EFFECTS OF LEAKY WAVEGUIDE ON THE CONTROL PERFORMANCE OF COMMUNICATION BASED TRAIN CONTROL SYSTEM BASED ON PATH-LOSS MODEL

A Thesis submitted towards the partial fulfilment of the requirement for the award of the degree of

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CERTIFICATE

This is to certify that the thesis report entitled, " **Effects of Leaky Waveguide on the control performance of Communication Based Train Control system based on Path-loss model** " being submitted by **Mohd Irfan Khan** to the *Department of Electronics and Communication Engineering and Applied Physics, Delhi Technological University, Delhi* in partial fulfilment of the requirement for award of Master of Technology degree in ***Microwave and Optical Communication*** is a record of bona fide work carried out by him under the supervision and guidance of Prof. Rajiv Kapoor. The matter embodied in this report has not been submitted for the award of any other degree.

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DECLARATION

I hereby declare that all the information in this document has been obtained and presented in accordance with academic rules and ethical conduct. This report is my own, unaided work. I have fully cited and referenced all material and results that are not original to this work. It is being submitted for the degree of Master of Technology in Engineering at the Delhi Technological University. It has not been submitted before for any degree or examination in any other university.

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ABSTRACT

In urban rail transit, systems using communication based train control (CBTC), it uses high accuracy of train locating, realizes a continuous automatic train control system. High resolution of locating the train permits the high line capacity and fewer Infrastructures is required than Track circuit based system therefore all over the world countries have more concerned about this technology. DCS system plays an important role in the information interaction between ground equipment and vehicle equipment in CBTC. DCS is WLAN which is short range radio networks based on IEEE 802.11, complete communication network is built with many closely deployed AP (Access Point). IEEE 802.11b is a physical layer amendment for operation in the 2.4 GHz band, adopted in CBTC system in which data transmits at 11Mbps and uses DSSS modulation. Data communications systems based in the 2.4 GHz ISM band has raised the concern of RF interference between CBTC equipped trains and the variety of new and existing users of this band. The reliability and safety of information transmission can be improved when leaky waveguide is used as transmission medium of train-ground wireless communication in CBTC (Communication Based Train Control), also it can provide better performance and stronger anti-interference ability than free space. These benefits of leaky waveguide insisting the research scholar of communication field to intervene in CBTC system.

Wireless LAN technologies are adopted in most train wayside communication systems in CBTC. Successful handoff plays an indispensable role in wireless communications. Running through the large wireless networks with numerous APs in urban mass transit, a train equipped with CBTC systems inevitably encounters the problems of handoff. Against the possibly negative phenomena such as Ping-Pong effect, handoff delay, packet loss and so on. Frequency Combination and Location based Handover scheme are analysed, both handover scheme are also

correlated with Leaky waveguide based CBTC system. After analysis, it is realized that Location Based Handover Scheme is best suited for Leaky waveguide based CBTC system in many aspects. Leaky waveguide also limits the implementation of various handover schemes.

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L	Propagation loss
λ	Wavelength
d	Distance
f_c	Cut off frequency
λ_c	waveguide cut-off wavelength
ρ_y	Electric equivalent dipole
m_x, m_z	Field normal component
P_{ram}	Magnetic dipole's radiated power
Zo	Free space wave impedance
d_{slots}	Distance between slots
n	Path-loss exponent
X_{ss}	Small-scale fading
t	Total number of measurements
ρ_{wg}	Resistivity of the material of leaky waveguide
a and b	Dimensions of leaky waveguide
α	Transmission loss

LIST OF ABBREVIATIONS

CBTC	Communication Based Train Control
ATP	Automatic Train Protection
ATO	Automatic Train Operation
ATS	Automatic Train Supervision
DTO	Driverless Train Operation
UTO	Unattended Train Operation
DLR	Docklands Light Railway
TC	Track circuit.
GUI	Graphical user interface
DCS	Data communications systems
ISM	Instruments Scientific and Medical
WLAN	Wireless Local Area Networks
MN	Mobile Node
AP	Access Point
FHSS	Frequency Hopping spread spectrum
DSSS	Direct sequenced spread spectrum
RAPs	Radio access points
ETCS	European Train Control Systems
MS	Mobile station
FCC	Federal Communications Commission
RFID	Radio Frequency Identification
Wi-Fi	Wireless Fidelity

CHAPTER 1

INTRODUCTION

In present railway industry, there are various types of train control systems. The main function of train control system is to avoid collisions when trains are traveling on the same track, either in the same or direction. These systems also license nonviolent movement of trains as cross from one to another track. Initial train control systems were very basic in architecture. As technology and operation grown over time, these regulator systems grew to have additional complex architectures. The newest architecture is known as CBTC. CBTC [1] uses bidirectional radio frequency (RF) data communication between the trains and control locations circulated lengthwise the tracks.

1.1 EVOLUTION OF COMMUNICATION BASED TRAIN CONTROL WORLDWIDE

1.1.1 Transit railways.

Transit railways are defined as light and heavy rail systems operating at short headways on dedicated rights-of-way, often in tunnels, and transport up to 80,000 passengers per hour per direction depending on the line and rolling stock designs. In addition to full Automatic Train Protection (ATP), transit railways also typically include Automatic Train Operation (ATO) and various levels of Automatic Train Supervision (ATS). There is also a recent trend to implement Driverless Train Operation (DTO) or Unattended Train Operation (UTO) on such transit railways, both for newly built lines and when re-signalling existing lines [2].

Any transit railway signifies a great investment in view of the right-of-way and station infrastructure, with important life-cycle costs to retain the infrastructure in a good condition. This capital is justified on the basis that the infrastructure offers the base for the drive of large passengers inside the network covered under infrastructure. The actual safe movement of passengers is however only possible through the execution of a train/signalling system. In practically, it is the train/ signalling controls system that empowers the arrival on the infrastructure expenditure to be realised.

While the train control/signalling system is the enabler of railway operations, the system can impose a restriction on operations for example by limiting the achievable line capacity or by limiting the flexibility of train movements. A fundamental goal of a modern train control system therefore is to optimise the utilisation of the rail transit infrastructure by not only providing for safety of train movements but also by maximising line capacity and permitting any train movements that can be safely supported by the infrastructure.

For transit railways, high system availability is also critical and it is an operational obligation to move trains safely in the event of subsystem failures, possibly at limited operating speeds and/or increased defined headways when compared to normal operations. As a consequence, train control systems must be designed to support degraded modes of operation in the event of failure.

1.1.2 Evolution of Train Signalling/Train Control.

The level of control that a signalling/train control system can exercise on a railway is driven by the input data to the system, the processing of that data, the means of communication of that data, and the system outputs. The evolution of railway signalling/train control systems is therefore also an evolution of the level of control provided by these systems as well as the data processing and data communications capabilities.

At its most basic, the object of a train control system is to keep trains from hitting one another, derailing or injuring work crews on the tracks. In early days, the system that informed driver when to slow down, when to stop and when and how to proceed is the train signal system. Since earliest days of the railways, these have been visual signals of red, yellow and green lights. While the technologies for determining track occupancy and controlling signals accordingly have evolved since the mid-nineteen century, the basic concepts behind train control and signalling have hardly changed. The similarity between train control system today and in the early twentieth century is that most of them still use rails for communication between train and the infrastructure. On most railways today, track circuits provide train detection and electromagnetic signals transmitted through the running rails are often used to send data on board systems for cab signalling, automatic train warning or protection and related functions.

While there have been many technology changes over the past century, the evolution of communication based signalling for transit train applications can be summarised as four basic generations of train control philosophy, as illustrated in Figure 1.1, with each generation providing an incremental improvement in operational safety and/or performance over the previous generation to accommodate more demanding user requirements.

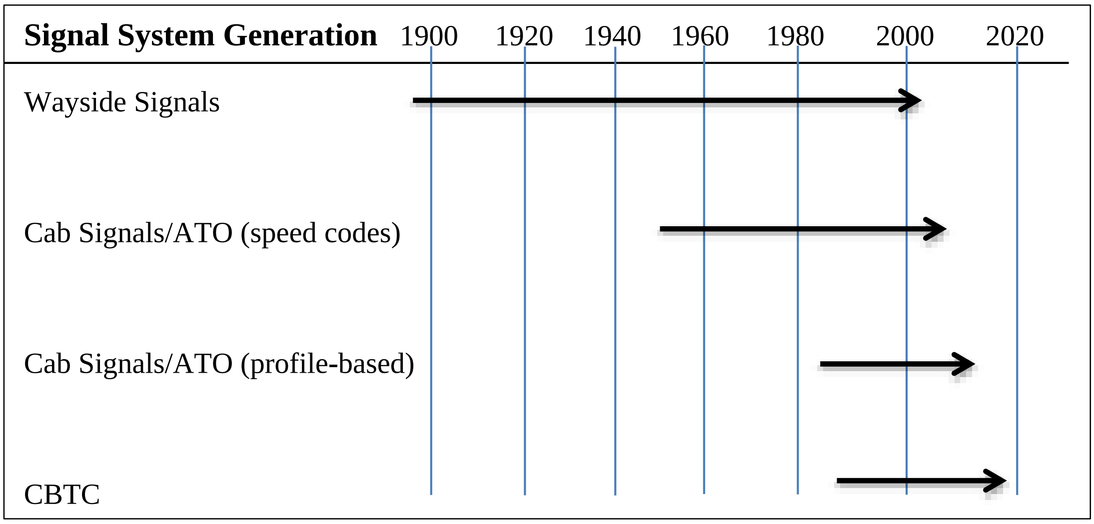

Figure 1.1: Train Control Evaluation[2].

1.2 GENERATIONS

1.2.1 First Generation Train Control Systems.

The first generation of transit train control architecture includes track circuits for train detection, wayside signals to provide movement authority indications to train operators, and trip stops to enforce a train stop if a signal is passed at danger (i.e. intermittent ATP)[2]. With this train control architecture virtually all of the train control logic and equipment is located on the wayside, with train-borne equipment limited to trip stops. Train operating modes are restricted to manual driving modes only and the achievable train throughput and operational flexibility is limited by the fixed-block, track circuit configuration and associated wayside signal aspects. This train control philosophy served the industry well and continues in revenue service operation at many major transit properties around the world.

1.2.2 Second Generation Train Control Systems.

The second generation of communication based train control architecture is also track circuit-based with the wayside signals replaced by in-cab signals, providing continuous ATP through the use of speed codes transmitted from the wayside through the running rails to the train. Such coded track circuits were developed by signalling suppliers in the USA around the middle of the last century and although they were not immediately applied to transit railways, they ultimately were to make a significant contribution to this next generation of train control systems.

With this train control architecture, a portion of the train control logic and equipment is transferred to the train, with equipment capable of detecting and reacting to speed codes, and displaying movement authority information (permitted speed and signal aspects) to the train operator. This generation of train control technology permits automatic driving modes (ATO), but train throughput and operational flexibility are still limited by the track circuit layout and the number of available speed codes.

This generation of signalling technology was applied to most new rail transit systems that entered service in the latter half of the 20th century including the Washington (WMATA), Atlanta (MARTA) and San Francisco (BART) systems in the USA, the London Underground's Victoria Line, and the initial rail lines in Hong Kong and Singapore. In beginning of 21st century this service comes into operation in DMRC, Delhi, India. Many rail transit agencies also adopted this technology in order to transition to automatic train operations (ATO) with continuous ATP, such as London Underground's Central Line re-signalling.

1.2.3 Third Generation Train Control System.

The next significant evolution in train control architecture continued the trend to provide more precise control of train movements by increasing the amount of data transmitted to the train such that the train could now be controlled and supervised to follow a specific speed/distance profile, rather than simply responding to a limited number of individual speed codes. This generation of train control technology, also referred to as “distance-to-go” technology, can support automatic driving modes, and provide for increased train throughput. Under this train control architecture, the limits of a train’s movement authority are still determined by track circuit occupancies as illustrated in Figure 1.2 below.

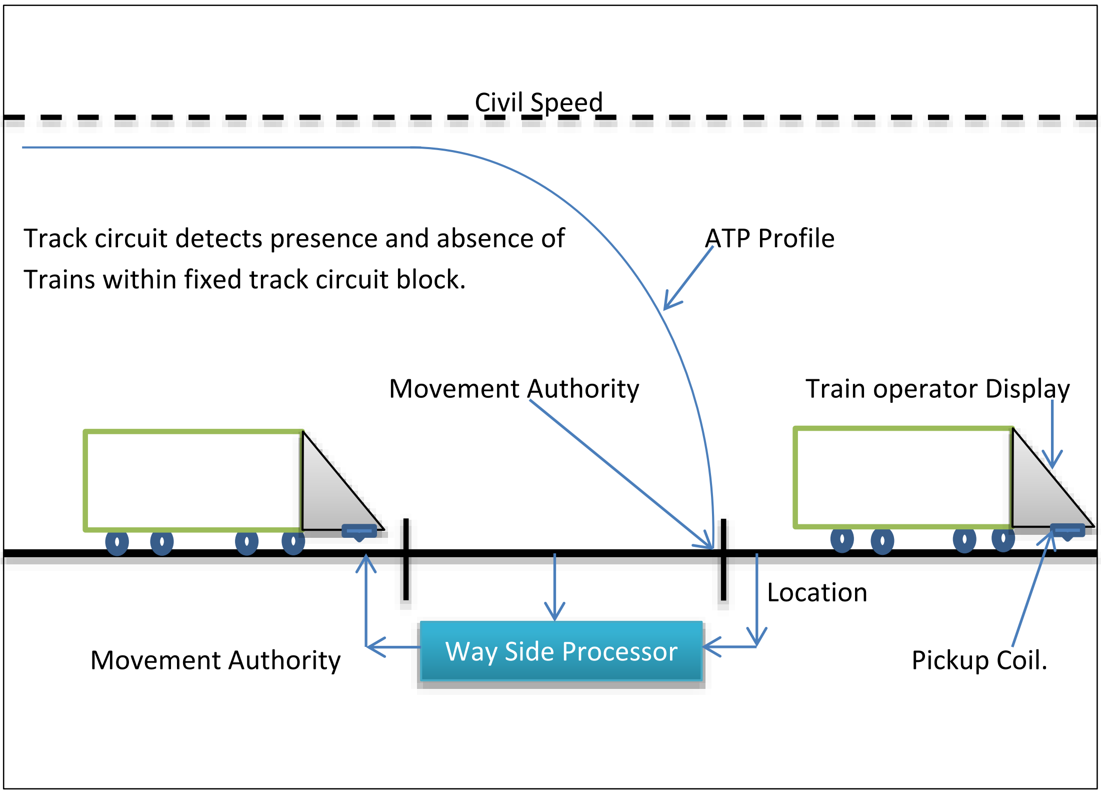

Figure 1.2: Profile Based Cab Signal System.

