system is under normal operation and only Data frames are being communicated.
9) The sampling rate is assumed to be 60 samples/second for all the traffic sources
10) The processing delays in gateways (10–100 microseconds [25]) are assumed to be zero. Here gateways are considered as forwarding nodes only to simulate communications. Data aggregation/ processing occur at end nodes/PDC only and we consider this delay as computation delay and not communication delay. The computation delays can be added at each end node for specific application without making it a part of the communication simulation.
11) We assumed that the communication is uniform i.e., no spikes in data.
12) To calculate propagation delay, we converted the network reactance into miles [26].
13) Propagation delay between server and gateway is assumed to be 1 microsecond.

TABLE VI
MAXIMUM DELAYS FOR DIFFERENT TRAFFIC TYPES

Network Topology	Type1 (ms)	Type2 (ms)	Type3 (ms)	Type4 (ms)	Type5 (ms)	Type6 (ms)
Min S.T.	49.9	40.3	45.1	46.3	44.0	40.3
1CC links	26.2	27.6	26.6	27.1	29.4	23.9
3CC links	19.2	19.1	25.2	25.5	29.3	16.4
5CC links	11.7	5.2	13.8	12.9	15.6	4.5

NS2 simulation is run after following the steps/assumptions discussed in Sections IV-A to IV-C above. NS2 generates a trace file with all the events (packet drop, packet receive, etc.) for each packet generated in the system. These files are analyzed using various computer programs [27] for results on latency and bandwidth presented in Sections IV-D and IV-E.

D. WECC Results

1) WECC 225 Bus Power System: The WECC 225 bus is a reduced model of the WECC transmission network though representing almost same geographical area. Power system statistics after following the methodology discussed in Section IV-B are presented in Table III. Note that we have only one control center and hence six traffic types for WECC.

2) Packet Size: As shown in Table IV the maximum packet size for type-1 traffic in a substation can be as much as 1540 bytes. Also, packet sizes for a given power system would be same for all communication topologies. We assumed type-1 to type-6 traffic packet size to be 250 bytes for the simulation purposes which is lower than the median of type-1 packet size.

3) Average Link Usage for Different Communication Topologies: As shown in Table V, we did simulation for four different cases. In the first simulation we used Kruskal's algorithm [28] to get minimum spanning tree (S.T.) for the communication network. This gives us the minimum number of links required for networked communication of a given power system. In next three simulations we used the complete graph as obtained after node reduction program with variation in number of control center links, for example, 3 CC link means connecting CC gateway to the three substation gateways (with maximum connectivity) in the network. Clearly, connecting control center with some substations geographically distant is really important as it makes the routing really efficient by avoiding bottlenecks and providing alternate shortest path to the traffic. Also, we must not use spanning tree configuration from reliability perspective. For full topology case, by adding just 4 more CC links we can save 40% on link usage and delays reduces to ¼ for 5CC link configuration compared to 1CC link configuration. Hence, this helps in decreasing delays by adding just few links. Also, notice that average bandwidth usage decreases because now packet takes shorter route and traverses lesser link to reach its destination.

4) Maximum Delays in Traffic for Different Communication Topologies: As shown in Table VI, we have figured out the maximum delays for the six identified traffic types. With the large bandwidth of fiber optics and meshed communication, it can be noted that maximum delays for all the traffic types are well within the latency requirements for most applications.

5) Queuing Delays: As shown in Table VII, we have calculated the queuing delays for each system. Notice that with the

TABLE VII
QUEUING DELAYS

Topology	Maximum (μs)	Minimum (μs)	Average (μs)	Links with queue delay as zero (%)
Min S.T.	586	0	17.7	53.1%
1CC links	441	0	13.7	60.1%
3CC links	259	0	12.0	60.2%
5CC links	354	0	12.6	60.8%

TABLE VIII
NUMBER OF HOPS

Topology	Max	Min	Average	Median
Min S.T.	43	2	19	18
1CC links	28	2	12.2	12
3CC links	26	2	10.6	10
5CC links	15	2	7.0	7

TABLE IX
ASSUMED BANDWIDTH FOR SIMULATIONS

Bandwidth	Base Case (D3-D6) (Mbps)	Actual Usage (Mbps)
Btw CC server and CC Gw	Duplex 622	50Mbps (Gw to Server) / 10Mbps(Server to Gw)
Btw Sps server and Sps Gw	Duplex 622	Simplex 2Mbps
Btw S/S server and S/S Gw	Duplex 155	Simplex 5Mbps
Btw CC Gw and S/S Gw	Duplex 622	Simplex Integer(actual)+1
Btw Sps Gw and S/S Gw	Duplex 622	Simplex Integer(actual)+1
Btw S/S Gw and S/S Gw	Duplex 155	Simplex Integer(actual)+1

huge bandwidth available queuing delays are almost negligible. Queuing delay can increase really fast if the network get congested or if the bandwidths on incoming link and outgoing link are disproportionate.

6) Number of Hops: As shown in Table VIII, we have calculated the number of hops that a packet has to traverse assuming shortest hop routing algorithm. This data will help us understand how much an issue can processing delays at gateways can be if they happen to increase due to more intense routing mechanisms or other reasons like security.

7) Simulations With Varying Bandwidth: In Sections IV-D-III–IV-D-VI, we calculated various network parameters using the base bandwidth mentioned in assumptions. In this section we assumed 3CC link configuration and used estimated bandwidth of Section IV-D-III as the actual required bandwidth. Table X shows the result on delays when we varied the bandwidth on the gateway to gateway links (G2G) as the multiple of actual bandwidth. Further for the first three cases of results in Table X, we assumed same bandwidth on gateway to server (G2S) links as pointed in Table IX. Notice that when we scale the bandwidth, we should scale it on the complete network i.e., both on G2G and G2S links or else queuing delay increases. Also as shown in Table X by using twice the actual bandwidth we can get delays similar to base case. Recalculated bandwidth consumption for each case is shown in Table XI.

TABLE X
DELAYS IN WECC SYSTEM WITH VARYING BANDWIDTH

Bandwidth of G2G links	Max. Delay (ms)	Avg. of Max Delay of each traffic type (ms)	Max. Queuing Delay(μs)	Avg. Queuing Delay(μs)
Actual BW/2	167.0	91.2	43736	3413
Actual BW	55.3	39.3	8018	694
*Actual BW*2*	40.8	31.3	8018	595
*Actual BW*2*	38.1	28.3	4009	342
*Actual BW*5*	32.1	24.0	1603	131
622Mbps and 155Mbps	29.3	22.4	259	12

TABLE XI
ACTUAL LINK BANDWIDTH REQUIREMENT FOR WECC

Communication infrastructure	Max. G2G Bandwidth (Mbps)	Average G2G Bandwidth (Mbps)	Median G2G Bandwidth (Mbps)
Actual BW/2	24	2.59	1
Actual BW	47	4.48	2
*Actual BW*2*	94	8.28	3
*Actual BW*2*	94	8.28	3
*Actual BW*5*	235	19.88	6
622Mbps and 155Mbps	622	194.56	155

E. Poland 2383 Bus System Results

1) Polish Power System: Polish power system discussed here is a high voltage power system of Poland above 110 kV which is divided into 6 zones. Zone 1–5 is shown in Fig. 3[29]. Zone-6 represents all the tie lines connected to the neighboring countries. For simulation purposes we included each of the Zone-6 bus into the respective Zone 1–5 to which it is actually connected. Each zone will have its own control center and the only interaction between zones is between their respective Control centers. The inter control center communication would have separate direct connection using optical fibers over transmission line. The number of substations being more than 225 in each zone, we used 5CC and 7CC link communication infrastructure to simulate traffic in each zone.

Network statistics following the methodology discussed in Section IV-B are presented here in Tables XII and XIII.

2) Packet Size for Different Zones: After node reduction, we calculate packet size for data traffic for each zone as shown in Table XIV.

3) Average Link Usage for Different Zones Using 5CC/7CC Link Communication Topologies: The bandwidth usage is estimated only on the G2G links and is shown in Table XV.

4) Maximum Delays in Traffic for Different Zones: From our understanding of the WECC system we used twice the actual bandwidth usage as our new bandwidth and estimated the delays for the Polish system as shown in Table XVI. This is well within the latency requirements for most applications.

5) Number of Hops: As shown in Table XVII, we have calculated the number of hops that a packet has to pass during the simulation assuming shortest path routing algorithm.

6) Control Center to Control Center Simulation: Once the data reaches its zonal control center, state estimation is performed for that particular zone. Each zonal control center then sends its information to all the neighboring control centers. Each

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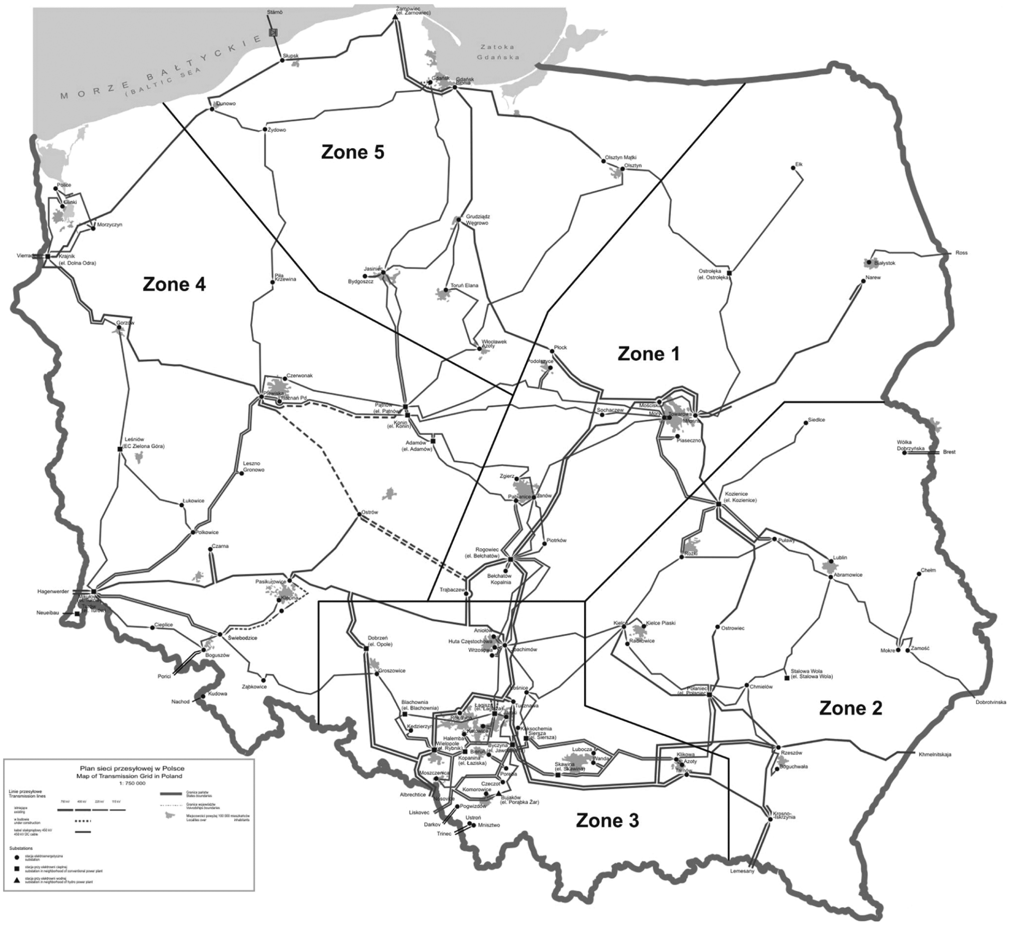

Fig. 3. Polish power system zones.

TABLE XII
OVERALL STATISTICS OF THE POLISH SYSTEM

S.No.	Parameter	Value
1	*Buses*	2383
2	*Substations*	2216
3	*Control Center*	6
4	*SPS*	219
5	*Generating S/S*	305
6	*Control S/S*	386
7	*SPS SS*	2190

TABLE XIII
ZONAL STATISTICS OF THE POLISH SYSTEM

Parameter	Zone1	Zone2	Zone3	Zone4	Zone5
Substations	*343*	259	831	515	268
Control Center	1	1	1	1	1
SPS	34	25	83	51	26
Generating S/S	42	36	88	92	47
Control S/S	56	51	104	112	63
SPS SS	340	250	830	510	260
CC links	5	5	7	7	5

control center has the static data of system topology for the complete national grid. Control center sometime performs the state estimation using full system topology, local measurements and usually state estimated data from neighboring grid. The problem in just sending the estimated states to the neighboring control center is that the changes in the substation configurations are not reflected in the state estimated data. To take this into account we

TABLE XIV
PACKET SIZE OF TRAFFIC TYPE-1

Zone	Maximum (Bytes)	Minimum (Bytes)	Average (Bytes)	Median (Bytes)
1	1438	148	290.7	262
2	1204	160	303.1	262
3	1540	148	265.6	262
4	1426	148	281.2	262
5	1078	148	293.8	262

TABLE XV
AVERAGE G2G LINK BANDWIDTH USAGE IN MBPS

Max. of used links (Mbps)	Min. of used links (Mbps)	Average of used links (Mbps)	Median of used links (Mbps)	% of unused G2G links
126.77	0.09	4.68	0.94	2.96

TABLE XVI
MAXIMUM DELAYS IN TRAFFIC FOR EACH ZONE

Zone	Type-1 (ms)	Type-2 (ms)	Type-3 (ms)	Type-4 (ms)	Type-5 (ms)	Type-6 (ms)
1	12.4	11.5	22.2	28.7	23.6	11.9
2	12.7	10.8	19.7	24.6	25.3	10.2
3	14.2	13.6	25.4	27.9	25.9	11.2
4	12.5	11.6	18.0	22.9	25.8	10.2
5	15.4	11.1	26.3	26.6	21.0	10.0

assume all the measurements from one system to another along with any changes in substation configurations are sent. Hence

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TABLE XVII
NUMBER OF HOPS

Zone	Max	Min	Average	Median
1	18	2	7.23	7
2	15	2	7.23	7
3	20	2	8.12	8
4	20	2	7.71	8
5	15	2	6.85	7

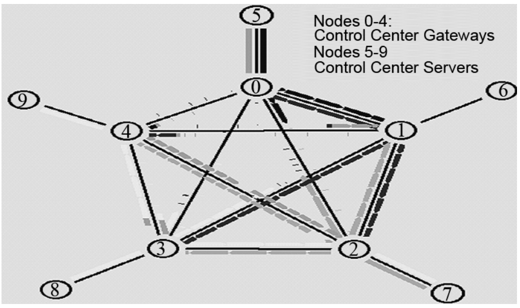

Fig. 4. Communication topology to connect control centers for Polish system.

TABLE XVIII
FILE SIZE OF RAW MEASUREMENTS AND BREAKER STATUS

Zone	File size (bytes)
1	99712
2	78514
3	220758
4	144842
5	78748

state estimation at control center can then be performed using local measurements and corrected using system wide measurements. The computation delays in the control center can be of significant importance here.

Currently, the data sharing between control centers is done using Inter Control Center Protocol (ICCP) which is a relatively slow protocol. The data shared between control centers being huge and latency being not the prime concern for EMS application we assumed FTP/TCP kind of traffic. Also it is not suggested to use TCP with UDP as TCP needs to allocate resources on the network before transmission and does get kicked out by UDP. Using TCP helps us in taking care of packet drops, as dropping packets is a concern for data which is collected approximately in a second. In communication infrastructure shown in Fig. 4, control center shares its information with the all control centers using point to point links. We obtained this network from the location of the zones and by finding shortest path to connect these zonal control centers assuming the optical fiber would run over transmission line. Because there would be only few changes in the system topology over time, mainly raw measurements results would constitute to the size of the file. The estimated size of the data file time tagged at one particular time is shown in Table XVIII.

In Table XIX we have shown that delays to send a complete chunk of file from one control center to another varies as we vary link bandwidth.

Based on our understanding for delays in inter control center communication we assumed 50 Mbps bandwidth and then calculated total delays shown in Table XX. These delays represent maximum total delay for packets tagged at time $t = 0$ to get distributed to all the control centers. Notice that at the control center separate files of raw measurements with different time tags are created. For state estimation purpose one file can be picked up and transmitted every one second.

TABLE XIX
DELAY FOR INTER CONTROL CENTER COMMUNICATIONS

Bandwidth for CC to CC links (Mbps)	Delay in CC to CC communication	
	Maximum (ms)	Average (ms)
25	118.4	69.1
50	84.3	46.3
75	71.1	39.2
100	65.5	35.5

TABLE XX
DELAY IN EXCHANGING COMPLETE INFORMATION ACROSS POLISH SYSTEM

Zone	Max delay for type-1 traffic (ms)	Max CC to CC delay (ms)	Total delay (ms)
1	12.4	66.5	78.9
2	12.7	65.0	77.7
3	14.2	50.8	65.0
4	12.5	61.3	73.8
5	15.4	84.3	99.7

V. CONCLUSION

The work presented here provides a basis for simulating the performance of communication network for Power Systems. In this paper a method is developed to determine the parameters to simulate a communications system for a power grid starting from the power network configuration and the knowledge of the measurement data and the on-line applications. In designing the smart grid infrastructure for a particular power system, the assumptions should reflect the actual design parameters of the communication infrastructure. Such a simulation tool can be used to develop, design and test the performance of the communication system.

We believe that given the actual applications and their precise data requirements further improvements in the results can be obtained on a case to case basis. For example further reduction in bandwidth and latency is possible by using multicast routing and packet tagging. In another scenario we may not send all the traffic to the control center and SPS's can be used as the distributed data bases. Slower EMS applications running in control center can then source the required data from SPSs using middleware architecture like Gridstat. These improvements have to be made based on individual network needs. However, the results in the paper provide us key insight that the average link bandwidth needed for smart grid applications should be in the range of 5–10 Mbps within one control area and 25–75 Mbps for inter control center communications. Using meshed topology, delays can be contained within the 100 ms latency requirement satisfying all applications. Also with packets traversing just 8–10 hops processing delays at routers should not be a problem.

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Classification of power quality events – A review

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A B S T R A C T

Power quality (PQ) interest has increasingly evolved over the past decade. The paper surveys the application of signal processing, intelligent techniques and optimization techniques in PQ analysis. This paper carries out a comprehensive review of articles that involves a comprehensive study of signal processing techniques used for PQ analysis. Within this context intelligent techniques such as fuzzy logic, neural network and genetic algorithm as well as their fusion are reviewed. Tabular presentation (i.e. highlighting the important techniques) has also been provided for comprehensive study. Although this review cannot be collectively exhaustive, it may be considered as a valuable guide for researchers who are interested in the domain of PQ and wish to explore the opportunities offered by these techniques for further improvement in the field of PQ.

1. Introduction

In the industrialized world, electric power systems have become polluted with unwanted variations in the voltage and current signal. PQ issues [1] are primarily due to continually increasing sources of disturbances that occur in interconnected power grids, which contain large numbers of power sources, transmission lines, transformers and loads. In addition, such systems are exposed to environmental disturbances like lighting strikes. Furthermore, nonlinear power electronic loads such as converter driven equipment have become increasingly common in power system. Poor quality [2,3] is attributed due to the various power line disturbances. In brief, PQ problems can cause system equipment malfunction; computer data loss and memory malfunction of sensitive loads such as computer, programmable logic controller controls, protection and relaying equipment; and erratic operation of electronic controls [4]. Therefore, it is necessary to monitor these disturbances. Continuous monitoring is required because of the increasing demand of clean power as suggested in Refs. [5–7] and monitoring standards are also given in Ref. [8].

Since, disturbances occur in the order of microseconds, a captured event recorded using monitoring system produces megabytes of data. As a result, the volume of the recorded data increases significantly, necessitating the development of an efficient technique to compress the data volume. Monitoring has significant implications in the area of PQ [9]. The volume of the data to be recorded and examined is prohibitively large, if all the waveform is to be saved into the instrument or a personal computer. With the advancements in PQ monitoring equipments, data compression has received great attention from those involved in the field [10]. In many countries, high-tech manufacturers often concentrate in industry parks, therefore any PQ events in the utility grid can affect a large number of manufacturers [11,12]. Therefore, if these unwanted variations in the voltage and current signal are not mitigated properly [13], they can lead to failures or malfunctions of many sensitive loads connected to the same system, which may be very costly for the end users. To mitigate the PQ events, it is necessary to identify the events through PQ events detection and classification system so that accordingly mitigation action can be carried out. Therefore, PQ events detection and classification area is having its own importance in the era of PQ. So, PQ analysis is becoming the most interesting area of research in past several years for characterization [14,15] and classification of events [16]. For the classification of PQ events, feature extraction and classification are the most important part of the generalized PQ event classification system. PQ event detection requires the feature extraction from the input PQ disturbance. Feature extraction plays an important role in PQ analysis. Better feature set should be able to represent the signal efficiently. Extracted feature set can be used for the classification process.

A brief survey on methods for PQ events classification reported earlier in [17,18] but little insight into the comprehensive analysis of different techniques. New and powerful tools for the analysis of PQ events diagnosis are currently available. Signal processing tools have been used for the feature extraction of power signal. Wavelets have been extensively used by the researchers during the last decade but other signal processing tools (i.e. such as S-transform (ST), Time-Time Transform (TTT), and Higher-Order Statistics (HOS)) have also been introduced to find out other salient features.

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In [19], slantlet transform has been proved better compression technique for PQ data. These new introduced signal processing tools make the classification system more robust.

2. Power quality

The term PQ has become one of the most prolific buzzwords in the power industry [20]. In the context of PQ, it may be worth studying the causes for various PQ disturbances as in Refs. [21–23]. PQ is the set of limits of electrical properties that allows electrical systems to function in their intended manner without significant loss of performance or life. The term is used to describe electric power that drives an electrical load and the load's ability to function properly with that electric power. Without the proper power, an electrical device (or load) may malfunction, fail prematurely or not operate at all. The major malfunctioning of the electrical equipments occurs due to the non-stationary disturbances. Thence, analysis of non-stationary disturbances attracts many multidisciplinary researchers in this provocative field. Basically, non-stationary signals (having multiple frequencies ranging from 300 to 1000 Hz such as oscillatory-transients, voltage spikes, multiple voltage notches due to solid-state converter switching and harmonics) characterized by wide range of frequency spectrum with transient and sub-harmonic components are difficult to analyze as in [24]. These disturbances can be monitored as in [25] and classified on the basis of time-variant statistical characteristics of the voltage and current waveforms as in [26–28] and they could be sinusoidal or non-sinusoidal as in [14]. For only non-stationary PQ events, dominating frequency components have been used as features for recognition of events in [29]. Since PQ disturbances can lead to poor power quality which may have negative impact on the economic operation of the electric power system, therefore evaluating the electric power quality becomes very essential for both utilities and consumers especially when moving towards smart grid.

During the last decade, power electronic technology plays an important role in distributed generation and integration of wind energy generation into the electric grid. It is due to the development in fast semiconductor switches, which are capable of switching quickly and handling high power, which have been widely used in wind energy system. The implementation of inverter switching technique will make the unity power factor at the point of common connection on the grid, irrespective of disruptive effects caused by wind turbines [30]. The increasing number of renewable energy sources and distributed generator requires new strategies for operation and management of electric grid, in order to improve the PQ norms. Today wind-generating system is connected into the power system to meet the consumer's demand. The addition of wind power into the electric grid affects the power quality. Due to the increased awareness of PQ particularly in highly sensitive industry like continuous process industry, complex machine part producing industry and security related industry where standardization and evaluation of performance is an important aspect. International standards are developed by the working groups of Technical Committee-88 of the International Electro Technical Commission (IEC); IEC 61400-21 describes the procedure of determining the PQ characteristics of wind turbine [31]. There is a need to address the PQ disturbances by the researchers due to interconnection of renewable energy sources connected to the electric grid.

A smart grid is a grid that is capable of delivering electricity from suppliers to consumers via a two-way digital technology, effectively controlling the consumers' energy consumption, reducing the cost of generation and transmission of this energy and hence increasing the system performance, efficiency and reliability. Moreover, it is expected that smart grid should be characterized by self-healing actions and improved PQ. Even though these concepts seem very attractive, there are still many reliability issues facing which put them in the research stages. The self-healing function is being confronted to automation and security concerns. On the PQ side, research is mostly focusing on smart meters to detect, localize and assess different types of distortion while the development of advanced power quality mitigation technologies helps suppressing these power distortions. Other issues such as renewable energy integration with the electric grid, forecast based production, unit dispatching, and energy storage systems still need to be investigated [32]. High PQ level represents one of the main objectives towards smart grid as exemplified. The currently used PQ indices that are a measure of the PQ level are defined under the umbrella of the Fourier foundation that produces unrealistic results in case of non-stationary PQ disturbances. In order to accurately measure those indices, Wavelet Packet Transform (WPT) used in [28] to reformulate the recommended PQ indices. In [28], authors gave some glance to PQ level of smart grid.

Hence, research in the field of PQ events analysis can be utilized in future because the use of renewable energy source and distributed generation in the future will increase. It can also play a vital role in smart grid as exemplified (i.e. self-healing function require in smart grid). Therefore, the area of PQ attracts many more researchers because it is of futuristic use in the power system.

3. Signal processing tools in PQ

PQ disturbances and their feature extraction rely on the fact that each disturbance has some feature values which distinguish it with other disturbances. So, the basic task involved in PQ is to devise those feature extraction techniques from a given disturbance and then, classify the PQ disturbances accordingly.

3.1. Fourier transform based methods

The power system often takes a rough estimate of the non-periodic and time-varying variations. Also for explicit information such as evaluating duration and localization of disturbance propagation, there is a demand for both time and frequency analysis methods. Short-Time Fourier Transform (STFT) have been used for applying stationary and periodic signals in frequency domains. STFT has also been applied to non-stationary signals but operated in fixed window size to focus a certain period of time, which can trace the magnitude variations to some extent. Non-stationary signals are difficult to analyze with STFT [24,33,34]. In [35], authors have been used the STFT and other techniques to extract the spectral information from the signal. In [36], authors have been used FT and WT for characterizing the events. Large number of features has been used which increases the computational burden in [36,35]. In [37], Tarasiuk investigated the hybrid potential of wavelet-Fourier algorithm for harmonics analysis of signal. Hybrid method enables jointly harmonics and transients analysis. Many frequency estimation techniques and spectral estimation of interharmonics have been proposed in [38,39] respectively. In [24], authors discussed the analysis of voltage disturbance recordings in the time–frequency domain and in the time-scale domain. It was experimentally proved the WT is better than STFT in [24].

3.2. Wavelet transform based methods

Wavelet Transform (WT) is having advantage over FT such as most interesting advantage between these two kinds of transforms is that individual wavelet functions are localized in space and many others are listed in [33]. WT has been extensively used by the researchers for characterization and classification of PQ events as discussed later on. WT has also been used in noisy environment [40]. In [36], authors investigated the potential of both FT and WT for characterizing the PQ events. In [41], authors investigated the performance of WT to detect and analyze voltage sag and transient by using a recursive algorithm. In [42], authors suggested the WT for detection of voltage sag only. WT is increasingly being used to overcome the above difficulties. The advantage of using WT is that it does not need to assume the stationarity or periodicity of signals. It detects signal change across the time-plane and simultaneously breaks the signal across the frequency-plane [43]. The breaking is made across the multiple frequency bands, instead of a discrete number of frequency components as in FT [44].

In [45], WT has been utilized to produce representative feature vectors for each disturbance. The approach is based on inductive learning by using decision trees. In [46], a methodology presented for developing a wavelet network based digital signal processing architecture capable of classification of only transient signals. In [47], authors suggested a classification method using a rule-based method and a wavelet packet-based Hidden Markov Model (HMM) for without noise practical data. In [48,49], authors presented a two-dimensional (2-D) representation of power system waveforms for the automatic analysis and detection of transient events. PQ events even with slow waveform variations were possible to detect. In [50], researchers introduced a simulated voltage disturbance detection approach based on WT with decision making techniques. In [51], researchers suggested a model of synthetic PQ disturbance detection using Adaptive Wavelet Networks (AWNs). AWNs take large training time and increase the computation cost. Authors utilized the statistical properties of white noise to remove the noise from the PQ signal and further WT is used for the classification purpose in [52]. WT also used in [53] for online recognition of PQ events, and nearest neighbor rule introduced to reduce the order of complexity. In [54], researchers presented a wavelet-based voltage detection scheme. Researchers could also analyze the presented system on three-phase to prove the robustness. In [55], researchers used an inductive learning by using decision trees and WT utilized for feature extraction of simulated PQ data. System [55] is having high computational cost. In [56], compression algorithm based on WT and 2-dimensional representation compression algorithm has been discussed in [49].

Multiwavelet Transform (MWT) is a concept in the framework of WT. MWT having upper hand over WT as in [57]. In particular, whereas WT has an associated one scaling and wavelet function, MWT has two or more scaling and wavelet functions. In [58], authors developed a framework for the recognition of PQ disturbances using MWT and neural networks. The computation cost is quite higher than WT because it contains more than one wavelet and scaling function.

3.3. Miscellaneous techniques

The use of wavelets bestows time and frequency information about a signal to be obtained simultaneously, which is of special interest in the processing of PQ disturbances. Wavelets are used in PQ when it is not important to know the exact frequency of a disturbance in voltage or current waveforms, but the time information is important. Applying WT, high time resolution is provided for high frequency components and low time resolution is obtained for low frequency components of the signal. Hence, WT is more appropriate where there is no requirement of the exact frequency as in [59]. In recent past, many PQ event detection and classification algorithms are reported using unique feature extraction through WT. WT addresses the problem of resolution by introducing a dilation (or scale) parameter. ST is obtained by multiplying WT with a phase factor. It is a time–frequency spectral localization method, similar to STFT but with Gaussian window whose width scales inversely and height linearly with the frequency. In [60], authors suggested higher-order cumulants as the feature parameter, and quadratic classifiers as the classification method. This method is having large computation time. In [45], authors suggested a framework based on Walsh transform and Fast Fourier transform (FFT) as features and the dynamic time warping algorithm as classifier. Complexity of [45] is quite high. In [61], authors suggested the ST over WT for features with decision-tree classifier for synthetic PQ data. Covariance behavior of several features, determined from the voltage waveform within a time window for PQ event detection and classification, was analyzed in [62]. Computation cost of [62] because of several features is quite high. In [63], authors presented an approach for short duration disturbances in the power networks using a phase-corrected WT known as S-transform (ST) and an Extended Kalman Filter (EKF). In [64], researchers suggested ST features and a novel decision-making system for practical PQ data classification. Because of the binary classifier the system takes less time. In [65], authors presented the design and development of a rule based system for intelligent classification of PQ disturbances using the S-transform features. S-transformed Module Time–Frequency Matrix (MTFM) has been proved to be an effective analyzing method to extract short duration disturbance characteristics in [66]. In [67], PQ data reconstructed and then analyzed using a modified WT known as S-transform. Noisy PQ data have also been analyzed to prove the robustness. ST has also been extensively used for PQ events classification as in [68–70].

Apart from the above techniques, some other techniques have played a significant role in the concerned field. In [71], HT and Clarke Transform (CT) for FE and K-nearest Neighbor (k-NN) technique for classification have been used. Several other techniques such as Hilbert Transform (HT) [72], Time–Time Transform [73], HOS method [74,75], Hyperbolic S-transform [66], Kalman filtering [76–78], Multi-way Principal Component Analysis (MW-PCA) [79], Adaline method [80], EMDRA method [81], Kalman filtering [82,83], Hidden Markov Model [84], and Fractal-based method [85] have played significant role for PQ events classification in the past years.

4. Intelligent techniques

Intelligent techniques are required for the decision making and classification. So, it becomes quite necessary to discuss the state-of-the-art. Artificial intelligence (AI) is related to human thinking, decision making, problem solving, learning, perception and reasoning. AI consists of following tools such as fuzzy logic [86–88], adaptive fuzzy logic, artificial neural network, expert system and also intelligent technique like genetic algorithm (GA) [89,88].

4.1. Fuzzy logic based methods

In fuzzy system, the knowledge base constitutes a set of rules derived from the statistical knowledge pre-processing the time-series data. The knowledge base requires addition of new rules if necessary and a correct choice of membership function to analyze PQ events. Fuzzy classifiers have extensively been used because of fuzzy rule offers human-line reasoning capabilities, provide transparent interface mechanics, rapid computation due to intrinsic parallel processing nature, ability to deal with imprecise or imperfect information, improved knowledge representation and uncertainty reasoning. Author in [90] proposed a Decision Tree-Fuzzy (DT-F) rule base for PQ event classification. The classification rate of [90] reduced for PQ events corrupted by noise. DT-F rule base system faces the problem of redundancy and complexity. In [91], authors address two issues such as selection of discriminative features and classifies event classes with minimum error. Wavelet features of PQ events extracted using WT and fuzzy classifiers classify events. The recognition rate reduced drastically if the PQ signal corrupted with noise and real-time data did not utilize by the authors. Researchers [92] proposed algorithm utilized the digitized samples of the voltage signal at the location where the PQ standards were implemented. The voltage signal was modeled as a fuzzy linear parameter estimation problem, where the coefficients were assumed to be fuzzy having certain middle and spread. Authors considered that the voltage flicker contains only one voltage signal with a low frequency and low amplitude compared to the main power system voltage. These assumptions create problems for practical implementation. In [93], authors proposed ST with fuzzy logic-based pattern recognition system to classify the various disturbances generated due to PQ violations. The classification rate decreases with the increase in the noise. In [94], authors provided a wavelet-based extended fuzzy reasoning approach. Authors might also be including the noise PQ pattern to prove the robustness of the system. In [95], FT and WT analysis were utilized to obtain unique features with the fuzzy expert system for making a decision regarding the type of the disturbance on the basis of simulation study. In [96], researchers presented a fuzzy expert system based on features extracted from both Fourier Transform (FT) and WT for synthetic without noise PQ data classification. In [82], authors suggested an expert system that was able to classify different types of power system events to the underlying causes and offer useful information in terms of PQ. In [97], authors presented a fuzzy expert system based classification system. In [98], authors proposed the concept of WT for feature extraction (FE) of PQ events combined with NN and fuzzy logic incorporated as a powerful tool for detecting and classifying PQ events. Complexity of NN is directly related to training time and the problem of error divergence due to system faces the problem of gradual increase in the complexity. Fuzzy classifiers have some limitations such as highly abstract and heuristic need experts for rule discovery (data relationships), lack of self-organizing and self-tuning mechanisms of NN which necessitates exploring other intelligent techniques.

4.2. Neural network based methods

Neural networks represent the promising new generation of information processing system. They are good at tasks such as pattern matching and classification, function approximation, and optimization and data clustering. ANN based methodologies have been used for solving several complex and real world problems. NN based classification method have salient features as no need to know data relationships, self-learning capability, self-tuning capability and applicability to model various systems. These salient features attract the researcher to use NN. In [99], authors suggested ANN based synthetic PQ events recognition system. Exhaustive training phase is required in [99]. In [100], authors provided a hybrid methodology with WT and ANN for recognition of synthetic data through graphical user interface. In [101], authors investigated the comparison between logistic regression (LR) and ANN for recognition of practical noisy PQ events. In [102], authors suggested wavelet analysis combined with neural systems as a powerful tool for the analysis of synthetic non-stationary signal. Authors in [103] compared the performances of different classifier on feature set extracted by WT. In [104], authors suggested a method based on wavelet entropy and ANN for power system transients classification. Authors considered only single feature which may sapless the system. In [105], authors provided theoretical foundation for PQ events classification system which was based on WT, ANN, and the mathematical theory of evidence and practical implementation explained in [106]. In [107], authors presented a integrated approach for PQ data compression using Spline WT and RBF neural network. In [108], researchers proposed approach for the WT and self-organizing learning array (SOLAR) system for synthetic PQ data classification. In [109], researchers presented certain pertinent feature vectors which were extracted using WT and ST with ANN as classifier. In [110], authors presented a wavelet norm entropy-based effective feature extraction method and wavelet neural network method for PQ disturbance classification. The concept of modularity in NN is the subdivision of complex task to a set of simple sub-tasks through an intuitive way. These subtasks are accomplished by a number of specialized computational systems, and their solution of the overall task is achieved by combining the result of each modules. In [111], authors presented an S-transform based Modular Neural Network (MNN) classifier. Authors used less number of features to reduce the computation required; considered with noise and without noise PQ events to prove the robustness; but MNN required large number of epoch to train the network.

Support Vector Machine (SVM) is a powerful tool for solving pattern classification problems as in [112–114]. In SVM, the inputs are mapped into some higher dimensional space by means of a nonlinear feature mapping for solving the classification problem separated by only higher complex decision boundaries in the input space. Thus, the problem changes into linearly separable case at the feature space. Multiclass SVM classifiers are obtained by combining two classes SVM. Therefore, in order to classify test data, pair wise competition between all the machines is performed. Each winner competes against another winner until a single winner remains. This final winner determines the class of the test data. In [115], authors proved SVM has upper-hand over optimal time–frequency representation [116,117] and low complexity event classification method [118]. In [119], authors designed a weighted SVM and trained by 5-dimension feature space points for making decision regarding the simulated without noise disturbances. In [120], authors proposed a novel SVM classification system for without noise voltage disturbances. Because of large number of features the system [119,120] have high computational cost. In [121], authors presented an integrated model for recognizing PQ disturbances using a novel wavelet multiclass SVM. In [122], Janik and Lobos provided a comparative study between SVM and radial basis function (RBF) network for simulated without noise PQ events recognition. In [123], authors proposed SVM based modeled PQ events recognition system. The analysis includes the data with noise and without noise which is able to prove the robustness of system. In [124], authors proposed classification system based on the WT and SVM using only single feature vector at 8th decomposition level. The increased decomposition level causes to increase the computational cost and for better classification system selected feature vectors must be strong enough. In [123], authors suggested combination of WT and SVM for the classification of simulated events. Extracted features are quite large in number which is able to increase the computation complexity. Some other significant techniques have been reported such as [125,126].

PNN is basically a pattern classifier which relies on non-parametric regression models. It is implemented using the probabilistic model such as Bayesian classifier. A PNN is provided with enough training data and does not require a learning process. In modular neural network, each module is independent of other module and is domain specific, has a simpler architecture as compared to the system as a whole and responds to a certain subset of the overall task. In [127], a prototype wavelet integrated PNN classifier for recognizing PQ disturbances was suggested under various simulated transient events. Considering a large number of features may result in high memory and computational overhead. In [128], authors presented a framework based S-transform and PNN for classification synthetic PQ data. In [129], authors presented an

S-transform based PNN classification system. The learning speed of PNN classifier is very fast making, it is suitable for real-time operation such as fault diagnosis and signal classification problems. Limitation of NN such as unable to handle linguistic information, unable to manage imprecise or vague information, unable to resolve conflicts, unable to combine numeric data with linguistic or logical data, difficult to reach global minimum, require training time, and rely on trial-and-errors to determine hidden layers and nodes compel to think of other methods.

4.3. Neuro-fuzzy based methods

Neuro-fuzzy based methods have advantage such as handle any kind of information (numeric, linguistic, logical, etc.), manage imprecise, partial, vague or imperfect information, resolve conflicts by collaboration and aggregation, self-learning, self-organizing and self-tuning capabilities, no need of prior knowledge of relationships of data, mimic human decision making process, and fast computation using fuzzy number operations. These systems are rare in use in the PQ field. In [130], authors presented neural networks with the architecture of frequency sensitive competitive learning and learning vector quantization (FSCL-LVQ) for classification of PQ events. Researchers provided a neural-fuzzy technology-based classifier. The classifier adopted neural networks in the architecture of frequency sensitive competitive learning and Learning Vector Quantization (LVQ). This scheme required large time for training because training was in two phases. Authors suggested adaptive neuro-fuzzy intelligent tool for PQ analysis and diagnosis. Authors in [131] proposed an adaptive neuro-fuzzy technique to classify the normal and abnormal PQ conditions in three-phase induction motor and opened the door for full automation of whole process.

4.4. Genetic algorithm based methods

Genetic algorithm (GA) is a method for solving optimization problems that is based on natural selection, the process that drives biological evolution. GA repeatedly modifies a population of individual solution. GA is a search technique used in computing to find exact or approximate solutions to optimization and search problems. At each step, GA selects individual at random from the current population to be parent and use them to produce children for next generation. Over successive generation, the population evolves towards an optimal solution. In [132], authors presented an automatic classification of different simulated PQ disturbances using Wavelet Packet Transform (WPT) and fuzzy *k*-nearest neighbor (FkNN) based classifier. WPT features were given to the fuzzy *k*-NN for effective classification. The genetic algorithm based feature vector selection was done to ensure good classification accuracy by selecting 16 better features from all 96 features generated from the WPT coefficients. Number of features is quite high which increases the complexity. In [133], feature items selected from well-known tools such as spectral information, wavelet extrema across several decomposition levels, and local statistical variations of the waveform. To further avoid specificity of the feature for a given classifier, two classifiers (Bayes and SVM) were tested. As a result of these analysis, the more useful set among a wider set of GA selected features for each classifier obtained. In [26], hyperbolic S-transform used for feature extraction and automatic simulated pattern recognition carried out using GA based fuzzy C-means algorithm. In [134], Liao suggested WT with genetic *k*-means algorithm (GKA)-based RBF network classification system for noisy PQ events presented. Juang provided an evolutionary recurrent network which automated the design of recurrent neural/fuzzy networks using a hybrid of GA and PSO in [135]. Because of hybrid optimization and pre-processing technique, the system is having high complexity. In [136], authors suggested a framework having learning vector quantization and NN combined with GA for PQ disturbances. To speed up the classification process, GA operator has also been introduced by the authors.

5. Optimization techniques

Particle Swarm Optimization (PSO) is a population based stochastic search process modeled after the social behavior of a bird flock. It starts with an initial group consisting of particle in a multi-dimensional search space. It is evident that some of the particles have better position than other. The particle changes their position in this space until they encounter the stop-criteria of the algorithm. This criterion approaches an optimal state or ends the number of specific representations in the algorithm. In fact, each particle is aware of its best previous position and the best position among all particles. In [137], authors utilized adaptive-PSO to determine accurately the parameters of the membership functions for the inputs to the fuzzy\expert system, adaptive-PSO used to improve classification rate. Learning of fuzzy expert system is quite efficient for classification because of the use of adaptive-PSO. In [138], authors suggested a combination of FT and WT for feature extraction and fuzzy logic with PSO algorithm for classification of single and multiple synthetic PQ events. In [139], authors presented TTT for the feature extraction and Fuzzy C-mean (FCM) clustering with Hybrid Ant Colony Optimization (HACO) algorithm for classification. Fuzzy C-means clustering is a standard clustering algorithm that groups the data points in multi-dimensional space into specific number of clusters. A fuzzy C-means tree used for power signal clustering. In [97], authors suggested a hybrid PSO-fuzzy expert system for synthetic data and recognition rate reduced with the increase in the noisy PQ patterns.

6. Analysis

In literature, large number of reported articles has been used large number of feature sets. Feature set are the strength of any classification system. This leaves a question that how these features will perform when applied to events therefore, it is important to investigate the discriminative power of each PQ identification feature proposed in the literature before one may use it for the purpose. In view of this, a comprehensive analysis is desirable. However, results reported were quite encouraging on most occasions, which were obtained using only a selected number of events in experimental study. Table 1 summarizes some of the benchmark work in PQ analysis where RR shows the recognition rate.

The papers by Masoum et al. [141], Hooshmand et al. [138], Meher et al. [91] and Eristi et al. [124] used WT for feature extraction. WT has been proved an effective tool for detecting and classifying the PQ events. Paper [58] utilizes an enhanced resolving capability of multiwavelet to recognize power system disturbances. The papers by Behera et al. [97], Panigrahi et al. [68] and Uyar et al. [140] implemented S-transform because ST has an advantage in that it provides multiresolution analysis while retaining the absolute phase of each frequency. However, it is noted that most of PQ event identification methods have been tested on parametric generated events and only few on real-time events [142,143, 116]. Table 1 most of the researchers reported the results on synthetic data which are quite far from real PQ disturbances. The sudden changes (depending on the types of load connected, types faults occurred, or other operating condition) in power signal exist only in real or practical power signal. Therefore, more scope of work is there for real power signal analysis.

Table 1
Comprehensive analysis.

Ref.	FE	Classifier/optimization	Data used (synthetic/practical)	Noisy data have been considered or not?	RR
Behera et al. [97]	ST	Fuzzy expert/PSO	Synthetic	Yes	99.00
Biswal et al. [137]	ST	Fuzzy C-means/PSO	Synthetic	No	95.41
Hooshmand and Enshaee [138]	FT, WT	Fuzzy system/PSO	Synthetic	Yes	98.00
Meher and Pradhan [91]	WT	Fuzzy system	Synthetic	Yes	96.87
Kaewarsa et al. [58]	MWT	MWBNC	Synthetic	No	98.03
Uyar et al. [140]	ST	NN	Synthetic	Yes	99.56
Eristri and Demir [124]	WT	SVM	Practical	Yes	95.81
Xiao et al. [68]	ST	SVM	Synthetic	No	92.30
Samantaray [90]	ST	DT-F	Practical	Yes	97.56
Eristri and Demir [124]	WT	SVM	Synthetic	Yes	95.43
He et al. [104]	WT	NN	Synthetic	No	95.5
Hu et al. [119]	WT	SVM	Synthetic	No	98.5
Gargoom et al. [71]	HT, CT	k-NN	Synthetic	No	80.6
Zhu et al. [94]	WT	Fuzzy system	Practical	Yes	95.31
Masoum et al. [141]	WT	NN	Practical	Yes	98.81
Uyar et al. [110]	WT	NN	Synthetic	Yes	97.81
Reaz et al. [98]	WT	NN, fuzzy system	Practical	No	98.91
Abdel-Galil et al. [84]	FT, WT	HMM	Synthetic	No	95.71
Ferreira et al. [74]	HOS	NN	Synthetic	No	100
Shukla et al. [72]	HT	PNN	Synthetic	No	97.5
He and Starzyk [108]	WT	SOLAR	Synthetic	No	94.7
Giang [127]	WT	NN	Synthetic	No	90.43
Lee and Dash [128]	ST	NN	Synthetic	Yes	94.7
Mishra et al. [129]	ST	PNN	Synthetic	No	97.6
Huang et al. [130]	WT	FSCL-LVQ	Practical	No	93.76
Liao [134]	WT	RBF	Synthetic	Yes	96.6
Biswal et al. [139]	TTT	FCM-HACO	Synthetic	No	94.8

In [144], authors presented a method for real-time detection and classification of voltage events in power systems. The method presented WT and an extended Kalman filtering to the voltage waveform. The method proposed has been optimized to be implemented online and in real-time in a PXI system. In [145,146], authors presented the instrumentation for PQ assessment, called the estimator–analyzer of PQ. It was consistent with the general idea of waveform parameters measurement set out in IEC Standard 61000-4-7, although it utilizes the authors' original methods of measurement of PQ parameters. Slantlet and wavelet transform have implemented in [147] and [148] respectively with the field-programmable gate array hardware realization for electrical power system disturbance detection. In [143], authors discussed a real-time classification method of PQ disturbances. The proposed method addressed the selection of discriminative features for detection and classification of PQ disturbances. Using a Rule-based Decision Tree (RBDT), the different types of PQ disturbances classified. In [116,149], authors presented a real-time PQ events classification which was implemented on a digital signal processor and optimized according to the DSP architecture to meet the hard real-time constraints. Hardware implementation of the detection and classification of PQ events will also the scope of PQ field in minimum time so that mitigation action can also be taken.

7. Conclusions and future scope

This paper presents a comprehensive survey on the development in PQ analysis technology which is the major area of research in the field of power system. Researchers have attempted to characterize the different PQ events using different feature set. Accordingly, the large arsenal of literature is available in concerned field, the recent requirements of power and spurt in number of microelectronic components have increased the awareness of the clean power and fault identification. That is why majority of the reported works are dated only during the last decades. Since, the present thrust in PQ research is of real-time analysis, so not many researchers have given so much enhancement in real-time detection and mitigation. However, it is concluded that PQ analysis technology still has a way to grow, especially for real-time PQ events. Therefore, there is an urgent need to work on real-time PQ events and in developing new techniques for performing mitigation task. As it is evident from the analysis, development in PQ technology lacks a generalized approach to the problem that can handle all different events, i.e. single and multiple events.

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Fault Prediction Using Statistical and Machine Learning Methods for Improving Software Quality

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Abstract—An understanding of quality attributes is relevant for the software organization to deliver high software reliability. An empirical assessment of metrics to predict the quality attributes is essential in order to gain insight about the quality of software in the early phases of software development and to ensure corrective actions. In this paper, we predict a model to estimate fault proneness using Object Oriented CK metrics and QMOOD metrics. We apply one statistical method and six machine learning methods to predict the models. The proposed models are validated using dataset collected from Open Source software. The results are analyzed using Area Under the Curve (AUC) obtained from Receiver Operating Characteristics (ROC) analysis. The results show that the model predicted using the random forest and bagging methods outperformed all the other models. Hence, based on these results it is reasonable to claim that quality models have a significant relevance with Object Oriented metrics and that machine learning methods have a comparable performance with statistical methods

Keywords—Empirical Validation, Object Oriented, Receiver Operating Characteristics, Statistical Methods, Machine Learning, Fault Prediction

1. INTRODUCTION

Software reliability is a critical field in software engineering and an important facet of software quality. Every organization wants to assess the quality of the software product as early as possible so that poor software design leading to lower quality product can be detected and hence be improved or redesigned. This would lead to significant savings in the development costs, decrease the development time, and make the software more reliable. The quality of the software can be measured in terms of various attributes such as fault proneness, maintenance effort, testing effort, etc. In this study, we have used fault proneness as the quality predictor. Fault proneness is defined as the probability of fault detection in a class [1-4]. Due to high complexity and constraints involved in the software development process, it is difficult to develop and produce software without faults. High cost is involved in finding and correcting faults in software projects. Thus, we need to identify or locate the areas where more attention is needed in order to find as many faults as possible within a specified time and budget. To address this issue, we predict fault proneness model using statistical and machine learning methods in this paper. One of the approaches to identify faulty classes early in the development cycle is to predict models by using software metrics. In the realm of an object oriented environment, object oriented soft-

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ware metrics have become increasingly popular with researchers. There are various object-oriented metrics available in the literature [5-11] to predict software quality attributes.

Hence, the main contributions of this paper are: (1) To establish relationship between object oriented metrics and fault proneness. There are a number of object oriented metrics such as CK metrics [5], MOOD [7], QMOOD metrics [8], etc., but not all the metrics are good predictors of fault proneness. Thus, it is very important to understand the relationship of object oriented metrics and fault proneness. In other words, we must find out which of the metrics are significant in predicting the faulty classes. Then, these significant metrics can be combined into one set to build the multivariate prediction models for predicting fault proneness. Identified metrics will help software practitioners to focus on fault prone classes and ensure a higher quality software product with the available resources. Software researchers may use these metrics in further studies. (2) To analyze machine learning methods (method of programming computers to optimize performance criterion using example data or past experience). Nowadays, machine learning is widely used in various domains (i.e., retail companies, financial institutions, bioinformatics, etc.) There are various machine learning methods available. We have used six machine learning methods to predict the accuracy of the model predicted. These six machine learning methods have been widely used in literature and have shown good results [4, 12-14]. Amongst the various models predicted, we must determine one of the models to be the best model, which can be used by researchers in further studies to predict the faulty classes.

In order to achieve this aim we have used dataset collected from open source software, poi [15]. This software was developed using Java language and consists of 422 classes. The different dataset used by us will provide an important insight to researchers for identifying the relevance of metrics with a given type of dataset. Since it is Open Source software, the users have freedom to study and modify the source code (written in Java) without paying royalties to previous developers. We have used one statistical method (logistic regression) and six machine learning methods (random forest, adaboost, bagging, multilayer perceptron, support vector machine, and genetic programming).

We have analyzed the performance of the models by calculating area under the Receiver Operating Characteristic (ROC) curve [16]. ROC curve is used to obtain a balance between the number of classes predicted as being fault prone, and the number of classes predicted as not being fault prone.

The paper is organized as follows: Section 2 reviews the key points of available literature in the domain. Section 3 explains the independent and dependent variables used in our study. The description of the metrics is also provided. Section 4 discusses the research methodology and gives the details of the data used for analysis. It also explains the various methods used and the performance evaluation measures. Section 5 analyzes the univariate and the multivariate results. We have compared our results with the results of the previous results in this section. The model predicted is evaluated using the ROC curve in Section 6. Finally, the work is concluded in Section 7.

2. LITERATURE REVIEW

Significant work has been done in the field of fault detection. The complete survey of fault prediction studies till 2008 is provided in the paper by C. Catal [17]. Highlights of select papers have been discussed in this section, including papers published post 2008. There are various categories of methods to predict faulty classes such as machine learning methods, statistical methods, etc. We have observed that much of the previous work used traditional statistical methods [18, 20, 21, 16] to bring out the results, but very few studies have used machine learning methods. Recently, the trend is shifting from traditional statistical methods to modern machine learning methods. The most common statistical methods used are univariate and multivariate logistic regression. A few key points of the papers using statistical methods are discussed. The paper by N. Ohlsson et al.[18] has worked on improving the techniques used by Khosgoftaar [19] (i.e., Principal Component Analysis and Discriminant Analysis). This paper [18] has discussed some problems that were faced while using these methods and thus suggested remedies to those problems. Another approach to identify faulty classes early in the development cycle is to construct prediction models. The paper [20] has constructed a model to predict faulty classes using the metrics that can be collected during the design stage. This model has used only object oriented design metrics. Tang et al. [21] conducted an empirical study on three industrial real time systems and validated the CK [5] object oriented metric suite. They found that only WMC and RFC are strong predictors of faulty classes. They have also proposed a new set of metrics, which are useful indicators of object oriented fault prone classes. It has been seen that most of the empirical studies have ignored the confounding effect of class size while validating the metrics. Various studies [6, 11, 22] have shown that class size is associated with many contemporary object oriented metrics. Thus, it becomes important to revalidate contemporary object oriented metrics after controlling or taking into account the effect of class size [16]. The two papers by El. Emam et al. [16, 23] showed a strong size confounding effect and thus concluded that the metrics that were strongly associated with fault proneness before being controlled for size were not associated with fault proneness anymore after being controlled for size. Another empirical investigation [11] by M.Cartwright et al. conducted on a real time C++ system discussed the use of object oriented constructs such as inheritance and therefore polymorphism. M. Cartwright et al. [11] have found high defect densities in classes that participated in inheritance as compared to classes that did not. The probable reasons for this observation have been discussed in the paper. Briand et al. [1] have empirically investigated 49 metrics (28 coupling measures, 10 cohesion measures, and 11 inheritance measures) for predicting faulty classes. There were 8 systems being studied (consisting of 180 classes in all), each of which was a medium sized management information system. They used univariate and multivariate analysis to find the individual and the combined effect of object oriented metrics and fault proneness. They did not examine the LCOM metric and found that all the other metrics are strong predictors of fault proneness except for NOC. Another paper by Briand et al. [24] has also validated the same 49 metrics. The system used for this study was the multi-agent development system, which consists of three classes. They found NOC metric to be insignificant, while DIT was found to be significant in an inverse manner. WMC, RFC, and CBO were found to be strongly significant. Yu et al. [25] empirically tested 8 metrics in a case study in which the client side of a large network service management system was studied. The system is written in Java and consists of 123 classes. The validation was carried out using regression analysis and discriminant analysis. They found that all the metrics were significant predictors of fault proneness except DIT, which was found to be insignificant.