The primary example of this train control architecture is the “SACEM” technology developed in the mid 1980’s to improve performance standards on heavy rail transit systems. Originally introduced on RER Line A in Paris in 1989, SACEM technology has subsequently been deployed on many other transit railways around the world including Mexico, Hong Kong, Santiago (Chile) and San Juan (Puerto Rico), for example.

Digitally-encoded AF track circuits providing a profile based train control philosophy have also been implemented on the Los Angeles Metro Green Line, on the driverless Copenhagen Metro, and on Shanghai Metro Line 2 and “distance-to-go” systems are implemented on Beijing Metro Line 5, Madrid Metro and DMRC Delhi, India.

1.2.4 Fourth Generation Train Control System.

The fourth generation of train control architecture is generally referred to as communications-based train control (CBTC). As with the previous generation of train control technology, CBTC supports automatic driving modes and controls/supervises train movements in accordance with a defined speed/distance profile. For CBTC systems, however, movement authority limits are no longer constrained by physical track circuit boundaries but are established through train position reports that can provide for “virtual block” or “moving block” control philosophies, as illustrated in Figure 1.3 below. With CBTC systems, a major portion of the train control logic is now located within the train-borne CBTC equipment and a geographically continuous wayside to- train and train-to-wayside data network permits the transfer of meaningfully more status and control information than is possible with the earlier generation control systems. As such, CBTC systems offer the greatest operational flexibility and can support the maximum train throughput, constrained only by the performance of the rolling stock and the limitations of the physical track alignment. In particular, the high level of control provided by CBTC systems makes this the technology of choice for driverless/unattended train operations.

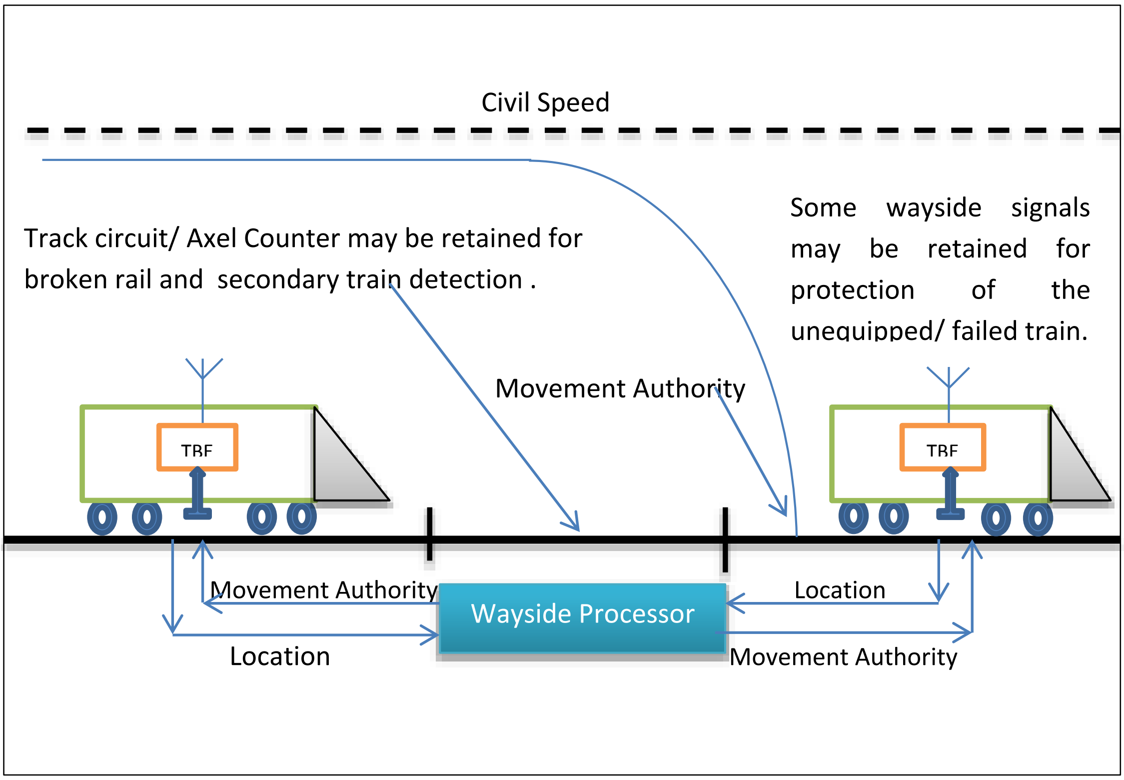

Figure 1.3: CBTC System.

Three things common about the CBTC systems are:

1. The use of technology other than track circuits for continuous data communications from / to trains (for both non-vital and vital data) to transmit information between wayside and train. In majority cases, the technology is some kind of radio frequency communication, including the use of inductive loop.
2. Primary train location detection is independent of track circuits that provides more precise method of determining train location compared to that by track circuits only.
3. The use of computers to continuously process information to determine the train's safe speed, and to trigger actions that will ensure safe operation.

A CBTC system is therefore comprised [2] of the following four vital subsystems:

1. CBTC ATS Equipment.
2. CBTC Wayside Equipment.
3. CBTC Train-borne Equipment.
4. CBTC Data Communications Equipment.

The CBTC ATS equipment includes equipment installed at central and/or wayside locations responsible for ATS functions such as identifying, tracking and displaying trains, providing manual and automatic route setting capabilities, and regulating train movements to maintain operating schedules.

The CBTC wayside equipment consists of a network of processor-based wayside controllers installed at central and/or wayside locations. The CBTC wayside system may interface with an external separate interlocking subsystem, or alternatively the interlocking functions may be incorporated within the CBTC wayside equipment. Each wayside controller also interfaces to the CBTC train-borne equipment and CBTC-ATS equipment. The wayside intelligence for ATP functions, such as movement authority situation based on the status of both CBTC-unequipped and equipped trains, as well as other concerned wayside ATP, ATO and ATS functions resides in the wayside controllers. The wayside equipment's also include any track based subsystem necessary to provide a unique exact positioning reference to the CBTC train-borne equipment. The CBTC train-borne equipment consists of one or more processor-based controllers and associated speed measurement and location determination sensors. The CBTC train-borne equipment interfaces with the train subsystems (including train operator displays) and also interfaces to the CBTC wayside equipment and the CBTC ATS equipment via the CBTC data communication equipment. The CBTC train-borne equipment is responsible for CBTC train location determination, the enforcement of permitted speed and movement authority limits, and other allocated train-borne ATP and ATO functions.

The CBTC data communications equipment includes equipment located at central and wayside locations, as well as on board trains, to support wayside-to-train and wayside-to-wayside data communications (as well as intra train data communications for those applications where the train-borne equipment consists of multiple processor-based controllers). The data links between the major CBTC subsystems supports bidirectional data transfer and has abandoned bandwidth and exhibit suitably low latency to support all defined ATS, ATP and ATO functions. The data links also exhibits a protocol structure to support secure, safe and timely delivery of train control messages.

The CBTC data communications equipment does not of itself perform any CBTC functions and are not required to be vital.

a) High resolution train location determination, by CBTC train-borne equipment, independent of track circuits.
b) Communication of this train location information, and other train status data, to CBTC wayside equipment over the CBTC train-to-wayside data communications link.
c) Determination of the movement authority for each CBTC-equipped train, by the CBTC wayside equipment, based on train location information and inputs from external inter-locking's (including a secondary train detection system, if provided) and other external devices capable of detecting hazards that affect train operations.
d) Communication of the movement authority, and other train control data, to the appropriate train over the CBTC wayside-to train data communications link.
e) Determination and implementation of the ATP profile by the CBTC train-borne equipment.
f) Communication of required commands from the CBTC wayside equipment to external inter locking's (to modify interlocking functions), and status from external interlocking to CBTC wayside equipment to support CBTC operations.
g) Communication of necessary information from one CBTC wayside controller to a neighbouring wayside controller to support the hand-off of train control.
h) Communication of necessary information between multiple sets of CBTC train-borne equipment, within a train, to support CBTC operations.

CBTC systems are now available from multiple suppliers and have been developed to meet the stringent availability, reliability, and maintainability criteria required by transit railways. Unless non-redundant equipment's are sufficiently reliable to fulfil the overall system availability requirements, necessary levels of equipment's redundancy are typically placed such that the failure of a single device, component, or processor shall not extract the CBTC system unavailable or an operationally critical function non-operative. CBTC systems also typically incorporate degraded modes of operation to minimise the operational impacts of equipment failures and to permit train movements to continue safely. Signalling system downtime, or unavailability of an operationally critical function, are further minimised through the use of local and remote diagnostic capabilities and appropriate operating and maintenance procedures.

1.3 CBTC INDUSTRY TRENDS

The first CBTC system entered revenue service in Toronto, Canada in 1985 on the Scarborough RT Line. By 1990, two additional CBTC systems had entered service, one in Vancouver on the fully automated (driverless) Vancouver SkyTrain system and one in Detroit on the fully automated Downtown People Mover. All of these initial CBTC systems were for “new start” applications. By the end of the last century, seven additional CBTC systems had entered revenue service, with new lines in Lyon, Ankara, Paris (Meteor Line) and Kuala Lumpur as well as the first re-signalling applications on the San Francisco MUNI Line and in London on the Docklands Light Railway (DLR). The DLR was also subsequently extended to Lewisham. All of these systems utilised inductive loops as the wayside-to-train communications medium.

By 2005, the number of in-service CBTC lines had grown to 19 and included the first radio-based CBTC systems on the new driverless heavy rail line in Singapore (North East Line) as well as on new Automated People Movers at San Francisco and Seattle airports and on the Las Vegas monorail system. Additional inductive loop-based CBTC systems also continued to enter service in Vancouver (Millennium Line), New York (JFK Airport), and Hong Kong (West Rail), for example. The major profits of radio-based systems include ease of installation and maintenance, fully redundant communications through overlapping radio coverage, faster recovery times due to individual system/component failure finding and replacement, and less susceptibility to vandalism

In recent years, in addition to the “new start” or “green field” applications, many existing transit operators around the world increasingly have to face the challenge of maintaining an aging signalling infrastructure in a state-of good- repair, while at the same time coping with increased ridership and passenger expectations for shorter journey times with improved reliability, safety, security and comfort. Re-signalling with CBTC is seen as one of the most cost effective solutions to meeting these business needs, particularly when integrated with rolling stock replacement/ refurbishment, control centre modernisation, passenger information system upgrades, and enhancements to backbone data communications networks. Other benefits of CBTC technology include the economic support of automatic and driverless train operations (both in maintenance depots and on the mainline), driverless turn back at terminal stations, reductions in maintenance costs and improved reliability through a reduction in wayside equipment's and real-time diagnostic information.

By end of 2010, the number of in-service CBTC systems will have grown to close to 50 and the range of applications includes re-signalled transit lines in New York (Canarsie Line), Philadelphia (SEPTA), London (Jubilee Line), Paris (Ouragan project), Madrid (Lines 1and 6), and Beijing (Line 2 and 4), Vancouver (Canada Line), London Docklands (City Airport and Woolwich extensions), Budapest (Lines 2 and 4), Lausanne (Line M2), Hong Kong (Disney Resort Line), Algiers (Line 1), Dubai (Red and Greed Lines), and well as various new lines in Guangzhou, Shanghai, Beijing and South Korea. Other CBTC systems are already under contract for implementation in 2010 and beyond and include various lines in Paris, London (Northern Line), Singapore (Circle Line), Sao Paulo (Line 4) and South Korea (Sin Bundang Metro Line), Incheon (Line 2), Bushan-Gimhae for example. Numerous other lines are currently in the development phase (e.g. New York City Transit's Flushing Line, New York/New Jersey PATH system, Toronto Yonge-University-Spadina Line, London Underground's Piccadilly Line, India's DMRC Phase III and KMRL.

1.4 INTERLOCKING FUNCTIONS

As discussed earlier, another important function of a control system is to guarantee safe movement of a train from one path track to another track. The term interlocking was originated in the initial days of control systems with the Saxby-Farmer mechanical interlocking machine. This device mechanically interlocked the movement of switches of wayside signals and machine, e.g., signals should be made to stop before switches of machine supposed to be moved, and signals could not be allow proceeding until the switches of machine are locked in the required position.

With the origination of TC, train position was incorporated into the Saxby- Farmer interlocking machine.

CHAPTER 2

LITERATURE REVIEW

Communication Based Train Control is very advanced technology in field of train control; this comes into operation around 1985 with consideration of safety, availability, and maintainability. Many researches have been done in different subsystems of CBTC Technology. Since advancement in technology never ends, research is still going on for better system with keeping all National and International standards.

2.1 STANDARDS

Any technology when comes into operation, specially dedicated to public use, all international and national must be fulfilled. Keeping in mind the importance of standards, following standards in coming paragraph have been studied for this research.

2.1.1 IEEE Standard 1482.1-1999.

This IEEE Standard meant for Rail Transit Vehicle Event Recorders, it includes On-board systems/devices with supporting crashworthy memory which records data to help in accident/ incident analysis for rail transit vehicles. The requirements of this standard are limited to event recorder functions and interfaces except Data transmission process and information is independent of the software and/or hardware employed for other vehicle systems in this standard [3].

2.1.2 IEEE Standard 1474.1-1999.

IEEE Standard for Communications-Based Train Control (CBTC) Performance and Functional Requirements for a communications-based train control

(CBTC) system has been established. This standard completely defines about CBTC system and its associated subsystems. In addition to CBTC functional requirements, this standard also defines headway criteria, system safety criteria, and system availability criteria for a CBTC system [4]. This standard subsequently revised as IEEE 1474.1- 2004.

2.1.3 IEEE Standard 1474.2-2003.

This Standard has been developed for User Interface Requirements in Communications- Based Train Control (CBTC) Systems. Interface of subsystems i.e. automatic train control (ATC), automatic train operation (ATO), automatic train protection (ATP), automatic train supervision (ATS) with communications-based train control (CBTC) have been discussed in detail. Graphical user interface (GUI) is also discussed [5].

2.1.4 IEEE Standard 1474.3-2008.

This standard is Recommended Practice for Communications-Based Train Control (CBTC) System Design and Functional Allocations builds on IEEE Standard 1474.1 by decomposing each identified ATP, ATO and ATS function to a level where each sub function can be allocated to one of the CBTC subsystems [6].

2.1.5 IEEE Standard 1474.4-2011.

This standard is Recommended Practice for Functional Testing of a CBTC System. Approach for functional testing of a communications-based train control (CBTC) system, based on the CBTC system design and functional allocations as defined in IEEE Standard 1474.3-2008, and is established in this recommended practice [7].

2.2 DIGITAL COMMUNICATION SYSTEM

DCS system plays an important role in the information interaction between vehicle equipment and ground equipment in CBTC. Based on OPNET simulation console [8], studied and analyses the designing of DCS network, simulation of communication process. Analyses the simulation of bidirectional transmission of data and network performance, and founded appropriate reference for design and optimization of DCS network [8].

2.2.1 IEEE 802.11 WLAN.

The Ethernet MAC protocol is adopted in WLAN, after the official approval of 802.11 in 1999, the IEEE 802.11 MAC has received wide market recognition and has become the de-facto standard for WLAN. The IEEE 802.11 standard includes 802.11a, 802.11b, and 802.11g. 802.11a is a physical layer modification to the 802.11 standard stating high speed operation in the 5 GHz band.802.11a states 54 Mbps OFDM operations; 802.11b is a physical layer revision for operation in the 2.4 GHz band. 802.11b/g transmits at 11Mbps and uses DSSS modulation [8]. Since 2.4 GHz frequency is considered in whole research, therefore IEEE 802.11b is chosen for my work.

2.2.2 Use of 2.5 GHz Frequency Band for CBTC System.

The use of data communications systems based in the 2.4 GHz ISM band has raised the concern of RF interference between CBTC equipped trains and the variety of new and existing users of this band. The vast numbers of RF devices that currently operate in this band (like microwave ovens, cordless telephones, medical devices etc.) have recently been augmented by the proliferation of "Wi-Fi" hotspots and wireless computers permitting untethered internet access by the public and RF identification (RFID) technology. Keeping in mind, the interference from other devices operating in same band can be mitigated if spread spectrum radios system and digital signal processing will be adopted with system [9].

2.3 RECTANGULAR WAVEGUIDE IN CBTC SYSTEM

Train to ground communication system is one of the vital subsystems of CBTC and its reliability ensures the degree of handoff from one access point to other access point. To avoid Ping-Pong handoff in this paper Rectangular leaky waveguide is proposed. The principles of leaky waveguide in very brief have been covered and comparison with the communication via free space propagation has been done. Since mass of data between trains and ground are bi-directionally transferred using a wireless communications system. Rectangular leaky waveguide laid continuously along the track has been used as transmission medium. It is found that when 802.11b/g is used in the system, the leaky waveguide section should be less than 500m. A measurement shows that communication through leaky waveguide has several advantages over free propagation when it comes to providing good signal quality and managing handover [9].

2.3.1 Propagation in Leaky Rectangular Waveguide.

Based on the theory proposed in [9] for leaky waveguide, the propagation characteristics of leaky waveguide by means a series of slots on leaky waveguide equivalent to a series of magnetic dipoles on 2.5 GHz operating frequency. The relationship between height of receiving antenna and received signal strength have been studied and found that the higher the receiving antenna is located, the smaller signal strength will be received. Thus, the height of receiving antenna is fixed and should not be higher than 500mm. The test results of propagation characteristics in after covering the leaky waveguide are analysed which can be used to analyse the influence on quality of train-ground communication in different situations of snow coverage [10]. The other propagation characteristics in CBTC, such as transmission rate etc., which have been not considered. Hence further research is also proposed.

2.3.2 Modelling of CBTC Radio Channel with Leaky Waveguide.

To provide better performance and stronger anti-interference ability than free space, Leaky waveguide has been proposed as the propagation medium. Based on the measurements of leaky waveguide, the path-loss model of large-scale fading for the channel with leaky waveguide of CBTC radio channel with leaky waveguide is build. Model shows that the large-scale fading is linear, and the path-loss exponent can be approximated by the transmission loss of leaky waveguide. The small-scale fading follows Log-normal distribution. The parameters of Log-normal distribution are also determined with AIC method. Future work “To study the effects of leaky waveguide on the control performance of CBTC systems based on the proposed channel model” is also proposed which is my research work [11].

2.4 HANDOVER

Generally, 802.11 series standards of WLAN were proposed to serve the wireless access in the office and campus environments and the handover schemes between the APs were not defined in the drafts. But if WLAN were used in the CBTC system, the train would need to switch from one AP to the next one frequently to guarantee continuous data transmission between the train and wayside devices [12]. In general during the handover process some data packets would be lost. The packets lost rate and the handover interruption time have been the key factor which affects the train-to-wayside communication. In this paper field tests were conducted and its analysis show that the handover interruption time of WLAN system is the most important parameter and the number of packets loss due to handover is much more than the loss due to the wireless transmission.

2.4.1 Location based handover scheme for WLAN.

A location based handover scheme for WLAN in tunnels is proposed in this paper for the CBTC system. By the proposed location based handover scheme, the mobile train can initiate the re-association request directly without the process of scanning and probe stage. The simulation results is analysed which show that the proposed scheme can reduce the handover interruption time for wireless LAN networks in CBTC system [12].

2.4.2 Frequency combination handover.

Handover with frequency combination is mostly, when the current field intensity is lower than the given threshold, to establish buffers between triggered handover processes to ensure the quality of channel against stochastic source jamming and time-varying channel and choose the precise handoff time in whole networks when handoff is engaged. The simulation results show that the algorithm can accurately grasp handoff opportunities, reduce handoff delay and eliminate packet loss, and is simple and reliable as well [13].

The above research papers have been studied in detail and conclusions of all papers are analysed with reference to selected research area. Hence, the main theme of research will be developed based on literature review in next chapter.

CHAPTER 3

COMMUNICATION BASED TRAIN CONTROL

Communications-based train control (CBTC) is an automated train control system using high capacity and bidirectional train-ground communications to ensure the safe operation of rail vehicles [14]. As a modern successor of traditional railway signaling systems using track circuits, inter-lockings, and signals, CBTC can improve the utilization of railway network infrastructure and enhance the level of safety and service offered to customers.

3.1 CBTC CHARACTERISTICS AND APPLICATION

3.1.1 CBTC characteristics.

The primary characteristics of a CBTC system, as defined in IEEE Standard 1474.1-2004 [7], include the following:

a) High-resolution train location determination, independent of track circuits.
b) Continuous, high capacity, bidirectional train-to-wayside data communications.
c) Train-borne and wayside processors performing vital functions.

The influence of these primary characteristics on the functional test process is summarized as follows.

3.1.2 Train location determination, independent of track circuits.

With train location determination independent of fixed-block track circuits, alternative control strategies become possible (where movement authority limits are not constrained by physical fixed-block track circuit boundaries) that should be reflected in the CBTC functional test process. Certain test practices for fixed block, track circuit-based signalling systems may no longer be applicable or practicable, and alternative test procedures are necessary to reflect the specific principles of operation of CBTC systems.

3.1.3 Bidirectional train-to-wayside data communications.

The performance and availability of a geographically continuous train-to-wayside and wayside-to-train data communications network is critical to CBTC operations. Hence, as an element of the system level functional testing, the network performance and availability (including network stability, data-link bandwidth, and message latency) should be verified, supported by analysis, as necessary, of worse-case conditions that cannot be easily duplicated in the factory or in the field.

3.1.4 Train-borne and wayside vital processors.

The distributed CBTC wayside and train-borne vital processors that process the train status and control data and provide continuous automatic train protection (ATP), automatic train operation (ATO), and automatic train supervision (ATS) functions are typically highly integrated. As a consequence, the final functional testing can only be performed at a systems level with all major CBTC subsystems operational and with multiple vehicles operating. CBTC systems also typically include significant levels of equipment redundancy to achieve the high system availability required. The need to verify the overall stability of such a distributed computer system and the need to verify switchover capabilities between redundant sets of wayside and/or train-borne CBTC equipment also should be reflected in the functional test process. CBTC systems typical of other advanced technology systems are software/database driven. In such complex software-based systems it is important to understand that whereas the majority of software development often occurs prior to field testing, the software development process does not end until the system is verified to be operating correctly in the field. Multiple software releases are also typically required in a given application (specifically for complex cut-overs in a re-signalling application) resulting in a need for a defined level of regression testing following each software update.

3.1.5 Application-specific requirements.

The correctness of application-specific data (i.e., infrastructure data, such as curves, grades, station locations, etc., and train-specific data, such as braking rates and response times, etc.) and that this data has been correctly implemented within the system databases, should also be verified as an element of the functional test process. When re-signalling with a CBTC system, application-specific external (legacy) equipment interfaces, application-specific operating modes, and application-specific functional requirements are common. This can result in application-specific designs that should be reflected in the application-specific functional test process. To exploit the operational capabilities of CBTC systems, the design of a CBTC system is often integrated with the design of other fixed operating elements of a rapid transit system such as traction power systems, tunnel and station ventilation systems, passenger information and security systems, and backbone communications networks, for example. In addition, the designs of the on-board train location/speed measurement subsystems are also often application-specific due to vehicle-specific interfaces. As such, the performance of these application-specific designs should be verified through the functional test process.

3.2 CBTC APPLICATIONS.

The CBTC functional test process for re-signaling applications can be significantly more onerous than signaling new lines, primarily because of the need to maintain revenue operations and the integrity of the existing signaling system during the migration to the new CBTC system, which in turn results in track access limitations and the need to support mixed modes of operation. In addition, the specific signaling/train control system being replaced is typically different from one application to another.

3.3 DCS FOR CBTC BASED ON 802.11

The channel, in which the data is transferred in the CBTC system, is called DCS (Digital Communication System).DCS is the core part of CBTC. WLAN (Wireless Local Area Networks) technology has experienced explosive growth. WLAN are playing a major role in the area of communication. Now we are using

WLAN technology in industrial applications, educational applications and even in urban rail transit environment.

3.3.1 IEEE 802.11 WLAN.

The Ethernet MAC protocol is broadly used in wired LAN. Since the official ratification of 802.11 in 1999, the IEEE 802.11 medium access protocol has received wide market acceptance and has become the de-facto standard for WLAN.
The IEEE 802.11 standard involves 802.11a, 802.11b, and 802.11g. 802.11a is a physical layer amendment to the 802.11 standard specifying high speed operations in the 5 GHz band. 802.11a specifies 54 Mbps OFDM operations; 802.11b is a physical layer amendment for operation in the 2.4 GHz band. 802.11b transmits at 11Mbps and uses DSSS modulation.

WLAN are short range radio networks. Large networks are built with many closely deployed AP (Access Point). To avoid interference, nearby AP must be deployed on independent frequencies or channels. All clients associated with an AP will be tuned to the same frequency as the AP. Other nearby AP, operating on non-overlapping or independent channels will be invisible to wireless clients. As AP operates on different channels, clients must switch between and search each channel independently.

The 2.4 GHz ISM band, which is used by 802.11b/g, devices is divided into 11 channels. To limit co-channel interference, each usable channel must be separated by 25 MHz. Consequently, only 3 channels are useable within the same area. The 5 GHz band, which is used by the 802.11a standard, is divided into 24 channels. All 24 of these channels are independent and non-overlapping. This greatly simplifies AP placement which is discussed in further detail in latter chapters. Wireless channels can be scanned using one of two mechanisms, passive or active scanning.

Wired networks have many limitations in the practical implementation of large networks because of maintaining big network infrastructures. Previously, the main difference between wireless and wired networks was only in transmission medium. There exist physical medium in wired networks, while on the other side physical medium does not exist on the wireless networks. WLAN became very popular in different applications considering the following factors: ease of installation, reliability, cost, bandwidth, total required power, security and performance of network .Therefore, the study of feasibility analysis of WLAN in Urban rail transit environment has very important significance.

3.3.2 Mobile IP and Wireless Mobility.

Mobile IP is a solution for mobility on the global Internet by IETF. It allows a Mobile Node (MN) to change its Access Point (AP) from an old AP to a new AP, across media of similar or dissimilar type; and allows Correspondent Node (CN) to send IP packets to the MN transparently. With the help of Mobile IP, people can freely access many different kinds of services in Internet.