Recently, researchers have also started using some machine learning techniques to predict the model. Gyimothy et al. [12] calculated CK [5] metrics from an open source web and email suite called Mozilla. To validate the metrics, regression and machine learning methods (decision tree and artificial neural networks) were used. The results concluded NOC to be insignificant, whereas all the other metrics were found to be strongly significant. Zhou et al. [26] have used logistic regression and machine learning methods to show how object oriented metrics and fault proneness are related when fault severity is taken into account. The results were calculated using the CK metrics suite and were based on the public domain NASA dataset. WMC, CBO, and SLOC were found to be strong predictors across all severity levels. Prior to this study, no previous work had assessed severity of faults. The paper by S. Kanmani et al. [13] has introduced two neural network based prediction models. The results were compared with two statistical methods and it was concluded that neural networks performed better as compared to statistical methods. Fenton et al. [27] introduced the use of bayesian belief networks (BBN) for the prediction of faulty classes. G.J. Pai et al. [2] also built a bayesian belief network (BN) and showed that the results gave comparable performance with the existing techniques. I. Gondra [14] has performed a comparison between the artificial neural network (ANN) and the support vector machine (SVM) by applying them to the problem of classifying classes as faulty or non-faulty. Another goal of this paper was to use the sensitivity analysis to select the metrics that are more likely to indicate the errors. After the work of Zhou et al. [26], the severity of faults was taken into account by Shatnawi et al. [28] and Singh et al. [4]. Shatnawi et al. used the subset of CK [5] and Lorenz & Kidd [9] metrics to validate the results. The data was collected from three releases of the Eclipse project. They concluded that the accuracy of prediction decreases from release to release and some alternative methods are needed to get more accurate prediction. The metrics, which were found to be very good predictors across all versions and across all severity levels, were WMC, RFC, and CBO. Singh et al. [4] used the public domain NASA dataset to determine the effect of metrics on fault proneness at different severity levels of faults. Machine learning methods (decision tree and artificial neural network networks) and statistical method (logistic regression) were used. The predicted model showed lower accuracy at a high severity level as compared to medium and low severities. It was also observed that performance of machine learning methods was better than statistical methods. Amongst all the CK metrics used CBO, WMC, RFC, and SLOC showed the best results across all the severity levels of faults. Malhotra et al. [29] have used LR and 7 machine learning techniques (i.e., artificial neural networks, random forest, bagging, boosting techniques [AB, LB], naive bayes, and kstar) to validate the metrics. The predicted model using LB technique showed the best result and the model predicted using LR showed low accuracy.

From the survey we have conducted, the following observations were made:

- We observed that among the number of metrics available in literature, the CK metric suite is most widely used. It has been seen that most of the studies have also defined their own metric suite and they have used them for carrying out the analysis.
- Among the various categories of methods available to predict the most accurate model such as machine learning methods, statistical methods, etc. the trend is shifting from the traditional statistical methods to the machine learning methods. It has been observed that machine learning is widely used in new bodies of research to predict fault prone classes. Results of various studies also show that better results are obtained with machine learning as compared to statistical methods.

- Papers have used different types of datasets, which are mostly public datasets, commercial datasets, open source, or students/university datasets. We have observed that the public datasets, which have been mostly used in the studies, are from the PROMISE and NASA repositories.

3. DEPENDENT AND INDEPENDENT VARIABLES

In this section, we present the independent and dependent variables used in this study along with a summary of the metrics studied in this paper.

In this paper, we have used object-oriented metrics as independent variables. A summary of the metrics used in this paper is given in Table 1. The dependent variable is fault proneness. Fault proneness is defined as the probability of fault detection in a class [1, 2, 3, 4]. We have

Table 1. Metrics Studied

S.No.	Metric	Definition
1.	WMC - Weighted methods per class	The WMC metric is the sum of the complexities of all methods in a class. Complexity can be measured in terms of cyclomatic complexity, or we can arbitrarily assign a complexity value of 1 to each method. The Ckjm program assigns a complexity value of 1 to each method. Therefore, the value of the WMC is equal to the number of methods in the class.
2.	DIT - Depth of Inheritance Tree	The Depth of Inheritance Tree (DIT) metric for each class is the maximum number of steps from the class node to the root of the tree. In Java, where all the classes inherit the object, the minimum value of the DIT is 1.
3.	NOC - Number of Children	A class' Number of Children (NOC) metric measures the number of immediate descendants of the class.
4.	CBO - Coupling Between Object classes	The CBO for a class represents the number of classes to which it is coupled and vice versa. This coupling can occur through method calls, field accesses, inheritance, arguments, return types, and exceptions.
5.	RFC - Response for a Class	The value of RFC is the sum of the number of methods called within the class' method bodies and the number of the class' methods.
6.	LCOM - Lack of Cohesion in Methods	LCOM measures the dissimilarity of methods in a class by looking at the instance variables used by the methods in that class.
7.	Ca - Afferent couplings (not a C&K metric)	A class' afferent couplings are the number of other classes that use a specific class.
8.	Ce - Efferent couplings (not a C&K metric)	A class' efferent couplings are the number of other classes that are used by the specific class.
9.	NPM - Number of Public Methods (not a C&K metric; CIS: Class Interface Size in the QMOOD metric suite)	The NPM metric counts all the methods in a class that are declared as being public.
10.	LCOM3 -Lack of cohesion in methods Henderson-Sellers version	LCOM3 varies between 0 and 2. m - number of procedures (methods) in class a - number of variables (attributes in class μ(A) - number of methods that access a variable (attribute) $\mathrm{LCOM3} = \frac{\left(\frac{1}{a}\sum_{j=1}^{a}\mu(A_j)\right) - m}{1 - m}$ The constructors and static initializations are taken into account as separate methods.

Table 1. Metrics Studied

S.No.	Metric	Definition
11.	LOC - Lines of Code (not a C&K metric)	The lines of code is calculated as the sum of the number of fields, the number of methods, and the number of instructions in a given class.
12.	DAM: Data Access Metric (QMOOD metric suite)	This metric is the ratio of the number of private (protected) attributes to the total number of attributes declared in the class. A high value is desired for DAM. (Range 0 to 1)
13.	MOA: Measure of Aggregation (QMOOD metric suite)	The count of the number of data declarations (class fields) whose types are user defined classes.
14.	MFA: Measure of Functional Abstraction (QMOOD metric suite)	This metric is the ratio of the number of methods inherited by a class to the total number of methods accessible by member methods of the class. The constructors and the java.lang.Object (as parent) are ignored. (Range 0 to 1)
15.	CAM: Cohesion Among Methods of Class (QMOOD metric suite)	The metric is computed using the summation of the number of different types of method parameters in every method divided by a multiplication of a number of different method parameter types in whole class and the number of methods. A metric value close to 1.0 is preferred. (Range 0 to 1).
16.	IC: Inheritance Coupling (quality oriented extension for the C&K metric suite)	This metric provides the number of parent classes to which a given class is coupled. A class is coupled to its parent class if one of the following conditions is satisfied: • One of its inherited methods uses a variable (or data member) that is defined in a new/redefined method. • One of its inherited methods calls a method that is defined in the parent class. • One of its inherited methods is called by a method that is defined in the parent class and uses a parameter that is defined in that method.
17.	CBM: Coupling Between Methods (quality oriented extension for the C&K metric suite)	The metric measures the total number of new/redefined methods to which all the inherited methods are coupled.
18.	AMC: Average Method Complexity (quality oriented extension to C&K metric suite)	This metric measures the average method size for each class. The size of a method is equal to the number of Java binary codes in the method.
19.	CC - McCabe's Cyclomatic Complexity	It is equal to the number of different paths in a method (function) plus one. The cyclomatic complexity is defined as: CC = E - N + P where: E - the number of edges of the graph N - the number of nodes of the graph P - the number of connected components

used logistic regression and machine learning methods, which are based on predicting probabilities [1-4]

The program Ckjm calculates six object oriented metrics specified by Chidamber and Kemerer by processing the bytecode of compiled Java files. It also calculates a few of the other metrics. Ckjm follows the UNIX tradition of doing one thing well. [30]

4. RESEARCH METHODOLOGY

In this section we present the descriptive statistics for all the metrics that we have considered. We have also explained the methodology used (i.e., one statistical method and six machine learning methods). The performance evaluation measures are also presented.

4.1 Empirical Data Collection

This study makes use of an Open Source dataset "Apache POI" [15]. Apache POI is a pure Java library for manipulating Microsoft documents. It is used to create and maintain Java API for manipulating file formats based upon the office open XML standards (OOXML) and Microsoft OLE2 compound document format (OLE2). In short, we can read and write MS Excel files using Java. In addition, we can also read and write MS word and MS PowerPoint files using Java. The important use of the Apache POI is for text extraction applications such as web spiders, index builders, and content management systems. This system consists of 422 classes. Out of 422 classes, there are 281 faulty classes containing 500 numbers of faults. It can be seen from Fig. 1 that 71.53% of classes contain 1 fault, 15.3 % of classes contain 2 faults and so on. As shown in the pie chart, the majority of classes consist of 1 fault. Table 2 summarizes the distribution of faults and faulty classes in the dataset.

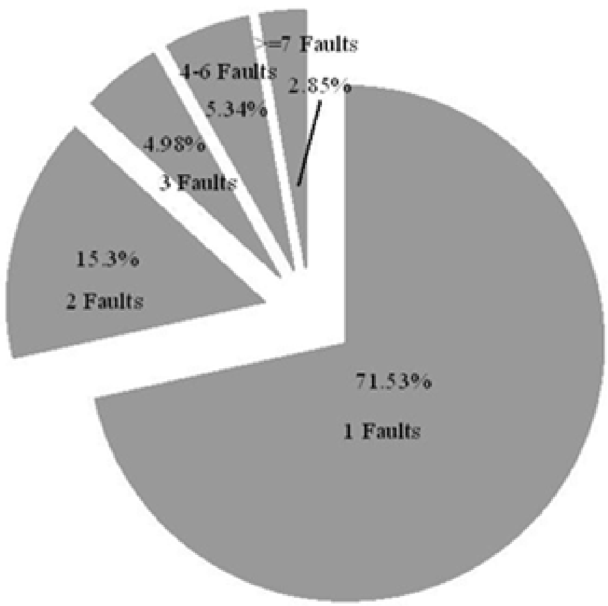

Fig. 1. Distribution of Faults

Table 2. Data Description

No. of faulty classes	281
% of faulty classes	63.57
No. of faults	500
Language used	Java

4.2 Descriptive Statistics

Table 3 shows the “mean," “median," “min," “max," “std dev," “25% quartile," “50% quartile,” and “75% quartile” of all the independent variables used in our study. We can make the following observations from Table 3.

Table 3. Descriptive Statistics

Metric	Mean	Std. Error of Mean	Median	Std. Deviation	Minimum	Maximum	Percentiles		
							25	50	75
WMC	13.501	0.698	10	14.677	0	134	5	10	16
DIT	1.869	0.040	2	0.850	1	6	1	2	2
NOC	0.738	0.331	0	6.963	0	134	0	0	0
CBO	10.120	0.932	6	19.585	0	214	4.75	6	9
RFC	30.351	1.763	21	37.067	0	390	13	21	36.25
LCOM	100.464	21.017	22	441.849	0	7059	1	22	53.25
CA	5.233	0.838	2	17.620	0	212	1	2	4
CE	5.224	0.431	4	9.059	0	133	2	4	6
NPM	11.600	0.606	9	12.747	0	101	4	9	14
LCOM3	0.999	0.025	0.85	0.534	0	2	0.749	0.85	1.129
LOC	292.595	30.046	124.5	631.675	0	9886	59.75	124.5	321.25
DAM	0.459	0.019	0.5	0.404	0	1	0	0.5	0.889
MOA	0.814	0.121	0	2.551	0	34	0	0	1
MFA	0.358	0.015	0.361	0.318	0	1	0	0.361	0.572
CAM	0.376	0.010	0.311	0.208	0	1	0.253	0.311	0.467
IC	0.577	0.026	1	0.555	0	3	0	1	1
CBM	1.952	0.116	1	2.439	0	20	0	1	4
AMC	19.362	1.880	12.192	39.516	0	616.375	6.375	12.192	20.544
MAX_CC	3.704	0.367	2	7.713	0	126	1	2	3
AVG_CC	1.188	0.052	0.976	1.090	0	17.125	0.814	0.975	1.289

The size of a class measured in terms of lines of source code ranges from 0 to 9886. We can observe that the NOC metric values are 0 in 75% of the classes. Also, the DIT metric values are low, the biggest DIT metric value is 6, and 75% of the classes have 2 levels of inheritance at most. This shows that inheritance is not used much in the system. Similar results were also observed by other authors [1, 11].There is a high cohesion observed in the system. The cohesion metrics (i.e., LCOM and LCOM3) have high values. The value of LCOM metric ranges from 0 to 7,059 and the LCOM3 metric ranges from 0 to 2 (which is the maximum LCOM3 value).

4.3 Methods Used

In this study, we have used one statistical model and six machine learning models to predict a fault proneness model.

4.3.1 The statistical model

Logistic regression is the commonly used statistical modelling method. Logistic regression is used to predict the dependent variable from a set of independent variables (a detailed description is given by [3, 31, 32]). It is used when the outcome variable is binary or dichotomous. We have used both univariate and multivariate regression. Univariate logistic regression finds the relationship between the dependent variable and each independent variable. It finds whether there is any significant association between them. Multivariate logistic regression is done to construct a prediction model for the fault proneness of classes. It analyzes which metrics are useful when they are used in combination. Logistic regression results in a subset of metrics that have significant parameters. To find the optimal set of independent variables (metrics), there are two stepwise selection methods, which are forward selection and backward elimination [32]. Forward selection examines the variables that are selected one at a time for entry at each step. The backward elimination method includes all the independent variables in the model and the variables are deleted one at a time from the model until the stopping criteria is fulfilled. We have used the forward stepwise selection method.

The general multivariate logistic regression formula is as follows [3]:

$$\text{Prob}\ (X_1, X_2, \ldots, X_n) = \frac{e^{g(x)}}{1+e^{g(x)}}$$

where $g(x) = B_0 + B_1 * X_1 + B_2 * X_2 + \ldots + B_n * X_n$
'prob' is the probability of a class being faulty
X_i, $(1 \leq i \leq n)$ are independent variables

The following statistics are reported for each metric from the above formula:

1. Odds Ratio: The odds ratio is calculated using Bi's. The formula for the odds ratio is R= exp (Bi). This is calculated for each independent variable. The odds ratio is the probability of the event divided by the probability of a non-event. The event in our study is the probability of having a fault and the non- event is the probability of not having a fault [4].
2. Maximum Likelihood Estimation (MLE) and coefficients (Bi's): MLE is the likelihood function that measures the probability of observing a set of dependent variables [4]. MLE finds the coefficient in such a way that the log of the likelihood function is as large as possible. The more the value of the coefficient the more the impact of the independent variables on predicted fault proneness is.

4.3.2 Machine Learning Models

Besides the statistical approach, we have used six machine learning methods. All the methods can be used to predict fault proneness by using just one metric or by using a combination of metrics together for prediction [12]. We have used machine learning techniques to predict the accuracy of the models when a combination of metrics is used. Not much of the work in the area of fault prediction is done using machine learning techniques. There are various machine learning techniques available. From amongst all of the methods, artificial neural networks (ANN) [33] and decision trees (DT) [34] have been widely used in literature [12, 13, 14, 4].The use of decision trees in predicting fault proneness has been proposed in Porter & Selly [35]. The paper [14] has used ANN to predict the value of a continuous measure of fault proneness. For performing the classification of classes as fault prone and non-fault prone, the paper [14] has used a support vector machine (SVM). The application of SVMs to the fault proneness prediction problem has been explained by Xing et al. [36]. The paper [29] has used ANN, random forest, bagging, boosting, and some more machine learning techniques in order to predict the faulty classes.

There are various variants of boosting algorithms available, but the authors have used two variants (i.e., AB [37] and LB [38]), which have been designed for classification purposes. In literature, boosting algorithms were not evaluated, but this paper [29] shows that the boosting technique LB gave the best results in terms of AUC. Thus, the authors concluded that boosting techniques may be effective in predicting faulty classes.

To predict the fault proneness of classes, we have used the following machine learning methods, and these machine learning algorithms are available in the WEKA open source tool [39]:

a. *Random Forest:* A random forest is made up of a number of decision trees. Each decision tree is made from a randomly selected subset of the training dataset using replacement. For building a decision tree, a random subset of available variables is used. This helps us to choose how best to partition the dataset at each node. The final result/outcome is chosen by the majority. Each decision tree in the random forest gives out its own vote for the result and the majority wins. In building a random forest, we can mention the number of decision trees we want in the forest. Each decision tree is built to its maximum size. There are various advantages of a random forest. Very little pre-processing of data is required. Also, we do not need to do any variable selection before starting to build the model. A random forest itself takes the most useful variables [40].
b. *Adaboost*: Adaboost is short for adaptive boosting. It is a machine learning algorithm that can be used along with many other learning algorithms. This leads to an improvement in efficiency and performance. Adaboost is adaptive as it adapts to the error rates of the individual weak hypothesis. Also, adaboost is a boosting algorithm as it can efficiently convert a weak learning algorithm into a strong learning algorithm. Adaboost calls a given weak algorithm repeatedly in a series of rounds. The important concept for an adaboost algorithm is to maintain a distribution of weights over the training set. Initially all the weights are equal but on each round the weights of incorrect classified examples are increased so that a weak learner is forced to focus on the hard examples in the training set. This is how a weak learning algorithm is changed to a strong learning algorithm. Adaboost is less susceptible to an over fitting problem than most learning algorithms [40].
c. *Bagging*: Bagging, which is also known as bootstrap aggregating, is a technique that repeatedly samples (with replacement) from a data set according to a uniform probability distribution [41]. Each bootstrap sample has the same size as the original data. Because the sampling is done with replacement, some instances may appear several times in the same training set, while others may be omitted from the training set. On average, a bootstrap sample D_i contains approximately 63% of the original training data because each sample has a probability $1- (1- 1/N)^N$ of being selected in each D_i. If N is sufficiently large, this probability converges to $1-1/e = 0.632$. After training the k classifiers, a test instance is assigned to the class that receives the highest number of votes [42].
d. *Multilayer Perceptron*: Multilayer Perceptron (MLP) is an example of an artificial neural network. It is used for solving different problems, example pattern recognition, interpolation, etc. It is an advancement to the perceptron neural network model. With one or two hidden layers, they can solve almost any problem. They are feedforward neural networks trained with the back propagation algorithm. Error back-propagation learning consists of two passes: a forward pass and a backward pass. In the forward pass, an input is presented to the neural network, and its effect is propagated through the network layer by layer. Dur-

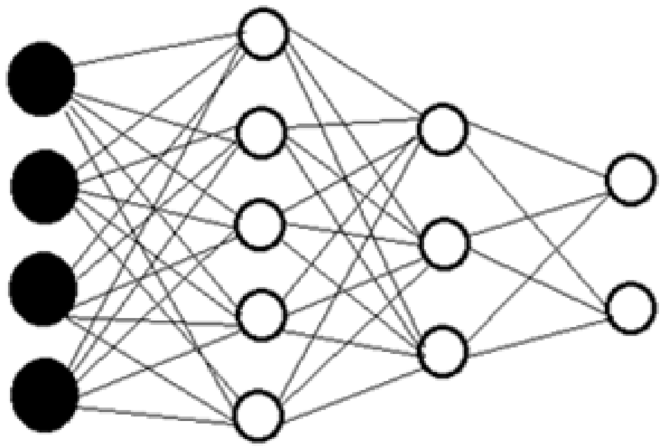

Fig. 2. Multilayer Perceptron

ing the forward pass the weights of the network are all fixed. During the backward pass the weights are all updated and adjusted according to the error computed. An error is composed from the difference between the desired response and the system output. This error information is fed back to the system and adjusts the system parameters in a systematic fashion (the learning rule). The process is repeated until the performance is acceptable [42].

e. *Support Vector Machine*: A Support Vector Machine (SVM) is a learning technique that is used for classifying unseen data correctly. For doing this, SVM builds a hyperplane, which separates the data into different categories. The dataset may or may not be linearly separable. By "linearly separable" we mean that the cases can be completely separated (i.e., the cases with one category are on the one side of the hyperplane and the cases with the other category are on the other side). For example, Fig. 3 shows the dataset where examples belong to two different categories - triangles and squares. Since these points are represented on a 2-dimensional plane, a 1-dimensional line can separate them. To separate these points into 2 different categories, there are an infinite number of lines possible. Two possible candidate lines are shown in Fig. 3. However, only one of the lines gives a maximum separation/margin and that line is selected. "Margin" is defined as the distance between the dashed lines (as shown in Fig. 3), which is drawn parallel to the separating lines. These dashed lines give the distance between the separating line and closest vectors to the line. These vectors are called support vectors. SVM can also be extended to the non-linear

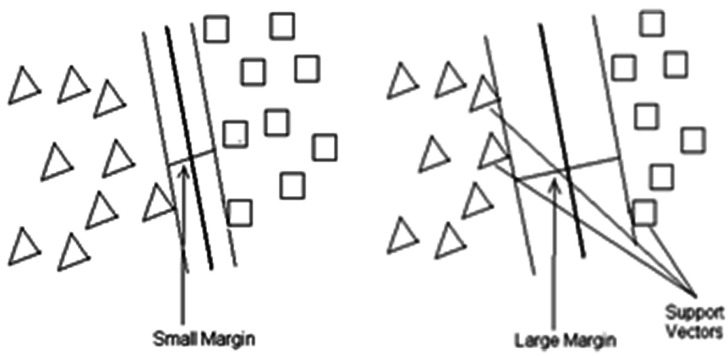

Fig. 3. Support Vector Machine

boundaries by using the kernel trick. The kernel function transforms the data into a higher dimensional space to make the separation easy. [16]

f. *Genetic Programming*: Genetic Programming is a branch of genetic algorithms. It is inspired by biological evolution. Genetic Programming creates computer programs that can perform a user defined task. For doing this, the following 4 steps are used:

i. First, all the computer programs are made.
ii. Then, each program is executed and assigned a fitness value according to how well it solves the problem.
iii. Then, a new population of computer programs is created:
   • From among all the programs the best existing programs are copied.
   • Mutation is carried out to create new programs.
   • Crossover is also carried out to create new programs.
iv. Finally, the best computer program created so far in any generation is the result of Genetic Programming.

4.4 Performance Evaluation Measures

To measure the performance of the predicted model, we have used the following performance evaluation measures:

Sensitivity: It measures the correctness of the predicted model. It is defined as the percentage of classes correctly predicted to be fault prone. Mathematically,
Sensitivity = ((Number of modules correctly predicted as fault prone) / (total number of actual faulty modules)) * 100

Specificity: It also measures the correctness of the predicted model. It is defined as the percentage of classes predicted that will not be fault prone. Mathematically,
Specificity = ((Number of modules correctly predicted as non- fault prone) / (total number of actual non faulty modules)) * 100

Precision or Accuracy: It is defined as the ratio of number of classes (including faulty and non- faulty) that are predicted correctly to the total number of classes.

Receiver Operating Characteristic (ROC) analysis: The performance of the outputs of the predicted models was evaluated using ROC analysis. It is an effective method of evaluating the performance of the model predicted. The ROC curve is defined as a plot of sensitivity on the y-coordinate versus its 1-specificity on the x-coordinate [16]. While constructing ROC curves, we selected many cutoff points between 0 and 1, and calculated sensitivity and specificity at each cutoff point. The ROC curve is used to obtain the required optimal cutoff point that maximizes both sensitivity and specificity [16, 4].

The *validation method* used in our study is k-cross validation (the value of k is taken as 10) in which the dataset is divided into approximately equal k partitions [43]. One partition at a time is used for testing the model and the remaining k-1 partitions are used for training the model. This is repeated for all the k partitions.

5. Result Analysis

In this section, we have analyzed the results of our study. In this study, we have validated the CK metric suite. To begin with the data analysis, the first step is to identify the subset of the object oriented metrics that are related to fault proneness and that are orthogonal to each other. The statistical modeling technique used for this purpose is univariate logistic regression. After identifying a subset of metrics, we have used the multivariate logistic regression technique to construct a multivariate model that can be used to predict the overall fault in the system. To predict the best model that gives the highest accuracy we have used various machine learning techniques. We performed the analysis of an Open Source software, poi [15], which consisted of 422 classes (see Section 4.1). The performance of each of the predicted models was determined using several performance measures (i.e., sensitivity, specificity, precision, and the ROC analysis).