According to the character in urban rail transit model about the wireless AP's scheme in liner, the MN's mobile trajectory is assurance, the adjacent AP along the track line with the same frequency wireless network structure ,which is pointed out the algorithm can be reduced delays very well and achieved the mobile communication's application needs between the train and ground. Wireless mobility is the capacity for devices to physically move through WLAN with minimal disruption to service. Slow or delayed mobility causes noticeable breaks in transmission.

Although the 802.11 standard was designed to allow mobility, it was assumed that usage of WLAN would be portable or nomadic whereby users halt network activity before moving large distances. Numerous studies have shown that mobility in WLAN is unacceptably slow for data communication applications. This is exacerbated by the short operating range of WLAN. With useable ranges commonly below 200m, campus and city-wide WLAN must be built with many closely deployed AP.

Users moving through large wireless networks must frequently transition their connectivity between APs to maintain their connection. The combination of frequent and lengthy handoff is a considerable problem in WLAN and can seriously degrade communication quality.

3.4 USE OF 2.4 GHZ FREQUENCY BAND FOR CBTC

The increasing deployment of Communication Based Train Control (CBTC) by public transit agencies (see Table 3.1) that use a data communications systems (DCS) based in the 2.4 GHz Industrial, Scientific, Medical (ISM) band has raised the concern of RF interference between CBTC equipped trains and the variety of new and existing users of this band. The vast number of RF devices that currently operate in this band (like microwave ovens, cordless telephones, medical devices etc.) has recently been augmented by the proliferation of "Wi-Fi" hotspots and wireless computers permitting untethered internet access by the public and RF identification (RFID) technology. This concern about interference can be extended to those agencies that are currently considering a CBTC deployment.

Singapore, Central line	2006
Singapore, Central line	2006
SanFrancisco, BART AATC	2007
Madrid Metro, lines 1 and 6	2007
Taipei, Taiwan, Muzha Line (Neihu) Ext.	2008
Heathrow Airport, T5 (APM)	2008
Budapest	2008
Seoul, Yong-In Project ART-Metro	2009

Table 3.1: CBTC Systems Using 2.4 GHz for DCS [16].

The 2.4 GHz ISM band has been designated by the FCC as an unlicensed band which means that it can be used by anyone (although some restrictions apply on the amount of radiated power permitted). Operation in this band is advantageous because no FCC license is required and there are many relatively inexpensive radios and associated hardware already developed; however, this is also a disadvantage as it means that there is no control with or coordination between the numerous other users of the band.

The lack of control and coordination with other users in the 2.4 GHz ISM band can seem, at first glance, unsettling and undesirable for any communication system that defines itself as vital or mission critical (as would be the case for most public transit agencies that use CBTC systems). The result of this lack of control and coordination is usually understood to mean an increased likelihood of interference between communication systems using the band. While interference is a possibility, it is by no means a certainty when recent developments in spread spectrum (SS) radios and error detection and correction coding techniques are considered as part of the overall CBTC system.

The level of concern (or risk) about interference revolves around how spectrum (which is the range of frequencies commonly used by radio transmitters and receivers to exchange information) is allocated and how this concept has changed as a result of recent technological developments. Historically, spectrum has been understood as being analogous to real estate ("...they aren't making more of it"). Spectrum was divided and allocated (i.e. licenses issued) between users thus ensuring no interference as long as users stayed on their own property (i.e. respected their allocation).

Recent technological advances like SS, signal processing for error detection and correction and the failing price of computational power have given rise to radios that communicate reliably across multiple channels within a band. Most noteworthy (and difficult to understand) is the fact that this communication is possible even when other users are operating their radios. The simultaneous operation of multiple communications systems in the same band has led to a new analogy for spectrum: it is like the ocean upon which ships travel carrying cargo (i.e. information). To get your cargo from source to destination it is not necessary to own the ocean, just the ship. The ocean is a common resource that can be used by all with the right navigation equipment. Interference is still possible but is less likely to occur.

Some advocate that recent technological advances in smart antennas, systems that work cooperatively (i.e. mesh networks) and "cognitive" radios (i.e. radios that dynamically adapted to their RF environment) will herald an age of spectrum abundance as opposed to the spectrum scarcity that most people understand to exist now.

3.4.1 Interference.

Any radio system that uses the electromagnetic spectrum (and they all do) is susceptible to interference. It is a misconception to think that communication systems in licensed bands are immune to interference. The use of a license band only provides a reduced likelihood of interference occurring as well as recourse for regulatory action against the operators of interfering devices. It does not provide a guarantee for interference-free operation.

SS radios that make use of sophisticated signal processing techniques for error detection and its correction, can and do operate in the 2.4 GHz ISM band reliably because they incorporate various interference mitigation techniques as part of their design. Generally there are two types of SS techniques: direct sequence spread spectrum (DSSS) and frequency hopping spread spectrum (FHSS).

FHSS is easily understood and is shown in Figure 3.1. A FHSS radio operates on a given frequency for a specific period of time (dwell time) and then changes (hops) to another frequency and keeps changing (hopping) in this fashion. The pattern of these changing frequencies is the hop sequence. The hop sequence between FHSS transmitter and receiver must be synchronized. If a given frequency is occupied by another user (the interferer), the FHSS radio might lose some data while it occupies this same frequency but will eventually hop away to another frequency once the dwell time expires. In this scenario, only the data transmitted during one dwell time is at risk of interference.

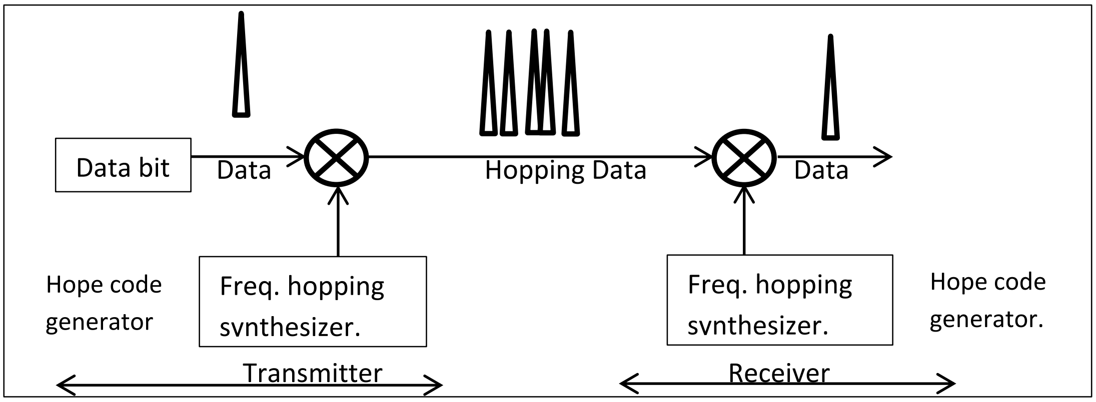

Figure 3.1: FHSS Radio Operation.

The DSSS radio is more difficult to understand as it involves some sophisticated signal processing. Prior to transmission, the DSSS radio basically performs a mathematical operation on the original baseband data such that the spectrum of the original data is greatly increased and its power level is greatly reduced. This operation is accomplished through the use of a spreading code. On reception, the DSSS radio performs the same mathematical operation to the incoming signal a second time which effectively de-spreads the signal and (with some filtering) reconstitutes the spectrum and increases the signal's power level as shown in Figure 3.2. The effect of DSSS is to spread the original signal so that, to other non-SS radios, it becomes indistinguishable from the ambient background noise. The DSSS radio has the added benefit of spreading sources of interference and thus greatly lessening their impact. Thus a DSSS signal can simultaneously occupy bands that are used by others and (to a certain extent) not suffer interference from them.

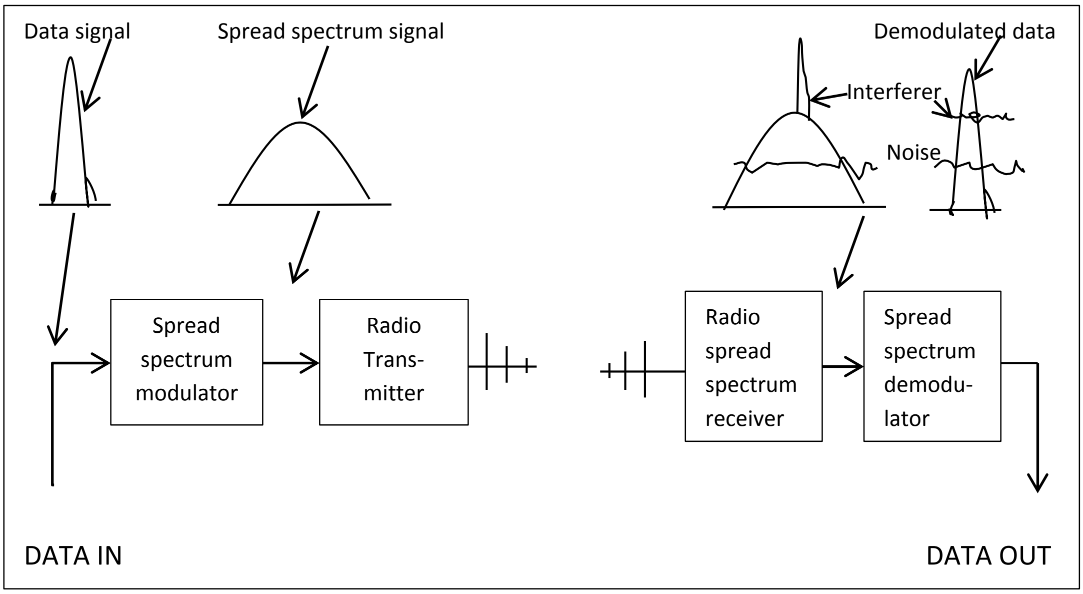

Figure 3.2: DSSS Radio Operation.

In addition to the designs of SS radios being inherently resistant to interference as discussed above, SS radio communication systems may also use sophisticated signal processing techniques to detect errors in transmission of digital data and either correct these errors or initiate a re-transmission. The way these signal processing techniques work is probably the least understood and most under-appreciated aspect of a SS radio communication system. Such techniques include turbo and convolution codes and what are known as low-density parity check codes. These codes can be used to recover data that might have been lost or corrupted during transmission as a result of interference from another source. Accordingly, their use can be viewed as a technique to mitigate the effects of interference.

3.4.2 Risk Management.

Until such time as deployable CBTC systems are available and sufficiently advanced that interference is no longer an issue, the risk of interference must be acknowledged and managed like any other risk that threatens the proper operation of the CBTC system. The options for handling this risk can be described as follows:

- Risk Assumption: Accept the risk: deal with the interference if and when it happens.
- Risk Avoidance: Don't accept the risk: Re-design system to eliminate this risk.
- Risk Prevention & mitigation: Take necessary measures to control the risk.
- Risk transfer: Share risk with others.

Risk avoidance is not possible when dealing with interference (since all radios must face some degree of interference) and risk transfer is not applicable. The only real options are risk assumption and risk prevention & mitigation. Clearly, the path of risk prevention & mitigation is the correct one given that there are such courses of action open in this case.

Arguably the best course of action to prevent and mitigate the risk of interference to a CBTC system is to seek and obtain dedicated spectrum from a regulatory agency. While desirable, obtaining dedicated spectrum is administratively difficult and not always possible because there is very little spectrum that is currently unallocated. The spectrum that is available for allocation usually exists in bands for which there is little or no existing radio equipment already designed and developed. Therefore allocations in these bands would then require a significant investment in research and development by a radio vendor prior to deploying a fully tested CBTC DCS.

Other risk prevention and mitigation measures that can be taken have already been mentioned: make use of SS radios with error detecting and correcting features. Additionally, a CBTC DCS can make use of the following to further prevent or mitigate the risk of interference:

- Narrow beam adaptive antennas (smart antennas): these antennas have very narrow beams to focus or steer their main beams in the direction of desired devices and simultaneously steer antenna pattern nulls or low gain regions towards sources of interference.

- Power Control: reduced power levels lessen the chance of generating harmful intermodulation (IM) products from a saturated receiver front end. IM interference can occur in many ways but this paper is concerned with RF amplifiers that are driven beyond their linear region of operation due to high powered signals.
- Physical Diversity: having multiple signal propagation paths to the receiver which are physically separated and independent. It is unlikely that the interference environment would be severe enough to adversely affect all paths simultaneously.
- Monitoring Program: establish metrics for assessing interference and monitor levels during system operation. This will allow a means of being alerted to the onset of interference conditions that can adversely affect operations and an opportunity to consider and deploy appropriate mitigation measures.

3.4.3 The Benefits of 2.4 GHz ISM Band.

Any CBTC DCS operating in an unlicensed band (like 2.4 GHz ISM) must be capable of withstanding the existing interference environment which (in dense urban areas) is likely to be high given the unlicensed nature and popularity of the band. While this is an obvious disadvantage, there are several advantages as follows:

- The popularity of the 2.4 GHz band means that there has been much research and development done for communications systems in this band and that hardware (radios, antennas, etc.) is already designed and developed. Furthermore, the propagation characteristics are well known. All this translates into reduced capital equipment costs and project risk for transit agencies that might be considering a CBTC deployment.
- The popularity of existing radio communications systems in the 2.4 GHz band has driven the development of ever more sophisticated security features (i.e. user authentication, data encryption, etc.). These features can be adopted for a CBTC system as well. While these features are probably not unique to the ISM band, they owe a large part of their development it.

- Many suppliers and manufacturers have made and continue to make hardware devices and components for use in the 2.4 GHz ISM band. This competition between numerous suppliers means that there is continuous pressure for product enhancements; more so than might exist for products developed for other bands. This large number of suppliers and manufacturers can also lead to reduced operations and maintenance costs over the CBTC system's lifecycle.

3.5 WAYSIDE COMMUNICATIONS SYSTEM WORLDWIDE.

The CBTC supplier, each has a unique CBTC product (or products) that they have developed over the years and used for subway/public transit projects are furnished below.

- Bombardier’s CBTC system is called CITYFLOW 650 and generally makes use of a DCS at 2.4 GHz with discrete antennas or radiating cables.
- Alstom’s CBTC system is called URBALIS and has a DCS that operates at 2.4 or 5.8 GHz using both discrete and continuous (i.e., waveguide and radiating cable) antennas.
- The Thales CBTC system is called SELTRAC (originally developed by Alcatel) with a DCS (called CommTrac) that operates at 2.4 GHz and uses discrete antennas.
- The CBTC system from Invensys is called SIRIUS and uses a DCS operating at either 900 MHz or 2.4 GHz with discrete antennas.
- Lastly, Siemens’ CBTC system is called TRAINGUARD MT and comes with a DCS (called Airlink) that operates at 2.4 or 5.9 GHz using discrete antennas.

3.5.1 DCS RF Coverage.

The most basic requirement for the DCS is to provide RF coverage to ensure uninterrupted data communications between a CBTC-equipped train and wayside elements from any point on the track, including yards and storage/maintenance areas. RF coverage is generally achieved using directional and omnidirectional antennas connected to devices commonly referred to as wayside radio units (WRUs) or radio access points (RAPs) or access points (APs) located along the wayside. The spacing and total number of the WRUs will depend on numerous factors, such as propagation losses at the operating frequency, the amount of curvature in the alignment, and the presence or absence of tunnels and portals.

A crucial aspect of the RF coverage is how the DCS manages the transition of a CBTC-equipped train from one WRU to another without an interruption in data communications. Often, this is done by having the CBTC equipped train communicate with the WRUs both ahead of and behind the train as it moves using DCS radios installed at both the front and the back of the train. The train is continuously trying to establish communications with the WRUs. As it approaches a WRU, communications are established via the front DCS radio, while the rear DCS radio continues searching for additional WRUs. Once the train passes the front WRU and loses communication with it (due to the orientation of antennas on train and on the WRU), the overall WRU spacing is such that the back of the train has already seen (i.e., is able to communicate with) a different WRU behind it and has established data communications so that the train as a whole remains in uninterrupted data communications with the wayside. This arrangement also allows trains to communicate with the wayside in the event that some obstruction (i.e., another train or work vehicle) is positioned between a train and the WRU.

Some DCSs position WRUs so closely together that the front of a train can see not just the WRU ahead of it but also the next one down the line. This type of over-provisioned DCS architecture can increase overall reliability since the CBTC system as a whole has twice as many WRUs as are needed, but this comes at the expense of increased capital and maintenance costs.

Another important aspect associated with RF coverage is the DCS's frequency of operation. I am unaware of any radio-based CBTC system that does not operate in one of the three frequencies bands designated as Industrial, Scientific, Medical (ISM) 900 MHz, 2.4 GHz, and 5.8 GHz. These frequency bands are often used for DCS since (in most countries) operation in these bands does not require a license from a regulatory agency (obtaining a license from a regulatory agency is often a lengthy administrative/legal process with no certainty of success). Most of the

CBTC systems operate in the 2.4-GHz band. The selection of the operating frequency will drive the number and location of WRUs due to the different propagation losses at different frequencies. Propagation loss in free space is given by L as shown in (3.1) and is a function of distance d and wavelength λ.

$$L=20\log_{10}\left[\frac{4\pi d}{\lambda}\right] \quad (3.1)$$

The selection of the DCS's operating frequency might also be dictated by the availability of inexpensive and service-proven radio equipment. Such radio equipment is more likely to be available at 2.4 GHz because of the existing large commercial market for Wi-Fi-compatible devices. Certain CBTC vendors would much rather provide a DCS based on readily available commercial off- the-shelf radios as opposed to developing their own proprietary radio hardware and software. The selection of DCS operating frequency may also be driven by the concern for RF interference, which is discussed in greater detail in the following section.

The selection of a DCS operating frequency is not made in isolation but done in concert with the consideration of the CBTC system as a whole. As a result, there is no single best DCS operating frequency, only an operating frequency that complements the operation of the rest of the CBTC system.

The RF coverage for a DCS is physically realized through the placement of antennas along the wayside and aboard the vehicles of CBTC-equipped trains. There are generally two types of wayside antennas that can be selected:

- A continuous antenna is a waveguide or coaxial cable with apertures machined into the waveguide's walls or the coaxial cable's outer conductor. Continuous antennas are often referred to as leaky or radiating waveguides or cables and are installed along the length of the train way to provide continuous RF coverage.
- A discrete antenna is a planar or Yagi–Uda array that provides directional coverage along the train way or an omnidirectional antenna for wide area coverage. Less commonly used are parabolic dish antennas. These antennas

are installed at specific locations only but oriented to provide RF coverage along the length of the train way.

Using continuous antennas for CBTC systems is not as popular as using discrete antennas, most likely because they are more costly, require more effort for installation, and (when used outdoors) may be more susceptible to signal degradation due to rain/snow/ice accumulation. Discrete antennas, which are typically light weight, inexpensive to install and maintain and have added the benefit of providing some signal gain for the DCS signal. In addition to supporting the data transport needs of a CBTC system, the IAGO waveguide is capable of transporting video signals from closed-circuit television (CCTV) cameras aboard trains. If this feature is not required, then the use of discrete antennas for the DCS of a CBTC system is the better choice to make to provide the needed RF coverage.

3.5.2 RF Interference to the DCS.

Every CBTC DCS must address the issue of RF interference since it has the potential to adversely affect the performance of a CBTC system. There is no single most effective mitigation that can be used as there is not just one type of RF interference but numerous types dependent on such things as the DCS operating frequency, the amount of segregation that exists between the train way and public areas, the directivity of the DCS antennas used, the regulatory environment within which the DCS must operate, and data traffic characteristics.

As discussed earlier, most (if not all) DCSs make use of one of three ISM bands (900 MHz, 2.4 GHz, and 5.8 GHz); however, the 2.4-GHz band is the most heavily used throughout the world's dense urban areas and represents a source of RF interference to other DCSs that also operate in the 2.4-GHz band. This is especially true as more transit agencies introduce Wi-Fi services to previously isolated underground transit stations and tunnels. A simple strategy to avoid the potential RF interference of the 2.4 GHz band is to avoid it completely and operate a DCS at a different frequency. Some CBTC vendors take this approach and operate at the 5.8-GHz band. This seems a prudent measure, given the ubiquity of Wi-Fi service at 2.4 GHz. The presence of potential Wi-Fi interference to a CBTC system can be determined from an RF survey, the results of which could be used to assess the risk of interference compared to the cost of avoiding the 2.4-GHz band.

Over the past decade, there was some discussion about and activity around obtaining separate and dedicated spectrum for use by CBTC systems. While this approach would minimize RF interference significantly (the only other RF signals would be from unauthorized sources against which enforcement action could be taken), it has not yet been realized, most likely because of the ever-increasing demands for spectrum placed upon regulatory agencies for one purpose or another.

Efforts to segregate the DCS from other potential in-band sources of RF interference can also be seen as important mitigation techniques. This segregation can occur in any of the following ways:

- **Physical**: Create as much distance between antennas for the DCS and any other in-band emitters. The greater the distance, the less influence these emitters will have and thus will pose less of a risk for RF interference.
- **Structural:** Use the physical structure of the environment to put obstructions between DCS antennas and any other in-band emitters. Train/subway tunnels are excellent ways to provide this type of structural separation.
- **Antenna:** Use highly directive antennas (i.e., those with narrow beamwidths) for the DCS. Such antennas will focus the RF energy only where it is needed and (more importantly) attenuate signals from any other in-band emitters that are not oriented along the antenna’s main beam. Also, avoid the use of omnidirectional antennas.

In RF environments where the DCS must compete with other in-band wireless data systems that transmit and receive data packets (like Wi-Fi), another mitigation technique is to adjust the DCS traffic characteristics to minimize the interference. Data collisions (a form of RF interference) can occur when the data packets from other wireless data systems are transmitted at the same time as DCS data packets. These collisions can corrupt the DCS data at the receiver and result in requests for retransmissions and increase the overall packet loss rate for the DCS. Adjustments to the DCS’s packet size, bit rate, and duty cycle can minimize the packet loss rate due to these collisions (higher bit rates and smaller packets will usually result in a reduction in the packet loss rate; however, absolute numerical results depend on the parameters of the system considered).

3.5.3 Multipath Fading.

In the context of the DCS for a CBTC system, multipath fading can be defined as follows: When radio signals simultaneously follow two or more paths of differing physical length, between the transmitter and receiver, these signals then suffer different transmission delays due to the finite propagation velocity involved. The vector combination of these signals at the receiver can range from destructive to additive, depending on the relative delays involved. This resultant variation of the observed signal level is known as multipath fading. DCSs operate in open cuts, at grade, on elevated trainways, and in tunnels, all of which (especially tunnels) are considered multipath environments due to the way signals reflect and scatter off the various structures, walls, pipes, and equipment cases typically located along the tracks. Figure 8 shows the signal variations due to multipath fading at a receiver measured over a short distance (in this case 50 wavelengths) where the rapid signal fluctuation typical of multipath fading can be readily observed. Note the deep signal fades or nulls that can occur over very short distances.

To mitigate the adverse effects of multipath fading, some DCSs use some or all of the following techniques:

- **Frequency diversity**: Multipath fading is sensitive to the frequency of operation of the DCS. If data can be transmitted (simultaneously or sequentially) at more than one frequency, then the chances that the DCS will not suffer because of a multipath signal null are greatly improved.
- **Space diversity**: Since multipath fading shows large fluctuations over short distances, a second DCS receiver antenna located a few meters away from the first will, on average, encounter signal levels that are different by several decibels. The offset between the two antennas can be either vertical or horizontal.
- **Rake receivers**: A rake receiver is designed to detect, align, and combine individual multipath components of a radio signal through the use of multiple correlators, the outputs of which are weighted and combined to provide an

optimized estimate of the received signal that is better than any single signal component estimate. It is called a rake receiver because each correlator represents a separate branch that collects and processes part of the original signal much like a garden rake collects leaves with its numerous times.

3.5.4 Spread Spectrum and Other Modulation Techniques.

A spread spectrum communications system is one that purposefully spreads the spectrum of the signal well beyond the required bandwidth for the information content of the message. While this approach may seem counterintuitive, it does offer significant advantages, especially when the communication system in question (i.e., a CBTC system) operates in unlicensed bands. Given that many of the DCSs shown in above Figure 3.1 and 3.2 make use of some form of spread spectrum modulation, it is worth examining the advantages of this technique and the different types that are commonly used.

The advantages of using spread spectrum signal modulation techniques that are relevant to CBTC systems are as follows:

- the rejection of intentional and unintentional interference and jamming
- a low probability of signal interception (due to spreading over a large bandwidth), which makes detection of the signal difficult
- inherent message privacy, since an unauthorized listener who lacks knowledge of the spreading code and precise timing cannot readily demodulate the signal
- good rejection of the interference caused by multipath fading.

The most well-known and easily understood spread spectrum modulation technique is frequency hopping spread spectrum (FHSS), which is illustrated in Figure 3.1. An FHSS radio operates on a given frequency for a specific period of time (dwell time) and then changes (hops) to another frequency and keeps changing (hopping) in this fashion. The pattern of these changing frequencies is the hop sequence. The hop sequence between the FHSS transmitter and receiver must be synchronized. If a given frequency is occupied by another user (the interferer), the FHSS radio might lose some data while it occupies this same frequency but will eventually hop away to another frequency once the dwell time expires. In this scenario, only the data transmitted during one dwell time is at risk of interference and receiver must be synchronized. If a given frequency is occupied by another user (the interferer), the FHSS radio might lose some data while it occupies this same frequency but will eventually hop away to another frequency once the dwell time expires. In this scenario, only the data transmitted during one dwell time is at risk of interference.

The direct sequence spread spectrum (DSSS) modulation technique is more subtle and difficult to understand as it involves some sophisticated signal processing. Before transmission, the DSSS radio basically performs a mathematical operation on the original baseband data such that the spectrum of the original data is greatly increased (in this case, spectrum is taken to mean the frequency content of a signal), and its power level is greatly reduced. This operation is accomplished using a pseudorandom spreading code. On reception, the DSSS radio performs the same mathematical operation to the incoming signal a second time, which effectively dispreads the signal and (with some filtering) reconstitutes the spectrum of the desired signal and increases its power level.

The DSSS process can be seen mathematically if we consider the following example: let the information or desired signal be $s(t)$, and let $c(t)$ be the pseudorandom spreading code. The signal that is transmitted is then $m(t)$ expressed as

$$m(t) = c(t) . s(t) \tag{3.2}$$

This process is also shown in Figure 3.3, where Tb and Tc are the bit duration of the information signal $s(t)$ and the chip duration in the spreading code $c(t)$, respectively. The received signal is then $r(t)$ and is equal to $m(t)$ plus any noise or inferring signal $i(t)$

$$r(t) = m(t) + i(t) = c(t) . s(t) + i(t) . \tag{3.3}$$

By multiplying the received signal a second time by the same spreading code we obtain $z(t)$, the recovered signal, as follows:

$$z(t) = r(t) . c(t) = c2(t) . s(t) + c(t) . i(t) \tag{3.4}$$

The spreading code is a binary string that consists of alternating −1 and +1 (also called chips), thus $c2\ (t) = 1$ for all values of t. As a result, $z(t)$ can then be expressed as

$$z(t) = s(t) + c(t)\ .\ i\ (t) \tag{3.5}$$

The recovered signal $z(t)$ can now be further processed and filtered to retrieve $s(t)$ and disregard the interference. This mathematical process clearly shows, without resorting to more sophisticated Fourier analysis, how the desired signal can be easily recovered from applying the spreading code twice. The effect of the DSSS technique is to spread the original signal so that, to other non-SS radios, it becomes indistinguishable from the ambient background noise. The DSSS radio has the added benefit of spreading sources of interference and thus greatly lessening their impact. Therefore, a DSSS signal can simultaneously occupy bands that are used by others and (to a certain extent) not suffer interference from them.