5.1 Univariate LR Analysis Results

We conducted univariate analysis to find whether each of the metrics (independent variables) is significantly associated with fault proneness (dependent variable). Table 4 represents the results of univariate analysis. It provides the coefficient (B), standard error (SE), statistical significance (sig.), and odds ratio (exp (B)) for each metric [4]. The parameter "sig" tells whether each of the metric is a significant predictor of fault proneness. If the "sig" value of a metric is below or at the significance threshold of 0.01, then the metric is said to be significant in predicting the

Table 4. Univariate Analysis

S.no	Metric	B	SE	Sig.	Exp(B)
1	WMC	0.123	0.018	**0.000**	1.131
2	DIT	-0.188	0.115	0.102	0.828
3	NOC	0.003	0.015	0.835	1.003
4	CBO	0.056	0.020	**0.004**	1.057
5	RFC	0.055	0.008	**0.000**	1.056
6	LCOM	0.012	0.003	**0.000**	1.012
7	CA	0.007	0.007	0.354	1.007
8	CE	0.251	0.043	**0.000**	1.285
9	NPM	0.109	0.018	**0.000**	1.115
10	LCOM3	-0.943	0.192	**0.000**	0.389
11	LOC	0.004	0.001	**0.000**	1.004
12	DAM	1.477	0.264	**0.000**	4.381
13	MOA	0.495	0.128	**0.000**	1.641
14	MFA	-0.004	0.311	0.991	0.996
15	CAM	-3.844	0.568	**0.000**	0.021
16	IC	1.460	0.206	**0.000**	4.307
17	CBM	0.511	0.065	**0.000**	1.668
18	AMC	0.013	0.006	**0.036**	1.013
19	MAX_CC	0.187	0.045	**0.000**	1.206
20	AVG_CC	0.828	0.192	**0.000**	2.289

faulty classes [4]. Table 4 shows the significant values in bold. The coefficient "(B)" shows the strength of the independent variable. The higher the value, the higher the impact of the independent variable is. The sign of the coefficient tells whether the impact is positive or negative. We can see that DIT, NOC, Ca, and MFA metrics are not significant and are therefore not taken for any further analysis. Thus, in this way we can reduce the number of independent variables and select only the best fault predictors. The following notations used in tables 5-9 shows the degree of the significance:

++ shows the significance of the metric at 0.01, + shows the significance of the metric at 0.05, -- shows the significance of the metric at 0.01 but in an inverse manner, − shows the significance of the metric at 0.05 but in an inverse manner, and 0 shows that the metric is insignificant.

Table 5. Univariate Results of Size Metrics

Metric	Notation
WMC	++
NPM	++
LOC	++
DAM	++
MOA	++
AMC	+

Table 6. Univariate Results of Coupling Metrics

Metric	Notation
RFC	++
CBO	+
CA	0
CE	++
IC	++
CBM	++

Table 7. Univariate Results of Cohesion Metrics

Metric	Notation
LCOM	++
LCOM3	--
CAM	--

Table 8. Univariate Results of Inheritance Metrics

Metric	Notation
DIT	0
NOC	0
MFA	0

Table 9. Univariate Results of the Complexity Metric

Metric	Notation
CC	++

5.2 Multivariate LR Analysis Results

Multivariate analysis is done to find the combined effect of all of the metrics together on fault proneness. For doing multivariate analysis, we have used forward stepwise selection to determine which variables should be included in the multivariate model. Out of all the variables, one variable in turn is selected as the dependent variable and the remaining others are used as independent variables [44]. In univariate analysis 16 metrics were found to be significant. Table 10 shows the results of the multivariate model. The coeff (B), statistical significance (Sig.), standard error (SE), and odds ratio (Exp (B)) are also shown in the table for all the metrics included in the model. We can see that only 3 metrics (i.e., DIT, RFC, and CBM) are included in the model.

Table 10. Multivariate Model Statistics

Metric	B	SE	Sig.	Exp(B)
DIT	-0.522	0.165	0.002	0.594
RFC	0.031	0.007	0.000	1.032
CBM	0.531	0.078	0.000	1.701
CONSTANT	-0.089	0.328	0.785	0.914

5.3 Obtaining a Relationship Between Object Oriented Metrics and Fault Proneness

In this section, we have discussed our results and also we have compared our results with the results of previous studies shown in Table 11.

Table 11. Results of Different Validation

Metric	Our results	Basili et al. (1996)	Tang et al. (1999)	Briand et al. (2000)	Briand et al. (2001)	El Emam et al. (2001)		Yu et al. (2002)	Gyimothy et al. (2005)	Zhou et al. (2006)		Olague et al. (2007)		
Lang. used	Java	C++	C++	C++	C++	C++		Java	C++	C++		Java		
Method used	LR,ML (RF,Ab,MLP, Bagging, SVM,GP)	LR	LR	LR	LR	LR		OLS	LR,ML (DT,ANN)	LR,ML (NNage, RF,NB)		LR		
Type of data		Univ.	Comm.	Univ.	Comm.	Comm.		Comm.	Open source	NASA dataset		Open source		
Fault severity taken	No	No	No	No	No	No		No	No	Yes		No		
						#1	#2			LSF/USF	HSF	R3	R4	R5
WMC	++	+	+	+	++	+	0	++	++	++	++	++	++	++
DIT	0	++	0	++	--	0	0	0	+	0	0	0	--	0
RFC	++	++	+	++	++	++	0	+	++	++	++	++	++	++
NOC	0	--	0	-	0			++	0	--		0	0	0
CBO	++	+	0	++	++	+	0	+	++	++	++	++	++	0
LCOM	++	0							+	+	++	++	++	++
SLOC	++			++		++	++		++	++	++			

Table 11. Results of Different Validation (cont'd…)

Metric	Shatnawi et al. (2008)												Aggarwal et al. (2008)	English et al. (2009)	Singh et al. (2009)				Zhou et al. (2010)			Burrows et al. (2010)		
Lang. used	java												Java	Java	C++				Java			1.Java 2.Java, AspectJ 3.Java AspectJ		
Method used	LR												LR	LR	LR,ML (DT,ANN)				LR			LR		
Type of data	Open source												Univ.	Open source	NASA dataset				Open source			1.open source 2.web based 3. S/w prod.		
Fault severity taken	No(UBA)			Yes(UMA)									No	No	Yes				No			No		
	2.0	2.1	3.0	2.0			2.1			3.0					HSF	MSF	LSF	USF	2.0	2.1	3.0	1.	2.	3.
				HSF	MSF	LSF	HSF	MSF	LSF	HSF	MSF	LSF												
WMC	++	++	++	++	++	++	++	++	++	++	++	++	++		++	++	++	++	++	++	++			
DIT	0	0	++	0	0	0	++	0	0	0	0	++	0	++	0	0	0	0				0	0	0
RFC	++	++	++	++	++	++	++	++	++	++	++	++	++	++	++	++	++	++						
NOC	0	0	0	0	0	0	0	0	0	0	0	0	0	++	0	--	0	--						
CBO	++	++	++	++	++	++	++	++	++	++	++	++	++	++	++	++	++	++						
LCOM													+		++	++	0	++						
SLOC													++	++	++	++	++	++	++	++	++			

++, Denotes the metric is significant at 0.01; +, denotes the metric is significant at 0.05; --, denotes the metric is significant at 0.01 but in an inverse manner; -, denotes the metric is significant at 0.05 but in an inverse manner; 0, denotes that the metric is not significant.
A blank entry means that our hypothesis was not examined or that the metric was calculated in a different way. LR, logistic regression; UMR, Univariate Multinomial Regression; UBR, Univariate Binary Regression; OLS, Ordinary Least Square; ML, Machine Learning; DT, Decision Tree; ANN, Artificial Neural Network; RF, Random Forest; NB, Naı¨ve Bayes ;MLP, Multilayer Perceptron; Ab, Adaboost; SVM, Support Vector Machine; GP, Genetic Programming; LSF, Low Severity Fault; USF, Ungraded Severity Fault; HSF, High Severity Fault; MSF, Medium Severity Faults; #1, without size control; #2, with size control; 2.0, Eclipse version 2.0; 2.1, Eclipse version 2.1; 3.0,Eclipse version 3.0; 1., iBATIS system; 2., HealthWatcher application; 3., MobileMedia system; R3,Rhino 15R3; R4, Rhino 15R4; R5, Rhino 15R5; comm.,commercial; univ., university

5.3.1 Discussion about our results

All the size metrics, except AMC, are significant at 0.01. AMC is significant at 0.05. Amongst the cohesion metrics, we can see that LCOM3 and CAM have negative coefficients indicating that they have a negative impact on fault proneness. By definition, if LCOM, LCOM3, and CAM are significant, it means that fault proneness increases with a decrease in cohesion. Since CAM and LCOM3 are negatively related to fault proneness, we can conclude that fault proneness decreases with the decrease in cohesion. We can observe that out of 3 cohesion metrics, the majority (i.e., 2) of the metrics are negatively related. All the coupling metrics, except CA, are found to be strongly relevant to determine the fault proneness of the class. CBO is not strongly related but it still has a positive impact. CA is not significant to fault proneness, meaning it has neither a positive nor a negative impact. None of the inheritance metrics is found to be significant. The complexity metrics CC is found to be strongly and positively related to fault proneness.

5.3.2 Discussion of previous studies

We have done the comparison of our results with the results of the previous studies. CBO was found to be a significant predictor in the majority of the studies except by Tang et al. (1999) [21], El Emam et al. (2001) [23], and Olague et al. (2007) [45]. In El Emam et al. [20], the results were analyzed for the projects with and without size control. When size control was not taken into account, then CBO was found to be insignificant. Similarly, Olague et al. [45] predicted the fault prone classes for various versions of RhiNo.For one of the versions, the CBO was found to be insignificant. RFC was also found to be a significant predictor of fault proneness in all the studies except by El Emam et al. (2001) [23] when size control was not considered. Most of the studies (i.e., Tang et al. (1999)[21], Briand et al. (2000) [1], Briand et al. (2001)[24], Yu et al.(2002)[25], Shatnawi et al. (2008)[28], English et al.(2009)[44], Zhou et al. (2010)[46], and Burrows et al. (2010)[47]) did not examine the LCOM metrics or they calculated it in a very different manner. Among the studies that examined LCOM, it was insignificant with Basili et al. (1996) [31] and Singh et al. (2009) [4] for the Low Severity Fault (LSF) prediction model. The metric NOC, which is not found to be a significant predictor in our study, showed a negative impact on fault proneness by Basili et al. (1996) [31], Briand et al. (2000) [1], and Zhou et al. (2006) [46] for the LSF prediction model and by Singh et al. (2009) [4] for the Medium Severity Fault (MSF) and Ungraded Severity Fault (USF) prediction model. For the remaining previous studies, NOC was not considered to be significant. NOC was found to be very significant in predicting faulty classes by Yu et al. (2002) [25] and English et al. (2009) [44]. SLOC is found to be strongly relevant to fault proneness in all the studies. Various studies (i.e. Tang et al. (1999) [21], El emam et al. (2001) [23], Yu et al. (2002) [25], Zhou et al. (2006) [46], Singh et al. (2009) [4], Burrows et al. (2010) [47], and Aggarwal et al. (2008) [3]) showed DIT results that were similar to our results. For Basili et al. (1996) [31], Briand et al. (2000) [1], Gyimothy et al. (2005) [12], and English et al. (2009) [44] was found to be positive significant predictor. WMC is also found to be quite significant in all the previous studies. Thus, we can conclude that WMC and SLOC have always been significant predictors. DIT is not much useful in predicting the faulty classes.

6. MODEL EVALUATION USING THE ROC CURVE

This section presents and summarizes the result analysis. We have used various machine learning methods to predict the accuracy of fault proneness. The validation method which we have used is k cross-validation, with the value of k as 10.

Table 12 summarizes the results of 10 cross-validation of the models predicted by using machine learning methods. It shows the sensitivity, specificity, precision, AUC, and the cutoff point for the model predicted using all the machine learning methods. We have used ROC analysis to find the cutoff point. The cutoff point is selected such that a balance is maintained between the number of classes predicted as being fault prone and not fault prone. The ROC

Table 12. Results of 10-cross Validation

S.No.	Method Used	Sensitivity	Specificity	Precision	Area under curve	Cut-off point
1	Random Forest	78.6	80.7	78.90	0.875	0.61
2.	Adaboost	80.8	78.3	79.86	0.861	0.62
3.	Bagging	82.9	80.1	81.99	0.876	0.57
4.	Multilayer Perceptron	77.6	77	77.25	0.799	0.54
5.	Support Vector Machine	89.3	51	76.30	0.70	0.5
6.	Genetic Programming	82.8	72.7	79.38	0.808	0.5
7.	Logistic Regression	74.7	73.9	74.4	0.791	0.59

curve is plotted with sensitivity on the y-axis and (1-specificity) on the y-axis. The point where sensitivity equals (1-specificity) is called the cutoff point. The ROC curves for the machine learning models are presented in Fig. 4.

We can see that the random forest and bagging give quite similar results. They show good results as compared to the results of the other methods. The specificity and AUC for both the models are quite similar. The specificity for the random forest is 80.7% whereas for bagging it is 80.1%. These values are quite high when compared to the values of the other methods. Also the ROC curve for the random forest and bagging gives high AUC values i.e. 0.875 and 0.876 respectively. The sensitivity of the random forest is 98.6%, whereas bagging shows a high sensitivity of 82.9%. The highest sensitivity is shown by the SVM method, which is 89.3%, but it

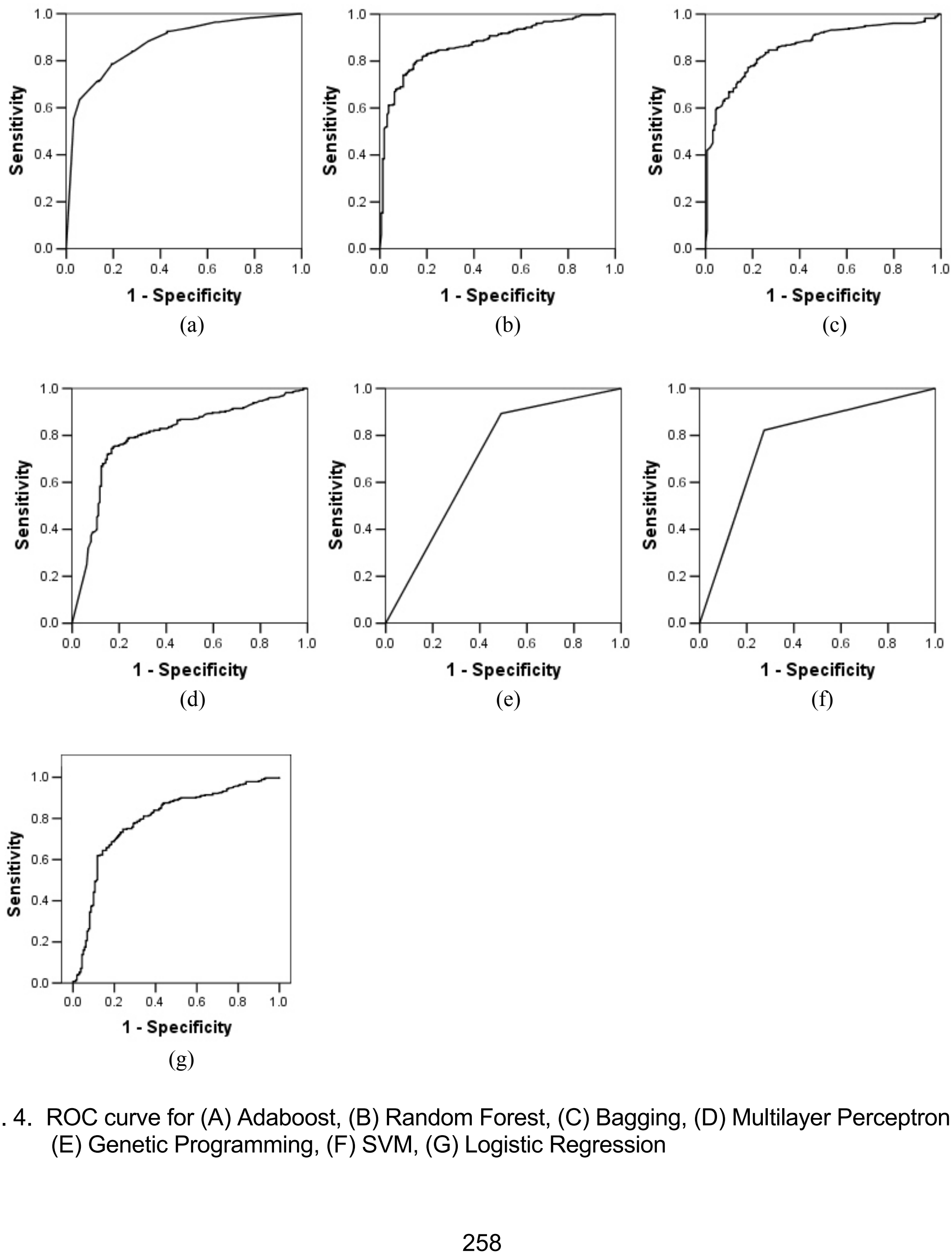

Fig. 4. ROC curve for (A) Adaboost, (B) Random Forest, (C) Bagging, (D) Multilayer Perceptron, (E) Genetic Programming, (F) SVM, (G) Logistic Regression

gives the lowest specificity of 51%. Also the AUC for the SVM model is 0.70. Thus, this method is not considered to be good. Adaboost and Genetic Programming show average results with a sensitivity of 80.8% and 82.8% respectively, with a specificity of 78.3% and 72.7%. Besides these machine learning models, we have also used a statistical method (i.e., logistic regression). We can observe that the sensitivity of logistic regression is the lowest as compared to other machine learning methods. Also, specificity is quite low when compared with most of the other machine learning methods. Thus, we can conclude from the discussion that the machine learning methods give better results as compared to the statistical methods. From amongst the machine learning methods under consideration, random forest and bagging are the best predicted models.

7. CONCLUSION

In any software project, there can be a number of faults. It is very essential to deal with these faults and to try to detect them as early as possible in the lifecycle of the project development. Thus, various techniques are available for this purpose in the literature, but previous research has shown that the object oriented metrics are useful in predicting the fault proneness of classes in object oriented software systems. The data is collected from an Open Source software Apache POI, which was developed in Java and consists of 422 classes. In this study, we have used object oriented metrics as the independent variables and fault proneness as the dependent variable. We have studied 19 object oriented metrics for predicting the faulty classes. Out of 19 metrics, we have identified a subset of metrics, which are significant predictors of fault proneness. For doing this, we have used univariate logistic regression. It was found that the metrics DIT, NOC, Ca, and MFA are not significant predictors of fault proneness and the remaining metrics that we have considered are found to be quite significant. We have also compared our results with those of previous studies and concluded that WMC and SLOC are significant predictors in the majority of the studies. After identifying a subset of metrics, we constructed a model that could predict the faulty classes in the system. Using multivariate analysis, we constructed the model in which only 3 metrics were included (i.e., DIT, RFC, and CBM). To predict the best model, we used six machine learning techniques that measured the accuracy in terms of sensitivity, specificity, precision, and AUC (Area Under the Curve). The cutoff point was also selected such that a balance is maintained between the number of classes predicted as fault and not fault prone. The ROC curve was used to calculate the cutoff point. We observed that the random forest and bagging gave the best results as compared to other models. Thus, we can conclude that practitioners and researchers may use bagging and the random forest for constructing the model to predict the faulty classes. The model can be used in the early phases of software development to measure the quality of the systems.

More similar type of studies can be carried out on different datasets to give generalized results across different organizations. We plan to replicate our study on larger datasets and industrial object oriented software systems. In future studies, we will take into account the severity of faults to get more accurate and efficient results. In this study, we have not taken into account the effect of size on fault proneness. In future work, we will also take into account some of the product properties such as size, and also process and resource related issues like the experience of people, the development environment, etc., which all effect fault proneness.

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Goal oriented Requirement Analysis for Web Applications

Shailey Chawla and Sangeeta Srivastava

***Abstract*—Web applications have mushroomed a great deal from static web pages to interactive web services. It has thus become important to engineer these applications methodologically. Goal integration from the early stages maximizes the product quality and prevents giving "requirements" amiss. We propose a Goal based Requirement Analysis for creating the web application. Both functional and non-functional requirements have been studied specific to the web applications. The requirements can be analysed according to the type of application being constructed. The web classification model aids in the understanding of web applications.**

***Index Terms*—Goals, requirements, web classification, web engineering, goal oriented requirements engineering.**

I. Introduction And Motivation

Goals are the objectives whose satisfaction requires the cooperation of the active components in the software and its environment. Goals may refer to functional concerns or quality attributes. A functional goal typically captures some desired scenarios; it can be established very clearly. Functional goals are used to build operational models such as use cases, state machine models, and the like. A quality goal typically captures some preferred behaviors among those captured by functional goals; in general it cannot be established in a clear-cut sense. In other words, Goals combine functional and non-functional Requirements. Functional Requirements are easily envisioned, the non-functional requirements can't be established or visualized with clarity but they are desirable requirements. The non-functiional requirements have significant impact on the Web web system projects[1]. The Goal oriented Requirement Engineering for web applications is therefore important. In a GORE process, quality goals are used to compare alternative options and select preferred ones, and to impose further constraints on goal operationalizations. Goal-oriented requirements engineering (GORE) is concerned with the use of goals for eliciting, elaborating, structuring, specifying, analyzing, negotiating, documenting, and modifying requirements [2]. Goals and scenarios are thus intrinsically interrelated, and RE activities may be articulated on them.

During the requirement engineering process the business and technology issues are tangled in such a way that these can't be considered in isolation and an integrated approach is required for web system development. The content in the websites has to be provided in an organized manner so that they can be usable. The commercial websites are constructed after careful analysis of competitive or similar websites using Web mining approaches [3]. Whatever the kind of websites, their development has to be based on an integration of the goal of the website and the technical issues. It becomes important to take notice that web community is enormous in size and several families of web applications exist which may be classified according to different criteria like domain, goals, content etc. The transistion from conceptual model to requirements engineering is a major step towards building a good web application[4]. However, a classification base on which the models for requirement engineering can be applied doesn't formally exist.

Goal oriented Requirement Engineering for web applications has been explored in [5]-[8]. They partly cater to the web applications. The work in this paper is in continuation of [9], wherein the Web Classification Model was proposed. We explore how this model aids in requirement analysis keeping in mind both functional and non-functional requirements. The next section explains different web application requirements and how they can be specified.

II. Web Application Requirements

For web application development, the requirements can be mapped with the web category from the multidimensional classification model and accordingly manifestation of requirements will be done. The web application requirements can be categorized as follows as specified in [10]:

A. Functional Requirements

The requirements that must be exhibited by the system in order to be complete. The functional requirements can be sub-categorized into the following:

Data Requirements: The contents or subject matter of the web site can either be *fixed* i.e. content is same from the server side or *variable* which means the content can be changed for different users by the server or the user himself. Formally, D is the set of Data Requirements s.t

D={Fixed, Variable}

Interface Requirements: The presentation of the website for delivering its information or services can be accomplished by three ways:- text, multimedia or form. Multimedia includes all kinds of media files, image files, audio files etc. The purpose of form in the interface is for receiving user input and interaction. This can be represented as

I={text:string, multimedia:set, form:html}

where multimedia is a subset of {image, video, audio}

Navigational Requirements: The navigation through the web pages can be performed via hyperlinks or form elements. Form elements like buttons, drop down menus, submit buttons can also be used for navigation. Formally,

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navigation requirement set, N can be specified as

N={hyperlink:string, hypermedia:multimedia, form:html}

Personalization Requirements: The web applications can be personalized according to users profile/ intersests either by the user himself or the server based on the past behavior or web mining techniques. In the context of semantic web, meta search plays a very important role in personalization requirements. We can describe this as a set P.

P={user, server, metasearch}

Transactional Requirements The users might need to access the database for its applications. These requirements appear when there is some user operation that requires some action/change on the server side. The transaction can be for getting information from the database or financial. In context of the semantic web, meta-database can also be accessed for retrieving certain linked information.

Example:For financial transactions like for purchase of products from a website , we have to specify the list of products purchased along with their quantity and price, total amount and the payment mode. The payment mode can be either through credit card, net banking or the user may opt for Cash on Delivery. This can be specified as follows:

f={s_list : set, amount: numeric, mode: set}

where

s_list={product_id : string, quantity : numeric, price : numeric}

mode={creditcard : numeric || netbanking : link || COD : boolean}

The database transactions can also be specified as

DT = {name: string, location: string, query: string}

Thus for representing the transaction requirements, set T can be used

T={database : set, financial : set, meta-database : set}

Any web site must exhibit a combination of the functional requirements. If FR denotes a set of functional requirements, then any website W having functional requirements say fr can be denoted as

$fr \subseteq \{ FR \mid FR = \{D \cup I \cup N \cup P \cup T\} \}$

B. *Non-Functional Requirements*

The softgoals or non functional requirements are the constraints or the quality parameters that are desirable from the system. Assuming quality parameters are represented by set Q={q1,……..,qn} and T={t1,……..,tn} be the set of threshold values for the corresponding quality attributes. Non functional requirements or softgoals can be represented by a set G.

$G = \{ q - t \mid q \in Q \ \& \ t \in T\}$

Any web application to be developed can be first categorized according to the classification model and its requirements can also be explored as mentioned above. Hence, a web application W can be created with a set of requirements R such that its functional requirements can be specified as a subset of FR and non functional requirements expressed as a subset of G.

$R \subseteq \{FR \cup G\}$

The next unit describes the web classification model proposed in [9] with the application of the model according to web application requirements.

III. Web Classification Model

The websites can be categorized according to the following criteria Fig. 1

a) **Content**: The content here refers to type and management of the content.

b) **Service:** The service the website is rendering and the goal is the criteria here.

c) **Technology:** The design and publishing techniques also keep evolving. This criteria classifies websites according to **the** technical aspects.

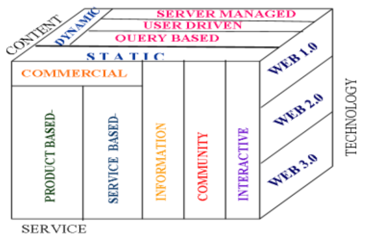

Fig. 1. Web classification model

A. *CONTENT*

The content on the web application can be classified broadly as static or dynamic in terms of the change in content. Most of the internet pages existing nowadays are dynamic in nature. Further refinement on how the change in content is managed results in further categorization also expressed in Table I.

TABLE I: Requirements in Content Dimension

CONTENT		FUNCTIONAL REQUIREMENTS					GOALS /NFRs	REMARKS
		D	I	N	P	T		
DYNAMIC	**Query based**	Var-iable	Text multimedia form	Link, form	Server, User	Database	Relevance, precision, Recall, Flexible	Search engines
	Server managed	Va-riable	Text multimedia	Link	Server	n/a	Interesting Organized User friendly	News websites
	User managed	Va-riable	Text Multimedia form	Link, form	User	n/a	Flexible Adaptable Light weighted	Blogs
STATIC		Fixed	Text multimedia	Link	n/a	n/a	Clarity Readability	Personal Websites

Managed at the server: The content of the web site is managed at the server. Owing to the changeable nature of the content the content keeps on changing. Example of such web pages are stock market websites, weather or news websites.

User driven: the content of the web pages is managed by the users. Community websites like discussion forums, usegroups, chatrooms, socializing websites are very good examples of such web pages. Here except for the basic design of the web sites the contents are managed by the users. Also personalized pages provided by various portals like yahoo and google (aka igoogle.com) are also user driven.

Query based web sites: the content of the web page in this case is in response to the query posted by the user. The main example being the search engine. Within other websites also like shopping or information oriented websites some web pages are a result of query based interaction with the user.

B. SERVICE

The second criteria for classifying the website are goal with which the website is being created. The purpose of web application development and the utilization of the web site come under this perspective. The utilization is classified as follows Table II.

TABLE II: REQUIREMENTS IN SERVICE DIMENSION

SERVICE		FUNCTIONAL REQUIREMENTS					GOALS /NFRs	REMARKS
		D	I	N	P	T		
COMMERCIAL	Product based	Variable	Text Multimedia, form	Form Link	Server, User	Financial Database	Security quality reliab-lility usability speed of delivery	Shopping web sites
	Service based	Variable	Text multimedia form	Form, link	Server, User	Financial Database	Security, reliability, user friendly	Banking Stock market
INFORMATION		Fix ed	Text multimedia	Link	Server, User	Database	Clarity, User friendly, Trust	Personal websites
COMMUNITY		Variable	Form, multimedia text	Link, form	Server, user	Database	Security, personalization	Blogs Social networking sites Newsgroups
INTERACTIVE		Variable	Multimedia, form, text	Link, form	User, server	n/a	User friendly, personalization, fast response time	Gaming websites

TABLE III: REQUIREMENTS IN TECHNOLOGY DIMENSION

TECHNOLOGY	FUNCTIONAL REQUIREMENTS					GOALS /NFRs	REMARKS
	D	I	N	P	T		
WEB 1.0	Fixed	Text, Multimedia	Link	n/a	n/a	User friendly	Html based websites/ without interaction
WEB 2.0	Variable	Form, text, multimedia	Link, form	User, server	Database financial	Personaliz-ation, Utility, usability	Interactive websites
WEB 3.0	Variable	Form, text, multimedia	Link, form	User, server, Web Crawler	Linked web data database,	Personalization, Linking/networking	Xml, Rdf, owl, Semantic web publishing

a) **Information** The main purpose of web application is to provide information. The information can be in any format including multimedia or textual. Information can be received in response to queries like search engines. The personal or corporate web pages that only provide information about some entity also come under this category. Website containing articles from magazines, newspapers or any domain knowledge also fall in this class.

b) **Commercial** All e-commerce web sites have a **commercial** motive. The business here can be based on either product or services. Shopping web sites come under the product based business. Banking, stock market websites are service based businesses. Most of the commercial websites involve transaction oriented interaction, where in there is transfer of money through some means.

c) **Community** The community web sites provide **platforms** for socializing, discussions forums, blogs, networking etc. These are for bringing people around the world closer who share common interests.

d) **Interactive** These web sites are for live interaction, though other website categories also have some form of interaction but it has been kept as separate category keeping in mind the web sites being build specifically for live interactions like online gaming, video conferencing wherein people from different parts of world can play the same game. Also the response of the web site is spontaneous for various actions.

C. TECHNOLOGY

The third criteria have been chosen to classify the websites according to the techniques used for publishing and installing the websites. Depending upon the usage of the website the technology of its creation also differs. Also with time the technologies have evolved and the way internet is used has also made a magnificent shift. The websites fall under the category of the categories Web 1.0, Web 2.0 or Web 3.0[13][14][15] (Table 3). These three terms represent the evolution of web in terms of technology and usage.

a) **Web 1.0** – That initial world wide web era was all about read-only content and static HTML websites. People preferred navigating the web through link directories of Yahoo! and dmoz. The applications here are native internet applications using HTML, XHTML, and basic javascript and vbscript etc. Web 1.0 is a retronym that refers to the state of the Web, and any website design style used before the advent of the Web 2.0 phenomenon.

b) **Web 2.0** – This is about user-generated content and the read-write web. People are consuming as well as contributing information through blogs or sites like Flickr, YouTube, Digg, etc. The line dividing a consumer and content publisher is increasingly getting blurred in the Web 2.0 era. The websites in category involve rich internet applications. A rich Internet application (RIA) is a Web application designed to deliver the same features and functions normally associated with desktop applications. The technologies used are flash, java etc.

c) **Web 3.0** – This is a new concept. This will be about semantic web (or the meaning of data), personalization (e.g. iGoogle), intelligent search and behavioral advertising among other things. The **Semantic Web** is the extension of the World Wide Web that enables people to share *content* beyond the boundaries of applications and websites. It has been described in different ways: *utopic vision*, *web of data*, or a *natural paradigm shift* in our daily use of the Web. The term was coined by Tim Oreilly who coined the term web 2.0 as well in a talk. Active research is going on in this area for converting the World Wide Web into a semantic web database, this will increase the utility of web manifolds.

IV. GOALS AND WEB APPLICATIONS

To capture declarative, behavioral and interactive aspects of systems, goal-oriented requirements analysis have been proposed [11]. Rather than just focusing on the Functional requirements in the initial phases, if goals are taken into consideration then the product achieved will be more closer to the user's expectations. Analysis of Goals that include both Functional and non functional requirements and the long term motives of the stakeholders allow exploration of alternatives, decision spaces, and tradeoffs by considering questions such as "why", "how" and "how else" instead of only considering functional concerns. A non functional requirement is an attribute of or a constraint on a system[12]. According to the work in [12], the attributes can be performance requirements like timing, speed, throughput or specific quality requirements like reliability, usability. The constraints can be physical, legal, cultural, interface related etc. The amalgamation of Goal oriented requirement engineering with web applications has enormous benefits. It is apparent that web applications are a necessity for every business. The incorporation of goal oriented approach for engineering such applications will reap assorted benefits and the final product will be fairly closer to the stakeholders expectations. There are models for building business applications like in [2], [5].

The above web site classification model helps in identifying the type of website that the user is asking for. The website category can be chosen for all the three dimensions according to the requirements. The web applications can be a hybrid category as well. The requirements listed according to the web category provide a basic framework for the requirement analysis. The non functional requirements that are more important in that category are also listed. This formulation helps the user also to clarify in their minds what they want.

Example: An Educational Institute Web application has to be developed that provides information about various courses running in the institute and other details like faculty, infrastructure etc. The web applications might have one or two web pages for accepting applications from students or job opportunities. The organization might even like to have an internal email or notice board system in form of web application.

After understanding the basic requirements, the Requirement Engineer might take help of the Web requirement classification model. The details can be furnished as Table 4. The example shown here is very basic, but eventually work can be done to create templates for each kind of category and web designers will have great help in choosing the requirement models, if required merging them and designing the web applications.

TABLE IV: REQUIREMENTS FOR EDUCATIONAL WEB SITE

Dimension/ Requirements	**D**	**I**	**N**	**P**	**T**	**NFR'S**
CONTENT Dynamic/server managed	variable	Text, multimedia, form	Link, form	n/a	n/a	Interesting, Organized, user friendly
SERVICE Information						
TECHNOLOGY Web 2.0						

V. CONCLUSION AND FUTURE WORK

We have presented a framework for goal analysis for Web application development. The analysis is coherent with the web classification model. Also, its being established that integration of goals with web requirement engineering would improve the quality and usability of web applications. Future work includes development of a goal oriented requirement model that suffices all kinds of websites provided in the classification and develop its tool support for engineering it automatically.

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MIXED SIGNAL LETTER

New CFOA-based sinusoidal oscillators retaining independent control of oscillation frequency even under the influence of parasitic impedances

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Abstract There have been two efforts earlier on evolving CFOA-based fully-uncoupled oscillators i.e. circuits in which none of the resistors controlling the frequency of oscillation (FO) appear in the condition of oscillation and vice versa. However, a non-ideal analysis of the earlier known circuits reveals that due to the effect of the parasitic impedances of the CFOAs, the independent controllability of FO is completely destroyed. The main objective of this paper is to present two new fully-uncoupled oscillators in which the independent controllability of the FO remains intact even under the influence of the non-ideal parameters/parasitics of the CFOAs employed. The workability of the proposed circuits has been confirmed by experimental results using AD844-type CFOAs.

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Keywords Sinusoidal oscillators · Current feedback-operational-amplifiers · Analog circuit design · Current mode circuits

1 Introduction

Sinusoidal oscillators find numerous applications in instrumentation, measurement, control and communication systems. During the past four decades, a class of sinusoidal oscillators referred as single resistance controlled oscillators (SRCO) have been of particular interest because of their applications in variable frequency oscillators in general and voltage controlled oscillators (VCO) in particular (which are obtainable by replacing the frequency-controlling resistor with FET-based or CMOS voltage controlled resistor). In fact, SRCOs have been a very prominent area of analog circuit research and a large number of circuits using a variety of commercially available devices such as op-amps, current conveyors (CC), current feedback op-amps (CFOA) and operational transconductance amplifiers (OTA) as well as using a number of newly proposed active building blocks (see [1]) have been reported in the earlier literature, for instance, see [2–44] and the references cited therein.

Interest in realizing sinusoidal oscillators using CFOAs grew when it was demonstrated by Martinez et al. [10, 26] that using a CFOA, rather than a VOA, in the classical Wien bridge oscillator configuration results in an oscillator which offers important advantages such as: (i) more accurate adjustment of oscillation frequency (ii) much wider frequency span of frequency of operation (iii) higher frequency and larger amplitudes because of much higher slew rates than VOAs and (iv) lower sensitivity of the frequency to the bandwidth variation of the active element thereby resulting in higher frequency stability. This stimulated considerable interest among the researchers to extend the realization of oscillators to the more popular and important class of SRCO with the hope that such oscillators when realized with CFOAs will, therefore, offer significant advantages over their VOA-based counterparts as well as with the hope that the 4-terminal CFOA-based new SRCOs may possess additional interesting features not available in 3-terminal VOA-based SRCOs known earlier. Consequently, there has been a widespread interest on CFOA-based SRCOs [10–15, 18, 20, 21, 23, 25, 26, 30, 31, 33–39, 41, 42, 44].

CFOA-based canonic SRCOs which employ a minimum of five passive components, namely, three resistors and two-grounded capacitors, as desirable from the view point of IC implementation and possessing tuning laws are such that both the condition of oscillation (CO) and frequency of oscillation (FO) can be controlled/adjusted by two independent resistors, require at least two CFOAs. A major drawback of such topologies is that as soon as various non-idealities/parasitic of the active building blocks are accounted for, the theoretically derived independence of CO and FO vanishes due to the frequency-controlling resistor also getting involved in the non-ideal expression for the CO.

However, in contrast to the class of SRCOs mentioned-above, the class of 'fully-uncoupled' SRCOs has not been considered adequately in the literature earlier; the only exception being the works reported in [20] and [44]. Note that CO and FO may be called fully-decoupled only when CO and FO are decided by two completely different sets of components, that is none of the components involved in CO are also involved in FO and vice versa. Such SRCOs would, therefore, be characterized by tuning laws of the type

$$\text{CO:}(R_1 - R_2) \leq 0 \tag{1}$$

and

$$\text{FO: } f_0 = \frac{1}{2\pi}\sqrt{\frac{1}{C_1 C_2 R_3 R_4}} \tag{2}$$

which shows that such circuits would, thus, need four resistors along with two capacitors. Such 'fully-uncoupled' SRCOs, however, are not feasible with only two active elements and call for the employment of at least three active elements as in [20, 44].

Due to the failure of two-CFOA-based SRCOs in maintaining the independence of CO and FO under the influence of non-ideal parameters and/or parasitic of the CFOAs (see Appendix A), a question was, therefore, asked as to whether 'fully-uncoupled' oscillators may (possibly) lead the intended property of retaining the independent control of FO even under the influence of non-ideal parameters or parasitic of the CFOAs? To this end, surprisingly we found (see Appendix A) that the quoted fully-uncoupled oscillators from [20, 44] also fail to retain the independent controllability of FO under the influence of non-ideal parasitic impedances of CFOAs as all the four resistors employed in the oscillators appear in the non-ideal expressions of both CO and FO, thereby completely disturbing the intended property.

This lead to the important question as to: could there be any alternative three CFOAs-two-GC-four- resistor fully-uncoupled oscillator circuits which can retain independent controllability of FO even under the influence of non-ideal parameters/parasitic of the CFOAs employed?

The main object of this paper is, therefore, to present two new 'fully-decoupled' SRCOs employing only three CFOAs, four resistors and two GCs and to show that the answer to the above question is, indeed, in the affirmative. To the best of authors' knowledge, any oscillators using CFOAs, which retain the independent single element controllability of FO even under the influence of non-ideal parameters or parasitic of the CFOAs, have not been reported in the literature earlier.

The practical workability of the proposed new circuits has been established by experimental results obtained from their realizations using commercially available AD844-type CFOAs.

2 The proposed fully-uncoupled SRCOs

The proposed new circuits are shown in Fig. 1. The circuits have been devised by using a cascade of three

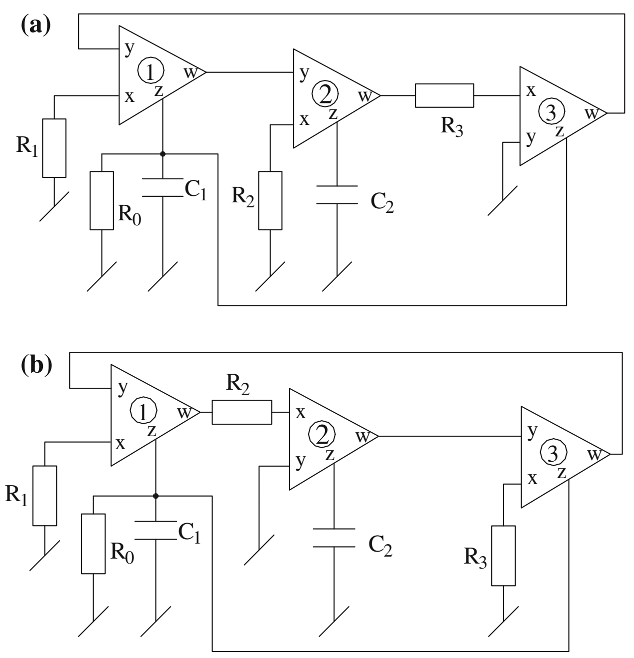

Fig. 1 Fully-uncoupled SRCOs

sub-circuits in a closed loop. These sub-circuits are as follows:

(i) One CFOA is employed as lossless non-inverting/inverting integrator see $CFOA_2$ in Fig. 1(a, b).
(ii) Another CFOA is employed as a non-inverting/inverting voltage controlled current source (VCCS) see $CFOA_3$ in Fig. 1(a, b).
(iii) The third CFOA is acting as a VCCS provides a current feedback/a summing operation at the z terminal of CFOA acting as lossy integrator (see $CFOA_1$).

It may be visualized that using the various kind of sub-circuits arranged as a cascade in closed loop many other structures appear feasible however, those alternative circuits which do not yield the intended properties have not been included in the set of Fig. 1.

Assuming that the CFOAs are characterized by: $i_y = 0$, $v_x = v_y$, $i_z = i_x$ and $v_w = v_z$, both the circuits are governed by a common characteristic equation (CE) given by:

$$s^2 + \frac{s}{C_1}\left(\frac{1}{R_0} - \frac{1}{R_1}\right) + \frac{1}{C_1C_2R_2R_3} = 0 \tag{3}$$

From this CE, the CO and FO can be seen to be

$$\text{CO:}(R_1 - R_0) \le 0 \tag{4}$$

and

$$\text{FO:} f_0 = \frac{1}{2\pi}\sqrt{\frac{1}{C_1C_2R_2R_3}} \tag{5}$$

The oscillators of Fig. 1(a, b) can be respectively modeled by the flow diagrams shown in Fig. 2 below each of which consists of a major closed loop with two integrators (one inverting and the other non-inverting, thus, forming a resonator) and two minor closed loops (around one of the integrators). Alternatively, if we look into the z terminal of the first CFOA and determine the total admittance it turns out that both the circuits are composed of a ±RLC resonators from where also it turns out that the FO is controlled only by C_1, C_2, R_2 and R_3 whereas the negative resistor R_0 provides the energy to compensate for the losses created by the positive resistor R_1.

For both the circuits, the major loop (resonator) sets The FO at

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{1}{C_1C_2R_2R_3}}$$

while the minor loops implement, respectively, the amplitude compressing and expanding mechanism which are required for any practical oscillator to work properly. Thus, the loop implemented by R_0 models the resonator losses and is, hence, responsible of the making the amplitude to decrease whenever its exceeds the equilibrium value corresponding to the oscillation amplitude On the other hand, the loop implemented by R_1 compensates the resonator losses by introducing energy into the system and is, hence, responsible of making the amplitude increasing when it becomes smaller than the equilibrium. At equilibrium, the amplitude adaptation mechanism should, therefore, make $R_1(A) = R_0(A)$. Also, stability of this mechanism requires $R_1(A) > R_0(A)$ for $A > A_0$, where A_0 is the oscillation amplitude.

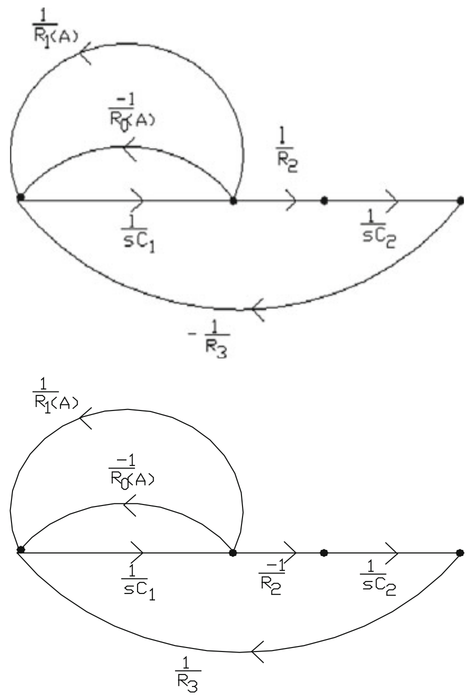

Fig. 2 The *signal flow-graph* representation of the proposed oscillators of Fig. 1

3 Analysis including the parasitic input and output impedances of the CFOAs

For an evaluation of the non-ideal performance of the new circuits, we consider the finite input resistance R_{xi} at the x port, $i = 1$–3, parasitic components R_{yi} in parallel with $1/sC_{yi}$ at the y port and parasitic components R_{zi} in parallel with $1/sC_{zi}$ at the z port of all the CFOAs $i = 1$–3. Analysis reveals that in both the cases the non-ideal CE of both the circuits continues to remain second order. The non-ideal CO and FO for both the circuits from the respective non-ideal CEs have been found to be as under:

For the circuits of Fig. 1(a, b)

$$\text{CO:}(C_2 + C_{z2})\left\{\frac{1}{R_0} - \frac{1}{R_1 + R_{x1}} + \frac{1}{R_{y1}} + \frac{1}{R_{z1}} + \frac{1}{R_{z3}}\right\} + \frac{C_1 + C_{z1} + C_{y1} + C_{z3}}{R_{z2}} \le 0 \tag{6}$$

$$f_0' = \frac{1}{2\pi}\sqrt{\frac{1}{C_1C_2R_2R_3}\left(\frac{1}{\left(1+\frac{C_{y1}+C_{z1}+C_{z3}}{C_1}\right)\left(1+\frac{C_{z2}}{C_2}\right)}\right)}^{1/2} \times \left[\frac{1}{\left(1+\frac{R_{x2}}{R_2}\right)\left(1+\frac{R_{x3}}{R_3}\right)} + \frac{R_2R_3}{R_{z2}}\left\{\frac{1}{R_0}+\frac{1}{R_{y1}}+\frac{1}{R_{z1}}+\frac{1}{R_{z3}}-\frac{1}{R_1+R_{x1}}\right\}\right]^{1/2} \tag{7}$$

From Eqs. (6–7), it may be observed: that in both the proposed new circuits, the frequency-controlling resistors R_2 and R_3 do not come into the non-ideal expressions for CO; therefore, the independent controllability of FO remains intact even under the influence of the non-ideal parameters/parasitic of the CFOAs employed.

To further confirm this, we have carried out a more elaborate analysis taking into account the non-unity current gains between i_x and i_z of the CFOAs as β_1, β_2 and β_3 and then modeling the relation between v_z and v_w of each CFOA by the equation $v_{wi} = v_{zi} = i_{wi} \cdot R_{wi}$, $i = 1$–3 also (in addition to the various x port, y port and z port parasitic impedances already mentioned earlier). By considering all the three CFOAs to be identical (for the sake of simplicity) it has been found that CE for both the circuits then becomes same and is given by:

$$a_4s^4 + a_3s^3 + a_2s^2 + a_1s + a_0 = 0$$

where

$$a_4 = (c_1 + 2c_z)(c_2 + c_z)c_y^2$$

The above complex equation clearly does not lend itself to any easy meaningful interpretation other than the observation that the two frequency-controlling resistors R_2 and R_3 still do not appear in any of the coefficients a_4, a_3, a_2 or a_1 and appear only in a_0! However, when numerical values are substituted corresponding to the typical practical design (later dealt with in Sect. 5) with component values taken as $R_3 = 1, R_0 = 10, R_1 = 7.95\ \text{k}\Omega, C_1 = C_2 = 1$ nF, with R_2 taken as variable along with nominal parameter values taken as $R_x = 50\ \Omega$, $R_y = 2\ \text{M}\Omega$, $R_z = 3\ \text{M}\Omega$, $R_w = 50\ \Omega$, $C_y = 2$ pF, $C_z = 4$ pF and $\beta_i = 1$ ($i = 1$–3), it has been found that the contribution of the coefficients of fourth and third powers of **s** is infinitesimally small over the frequency range of interest (in fact, MATLAB program rounded these coefficients to exactly zero !). It is hence, concluded that the resulting dynamics of the circuit is dominantly second order from which the real and imaginary parts of the complex conjugate roots of the resulting equation have been determined by varying R_2 and keeping R_3 fixed. These are shown in Table 1 from where it is seen that although the imaginary part representing the oscillation frequency keeps on changing (as should be), however, the real part, representing the oscillation condition, remains invariant (as expected).

It is worth mentioning that if the circuits are to be converted into VCO by replacing the frequency-controlling resistors R_2 and/or R_3 by FET-based or CMOS voltage controlled-resistors (VCR), this does not pose any difficulty since it is well known that grounded/floating VCRs using any of the above mentioned devices could be realized with exactly the same amount of hardware, for instance, see [45–48].

$$a_3 = 2c_y(c_1+2c_z)(c_2+c_z)\left(\frac{1}{R_y}+\frac{1}{R_w}\right) + c_y^2\left\{\frac{c_1+2c_z}{R_z} + (c_2+c_z)\left(\frac{1}{R_0//\frac{R_z}{2}}\right)\right\}$$

$$a_2 = (c_1+2c_z)\left(\frac{1}{R_y}+\frac{1}{R_w}\right)\left\{(c_2+c_z)\left(\frac{1}{R_y}+\frac{1}{R_w}\right)+2\frac{C_y}{R_z}\right\} + c_y(c_2+c_z)\left\{2\left(\frac{1}{R_y}+\frac{1}{R_w}\right)\left(\frac{1}{R_0//\frac{R_z}{2}}\right) - \left(\frac{\beta_1}{R_1+R_x}\right)\left(\frac{1}{R_w}\right)\right\} + \frac{c_y^2}{R_z}\left(\frac{1}{R_0//\frac{R_z}{2}}\right)$$

$$a_1 = \left(\frac{1}{R_y}+\frac{1}{R_w}\right)^2\left\{\frac{c_1+2c_z}{R_z}+\frac{c_2+c_z}{R_0//\frac{R_z}{2}}\right\} + \frac{2c_y}{R_z}\left(\frac{1}{R_y}+\frac{1}{R_w}\right)\left(\frac{1}{R_0//\frac{R_z}{2}}\right) - \frac{(c_2+c_z)\beta_1}{(R_1+R_x)R_w}\left(\frac{1}{R_y}+\frac{1}{R_w}\right) - \frac{c_y\beta_1}{R_zR_w}\left(\frac{1}{R_1+R_x}\right) + \left(\frac{c_y\beta_2\beta_3}{R_w}\right)\left(\frac{1}{R_2+R_x}\right)\left(\frac{1}{R_3+R_x+R_w}\right)$$

$$a_0 = \left(\frac{1}{R_y}+\frac{1}{R_w}\right)\left\{\left(\frac{1}{R_y}+\frac{1}{R_w}\right)\frac{1}{R_z}\left(\frac{1}{R_0//\frac{R_z}{2}}\right) - \left(\frac{\beta_1}{R_zR_w}\right)\left(\frac{1}{R_1+R_x}\right) + \frac{\beta_2\beta_3}{R_w}\left(\frac{1}{R_2+R_x}\right)\left(\frac{1}{R_3+R_x+R_w}\right)\right\}$$

Table 1 Variation of real and imaginary parts of the roots of CE for the proposed circuits of Fig. 1

R_2 (kΩ)	Real part	Imaginary part	FO (kHz)
1	0.0061	922×10^3	146.598
2	0.0061	659×10^3	104.781
3	0.0061	539×10^3	85.701
4	0.0061	467×10^3	74.253
5	0.0061	417×10^3	66.303
6	0.0061	380×10^3	60.420
7	0.0061	351×10^3	55.809
8	0.0061	328×10^3	52.152
9	0.0061	309×10^3	49.131
10	0.0061	292×10^3	46.428

4 Frequency stability

Frequency stability is an important figure of merit for sinusoidal oscillators. Using the definition of frequency stability factor (S_F) as per [14] to be $S_F = \frac{d\varphi(u)}{du}\Big|_{u=1}$ where $u = \frac{\omega}{\omega_o}$ is the normalized frequency and $\varphi(u)$denotes the phase function of the open loop transfer function, with $C_1 = C_2 = C$, $R_0 = R_1 = R_2 = R$ and $R_3 = R/n$, S_F for the proposed oscillators is found to be $S_F = 2\sqrt{n}$. While varying both the resistors simultaneously i.e., $R_2 = R_3 = R/n$, S_F becomes $2n$. This figure appears to be the highest (like that of [44]) attained so far as compared to all SRCOs [10–18, 20, 21, 23, 25, 26, 30–39, 41, 42] known earlier. Thus, both the new circuits offer very high frequency stability factors for larger values of n.

5 Experimental results

To verify the workability of the new oscillators, they were constructed from AD844-type CFOAs biased with ±12 volts DC power supplies along with $R_3 = 1$ kΩ, $R_0 = 10$ kΩ, $C_1 = C_2 = 1$ nF and were found to work satisfactorily in accordance with the theory. Some sample experimental results are shown in Figs. 3 and 4 respectively. Figure 3 shows the variation of oscillation frequency with R_2 for the oscillator of Fig. 1(b) whereas Fig. 4 shows a typical waveform obtained from the circuit of Fig. 1(a). The workability of the proposed new configurations has, thus, been confirmed experimentally.

It may be mentioned that no external amplitude stabilization/control circuitry has been devised for the proposed oscillators so far. In the absence of this, the oscillation amplitude is limited by the nonlinearities of the CFOAs.