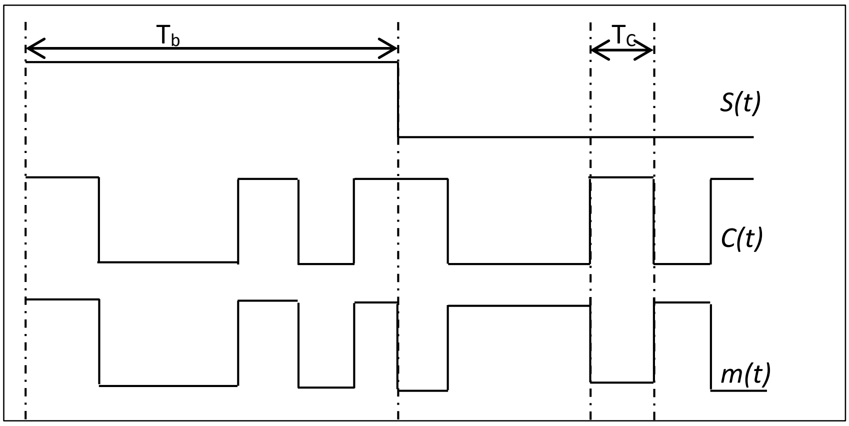

Figure 3.3: DSSS Signal modulation.

Another modulation technique less often used in some DCSs is known as orthogonal frequency-division multiplexing (OFDM). OFDM subdivides the frequency band of operation (usually 5 GHz) into a number of subcarriers, with each subcarrier used to transmit part of the data at a relatively slow rate, which is less susceptible to multipath interference. While the date rate for each subcarrier is relatively low, the aggregate data rate for all subcarriers combined is very high, which leads to another advantage for OFDM: high data throughput for a given bandwidth (i.e., high spectral efficiency). Orthogonal means that a minimum of each modulated subcarrier signal coincides with a maximum for the adjacent modulated subcarriers, which minimizes mutual interference between subcarriers. All this signal processing adds to the cost and complexity of a DCS based on an OFDM system, but the advantages of resistance to multipath interference and high data throughput are attractive.

Some CBTC systems in Europe are described as European Train Control Systems (ETCS, levels 3 and 4) and make use of a DCS that is based on a variation of the popular cellular digital communication technology known as global system for mobile communications (GSM). GSM technology is based on providing different simultaneous users time slots in a data frame so as to transmit and receive their data (up to eight simultaneous users on one RF channel). This approach is called time-division multiple- access (TDMA). The GSM variant used for ETCS is called GSM-railroad (GSM-R), and it provides enhanced functionality relevant to railroad operations, but most importantly, it can support voice and data communications between a train and the wayside at speeds of up to 500 km/h, including during handover areas, which are locations where trains transition from one GSM-R wayside base station to another. The differences between CBTC and ETCS are beyond the scope of this article; however, some people argue that these two train control systems are actually converging to be effectively the same.

3.6 IMPLEMENTING CBTC TECHNOLOGY SYSTEM

The latest generation of CBTC train control system represents a cost-effective means of improving the level of service offered to transit passengers in terms of safety, dependability and comfort while providing increased capacity and reduced travel times on an existing transportation infrastructure. Such systems allow trains to operate safely at shorter headways and permit system operations to recover more rapidly in the event of a disturbance; all of which provides more regular and improved passenger service and translates directly to increased line capacity and measurable increases in ridership.

CBTC systems can also provide lower maintenance costs (resulting from less trackside equipment and improved diagnostics), greater operational flexibility, enhanced safety (due to continuous automatic train protection), smoother and more predictable operation, and improved reliability and availability (through redundant/fault tolerant designs). They can also provide a foundation for further integration of transit system control functions. For example, the wayside-to-train data communications link can also be used to support other non-train control functions, such as triggering passenger information displays and automatic announcements on board trains, and downloading train health monitoring information to wayside maintenance centres.

The increased dependency on communications-based, computer-based, and software-based technologies associated with these systems does introduce new project risks, however, and it is clear that realising the benefits of new technology does not come without significant challenges. Experience from around the world has shown that a top-down systems engineering and systems integration approach to design, procurement and construction management are essential ingredients to project success.

3.6.1 System Requirements.

The first step in assuring project success in implementing any new technology system is to establish a complete definition of the performance and functional requirements for the system. While the need for a clear definition of system requirements may be self-evident, experience would indicate that capturing these requirements in a consistent and unambiguous form is often the most difficult aspect of any project. It is critically important therefore to first capture the “vision” for the new system in terms of operating needs, and benefits to be realised. This “vision” can then be used to consistently drive the more detailed system requirements.

Once the top-level “vision” has been established, the detailed technical specification can then be developed as the basis for the system procurement. The technical specification should specify the operational needs, performance requirements and implementation strategy, focusing on “what” functions the new system is required to perform, rather than on “how” these functions are to be implemented. The technical specification should avoid imposing explicit design solutions as experience has shown that the suppliers of new technology train control systems are well qualified to develop an appropriate system design, once the transit agency has clearly established the functional requirements to meet its operational and strategic goals.

In defining the functional requirements, it is not unusual for a technical specification to focus predominantly on the generic requirements for the system, and in particular the requirements during normal operations. Experience has shown however, that satisfying the general functional requirements of the specification under normal operating conditions can be relatively straightforward, and the more significant challenge is complying with any application specific requirements, specifically the handling of the various failure modes.

Train control systems are also rarely “stand alone” systems and are typically required to interface with conventional signalling equipment and other train management and customer information systems. These interfaces can be complex, and particular attention needs to give to appropriately defining such interfaces in the technical specification. Similarly, the technical specification needs to clearly and completely define all of the physical constraints imposed by the train and infrastructure characteristics that can impact the design and installation of the train control system.

3.6.2 System Selection.

In selecting a train control system for a specific application, while the cost of the proposed system (both initial cost and life cycle cost) is certainly an important evaluation factor, other important factors that need to be considered include the maturity of the proposed train control system with respect to the requirements of the technical specification, and the technical risks associated with any system adaptations, as well as the capabilities of the system supplier to implement the proposed train control system on schedule and within budget. In assessing technical risks with CBTC systems, the critical areas are the train location determination subsystem, the data communications subsystem, and the vital computer systems.

For example, the design of any train-borne positioning subsystem involves a complex trade-off between safety, availability and system performance. Managing this trade-off represents a generic and application-specific technical risk since the design of the positioning subsystem needs to take account of the specific train and infrastructure characteristics. Similarly, the availability of a continuous train-to-wayside and wayside-to-train data communication link along the application-specific right-of-way is also critical to the performance of a CBTC system. Key performance parameters that need to be considered are bandwidth, message latency and the reliability and security of message delivery.

Distributed, vital computer systems on the trains and along the wayside represent the final building blocks of any CBTC system. These computer systems are complex devices, difficult to design and validate, because they must not only be designed to exhibit high system availability and have sufficient processing capability to accommodate the specific application functions, but must also be designed to stringent “fail-safe” standards.

3.6.3 System Implementation.

Having selected the most appropriate train control system, experience from around the world indicates that in order to successfully implement the new train control system, particularly in a re-signalling application, rigorous design management and project management processes need to be instituted by both the supplier and the transit agency. To this end, experience also strongly suggests that an integrated, and co-located, project team is most effective, utilising a true partnering philosophy focused on implementing the project “vision”. From a design and project management perspective, the following implementation issues are considered particularly critical:

a) Establishing realistic project cost and schedule estimates that draw on “lessons learned” from other similar projects.
b) Adopting a structured system development process to ensure there is a complete and common understanding between the agency and the supplier on the requirements to be implemented. For example, for conventional train control systems, each transit agency often has its own "typical circuits" for implementing interlocking and signalling functions based on its specific "signalling principles" and operating practices. CBTC systems offer

significant advantages in terms of increased operational flexibility, but in order to realise these benefits in practice, a re-evaluation of the agency's operating practices and signalling principles is often required. Reaching a common understanding between the agency and the supplier on the required "signalling principles" for the new CBTC system is a critical first step in implementing such as system since only when the "signalling principles" have been agreed, can site specific application designs be developed.

c) Establishing clear requirements for an overall test and commissioning strategy that recognises that with CBTC technology (since a significant portion of the train control logic is now located on the train), the majority of the field testing will require the availability of one or more CBTC-equipped trains and associated track access. Prototypes, simulation tests and other facilities should be used to minimise actual field-testing requirements.
d) Reaching early agreement between all stakeholders on the safety certification process. The safety standards and validation requirements for deployment and validation of safety critical train control systems are becoming increasingly rigorous and the safety certification process can represent a significant component of the project schedule and budget. Early agreement on the certification process is therefore critical to ensure that necessary documentation to provide evidence of an acceptable safety assurance process is prepared, submitted and approved at the appropriate milestones in the project implementation.
e) Utilising well-defined transition plans to develop and implement new operating and maintenance practices and procedures, and to operationally manage the cutover to the new train control system.

3.7 SYSTEM INTEGRATION

Numerous interface issues need to be managed to ensure the success of any new train control project. This includes, for example:

a) Institutional interfaces – to ensure all of the stakeholders who can affect, or will be affected by, the introduction of the new train control system (including regulatory agencies) have an opportunity to provide timely input into the system requirements.

b) Operational interfaces – to ensure that the design of the new train control system is fully compatible with the operational practices and operational goals of the transit agency.
c) Technical interfaces – to ensure that the design of the new train control system is functional compatible with all interfacing systems and subsystems.
d) Physical interfaces – to ensure that the new train control system can be physically installed and implemented within the constraints of the train and infrastructure characteristics.
e) Schedule interfaces – to ensure that the institutional, operational, functional and physical design interface information for the new train control system is available in a timely fashion, and that the installation, test and commissioning of the system is carried out in a logical and structured manner consistent with the needs of the transit agency.
f) Contractual interfaces – to ensure that the obligations of the system supplier, the transit agency, and other stakeholders, are completely defined in the appropriate scopes-of-work with responsibilities for management of all interfaces and all project risk items clearly identified.

Systems integration, or interface management in its broadest sense, therefore plays a critical role in project success. Systems integration should not be viewed as a stand-alone discipline, but rather an inherent component of design management and project management, requiring an appropriate balance between people and process. People with the necessary expertise and experience to be able to identify and resolve the institutional, operational, technical, physical, schedule and contractual interfaces, supported by proven design and project management tools and processes, such as Requirements Traceability Management tools, Interface Control Documents, Critical Path Schedules, Project Collaboration tools, and Operations/Maintenance Transition Plans, etc. While not a requirement for many transit operators, there are some operators who seek or require interoperability and/or interchangeability of CBTC subsystems/components from different suppliers.

3.7.1 Interoperability.

"Interoperability" is driven primarily by operating requirements, and is the ability to operate a train equipped with CBTC on-board equipment provided by one supplier on lines or line segments equipped with CBTC wayside equipment provided by a different supplier. Interoperability is generally only of concern to those transit operators with large complex rail networks, where trains are not dedicated to specific lines and can/could operate on multiple lines within the rail network, and where individual lines may be re-signalled at different times by different suppliers. Interoperability is also of interest to transit operators who are not only re-signalling existing lines but have future plans for significant line extensions and do not wish to be locked into a single supplier for all future network upgrades.

3.7.2 Interchangeability.

"Interchangeability" on the other hand is driven primarily by maintenance/equipment availability issues in order to provide the transit operator with the flexibility, over the long term, to exchange elements of the overall CBTC system with subsystems/components provided by a supplier different to the original system supplier. As with "interoperability", "interchangeability" is typically only of concern to the larger transit operators and those operators who may wish to retain the flexibility in the future to replace or expand elements of a train control system without being required to replace the complete system. Interoperability and interchangeability both require a definition of those subsystems/components that are to be interoperable and/or interchangeable, and both require a precise definition of the interface requirements between these subsystems/components. In order to define such interfaces, it is first necessary to standardise the CBTC system architecture, principles of operation, and allocation of functions to the various CBTC subsystems/components.

This in turn also requires the standardisation of the CBTC performance and functional requirements; both mandatory and optional requirements.

The interfaces defined to support interoperability may not necessarily be the same interfaces defined to support interchangeability. For example, to support interoperability, one logical interface to be standardised could be the air-gap interface between the wayside and onboard data transmission subsystems. On the other hand, from an interchangeability perspective, the complete data communications system could be considered an interchangeable item. In this case, there would be no requirement to standardise the air-gap interface, but rather it would become necessary to standardise the (internal) interfaces between the data communications system and both the wayside and the onboard CBTC subsystems. There is currently a lack of international standards for interoperability and interchangeability for CBTC technology although various efforts are underway to develop consensus-based industry standards, as well as standards specific to a given transit operator.

3.7.3 North American Standards Initiatives.

In North America, the Institute of Electrical and Electronics Engineers (IEEE) has published performance and functional requirements standards for CBTC technology (IEEE Std. 1474.1-2004), User Interface Requirements standards for Communications- Based Train Control (CBTC) Systems (IEEE Std. 1474.2- 2003), Recommended Practice for CBTC System Design and Functional Allocations (IEEE Std. 1474.3- 2008) and Recommended Practice for Functional Testing of a CBTC System (IEEE Std. 1474.4-2011).

3.7.4 European Standards Initiatives.

In Europe, the IEC TC9 Working Group 40 has also embarked on a standards initiative to define functional, system and interface requirements for command, control, and management systems used on urban, guided passenger transport lines and networks. Part 1 of this standard, "System Principles and Fundamental Concepts” and Part 2 is “Functional Specifications”. The European research project, MODURBAN, has similar objectives to develop new train control systems for urban transit applications through the definition of functional requirements, system architecture, subsystem requirements, and subsystem interfaces.