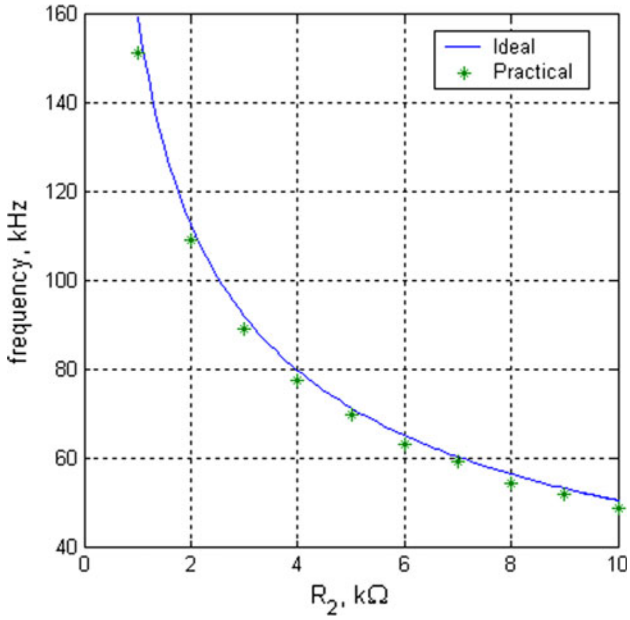

Fig. 3 Plot of R_2 versus FO for the oscillator of Fig. 1(b)

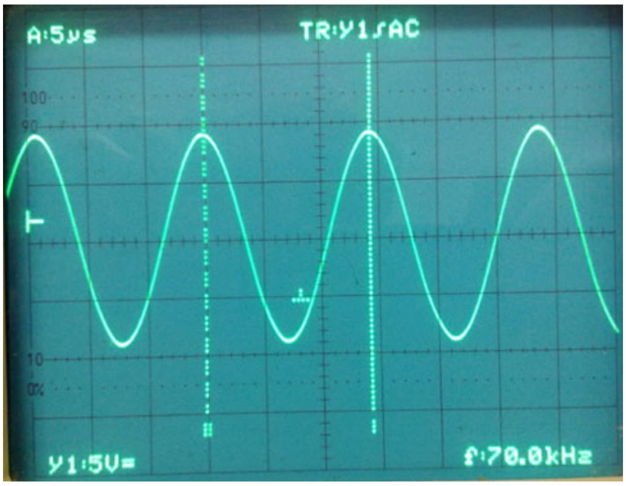

Fig. 4 A typical waveform obtained from the oscillator circuit of Fig. 1(a)

6 Concluding remarks

A large number of CFOA-based SRCOs are known in the earlier literature that requires two CFOAs and three resistors to provide independent controls of both CO and FO through separate resistors while employing both grounded capacitors as preferred for IC implementation. In all such circuits, the independent controllability gets lost when the effect of parasitic impedances of CFOAs are accounted for. Independence of FO also gets lost even in the three-CFOA-two-GC-four-resistor fully- uncoupled oscillators of [20, 44] when the effects of the parasitic impedances of CFOAs are accounted for.

In this paper, two new fully-uncoupled oscillators have been introduced in which independent controllability of FO remains intact even under the influence of non-ideal parameters of the CFOAs employed. To the best of the authors' knowledge, no CFOA-based oscillators possessing this property have been published in the literature earlier. Another notable property of the new circuits is the high value of frequency stability factor. The workability of the new circuits has been established by experimental results based on the hardware implementation of the proposed circuits using commercially available AD844-type CFOAs. This paper has, thus, added two new circuits with practically important properties not available in any of the earlier known CFOA-based SRCOs of [10–18, 20, 21, 23, 25, 26, 30–39, 41, 42, 44].

Lastly, it must be mentioned that the generation of any new three-CFOA-two-GC-four-resistor fully-uncoupled oscillators which, apart from retaining independent controllability of FO, can also retain independent controllability of CO even under the influence of the non-ideal parameters/parasitic of the CFOAs, appears to be an interesting but challenging problem and is open to investigation.

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Appendix A

Analysis of the previously known CFOA-based grounded capacitor SRCOs taking into account the effect of parasitic impedances of the CFOAs

In the earlier literature, there appear to be only two circuits employing CFOAs which belong to the category of *fully-uncoupled oscillators*, namely, the circuit presented by Soliman [20] and the circuit presented by Bhaskarc [44], which are shown here in Figs. 5 and 6 respectively.

Both these circuits employ exactly the same number of active and passive components as in the circuits presented in this paper. Ideal CO and FO for the circuits of Figs. 5 and 6 are respectively given by:

$$\begin{aligned} &R_3 = R_4 \quad (\text{for Fig. 5}) \\ &R_1 = R_2 \quad (\text{for Fig. 6}) \end{aligned} \tag{8}$$

$$\begin{aligned} f_0 &= \frac{1}{2\pi}\sqrt{\frac{1}{C_1C_2R_1R_2}} \quad (\text{for Fig. 5}) \\ f_0 &= \frac{1}{2\pi}\sqrt{\frac{1}{C_1C_2R_3R_4}} \quad (\text{for Fig. 6}) \end{aligned} \tag{9}$$

From a non-ideal analysis, CE, CO and FO of the oscillator of Fig. 5 are respectively given by:

$$\begin{aligned} &s^3\left(C_1'C_2'C_{z2}R_{x3}\right) + s^2\left\{C_1'C_2'\left(1+\frac{R_{x3}}{R_3'}\right) + C_2'C_{z2}\left(\frac{R_{x3}}{R_{z1}}\right) + C_1'C_{z2}\left(\frac{R_{x3}}{R_4'}-1\right)\right\} \\ &+ s\left[C_1'\left\{\left(1+\frac{R_{x3}}{R_3'}\right)\left(\frac{1}{R_4'}\right) - \frac{1}{R_3'}\right\} + C_2'\left(1+\frac{R_{x3}}{R_3'}\right)\left(\frac{1}{R_{z1}}\right) + C_{z2}\left(\frac{R_{x3}}{R_4'}-1\right)\left(\frac{1}{R_{z1}}\right)\right] \\ &+ \left[\frac{1}{R_{z1}}\left\{\left(1+\frac{R_{x3}}{R_3'}\right)\left(\frac{1}{R_4'}\right) - \frac{1}{R_3'}\right\} + \frac{1}{R_1'R_2'}\right] = 0 \text{ where} \\ &C_1' = (C_1 + C_{z1});\ C_2' = (C_2 + C_{z2});\ R_1' = (R_1 + R_{x1});\ R_2' = (R_2 + R_{x2});\ R_3' = (R_3 \| R_{z2});\ R_4' = (R_4 \| R_{z3}) \end{aligned} \tag{10}$$

$$\begin{aligned} &1 - \frac{R_4'}{R_3'} + \frac{C_2'R_4'R_{x3}^2}{C_1'R_3'^2R_{z1}} + \frac{2C_2'R_4'R_{x3}}{C_1'R_3'R_{z1}} + \frac{C_2'R_4'}{C_1'R_{z1}} + \frac{C_2'R_4'R_{x3}^2C_{z2}}{C_1'^2R_3'R_{z1}^2} + \frac{C_2'R_4'R_{x3}C_{z2}}{C_1'^2R_{z1}'} - \frac{2R_4'R_{x3}C_{z2}}{C_1'R_3'R_{z1}} - \frac{2R_4'C_{z2}}{C_1^1R_{z1}} + \frac{R_{x3}^2}{R_3'^2} + \frac{2R_{x3}}{R_3'} \\ &+ \frac{2R_{x3}^2C_{z2}}{C_1'R_3'R_{z1}} + \frac{2R_{x3}C_{z2}}{C_1'R_{z1}} + \frac{R_{x3}^2C_{z2}}{C_2'R_3'R_4'} + \frac{R_{x3}C_{z2}}{C_2'R_4'} - \frac{2R_{x3}C_{z2}}{C_2'R_3'} - \frac{C_{z2}}{C_2'} - \frac{R_4'R_{x3}}{R_3'^2} + \left(\frac{R_{x3}C_{z2}}{C_1'R_{z1}}\right)^2 + \frac{(R_{x3}C_{z2})^2}{C_1'C_2'R_4'R_{z1}} - \frac{2R_{x3}C_{z2}^2}{C_1'C_2'R_{z1}} \\ &+ \frac{R_4'C_{z2}}{C_2'R_3'} - \frac{R_4'R_{x3}C_{z2}^2}{C_1'^2R_{z1}^2} + \frac{R_4'C_{z2}^2}{C_1'C_2'R_{z1}} - \frac{R_4'R_{x3}C_{z2}}{C_1'R_1'R_2'} = 0 \end{aligned} \tag{11}$$

$$f_0' = \frac{1}{2\pi}\sqrt{\frac{1}{C_1C_2R_1R_2}\left[\frac{\frac{1}{\left(1+\frac{R_{x1}}{R_1}\right)\left(1+\frac{R_{x2}}{R_2}\right)}+\frac{R_1R_2}{R_{z1}}\left\{\left(\frac{1}{R_4}+\frac{1}{R_{z3}}\right)\left(1+\frac{R_{x3}}{R_3}+\frac{R_{x3}}{R_{z2}}\right)-\frac{1}{R_3}-\frac{1}{R_{z2}}\right\}}{\left(1+\frac{C_{z1}}{C_1}\right)\left(1+\frac{C_{z2}}{C_2}\right)\left(1+\frac{R_{x3}}{R_3}+\frac{R_{x3}}{R_{z2}}\right)} + C_{z3}R_{x3}\left\{\frac{\left(1+\frac{C_{z2}}{C_2}\right)}{C_1R_{z1}}+\frac{\left(1+\frac{C_{z1}}{C_1}\right)\left(\frac{1}{R_4}+\frac{1}{R_{z3}}\right)}{C_2}\right\}-\frac{C_{z2}}{C_2}\left(1+\frac{C_{z1}}{C_1}\right)\right]^{1/2}} \tag{12}$$

The CE, CO and FO for the oscillator of Fig. 6 are respectively given by:

$$s^3\left(C_1'C_2'C_{z3}\right)+s^2\left\{C_1'C_2'\left(\frac{1}{R_1}+\frac{1}{R_{z3}}\right)+C_1'C_{z3}\left(\frac{1}{R_z}\right)+C_2'C_{z3}\left(\frac{1}{R_{z1}}\right)\right\}$$
$$+s\left[C_1'\left(\frac{1}{R_z}\right)\left(\frac{1}{R_1}+\frac{1}{R_{z3}}\right)+C_2'\left\{\left(\frac{1}{R_{z1}}\right)\left(\frac{1}{R_1}+\frac{1}{R_{z3}}\right)+\left(\frac{1}{R_3'}\right)\left(\frac{1}{R_1}-\frac{1}{R_2'}\right)\right\}+C_{z3}\left(\frac{1}{R_3'R_4'}\right)\right]$$
$$+\left[\frac{1}{R_zR_3'}\left(\frac{1}{R_1}-\frac{1}{R_2'}\right)+\frac{1}{R_3'R_4'}\left(\frac{1}{R_1}+\frac{1}{R_{z3}}\right)\right]=0 \; where \; C_1'=(C_1+C_{z1});\; C_2'=\left(C_2+C_{z2}+C_{y1}\right);$$
$$R_2'=(R_2+R_{x2});\; R_3'=(R_3+R_{x1});\; R_4'=(R_4+R_{x2});\; R_z=\left(R_{y1}\|R_{z2}\right) \tag{13}$$

$$C_1'C_2'^2\left(\frac{1}{R_3+R_{x1}}\right)\left(\frac{1}{R_1}-\frac{1}{R_2+R_{x3}}\right)\left(\frac{1}{R_1}+\frac{1}{R_{z3}}\right)+C_1'^2C_2'\left(\frac{1}{R_1}+\frac{1}{R_{z3}}\right)^2\left(\frac{1}{R_{y1}}+\frac{1}{R_{z2}}\right)$$
$$+C_1'C_2'^2\left(\frac{1}{R_1}+\frac{1}{R_{z3}}\right)^2\left(\frac{1}{R_{z1}}\right)+C_1'^2C_{z3}\left(\frac{1}{R_1}+\frac{1}{R_{z3}}\right)\left(\frac{1}{R_{y1}}+\frac{1}{R_{z2}}\right)^2+2C_1'C_2'C_{z3}\left(\frac{1}{R_{y1}}+\frac{1}{R_{z2}}\right)\left(\frac{1}{R_1}+\frac{1}{R_{z3}}\right)\left(\frac{1}{R_{z1}}\right)$$
$$+C_2'^2C_{z3}\left(\frac{1}{R_1}+\frac{1}{R_{z3}}\right)\left(\frac{1}{R_{z1}}\right)^2+C_1'C_{z3}^2\left(\frac{1}{R_3+R_{x1}}\right)\left(\frac{1}{R_4+R_{x2}}\right)\left(\frac{1}{R_{y1}}+\frac{1}{R_{z2}}\right)+C_2'C_{z3}^2\left(\frac{1}{R_3+R_{x1}}\right)\left(\frac{1}{R_4+R_{x2}}\right)\left(\frac{1}{R_{z1}}\right)$$
$$+C_2'^2C_{z3}\left(\frac{1}{R_3+R_{x1}}\right)\left(\frac{1}{R_1}-\frac{1}{R_2+R_{x3}}\right)\left(\frac{1}{R_{z1}}\right)=0 \tag{14}$$

$$f_0' = \frac{1}{2\pi}\sqrt{\frac{1}{C_1C_2R_3R_4}\left[\frac{\frac{\left(\frac{1}{R_1}+\frac{1}{R_{z3}}\right)}{\left(1+\frac{R_{x1}}{R_3}\right)\left(1+\frac{R_{x2}}{R_4}\right)}+\frac{R_4\left(\frac{1}{R_1}-\frac{1}{R_2\left(1+\frac{R_{x3}}{R_2}\right)}\right)\left(\frac{1}{R_{y1}}+\frac{1}{R_{z2}}\right)}{\left(1+\frac{R_{x1}}{R_3}\right)}}{\left(1+\frac{C_{z1}}{C_1}\right)\left(1+\frac{C_{z2}+C_{y2}}{C_2}\right)\left(\frac{1}{R_1}+\frac{1}{R_{z3}}\right)+\left(1+\frac{C_{z1}}{C_1}\right)\left(\frac{C_{z3}}{C_2}\right)\left(\frac{1}{R_{y1}}+\frac{1}{R_{z2}}\right)+\left(1+\frac{C_{z2}+C_{y2}}{C_2}\right)\left(\frac{1}{R_{z1}}\right)\left(\frac{C_{z3}}{C_1}\right)}\right]^{1/2}} \tag{15}$$

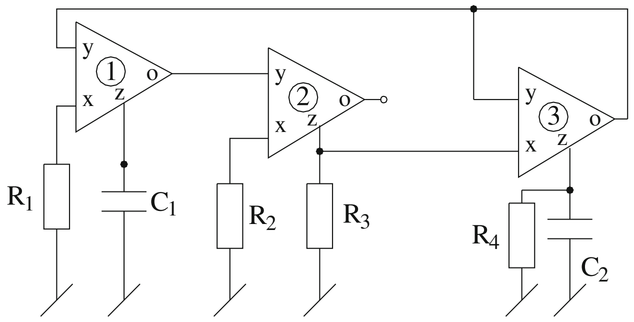

Fig. 5 Fully-uncoupled oscillator proposed by Soliman [20]

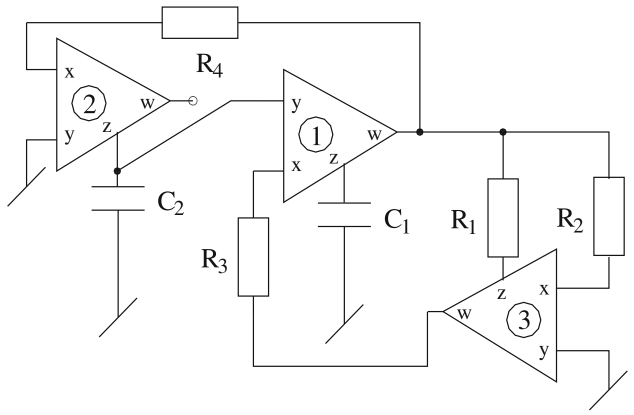

Fig. 6 Fully-uncoupled oscillator proposed by Bhaskar [44]

From Eqs. (10–12), and (13–15) it may be seen that in both the circuits of Figs. 5 and 6, all the four resistors employed therein are present in the CO as well as in FO. It is, therefore, concluded that in both these circuits *the fully-uncoupled nature of CO and FO is completely disturbed when the effect of parasitic of the CFOAs is accounted for.*

For the sake of comparison with previously known conventional type of CFOA-based SRCOs, a similar non-ideal

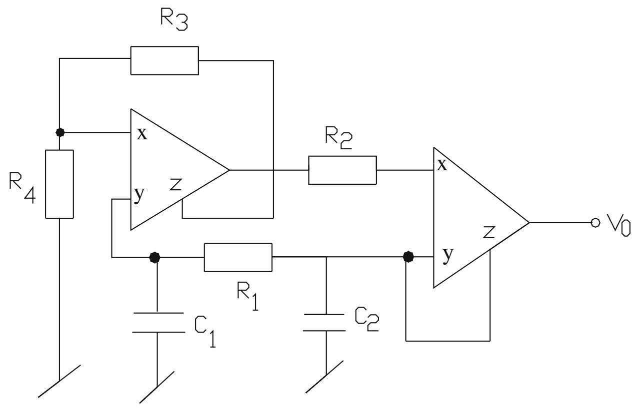

Fig. 7 An exemplary two-CFOA-GC oscillator proposed by Liu and Tsay [31]

analysis has been carried out for an exemplary two-CFOA-two-grounded capacitors (GC) SRCO from [31] shown in Fig. 7. In this context it may be noted that none of the single-CFOA SRCOs known till date employ both grounded capacitors while two-CFOA-based SRCOs do employ both grounded capacitors. However, out of various such two-CFOA-GC SRCOs, the closest to the present class appears to be the one proposed in [31] which also provides control of FO through two resistors (like the circuits proposed in this paper) and hence, the choice.

The circuit of Fig. 7 is ideally characterized by the following CO and FO:

$$\text{CO}: \left(1+\frac{C_2}{C_1}\right)=\frac{R_1}{R_2}$$

$$f_0=\frac{1}{2\Pi}\sqrt{\frac{R_3}{2C_1C_2R_1R_2R_4}}$$

However, a re-analysis of this circuit reveals that its non-ideal CE is given by:

$$s^3+s^2\left[\frac{1}{C_1'}\left(\frac{1}{R_1}+\frac{1}{R_{y1}}\right)+\frac{1}{C_2'}\left(\frac{1}{R_1}+\frac{1}{R'}-\frac{1}{R_2'}\right)+\frac{1}{C_{z1}}\left(\frac{1}{R_{z1}}+\frac{R_{x1}+2R_4}{R_{x1}R_3+R_{x1}R_4+R_3R_4}\right)\right]$$
$$+s\left[\frac{1}{C_1'C_2'}\left\{\frac{1}{R_{y1}}\left(\frac{1}{R_1}+\frac{1}{R'}-\frac{1}{R_2'}\right)+\frac{1}{R_1}\left(\frac{1}{R'}-\frac{1}{R_2'}\right)\right\}+\frac{1}{C_{z1}C_2'}\left\{\frac{1}{R_{z1}}\left(\frac{1}{R_1}+\frac{1}{R'}-\frac{1}{R_2'}\right)\right\}\right.$$
$$\left.+\frac{1}{C_{z1}C_1'}\left\{\frac{1}{R_{z1}}\left(\frac{1}{R_{y1}}+\frac{1}{R_1}\right)\right\}+\left(\frac{R_{x1}+2R_4}{R_{x1}R_3+R_{x1}R_4+R_3R_4}\right)\left\{\frac{1}{C_{z1}C_2'}\left(\frac{1}{R_1}+\frac{1}{R'}-\frac{1}{R_2'}\right)+\frac{1}{C_{z1}C_1'}\left(\frac{1}{R_{y1}}+\frac{1}{R_1}\right)\right\}\right]$$
$$+\frac{1}{C_1'C_2'C_{z1}}\left[\left(\frac{1}{R_{z1}}+\frac{1}{R_3}\right)\left\{\frac{1}{R_{y1}}\left(\frac{1}{R_1}+\frac{1}{R'}-\frac{1}{R_2'}\right)+\frac{1}{R_1}\left(\frac{1}{R'}-\frac{1}{R_2'}\right)\right\}+\frac{\left(\frac{1}{R_3}-\frac{1}{R_{x1}}\right)\left(\frac{1}{R_1}\frac{1}{R_{x1}}\frac{1}{R_2'}\right)-\frac{1}{R_3}\left(\frac{1}{R_{y1}}+\frac{1}{R_1}\right)\left(\frac{1}{R_1}+\frac{1}{R'}-\frac{1}{R_2'}\right)}{\frac{1}{R_{x1}}+\frac{1}{R_3}+\frac{1}{R_4}}\right]$$

where $R' = R_{y2} \| R_{z2}$, $C_2' = C_2 + C_{z2}$, $C_1' = C_1 + C_{y1}$, $R_2' = R_{w1} + R_2 + R_{x2}$.

From above equation it is, thus, seen that, as expected, in this circuit also, when the various parasitic non-ideal effects of the CFOAs are accounted for, both the frequency-controlling resistors R_3 and R_4 creep into all the coefficients of the CE and hence, also in the CO.

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MIXED SIGNAL LETTER

New lossy/loss-less synthetic floating inductance configuration realized with only two CFOAs

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Abstract A new CFOA-based lossy/loss-less floating inductance circuit is introduced which, in contrast to previously known configuration requiring three to four CFOAs, employs only two CFOAs along with only five passive components. The workability of the new FI circuit has been demonstrated by using it to design a second order notch filter and a fourth order Butterworth low pass filter by realizing the circuit using commercially available AD844-type CFOAs.

Keywords Current feedback op-amps · Floating inductance simulation · Analog circuits

1 Introduction

Although a number of Current feedback op-amps (CFOA) based circuits are known for realizing lossless/lossy grounded inductance simulation have been made see [1–5], the number of CFOA-based circuits capable of simulating a lossless floating inductance (FI) have been rather limited and only the earlier works [6–9] can be cited in this context. A critical survey of CFOA-based FI circuits from the quoted references reveals that the FI circuits known so far require three (as in [6] and [7]) or four (as in [8] and [9]) CFOAs. To the best knowledge of the authors, any circuit for realizing a lossless FI using less than three CFOAs has not been reported in the open literature so far.

It may be mentioned that two dual outputs CCII (DO CCII) (characterized by $i_y = 0, v_x = v_y; i_{z+} = i_{x+}, i_{z-} = i_{x-}$) along with only two resistors and a capacitor can be used to simulate a loss-less inductance, however, such a device, unfortunately, is not yet available commercially as an off-the-shelf IC. By contrast, the CFOA which embodies a three-terminal CCII + (characterized by $i_y = 0, v_x = v_y; i_z = i_x$) with its second output as a voltage output thereby leading to the fourth terminal 'w' providing $v_w = v_z$, is commercially available as an off-the-shelf IC. It is widely recognized that a CFOA with an externally excessive z-pin such as AD844 provides more versatility and flexibility in analog circuit design as demonstrated in [7, 10, 11].

The main objective of this paper is, therefore, to present a new circuit which employs only two CFOAs along with only five passive components (namely two capacitors and three resistors) to realize a lossy/loss-less FI. To verify and demonstrate the practical workability of the new FI circuit, two application examples, well supported by appropriate hardware implementation and SPICE simulation results based upon AD844- type CFOAs, have been presented.

2 The proposed circuit configuration

The proposed new FI configuration is shown in Fig. 1. Assuming CFOAs to be characterized by $i_y = 0, v_x = v_y, i_z = i_x$ and $v_w = v_z$, a straight forward analysis of the circuit reveals its y- matrix to be given by

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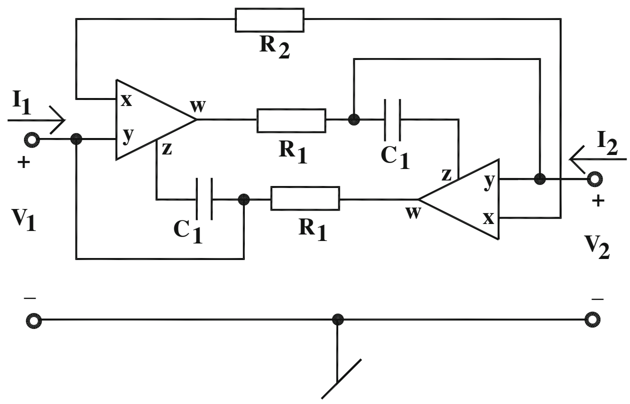

Fig. 1 Proposed new FI configuration

$$[Y] = \left[\left(\frac{1}{R_1} - \frac{1}{R_2}\right) + \frac{1}{sC_1R_1R_2}\right]\begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix} \tag{1}$$

Thus, with $R_1 < R_2$, the circuit simulates floating parallel-RL admittance with equivalent resistance R_{eq} and equivalent inductance L_{eq} are given by

$$\frac{1}{R_{eq}} = \frac{1}{R_1} - \frac{1}{R_2};\ L_{eq} = C_1R_1R_2. \tag{2}$$

On the other hand, with $R_1 = R_2 = R_0$, the circuit simulates a lossless FI with

$$L_{eq} = C_1R_0^2 \tag{3}$$

3 Sensitivity analysis

For determining the classical sensitivity coefficients, the circuit is re-analyzed for unequal values of passive components where the resistor R_1 between w-terminal of the first CFOA and y-terminal of the second CFOA has been renamed as R_3 while the capacitor C_1 connected between the y-terminal and z-terminal of second CFOA has been renamed as C_2. This leads to the following y-parameters:

$$y_{11} = \left(\frac{1}{R_1} - \frac{1}{R_2}\right) + \frac{1}{sC_2R_1R_2} \quad \text{which gives} \quad R_{11} = \frac{R_1R_2}{R_2 - R_1}; L_{11} = C_2R_1R_2 \tag{4}$$

$$y_{12} = -\left[\left(\frac{1}{R_1} - \frac{1}{R_2}\right) + \frac{1}{sC_2R_1R_2}\right] \quad \text{which gives} \quad R_{12} = \frac{R_1R_2}{R_2 - R_1}; L_{12} = C_2R_1R_2 \tag{5}$$

$$y_{21} = -\left[\left(\frac{1}{R_3} - \frac{1}{R_2}\right) + \frac{1}{sC_1R_3R_2}\right] \quad \text{which gives} \quad R_{21} = \frac{R_3R_2}{R_2 - R_3}; L_{21} = C_1R_3R_2 \tag{6}$$

$$y_{22} = \left(\frac{1}{R_3} - \frac{1}{R_2}\right) + \frac{1}{sC_1R_3R_2} \quad \text{which gives} \quad R_{22} = \frac{R_3R_2}{R_2 - R_3}; L_{22} = C_1R_3R_2 \tag{7}$$

The various sensitivity coefficients with respect to passive elements are given by

$$S_{R_1}^{R_{11}} = \frac{R_2}{R_2 - R_1}, S_{R_2}^{R_{11}} = -\frac{R_1}{R_2 - R_1}, S_{C_1}^{R_{11}} = S_{C_2}^{R_{11}} = S_{R_3}^{R_{11}} = 0$$
$$S_{R_1}^{L_{11}} = S_{R_2}^{L_{11}} = S_{C_2}^{L_{11}} = 1, S_{C_1}^{L_{11}} = S_{R_3}^{L_{11}} = 0$$
$$S_{R_1}^{R_{12}} = \frac{R_2}{R_2 - R_1}, S_{R_2}^{R_{12}} = -\frac{R_1}{R_2 - R_1}, S_{C_1}^{R_{12}} = S_{C_2}^{R_{12}} = S_{R_3}^{R_{12}} = 0$$
$$S_{R_1}^{L_{12}} = S_{R_2}^{L_{12}} = S_{C_2}^{L_{12}} = -1, S_{C_1}^{L_{12}} = S_{R_3}^{L_{12}} = 0$$
$$S_{R_2}^{R_{21}} = \frac{R_3}{R_3 - R_2}, S_{R_3}^{R_{21}} = -\frac{R_2}{R_3 - R_2}, S_{C_1}^{R_{21}} = S_{C_2}^{R_{21}} = S_{R_1}^{R_{21}} = 0$$
$$S_{R_3}^{L_{21}} = S_{R_2}^{L_{21}} = S_{C_1}^{L_{21}} = -1, S_{C_2}^{L_{21}} = S_{R_1}^{L_{21}} = 0$$
$$S_{R_2}^{R_{22}} = \frac{R_3}{R_3 - R_2}, S_{R_3}^{R_{22}} = -\frac{R_2}{R_3 - R_2}, S_{C_1}^{R_{22}} = S_{C_2}^{R_{22}} = S_{R_1}^{R_{22}} = 0$$
$$S_{R_3}^{L_{22}} = S_{R_2}^{L_{22}} = S_{C_1}^{L_{22}} = 1, S_{C_2}^{L_{22}} = S_{R_1}^{L_{22}} = 0$$

From the above, it may be seen that although the sensitivities of the inductive parts of all the four y-parameters are very small, on the other hand, the sensitivities of equivalent resistive parts could be quite large for $R_1 \approx R_2$ and $R_2 \approx R_3$. However, the magnitudes of these sensitivities can be made less than or equal to 1 by either taking $R_1 \ll R_2$ and $R_3 \ll R_2$ (i.e. using the circuit as a non-ideal FI with *positive* series resistance) or else by taking $R_1 \gg R_2$ and $R_3 \gg R2$ (in which case the realization will still be non-ideal but the associated series resistance will be *negative*). It may, however, be pointed out that using appropriate network transformations presented earlier in [19, 20] even non-ideal simulated inductances can be employed *directly* as elements in the design of higher order ladder filters. Also, it must also be kept in mind that classical sensitivity coefficients give an idea about the incremental changes in the functions/parameters of interest with respect to incremental changes in one component value at a time, assuming that incremental changes in all other component values are zero and hence, do not give a realistic picture. In practice, to realize a lossless FI from the proposed circuit, perfectly-matched (verified by actual measurements) resistors R_1, R_2 and R_3 have been employed and the performance of the low pass Butterworth filter, employing two lossless FIs of the proposed kind, has been found to be quite satisfactory. It can be easily checked that even with 1 % mismatch in resistance values say $R_2 = 1.01$ kΩ and $R_1 = 1$ KΩ, the equivalent parallel resistance, instead of infinity, would still be of the order of 101 KΩ and hence, fairly larger than the inductive reactance at the frequency of interest so that

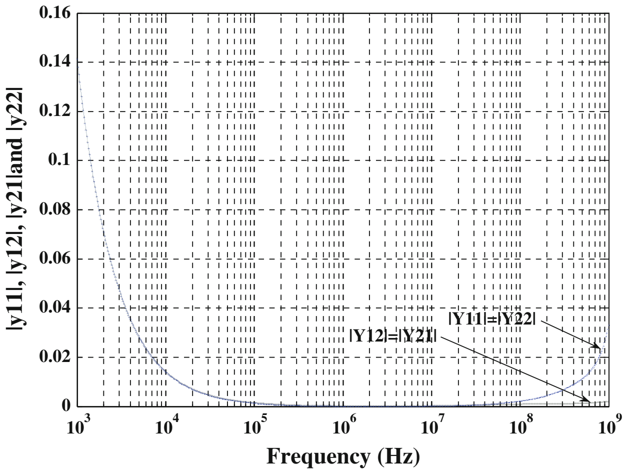

Fig. 2 Frequency response of $|Y_{11}| = |Y_{22}|$ and $|Y_{12}| = |Y_{21}|$

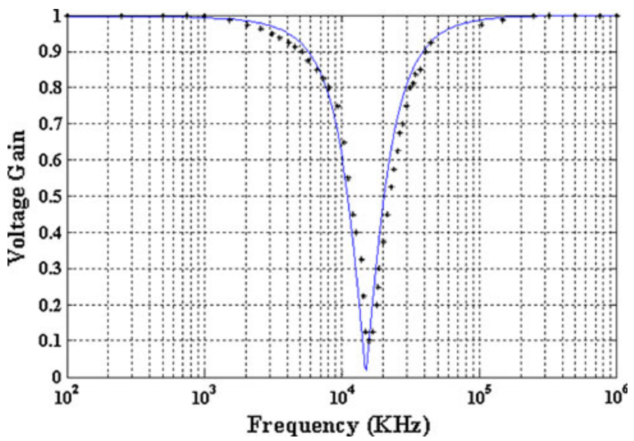

Fig. 3 Experimentally obtained frequency response of the notch filter realized from the proposed FI

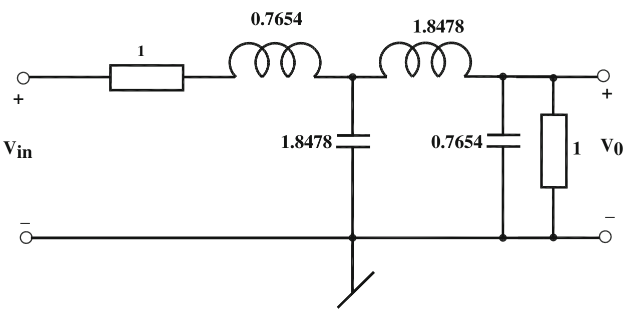

Fig. 4 Normalized 4th-order Butterworth low pass filter

the behavior of the circuit would remain dominantly inductive and due to this, the performance of the circuit in which the proposed kind of FIs are employed will not be having any noticeable degradation. In view of this, a more realistic assessment about the effect of mismatches of identical component values used in the proposed FI, on the performance of the circuit in which the proposed FIs have been employed, can be obtained through MONTE CARLO (MC) analysis, the results of which (included in Fig. 6 of Sect. 5) corroborate the above inference.

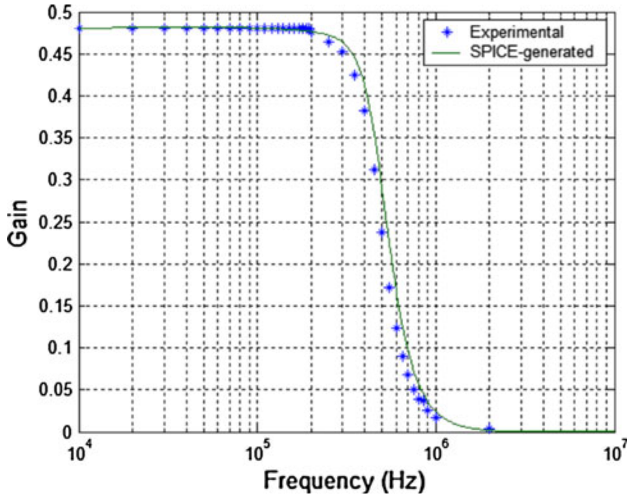

Fig. 5 Frequency response of 4th-order Butterworth low pass filter

4 The non-ideal effects

With the parasitic impedances of the CFOAs accounted for, i.e. considering the finite input impedance looking into terminal-X as R_x and the output impedance looking into terminal-Z consisting of a parasitic resistance R_p in parallel with a parasitic capacitance C_p, it is found that in view of the symmetry of the circuit, the non-ideal y-parameters are such that $Y'_{11} = Y'_{22}$ and $Y'_{12} = Y'_{21}$. The values of these admittance parameters are found to be.

$$Y'_{11} = Y'_{22} = \frac{1}{R_1} + \frac{sC_1}{(1 + sC_1Z_p)} - \frac{sC_1Z_p}{(1 + sC_1Z_p)(R_2 + 2R_x)} + \frac{Z_p}{(1 + sC_1Z_p)(R_1R_2 + 2R_1R_x)} \tag{8}$$

$$Y'_{12} = Y'_{21} = -\left[\frac{sC_1Z_p}{R_1(1 + sC_1Z_p)} - \frac{sC_1Z_p}{(1 + sC_1Z_p)(R_2 + 2R_x)} + \frac{Z_p}{(1 + sC_1Z_p)(R_1R_2 + 2R_1R_x)}\right] \tag{9}$$

It may be seen that with $Z_p \rightarrow \infty$, $R_x \rightarrow 0$, the y-parameters in Eqs. (8) and (9) reduce to those in (1). From the non-ideal expressions of the y-parameters of the proposed circuit it may be easily visualized that the high frequency

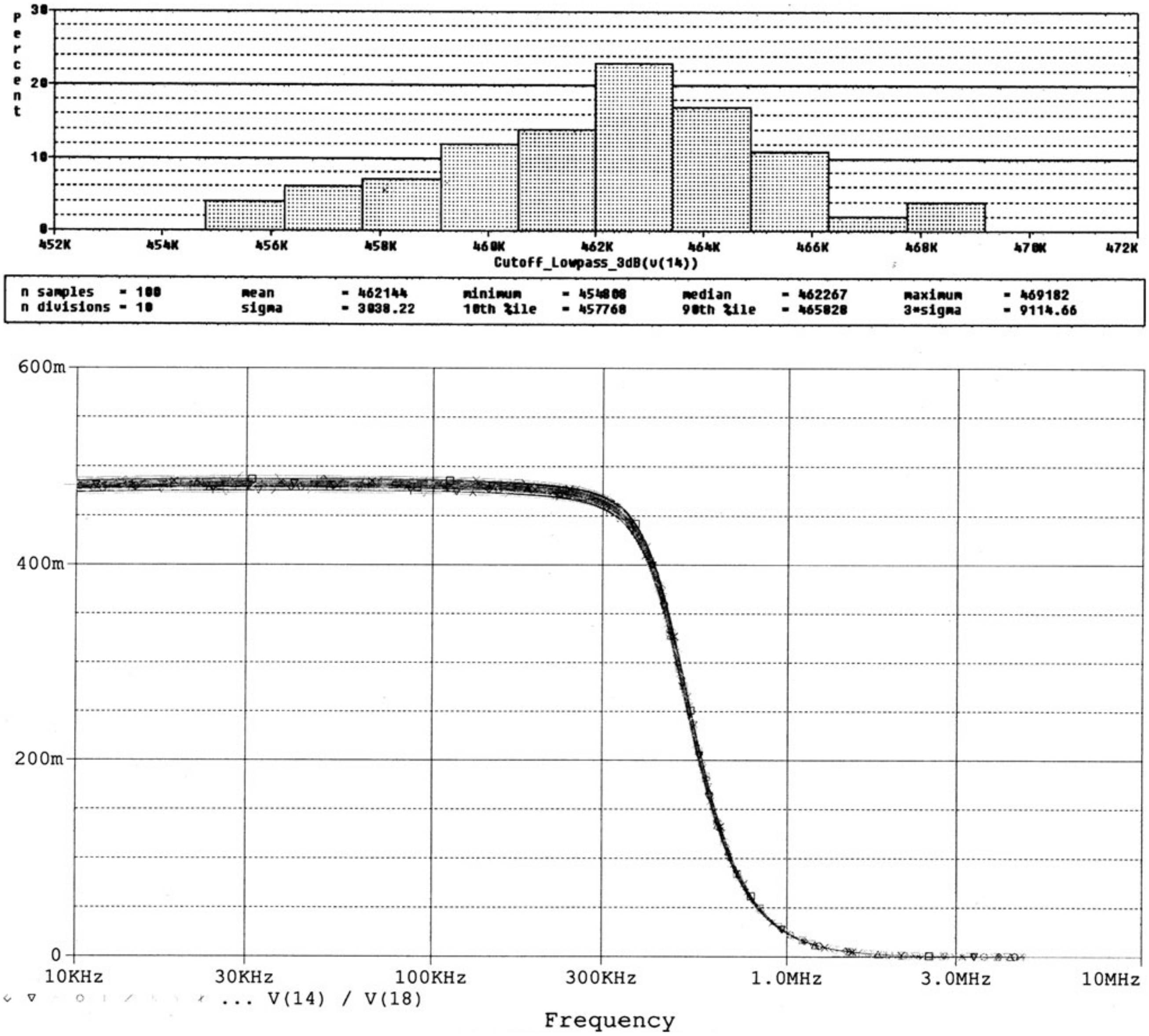

Fig. 6 Simulation results of MONTE CARLO analysis

performance would be affected because of these parasitic impedances. However, this is a common limitation exhibited by all inductance simulation circuits known so far and hence, is not a drawback with our circuit only. Also, it may be readily visualized that the equivalent non-ideal inductive and resistive components resulting from all the four y-parameters of Eqs. (8) and (9) would be frequency-dependent. With $R_x = 50\Omega, R_p = 3M\Omega, C_p = 4.5pF$ and the circuit designed with $C_1 = 1nF, R_0 = 1k\Omega$ to realize a lossless FI of 1mH, from MATLAB frequency responses of $|Y_{11}| = |Y_{22}|$, $|Y_{12}| = |Y_{21}|$ have been obtained which are shown in Fig. 2. The MATLAB plots of non-ideal y-parameters of the proposed circuit shown in Fig. 2 (Sect. 4) show that in the proposed circuit, the y-parameters remain intact (and hence, the circuit is useable) up to a frequency of around 10 MHz which is reasonably good. This frequency range of the circuit has also been confirmed from a SPICE simulation of the circuit for the same component values using a macro model of AD844.

5 Application examples

To demonstrate the workability of the new lossless FI circuit, we present here two application examples.

Table 1 Comparison of the proposed configuration with earlier published FIs using CFOAs, OTAs and OAs

Reference Number	Building block used	Number of resistors used	Number of capacitors used	Number of active building blocks used	Commercial availability of the building block
Chang and Hwang [6]	CFOA	02	01	03	Yes
Senani [7]	CFOA	02	01	03	Yes
Senani et al. [8]	CFOA	02	01	04	Yes
Psychalinos et al. [9]	CFOA	04	01	05	Yes
Yuce and Minaei [14]	MCFOA	02	01	02 (equivalently 06 CFOAs)	No
Nandi [15]	OTA	Nil	01	03	Yes
Senani [16]	OA	07	01	03	Yes
Singh [17]	OA	16	01	04	Yes
Senani [18]	OA	12	01	02	Yes
Proposed	CFOA	03	02	02	Yes

(i) As the first application of the new FI circuit, it was used to realize in hardware, a second order RLC notch filter[1] consisting of a parallel combination of Leq and C_0 and a shunt resistor R_0, with component values taken as $C_1 = 1$ nF, $C_0 = 0.1$ µF, $R1 = R_2 = 1$ kΩ, $R_0 = 0.1$ kΩ corresponding to the design parameters of the filter as $f_0 = 15.9$ kHz, $H_0 = 1$ and bandwidth = 15.9 kHz. The experimentally observed frequency response of the notch filter using AD844-type CFOAs, biased with ± 15 volts DC power supplies, is shown in Fig. 3 which is found to be in reasonable good agreement with the ideal one and thus, confirms the workability of the circuit as an FI.

(ii) To check the usability of the new lossless FI circuit in a higher order filter design, a fourth order Butterworth low pass filter with a cutoff frequency of 500 kHz was designed using the normalized proto-type shown is Fig. 4. The component values, after appropriate frequency and impedance scaling, were taken as $R_s = R_L = 1$ kΩ, $L_{1d} = 0.2437$ mH ($R_1 = R_2 = 1$ kΩ and $C_1 = C_2 = 0.1$ nF), $C_{1d} = 0.5884$ nF, $L_{2d} = 0.5884$ mH ($R_1 = R_2 = 1$ kΩ and $C_1 = C_2 = 0.1$ nF), $C_{2d} = 0.2437$ nF. AD844 were biased with DC power supplies ± 12 volts. The experimental frequency response obtained by MATLAB and the simulated through PSPICE simulations by realizing the two lossless FIs by AD844-type CFOAs is shown in Fig. 5.

The results demonstrated in Figs. 2, 3, 4, 5, thus, confirm the practical applicability of the new FI configuration.

To study the effect of mismatches in the component values within the FIs, on the performance of the circuit of Fig. 4, MC simulations have been carried out by allocating 1 % tolerances to the component values within both FIs and performing 100 runs in each case. The results for the case of 1 % tolerance have been shown in Fig. 6. It has been found that while SPICE-determined cut-off frequency for nominal design was $f_o = 463.291$ kHz, the MC analysis shows the median value as 462.267 kHz which indicates that the mismatches in the component values within the proposed FIs do not have large effect on the realized cutoff frequency (which is seen to be in contrast to the inference emerging from the classical sensitivity analysis) and are well within the acceptable limits.

6 Comparison of proposed FI with previously known CFOA and OTA based FIs

A comparison of the various salient features of the proposed circuit as compared to other previously known OA-based, CFOA-based and OTA-based FI simulators has been carried out in Table 1.

It may be noted that Ref. [14] has described two FI circuits using the so-called modified CFOA (MCFOA). Each circuit therein employs two MCFOAs, two resistors and a single (grounded) capacitor. However, a MCFOA is not available commercially. On the other hand, when an MCFOA is implemented with AD844 type CFOAs, as many as three AD844 type CFOAs are needed for each MCFOA. Thus, each of the proposed FI circuit of Figs. 4 and 5 of [14] would require six CFOAs of the normal kind. Thus, whereas the circuits of Figs. 4 and 5 of [14] have the advantage of employing only one (grounded) capacitor, on the other hand, the proposed circuit, although requires two identical capacitors and three resistors, it has the advantage of employing only two AD844 type CFOAs.

[1] For single CFOA-based biquadratic filter realizations, the reader is referred to [12], [13].

7 Concluding remarks

A new configuration for realizing a lossy/loss-less FI using commercially available CFOAs is introduced which provides the following advantages, not available in the previously known FI circuits of [6–9]:

(i) employment of only two CFOAs in contrast to previously known CFOA-based FIs of [6–9] requiring three to four CFOAs.
(ii) the flexibility of realizing either lossless or lossy FI from the same circuit.
(iii) employment of a small number (only five) of passive components and.
(iv) requirement of simple component-matching condition (only in case of lossless FI realization).

The workability and the applications of the new FI configuration have been demonstrated through implementation of a second order notch filter and a 4th order Butterworth low pass filter using SPICE simulations (including Monte Carlo analysis) and hardware implementation results using AD844 type commercially available IC CFOAs.

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OPTIMIZATION OF QOS PARAMETERS IN COGNITIVE RADIO USING ADAPTIVE GENETIC ALGORITHM

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ABSTRACT

Genetic algorithm based optimization rely on explicit relationships between parameters, observations and criteria. GA based optimization when done in cognitive radio can provide a criteria to accommodate the secondary users in best possible space in the spectrum by interacting with the dynamic radio environment at real time. In this paper we have proposed adaptive genetic algorithm with adaptive crossover and mutation parameters for the reasoning engine in cognitive radio to obtain the optimum radio configurations. This method ensure better controlling of the algorithm parameters and hence the increasing the performance. The main advantage of genetic algorithm over other soft computing techniques is its multi € objective handling capability. We focus on spectrum management with a hypothesis that inputs are provided by either sensing information from the radio environment or the secondary user. Also the QoS requirements condition is also specified in the hypothesis. The cognitive radio will sense the radio frequency parameter from the environment and the reasoning engine in the cognitive radio will take the required decisions in order to provide new spectrum allocation as demanded by the user. The transmission parameters which can be taken into consideration are modulation method, bandwidth, data rate, symbol rate, power consumption etc. We simulated cognitive radio engine which is driven by genetic algorithm to determine the optimal set of radio transmission parameters. We have fitness objectives to guide one system to an optimal state. These objectives are combined to one multi € objective fitness function using weighted sum approach so that each objective can be represented by a rank which represents the importance of each objective. We have transmission parameters as decision variables and environmental parameters are used as inputs to the objective function. We have compared the proposed adaptive genetic algorithm (AGA) with conventional genetic algorithm (CGA) with same set of conditions. MATLAB simulations were used to analyze the scenarios.

KEYWORDS

Cognitive Radio, Genetic Algorithm, Optimization

1. INTRODUCTION

Because of the growth of the number of services, the spectrum which is a limited natural resource is becoming scarce. Various studies and measurements show that the spectrum is not being

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utilized efficiently at any given time and space [1]. It has been noticed that the peak traffic of each system occurs during specific times and within specific locations. There have been many studies on the challenges associated with the realization of cognitive radio, some of these are (1) efficient use of the available spectrum (spectrum holes) (2) Spectrum Mobility (3) Energy efficiency (4) Spectrum Decision (5) Accurate Sensing and (6) QoS provisioning. The support of quality of service in optimization of the cognitive radio scenario is also a challenging problem.

The key question is "How the secondary user would find (in the fastest way) about the free slot of the available spectrum and make necessary decisions to occupy it and at the same time guarantee the QoS of the primary as well as secondary users". The answer to this question depends on various factors like the degree of cooperation between the primary and secondary users, the reliability of the spectrum sensing and sharing scheme, the capabilities of the secondary and primary networks etc. This paper focuses on the QoS provisioning of the cognitive radio. Also the integration of real time or practical learning capabilities is also a challenge in cognitive radios. Investigation of applications of lesser-known soft computing techniques can result in several benefits as it enables making decisions through predictions and also when accurate real time information is not available.

In this work, we focus on two methods. Firstly the Spectrum Sensing, in which the reliability of the spectrum sensing technique using fuzzy logic is studied and evaluated for QoS provisioning. Secondly, Spectrum Management, to control the QoS of the cognitive radio system by optimization of the system using genetic algorithm is studied and evaluated. We can combine the two methods to collectively address it as Spectrum Optimization.

2. GENETIC ALGORITHM

The concept of genetic algorithm lies on the fact that the measure of success of an individual is its fitness i.e. "survival of fittest". It states that the best combination of genes and their resulting chromosomes yields the strongest individual, which will survive the longest. The first step of GA requires the solutions to be encoded into chromosomes. In case of cognitive radio scenario, the configurable radio parameters like transmit power, modulation, coding rate, symbol rate, packet size etc. represent genes of a chromosome. We have taken such parameters for the chromosome construction; transmit power (P), bandwidth (BW) and symbol rate (Rs), modulation, bit rate (Rb) and one environmental parameter as noise power (N). These six genes will define the structure of the chromosome. We have considered the values of the parameters as discussed [2], for the implementation of cognitive radio as per IEEE 802.22 standard.

The structure of chromosome comprises of the above mentioned six parameters or genes. The parameters or genes are concatenated to form a string (chromosome). Table 1 gives the summarized values of the order of the genes, the ranges of operation and the binary bits required to encode the corresponding integer values.

Table 1 Summarized Values of the Chromosome Structure

Order	1	2	3	4	5	6
Gene	Power	Bandwidth	Symbol Rate	Bit Rate	Modulation	Noise Power
Ranges	-30dBm to 30dBm	40 to 840 MHz	1Mbps to 8Mbps	0 to 2 Mbps	-	-20 dBm - -15 dBm
Step Size	1 dBm	8 MHz	1 Mbps	125 Kbps	-	1 dBm
Integer Value Range	0 , 59	0 , 99	0 , 7	0 , 15	0 , 3	0 , 5
Binary Bits Required	6	7	3	4	2	3

The six parameters specified as genes in chromosome structure need 25 bits for its construction. The composition of this bit string is important because the mutation operation performs at bit level. Let us assume the parameters be x_1, x_2, x_3, x_4, x_5 and x_6 corresponding to the power, bandwidth, symbol rate, bit rate, modulation and noise power respectively. Fitness function for each parameter are generated by the following formula initiated in [3] is given as:

$$f_i = \left[\frac{w_i \cdot |x_i - x_i^d|}{x_i^d} \right] \text{ if } |x_i - x_i^d| < x_i^d \quad \ldots (1)$$

where x_i^d is the required QoS parameter, w_i is the weight subject to $\sum_{i=1}^{6} w_i = 1$, where $i = 1, 2, \ldots, 6$. Overall fitness function f_{total} is the cumulative sum of individual fitness functions of the parameters given as:

$$f_{total} = \sum_{i=1}^{6} f_i \quad \ldots (2)$$

The overall fitness value of the chromosomes in percentage is

$$\text{Total fitness value (\%)} = 100\left[1 - \sum_{i=1}^{6} f_i\right] \quad \ldots (3)$$

Ideally each w_i should be 16.7 %, that means each gene will have the same weight. But in practical scenario, the weighing factor w_i can vary according to QoS specifications. Selection - We compare the total fitness of the chromosomes using equation 3 and the best solutions from pool of chromosomes are selected using „Roulette wheel selection…. It states that the probability of selection for each individual (chromosome) is given by:

$$p_i = \frac{f_i}{\sum_{i=1}^{n} f_i} \quad \ldots (4)$$

p_i is the probability of selection of individual chromosome i. f_i is the fitness of the individual gene i. n is the number of chromosome in the population. The individuals (chromosomes) having the maximum probability value are transferred to the next generation. Subsequently, with each generation the fittest chromosomes are selected and transferred to next generation and made new population until the termination criteria is reached

Table 2 Performance Objective Functions and Objective Functions

S.No.	Objective Function	Equation	Remarks
1	Power Consumption (Pc)	$Pc = PR_s K$ [4]	P=Transmit Power (dBm); Rs= Symbol Rate(kbit/s); K=Signal Space dimensions (e.g. For PSK, K=1, for QAM, K=2);
2	Spectral Efficiency(η_B)	$\eta_B = \frac{R_b}{BW}$	R_b=bit rate (kbit/s); BW= Bandwidth;
3	Throughput (T)	$T = \frac{M_i}{Ni.M_{max}}$	M_i=Modulation index on channel i; Ni = Number of channels; M_{max}=Max Modulation Index
4	Signal to Noise Interference Ratio (SINR)	$SINR = \frac{P}{N + \sum_i I_i}$, where N = kTBW	P=Transmit Power(dBm); I = Interference ; k = Bolzmann constant = $1.38065x10^{23}$ J/K; T=Temperature; BW =Bandwidth.

Table 2 shows the performance objectives to be achieved to lead a system to an optimal state. We have specifies power consumption which has to be minimized, spectral efficiency which has to be maximized, throughput has to be maximized and signal to noise ratio to be maximized.

3. CONVENTIONAL GENETIC ALGORITHM

The QoS requirements of different parameters are evaluated for different channel bandwidths. This algorithm will have the flexibility to allow tradeoff between power consumption and spectral efficiency according to the specific QoS requirements. The algorithm is tested over a number of different initial GA settings and different adjustable parameters to compare numerical optimization performance.

Elitism, In this dissertation, we have used one more method of selection called elitism. With the process of elitism, some of the best chromosomes are selected from the current population and are transferred directly to the next generation before the crossover and mutation operations. We have set elitism rate of 2%. Crossover, Two chromosomes are selected from the current generation of population, arbitrarily and multi-point crossover operation is applied giving new pair of chromosomes. We have taken crossover rate of 90 %. This means that 90 out of 100 chromosomes will undergo crossover operation. Mutation , In this operation some randomly selected bits are made to flip and fit into any of any of the six genes of the chromosome. This operation will provide new solution space to the algorithm. The mutation rate we have taken is 5%. This rate can be increased to increase the fitness of the chromosomes. Termination criteria€ The steps above selection, crossover and mutation will repeat until termination criteria (best solution) is reached. We have used two termination criteria. Firstly, the number of generations is set to 1000 generations; secondly the convergence of population is set at .95. This means that as the generation progresses and reaches 95% (means 95% of the chromosomes share the same gene), the iterations are stopped. Here the average fitness approaches the best individual and the best solution is selected.