3.8 OVERALL TEST PROCESS

3.8.1 General.

This recommended practice addresses system-level functional testing only, as an integral element of the overall test process, to verify in the factory, on a CBTC test track, and in the field that the CBTC system functional requirements have been satisfied, as highlighted in Figure 3.4. This recommended practice does not address unit testing at a module level, subsystem tests, hardware qualification tests, hardware post-installation check-out testing, and data communications coverage testing, which are all necessary prerequisites to system-level functional testing. Trial operations, reliability/availability/maintainability demonstrations and other customer-specific final acceptance testing are also not included. If a function/sub-function has been previously verified in one application, it may not be necessary to retest the function/sub-function in a subsequent application, based on consideration of any differences in hardware, software, system databases, and operating environment.

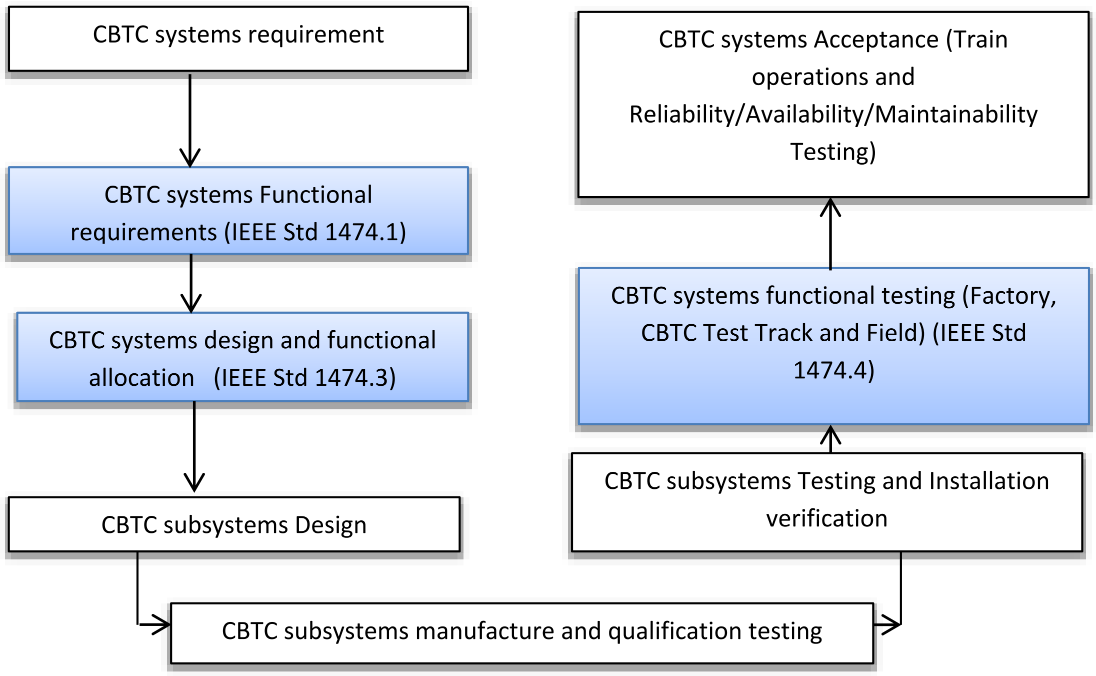

Figure 3.4: CBTC System design / Verification.

IEEE Standard 1474.1-2004[7] defines the CBTC system-level functional requirements addressed by this recommended practice.

A CBTC system comprises the following major subsystems:

a) CBTC ATS equipment

b) CBTC wayside equipment

c) CBTC train-borne equipment

d) CBTC data communications equipment

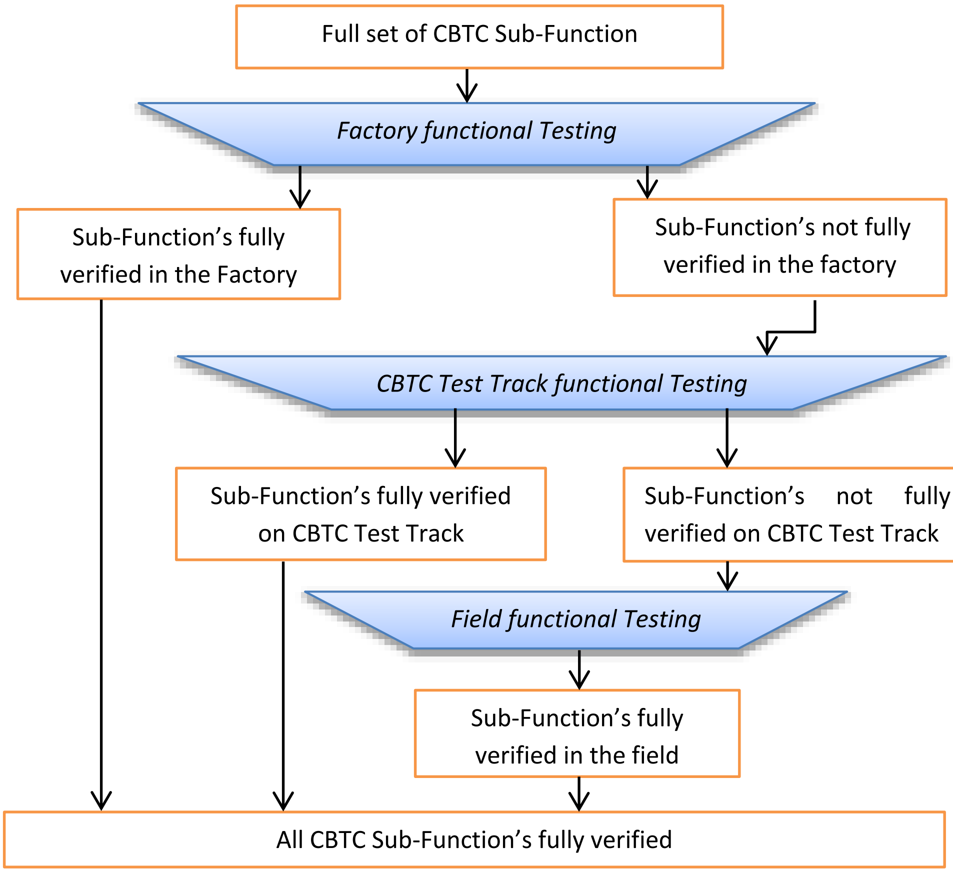

Figure 3.5: Functional Test Process.

The recommended allocation of ATP, ATO, and ATS sub-functions to the preceding major CBTC subsystems is defined in IEEE Standard 1474.3-2008 [6].

A CBTC system also interfaces to external interfaces such as the following:

a) Interlocking's and secondary train detection systems
b) Train subsystems (propulsion/braking systems, train doors)
c) Platform edge doors (if provided)
d) Highway grade crossing warning devices (if provided)
e) Passenger information systems (if provided)
f) User interfaces
g) Other external interfaces as may be specified by the authority having jurisdiction.

Figure 3.5 summarizes the recommended functional test process to verify that all of these functional requirements have been satisfied

The objective of the factory functional testing should be to verify to the maximum extent possible that all of the CBTC functional requirements have been satisfied. When testing a specific functional requirement, if the test outcome cannot be affected by factors outside of the test environment, it should not be necessary to have to repeat this test on the test track or in the field, i.e., such requirements should be fully verified through the factory testing. Where a factory test outcome is dependent upon simulated interfaces to the CBTC system, it would generally be necessary to repeat such tests either on the test track or in the field with the real interfaces, depending on the complexity of the interface and the ability to simulate the interface in the factory.

3.9 HANDOVER SCHEMES IN WLAN SYSTEM

In urban mass transit system the rails are fixed and the wayside devices need only communicate with the mobile station (MS) in the trains on the rails. So the coverage areas of the AP on the wayside are just the regions of the rail where the train runs. And in urban mass transit system the tunnels are most possible operation environments.

The directional antennae are usually used with AP and mobile station to transmit or acquire more power in some directions so that the coverage of AP can be improved. The AP with directional antennae and the corresponding coverage are shown in Figure 3.6.

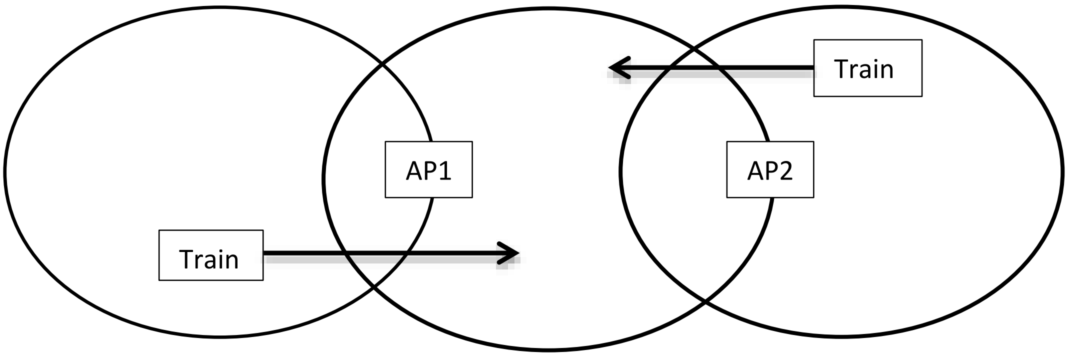

Figure 3.6: Coverage of APs with directional antenna.

As in the Figure 3.6 the trains can run towards the direction of the antennas or opposite to the direction. When the train switches the communication link from API to AP2, the handover process happens and during the process data communication may be interrupted and some packets would be lost.

3.9.1 Handover schemes in 802.11.

No rules are made for the mobile station on how to hand over from one AP to the other in existing 802.11 series standards, and the handover algorithms of the WLAN products are designed and implemented by the manufactures themselves. But in 802.11-2007 the synchronization, authentication, association and re-association process are defined and from these processes we can deduce the flowchart of the handover process. According to the protocols in the standard, the handover process includes the following three stages:

STEP 1: Scanning Stage.

The scanning is the process for the mobile station to find new AP and by the way of scanning it can be classified into passive scanning and active scanning. In the passive scanning process, the mobile station waits for and scans the beacon frame transmitted from the AP periodically. While in the active scanning process, the mobile station will send the Probe Request signal to find new APs and the APs who receive the signal will send back a Probe Response signal to the mobile station. The mobile station will choose the best AP as its candidate AP to be synchronized with and access in. The WLAN system usually adopts the active scanning process because of its smaller delay. The handover process which uses active scanning is show in Figure 3.7.

Generally the mobile station needs to probe all the channels of 802.11 in turn and 11 channels are defined in China, so the probe process needs a lot of time.

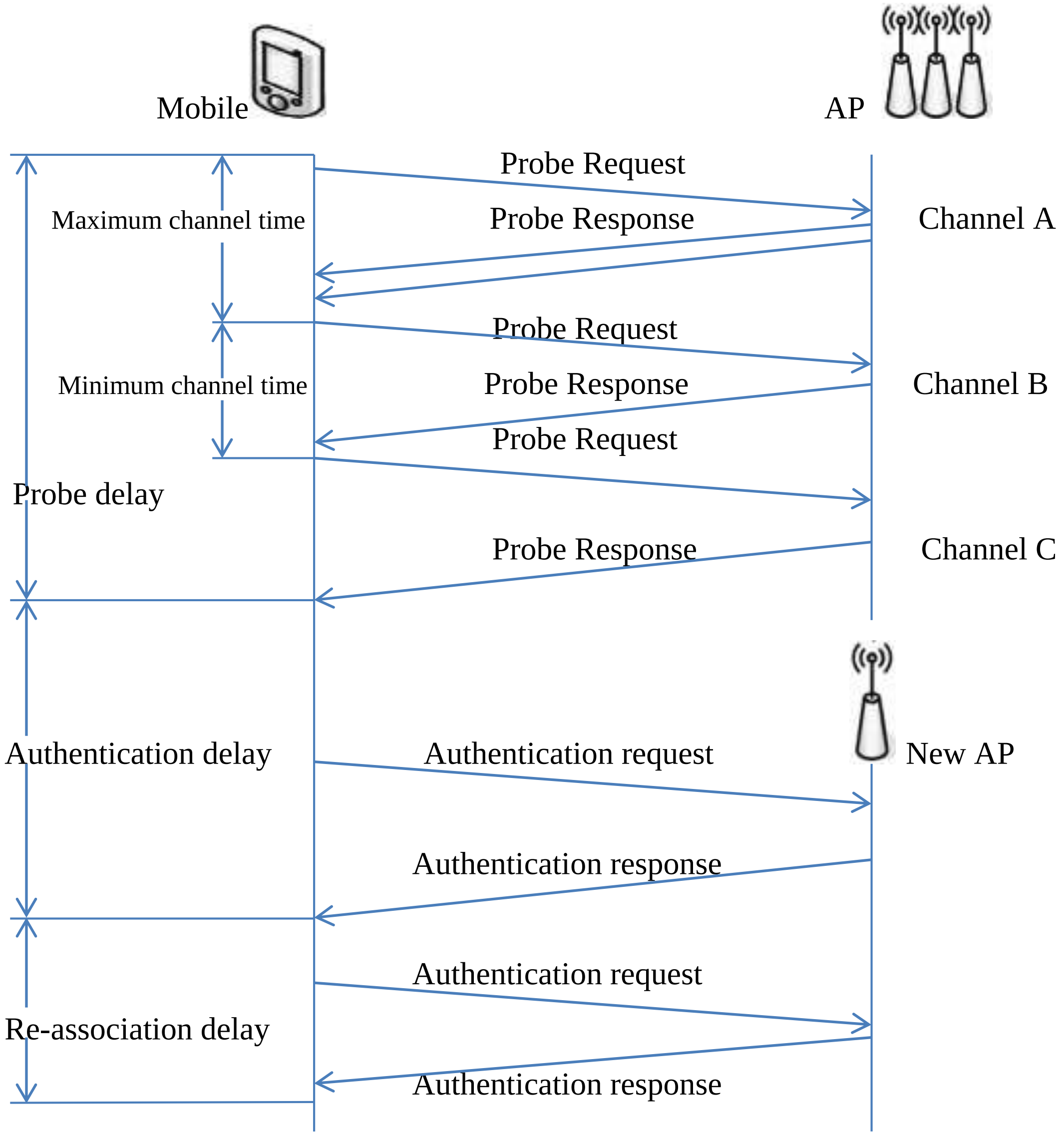

Figure 3.7: Handover Process with Active Scanning.