Drawback of conventional genetic algorithm

While applying genetic algorithm to solve optimization problem, we come across a phenomenon is called premature convergence [5]. When premature convergence occurs, the algorithm is converged too fast to a solution, which causes it to be trapped in local minima. The main cause of premature convergence is the lack of diversity because of the ineffectiveness or crossover and mutation operators. Because of premature convergence, the evolutionary algorithm cannot progress and some important genetic solutions are lost. To improve the performance of genetic algorithm we address this issue in our next section. We propose adaptive genetic algorithm with adapting operators and parameters. This is done by controlling the operators and parameters in such a way that they will change the values if the population is not producing enough fit individuals. This in turn will affect diversity and hence the performance of the algorithm will increase. Moreover, it will increase the adaptability of the cognitive radio that is its one of the main characteristic. The performance of the genetic algorithm is calculated by the average fitness convergence values. The higher the fitness score, the fitter the individuals in that generation and therefore the best solution can be achieved.

Table 3 Pseudo Code for a Conventional Genetic Algorithm

Inputs
‡ , Size of population
ˆ , Rate of mutation
‰, Number of Generations Output X , Solution
€ • Rate of crossover
Begin:
// Initialization
1. Sense the environment for inputs;
2. Convert the inputs into chromosomes by encoding them;
3. Generate ‡ feasible random solutions;
4. Save them in population Pop;
// Loop until the termination criteria is reached
5. for i = 1 to ‰ do;
// Selection Based on elitism and fitness function
6. ne = •.,;
7. Selection of best ne solutions from Pop and save them in Pop_1;
//Crossover
8. crossover nc = (•-ne).ƒ;
9. for j = 1 to nc do;
10. Select two solutions randomly from Pop, X_A and X_B;
11. Generate X_C and X_D by two point crossover to X_A and X_B;
12. Save X_C and X_D to Pop_2;
13. end for
//Mutation
14. for j = 1 to nc do;
15. Select a solution Xj from Pop_2;
16. Mutate each bit of Xj under the rate ˆ and generate a new solution Xj„
17. If Xj„ is unfeasible ;
18. Update Xj„ with a new feasible solution by repairing Xj„;
19. end if
20. update Xj„ with Xj„ in Pop_2;
21. end for
// Updation of Population
22. update Pop = Pop_1 + Pop_2;
23. end for
// Best Solution
24. Return the best solution X in Pop;

4. Proposed Adaptive Genetic Algorithm

The crossover and mutation operations are very important in the genetic algorithm for optimization in cognitive radio. Population adaptation was proposed by Newman et al. [3] in which the results from previous evolutions were utilized by seeding percentage of the initial generation with chromosomes from final generation of the last cognition cycle. This method improved the convergence rate of the algorithm to quite an extent. Subsequently, in [6] parameter adaptation in multicarrier environment was proposed by cognitive radio itself. It used binary ant colony optimization method to optimize the cognitive radio parameters given a set of objectives. The automation of the parameter and operator settings in genetic algorithm for optimization in cognitive radio still remains an unexplored area so far. We have focused our research on this issue. Therefore, we propose a generic scheme for adaptive crossover and mutation rates.

In conventional genetic algorithm, the genetic operators such as crossover and mutation work with a constant probability. However if we have different crossover and mutation rates, the algorithm traverses different search directions in the search space thus improving the performance. The essential design criterion of a cognitive radio is to adapt itself to the surrounding changing environment. Due to this dynamic changing scenario, the proposed method depends on maintaining an acceptable level of productivity throughout the process of evolution and thus it is essential that the designed algorithm adapt itself to the appropriate crossover and mutation rates, and thus optimizing out cognitive radio scenario.

Let the probability of crossover be p_c and probability of mutation be p_m. We use the progress value concept as in [7] for calculating the progress (adjustment rates) for the probabilities. Let X_A and X_B be two offsprings after crossover operation. Let F_{Sum_S} be the fitness sum of two offsprings and F_{Sum_P} denotes the sum of the parent individuals.

$$\text{Value } CP = F_{Sum\_S} + F_{Sum\_P} \qquad \ldots (5)$$

The generation undergoes n_c crossover operations. Average crossover progress is given by $\overline{CP}$

$$\overline{CP} = \frac{1}{n_c} \sum CP \qquad \ldots (6)$$

$\overline{CP}$ measures the overall performance of crossover operator in a generation. Similarly, the overall performance of mutation operator in a generation is calculated as follows:

$$MP = f_{new} + f_{old} \qquad \ldots (7)$$

where f_{new} is the fitness of new offspring and f_{old} is the fitness of the old offspring after mutation.

$$\overline{MP} = \frac{1}{n_m} \sum MP \qquad \ldots (8)$$

The crossover and mutation operator performances are calculated each generation and adjusted using the average progress values. The adjusted values of operators are as follows:

$$p_c = p_c + \mu_1 \quad \text{if} \quad \overline{CP} > \overline{MP} \qquad \ldots (9)$$

$$p_c = p_c - \mu_1 \quad \text{if} \quad \overline{CP} < \overline{MP} \qquad \ldots (10)$$

and

$$p_m = p_m + \mu_2 \quad \text{if} \quad \overline{CP} > \overline{MP} \qquad \ldots (11)$$

$$p_m = p_m - \mu_2 \quad \text{if} \quad \overline{CP} < \overline{MP} \qquad \ldots (12)$$

where μ_1 and μ_2 represent the amount of adjustments of p_c and p_m. Experimental results in [8] gives the values of the adjustments as:

$$\mu_1 = \mu_2 = 0.01 \frac{f_{max} - f_{avg}}{f_{max} - f_{min}} \quad \text{if} \quad f_{max} > f_{min} \qquad \ldots (13)$$

$$ð\eta_1 = ð\eta_2 = 0.01 \quad \text{if} \quad f_{max} = f_{avg} \qquad f \; (14)$$

Table 2 Pseudo Code for Proposed Adaptive Genetic Algorithm

Inputs
‡ , Size of Population
ˆ , Rate of Mutation
‰, Number of Iterations
Š, Rate of Crossover Output X , Solutions
Begin
// Initialization
1. Sense the environment for inputs;
2. Convert the inputs into chromosomes by encoding them;
3. Generate feasible random solution;
4. Save them in Pop;
// Loop1 until termination criteria is reached
5. for i = 1 to ‰ do;
// Selection based on fitness function
6. Selection of best individuals in Pop;
7. Save them in Pop_1;
//Loop2 Start
// Crossover and Mutation
8. Select two parents from Pop_1;
9. Perform Crossover operation;
10. Save the offspring values in Pop2;
10. Accumulate the crossover progress value CP;
11. Perform Mutation Operation;
12. Mutate each bit of Xj in Pop_2 under the rate ˆ and generate a new solution Xj_n
13. Update the offspring value Xj_n in Pop_2;
14. Accumulate the mutation progress value MP;
// Loop2 end
// Progress Rates and Adjustments
15. Calculate $\overline{CP}$;
16. Adjust crossover rate Š;
17.Calculate $\overline{MP}$;
18. Adjust Mutation rate ˆ;
// Updation of Population
19. Update Pop= Pop_1+Pop_2;
// End Loop1
// Best Solution
20. Return the best solution X in Pop;

5. SIMULATION RESULTS

Our simulation is targeted to determine the convergence speed of the fitness function using conventional genetic algorithm. We also analyze the fitness value the system converges to. Weights are defined in Table 6, which are used to create four different search modes for the cognitive radio. Mode 1 is the low power mode (for applications e.g. text messaging), Mode 2 is the high efficiency mode (e.g. ECG data), Mode 3 is the high throughput mode (e.g. broadband video download) and Mode 4 is specifies for high reliability (e.g. defense services).

Table 5 Genetic Algorithm Settings

S. No.	Parameter	Value
1.	Population Size	50
2.	Length of Chromosomes	25 bits
3.	Number of Generations	1000
4.	Crossover Rate	90%
5.	Mutation Rate	5%
6	Elitism Rate	2%

We aimed at targeting the speed of convergence of the fitness function using CGA(Conventional Genetic Algorithm) and AGA (Adaptive Genetic Algorithm). Figure 1 shows the comparison of the fitness convergence for CGA and AGA in lower power mode (Mode 1), Figure 2 shows the comparison of the fitness convergence scenario for CGA and AGA in high efficiency mode (Mode 2). Figure 3 shows the comparison of the fitness convergence scenario for CGA and AGA in high throughput mode (Mode 3). And Figure 4 shows the comparison of fitness convergence scenarios for CGA and AGA in high reliability mode(Mode 4).

Table 6 Weight Values

Objective	w1	w2	w3	w4
Mode 1	0.65	0.15	0.08	0.12
Mode 2	0.12	0.65	0.15	0.08
Mode 3	0.08	0.12	0.65	0.15
Mode 4	0.15	0.08	0.12	0.65

Figure 1 Comparison of Average Fitness Scores of CGA and AGA for Mode 1 (Low Power Mode)

Figure 2 Comparison of Average Fitness Scores of CGA and AGA for Mode 2 (High Efficiency Mode)

Figure 3 Comparison of Average Fitness Scores of CGA and AGA for Mode 3 (High Throughput Mode)

Figure 4 Comparison of Average Fitness Scores of CGA and AGA for Mode 4 (High Reliability Mode)

The results clearly show that the AGA (Adaptive Genetic Algorithm) outperforms the CGA (Conventional Genetic Algorithm) in all the four modes of operation. The fitness convergence values for the two algorithms are compared in Table 7.

Table 7 Comparison of Fitness Convergence Values

Generation Number	Mode 1		Mode 2		Mode 3		Mode 4	
	CGA	AGA	CGA	AGA	CGA	AGA	CGA	AGA
100	.8526	.8967	.7236	.8765	.6833	.8345	.8491	.9345
500	.9033	.9287	.7625	.8914	.6912	.8582	.8782	.9647
1000	.9567	.9654	.7989	.9581	.7087	.8999	.9579	.9737

It was analyzed that the best solution with the fitness value of the gene converging to zero, but in our result the converging point is 0.2016 as shown in Figure 5.

Figure 5 Overall Fitness Value Plot for AGA

Figure 6 Generation Vs. Parameter Value (%) for AGA

With the proposed algorithm, it is found that the best value of the parameter to obtain the required QoS specification for the cognitive radios system is for the frequency as shown in Figure 6. The percentage of the best total fitness values against the average fitness values for AGA is shown in Figure 7. It shows that the proposed algorithm has 84 % of best fitness values, which is more than the previous algorithms proposed by the researchers.

Figure 7 Plot of the Fitness Values in (%) for AGA

Table 8 Comparison for the transmission parameter values after 1000 iterations.

Objective	Average Power (Pt) (dBm)		Bit Rate (Rb) (Mbps)		Modulation index (Mi)	
	CGA	AGA	CGA	AGA	CGA	AGA
Low Power Mode	3.267	2.763	0.687	0.834	4.768	2.76
High Efficiency Mode	10.45	9.76	0.852	0.966	4.891	3.48
High Throughput Mode	12.678	10.456	1.783	1.968	8.873	7.12
High Reliability Mode	5.463	4.113	1.569	1.683	6.873	5.76

Finally, the values of the transmission parameters were calculated and analyzed for both the algorithms as summarized in Table 8. It shows that the goal was achieved in every mode of operation. After 1000 iterations, the cognitive radio was able to decrease the power to an average of 2.763 dBm. For the second goal to increase the efficiency the power had to be increased but the modulation index was reduced. For high throughput mode, the power is increase to increase the bit rate for high throughput transmission purposes. And for the fourth mode to increase the reliability the balanced approach is applied, the power is kept not too high or not too low for ensuring the reliability of the transmission.

6. CONCLUSION

In this paper, we developed performance objective fitness functions representing the relationship between the transmission and environmental parameters that were identified in the literature survey. For the implementation to be simple, we have not considered all the parameters, which contribute to the cognitive radios system but a set of parameters that contribute to good extent. The parameters were encoded using binary encoded method into chromosomes. The chromosome of 25-bit length string was used. We first carried out the simulation scenario on conventional genetic algorithm (CGA). The pseudo code was developed for step-by-step implementation of the genetic algorithm implementation. The same set of conditions were tested upon the proposed adaptive genetic algorithm (ADA) in which the crossover and mutation rates were automated. This automation was based upon the previous fitness values and previous crossover and mutation rates. The progress _value function was initialized, which measures the overall performance of the crossover and mutation operators in a generation. The required adjustments are made for the crossover and mutation rates that are decided by the progress _value function. The results of the proposed algorithm show that the optimal solutions give the values for individual genes that accommodate the secondary user with a specific QoS requirement. But the tradeoff between the parameters has to be managed as the behavior is not linear. The simulation results shows that the proposed method gives better solution to the cognitive system with adapting capabilities and converges faster than the conventional methods of optimization of cognitive radio parameters. The QoS parameters optimized by the proposed algorithm have higher fitness values and also have the capability to manage the tradeoff between multiple objectives more effectively. The convergence plots illustrated the expected trends but the best convergence fitness value reaches stability at 95% in case of the proposed adaptive genetic algorithm. The problem of premature convergence was also solved as the proposed adaptive genetic algorithm adjusts to the suitable crossover and mutation rates to reduce the effort of searching for appropriate crossover and mutation rates.

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PROPOSING SECURITY REQUIREMENT PRIORITIZATION FRAMEWORK

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ABSTRACT

Security has always been a great concern for all software systems due to the increased incursion of the wireless devices in recent years. Generally software engineering processes tries to compel the security measures during the various design phases which results into an inefficient measure. So this calls for a new process of software engineering in which we would try to give a proper framework for integrating the security requirements with the SDLC, and in this requirement engineers must discover all the security requirements related to a particular system, so security requirements could be analyzed and simultaneously prioritized in one go. In this paper we will present a new technique for prioritizing these requirement based on the risk measurement techniques. The true security requirements should be easily identified as early as possible so that these could be systematically analyzed and then every architecture team can choose the most appropriate mechanism to implement them.

Keywords

Security Requirements, Threats, Vulnerabilities, Assets, Prioritization

1. INTRODUCTION

Whenever there is the case of security issues attached with any particular system, it is of a great concern for the software applications. And so to develop a secure software application which would be efficient enough, there is always the need to use the security engineering process which consists of activities such as security requirement elicitations, analysis & prioritizations, specification and management, etc. In SDLC [4], the security requirement process is generally defined with several functional and non functional requirements. And these days, the security of the software applications is the main priority so security requirements processes should be implemented during the different design and the development phases of the SDLC process of a particular system. And so we should also analyze and prioritize them according to the threat severity of a system

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And these days the applications for different softwares are also becoming very heterogeneous and vulnerable in some way. As reported in CERT [1] Security vulnerabilities have grown exponentially in this period. Attackers have sophisticated attack techniques to break security measures enforced by developers, which has lead to many crushing consequences like denial of services, etc.

Generally software engineering processes compels the security measures during the various design phases which results in using an inefficient measure. So this calls for a new software engineering process, so it is dedicated to designing, implementing and modifying software so that it is of high quality, affordable, maintainable, and fast to build. In simple terms the software engineering could be defined as the, "systematic approach to the analysis, design, assessment, implementation, test, maintenance and reengineering of software, that is, the application of engineering to software"[2].

The basic idea in this research work will move around the concept of Security Requirements and its Prioritization. Prioritization is one of the important activities in the requirements engineering process, which aims in identifying the most fitting requirements for a specific release of a system. Generally, projects face limited resources such as short timelines, small budgets, restricted human power, and limited technology. As a result, projects often contain more candidate requirements that can be implemented in one product release time. Stakeholders need to decide which requirements should be implemented.[3] Requirements prioritization helps the project developers to select the final candidate requirements within their resource constraints. As Firesmith [4] has defined security requirement to be high level requirement that gives detailed specification of system behaviour that is not acceptable which is also distinguish these from security related architectural constraints. This is done so that requirement engineer can discover all the true security requirements [5].

Before we can determine that a program is secure, we always have to determine that what exactly its actual security requirements. There is an international standard for identifying and defining these security requirements which are useful for many such circumstances which is the Common Criteria (CC).[6] The CC is basically used for the work to identify the information technology security requirements. There are also many other schemes which are available for defining security requirements and evaluating products to see if products meet the requirements, but some other schemes are generally focused on a specialized area and won't be considered further.

The requirements for eliciting different methods for a software are much, but we very less often see these elicitation performed specifically for security requirements. The one main reason for this is that few elicitation methods are specifically directed at security requirements. Another factor is that organizations not often address these security requirements elicitation specifically and instead chunk of them in with other traditional requirements elicitation methods. The requirements using templates [7] uses these different eliciting security methods but these are not integrated in conventional requirements engineering process.

2. Related Work

In software engineering, the securities and its requirements must be discovered along with the other requirements of the system. Security requirements should be precise, adequate, complete and non-conflicting with other requirements. Once these requirements are clearly specified, they can then be implemented and maintained [4].

There is always a need to discover the requirement techniques which are presented by many other papers in their earlier work. The main concern would be the true security requirements identified as early as possible and systematically analyzed in such a way that we could present any technique for prioritizing these requirements based on risk measure techniques. So in this paper we will determine the relative necessity of the requirements, whereas all requirements are mandatory, some are more critical than others. So for this we need to propose a proper framework so these requirements could be prioritised efficiently.

As we are using different tools for this requirement prioritization framework we would use different methodologies such as STRIDE which classifies the schemes for characterizing the discovered threats according to the kinds of exploitation that are used [8], DREAD which provides a means to rate threats identified [9], CRAMM which simply calculate the measure of risk for each threat to an asset and vulnerability [10], etc. but there are some loopholes in these methods in terms of its implementation part or there process time. So we need to remove these loopholes in such a manner so that we could result into a framework which could combine these methodologies to prioritise the requirements subsequently removing all these loopholes.

And also there are many approaches are there for systematically performing this activity of requirement prioritization such as Numerical assignment which is a simple requirements prioritization technique based on grouping requirements into different priority groups. The number of priority groups can vary, but three is common i.e. •critical€, •standard€, and •optional€, or AHP in which it compares all possible pairs of hierarchical requirements to determine the priority, or Hundred Dollar Method and in this each stakeholder is asked to assume he/she has $100 to distribute to the requirements. The result is presented on a ratio scale. The ratio scale result can provide the information on how much one requirement is more/less important than another one. Most of these techniques are based on the attributes such as time, importance, cost, and the risk [3].

3. PROPOSED WORK

While Proposing a Security Requirement Prioritization Framework based on the threat analysis, we are giving a brief of all those steps which are necessary for achieving the final prioritized values of different security requirements and which are discussed below.

Figure 1. Proposed Framework for Security Requirement Prioritization

3.1 Assembling the Required Threats

In this we will assemble all those threats which are a source of each security requirements. As in common criteria based approach we shall be developing storage of deposits of all the threats [11]. Predefined threats can be retrieved from this storage area according to the profile of the user or the stakeholder and the list of all those predefined threats are:

a) Change Data
b) Data Theft
c) Deny Service
d) Disclose Data
e) Impersonate
f) Insider
g) Outsider
h) Privacy Violated
i) Repudiate Receive
j) Repudiate Send
k) Spoofing
l) Social Engineer

3.2 Characterising all the Known Threats using STRIDE Methodology

In this we generally classify the schemes for characterizing the discovered or known threats according to the kinds of exploitation that are used. It is used to simply help non-technical persons in the business world so that they could relate certain things according to their needs. This could be taken as a pen checklist which we use in our daily routine [8]

3.3 Rate the Assembled Threats using DREAD Methodology

This method provides a means to rate threats identified and operates hand in hand with the STRIDE mechanism which categorizes threats. DREAD is an acronym, each letter of which stands for a threat attribute. Each of the attributes are ranked using one of 10 criticality ratings with being the lowest rating and 10 being the highest rating [9]. The attributes are:

a) Damage potential
b) Reproducibility
c) Exploitability
d) Affected Users
e) Discoverability

This algorithm is used to compute a risk value, which is an average of all five categories.
DREAD = (Damage + Reproducibility + Exploitability + Affected Users +Discoverability) / 5

3.4 Assigning the Values to Vulnerabilities

Vulnerability is defined as the weakness in the system that makes an attack more likely to succeed. All the values are generally project specific. Values of vulnerability are defined by the CRAMM method and these can be assigned according to following Table [10]

Table 1. Measure of Vulnerability

Condition	Rating
If an incident was to occur, there would be no more than a 33% chance of the worst case scenario.	Low (0.1)
If an incident was to occur, there would be a 33% to 66% chance of the worst case scenario.	Medium (0.5)
If an incident was to occur, there would be a higher than 66% chance of the worst case scenario	High (1.0)

3.5 Values Given to Affected Assets

An asset can be anything that has a value to an organization (e.g. IT systems, information, staff, reputation, etc) and this is project specific. Different asset in project is identified and their value is measured by weighing the impact of it when threat will occur.

3.6 The Risk Level is Calculated

Risk is defined [10] , as the probability that a threat agent (cause) will exploit system vulnerability (weakness) and thereby create an effect detrimental to the system. Here, the Risk = Value based on Measure of Threat, Vulnerability and Asset.

After we have rated the threats, assigned vulnerability value and asset value we will use the 3 dimensional lookup table given by the CRAMM, in which we can calculate the measure of risk for each threat to an asset and vulnerability and then we can evaluate the threats based on their measure of risk.

3.7 Find the Security Requirement to Lessen the Threats

In this method we simply try to identify the various security requirement corresponding to threats so that we can give them priority to mitigate the threats.

3.8 Backtracking the Security Requirements Prioritizations

For this methodology we will identify the measures of risk to all the threats and prioritize them based on value of risk and assign them a final value for the prioritization.

4. CASE STUDY

Now in this case study, all the above discussed steps are defined below and are explained with an example of Air Reservation System. We have chosen various methods like STRIDE, DREAD, CRAMM method for final identification of risk as it offers structured and fast approach to risk analysis over other methods.

4.1 Threat Assembling

Using a common criteria based approach for assembling threats which are identified for our example are:

a) Change Data (CD)
b) Repudiate Receive (RR)
c) Spoofing (Sp)
d) Flooding (F)
e) Privacy Violated (PV)
f) Outsider (O)
g) Physical (P)

4.2 Characterising Known Threats

While threats are characterised, this uses the STRIDE model which is an acronym for six threat categories that are listed below :

a) Spoofing identity (S)
b) Tampering with data (T)
c) Repudiation (R)
d) Information disclosure (I)
e) Denial of service (D)
f) Elevation of privilege (E)

The tabular representation is shown in the table, 2 where the assembled threats are correspondingly shown with their categories of these threats using the number 1 at their identified place.

Table 2. Checklist for Discovered Threats

	S	T	R	I	D	E
CD	-	1	-	-	-	-
RR	-	-	1	-	-	-
Sp	1	-	-	-	-	-
F	-	-	-	-	1	-
PV	1	-	-	1	-	-
O	-	-	-	-	-	1
P	-	-	-	-	-	1

4.3 Rating Threats

For the calculation of the overall risk for different threats, it always produces a number between 0 and 10, the higher the number, the more serious the risk. And these could be then scaled up or down according to the needs. As in our case we are scaling down these values because of the CRAMM matrix used for further calculations in the next forthcoming steps, this could be seen in the table 3

Table 3. Measure of Risk

ID	D	R	E	A	D	Overall Risk
CD	5	5	5	10	5	6
RR	10	5	5	10	5	7
Sp	10	10	5	10	5	8
F	0	10	5	0	5	4
PV	5	5	5	0	0	2
O	10	0	5	10	10	7
P	0	0	5	0	5	2

Now, after this risk rating method, we can simply scale down our observed 10-point scaled values lower to the 2-point scaling system as shown in table.4

Table 4. Scaling down the Values

DREAD 10 point Scale	DREAD 2 point Scale
1-2	Very Low
3-4	Low
5-6	Medium
7-8	High
9-10	Very High

Whatever threats have been identified we have to assign them a value according to CRAMM evaluation so for this we have to consider the table 5 and here all values are project specific and are taken by observation.

Table 5. Measure of various Threats

4.4 Assigning Value to Corresponding Vulnerability

Here the values of vulnerabilities are defined by CRAMM method and will be taken as low (0.1), medium (0.5) and high (1).

4.5 Give Values to Affected Assets

The different assets identified in our particular example are :

a) Traveler Information
b) User Login Information
c) Credit Card Information
d) Communication Channels
e) Ticket Information

Now we have to define various vulnerable assets that will be affected that corresponds to the threat are as in Table 6.

Table 6. Possible Vulnerable Assets

Threat	Affected Assets
CD	Traveller information, Ticket Information
RR	User Login Information, Credit Card Informatior
Sp	Credit Card Information, Communication Chan
F	Credit Card Information, Traveller Informatior
PV	Ticket Information
O	Communication Channel, User Login Informatio
P	User Login Information

And the different values of various assets are depicted in Table 7.

Table 7. Measure of Assets

Asset	Value (1 to 10)
Traveler information	7
Ticket Information	5
Credit Card Information	9
User Login Information	4
Communication Channel	6

4.6 Estimate the Risk Level

After we have rated the threats, assigned vulnerability value and asset value we will use the 3 dimensional lookup table given by the CRAMM where the strength of the threat, the level of the vulnerability and the value of the asset are input parameters, gives the final value of risk in the range 1 through 7.

For eg. suppose asset is Credit Card Information (9) the threat to this is Spoofing (3.33) and Vulnerability being medium (0.5) the measure of risk will be 6. In the similar fashion we can calculate the measure of risk for each threat to an asset and vulnerability and then we can evaluate the threats based on their measure of risk as given in the Table 8.

4.7 Identify the Security Requirements

Here the different security requirements corresponding to the threats in the table are identified. For eg. the measure of the risk for the change_data for affected assets ticket and traveller info is 4 and 5 respectively so its threat prioritization value will be the sum of them i.e. 9. And the total measure of risk for the repudiate_receive for affected assets like user login info and credit card info will be 4 and 6 respectively and which will be added to form its threat prioritization value to total of 10 as given in the table 8.

4.8 Backtrack to Find Priority of Security Requirement

This particular step is the real part of our progress what we have done till now as in this we will backtrack all the gathered values of different threats which are discovered earlier and assign them a final value which will prioritize all the security requirements. For.eg. the value of threat prioritization for change_data is 9 and for repudiate_receive is 10, so here the overall security requirement prioritization value say authorization will be a sum of them which is 19.

Table 8: Detailed computed values of Security Requirements

Figure 2 Measure of Security Requirement Prioritization

5. CONCLUSION

In this paper we have reviewed the security engineering process for eliciting security requirements and process these to prioritize based on risk estimation techniques, and then will identify the threats, analyze them and finally evaluate them so that all the threats that may occur in the project later will be detected in early phase. At last the associated risk will be estimated that will help in security requirement prioritization and so a good quality secure software is developed. As in our case study, we have concluded the values of Air Reservation System as shown above in figure 2.

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