STEP: 2 Authentication Stage.

At the authentication stage the mobile station will authenticate with the best AP found in the first stage. Some 802.11 products would provide IAPP (Inter-Access Point Protocol) based pre-authentication method to reduce the latency of the stage. In IAPP protocol when the mobile station has associated with the first AP of ESS (Extended Service Set), the IAPP would send the authentication information to all the AP in the ESS. Therefore, when the authentication with one AP has been finished, the authentication processed is not needed anymore.

STEP 3: Re-association Stage.

Re-association is the process that the mobile station switched the association from one AP to another one. It includes two processes as follows:

a) The mobile station sends the Re-association Request signal to the candidate AP.
b) The candidate AP sends the Re-association Response signal to the mobile station.

The re-association process is the last stage in the handover process and its latency can't be reduced by any new methods.

3.10 RECTANGULAR LEAKY WAVEGUIDE

Train-ground communication, which is the basis for train control system, is one of the key technologies for CBTC. At present, IEEE 802.11-based wireless local area networks (WLANs) have become promising candidates for CBTC. The 802.11 associated access point (AP), and work bridge group (WGB) has to work in specific propagation channels. Usually, APs on the ground side are connected to antennas a few hundred meters apart, WGBs are installed on the train with their antennas pointing to the APs' antennas. Although it is easy to install equipment this way, the wireless signal will be affected significantly by great path loss, shadow fading, fast fading and co-channel interference caused by complicated environment .In order to cope with this problem, the APs can be connected using a continuous radiating structure. The leaky coaxial cables are used when the frequency is below 1 GHz. Since WLAN is working between 2 GHz and 6 GHz, leaky wave-guide is a good choice as the radiating structure.

3.10.1 Principle.

A rectangular air-filled waveguide is considered; because it is easy to install and maintain equipment’s along the track Figure 3.8 illustrates rectangular waveguide geometry.

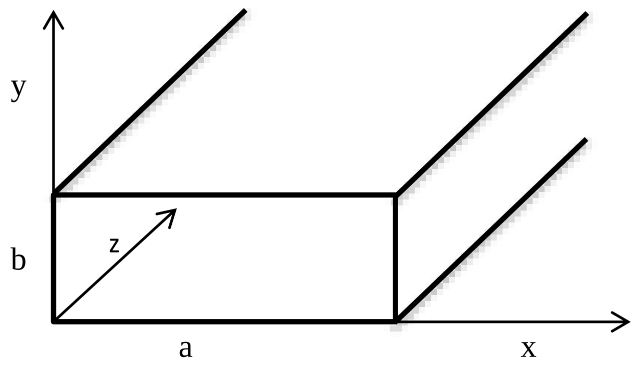

Figure 3.8: Typical Rectangular Waveguide Geometry.

Since rectangular waveguide has a cut off frequency; the wireless signal propagating in the waveguide should have a frequency greater than the cut off frequency. The waveguide cut off frequency, denoted as f_c , is given by:

$$f_{c(\mathrm{TE}_{mn},\mathrm{TM}_{mn})} = \frac{c}{\lambda_{c(\mathrm{TE}_{mn},\mathrm{TM}_{mn})}} = \frac{\sqrt{\left(\frac{m\pi}{a}\right)^2+\left(\frac{n\pi}{b}\right)^2}}{2\pi\sqrt{\mu\varepsilon}} \tag{3.6}$$

Where c is the light speed, λ_c is the waveguide cut-off wavelength. Substitute m, n into (3.6), we get the cut-off wavelength of waveguide,

$$\lambda_{c\mathrm{TE}_{10}} = 2a \quad \lambda_{c\mathrm{TE}_{20}} = a \quad \lambda_{c\mathrm{TE}_{01}} = 2b \tag{3.7}$$

The λ_c of different modes is illustrated in Figure 3.9:

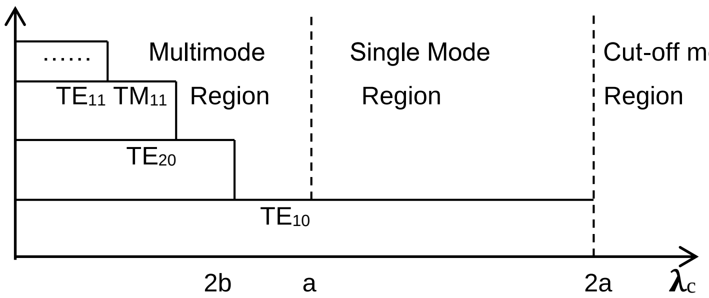

Figure 3.9: The cut-off Wavelength of different modes.

In order to get the lowest longitudinal attenuation, the waveguide needs to operate in single mode, which means the signal wavelength λ should be:

$$\left.\begin{matrix}\lambda_{\mathrm{TE20}}\\ \lambda_{\mathrm{TE01}}\end{matrix}\right\} < \lambda < \lambda_{\mathrm{TE10}} \tag{3.8}$$

and:

$$\left.\begin{matrix}a\\ 2b\end{matrix}\right\} < \lambda < 2a \tag{3.9}$$

From (3.9), we get:

$$0 < \mathrm{b} < \frac{\lambda}{2} < a < \lambda \tag{3.10}$$

When we use the leaky wave-guide, we need to make sure that its width and height meet the requirement in (3.10). In order to receive the wireless signal propagating in the waveguide, the waveguide should be perforated along a broad side with thin and short slots. Figure 3.10 shows such an elementary slot perforation on the rectangular waveguide. The slot is l_1 long by l_2 wide.

Bethe's small-hole theory is used to analyse the radiation of these small slots, according to Bethe's theory; we consider that the radiation of this elementary slot is mainly equivalent to the one of equivalent dipoles. This equivalence is valid if the dimensions of the slots are relatively short compared the wavelength. The slot equivalent elementary dipole is shown in Figure 3.10.

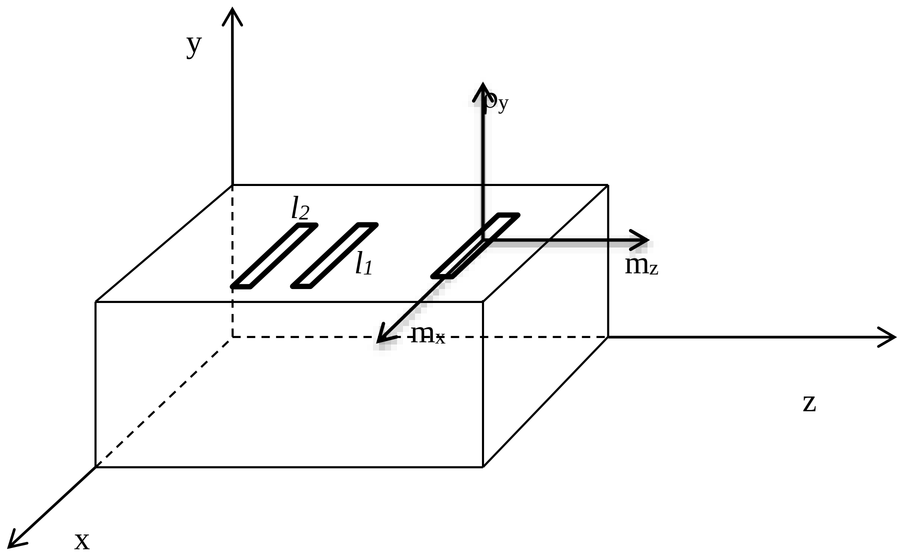

Figure 3.10: Slot Perforation and Equivalent Dipole.

In Figure 3.10, ρ_y represents the electric equivalent dipole corresponding to the propagation of the illuminated electric m_x, m_z field normal component through the slot. *x* and *z* represent the magnetic dipoles created by the presence of the slot.

The power radiated by the elementary slot is mainly from the magnetic dipole. A single magnetic dipole's radiated power is given by [16]:

$$P_{ram} = Z_O \frac{4}{3} \frac{\pi^3}{\lambda^4} m_x^2 \tag{3.11}$$

Where, Zo is the free space wave impedance, m_x is related to the magnetic field inside the waveguide and the length of the slot.

The distance between the slots which noted as d_{slots} is adjusted so that, in the considered frequency range, moving along the waveguide, the total electric field remains almost constant over the waveguide.

When the Leaky Wave-guide is laid alone the track, each of elementary slots located along the waveguide can now be considered as a separate source radiating along the track, and two consecutive sources are separated by d_{slots} .The antenna on the train can receive the radiated signal from these consecutive sources.

3.10.2 Leaky waveguide based train-ground communication system design.

The function of the Train-Ground Communication system is to provide the trackside equipment and train borne equipment with continuous bi-directional communication services for signaling data over the complete line. Since CBTC is a safety critical system, the wayside and train born equipment both are redundant to get a high reliability. The radio coverage for signaling data stream should be redundant too. Figure 3.11 shows a simple view of a leaky waveguide based train-ground communication system.

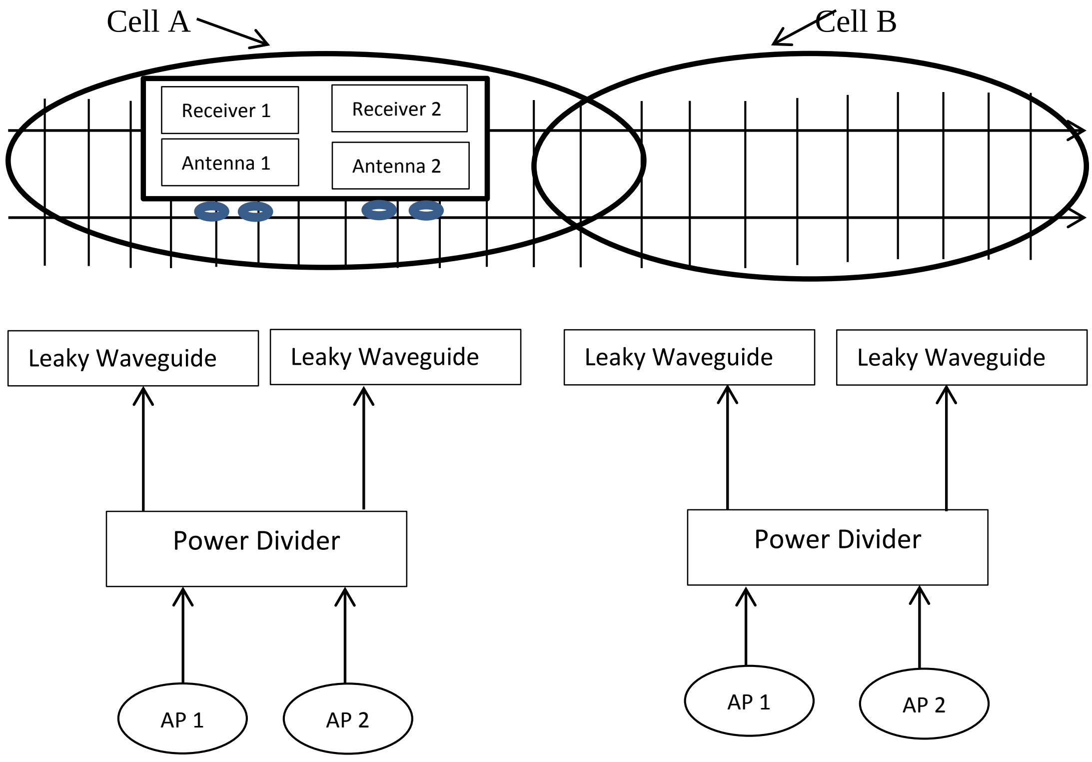

Figure 3.11: A simple view of Leaky Waveguide Based Train-Ground Communication System.

The leaky waveguide is installed on one side of the track. The train-board communication antenna moves along the track, approximately 20 cm-50cm over the waveguide.

The waveguides creates a set of overlapping radio cells along the track. The dimension of a radio cell is two times the dimension of a leaky waveguide section with an extension of a few meters. There are two receivers on the train. Two APs' signal is broadcasting in the same radio cell. Each receiver on the train is associated with different APs, and they belong to the different subnet.

When the train arrives in the overlapped area between Cell A and Cell B, the receiver on the train will receive beacons generated cyclically by AP 1(A) and AP l(B). The receiver will then measure and compare both the received power and perform handover from AP 1(A) to AP l(B). The two receivers were installed in the head and tail of the train, when the receiver in the head arrives in the overlapped area, the receiver in the train's tail is still in the old cell. Since there is no chance that the two receivers are both processing handover, there is always an available radio link between the train and ground. The bi-directional communication between trains and ground would not be interrupted by handover. Without loss of generality, only 802.11g is considered here. Current requirements for CBTC, especially for automated subway systems, necessitate significantly high data rates, typically several Mbits/s. There are 6 data rates specified in 802.11g, among which 6Mbits/s is chosen in the system, because it has the lowest BER under the same noise power. The receiver sensitivity specified in 802.11g is -82dbm, while in CBTC engineering, in order to assure reliability, the power received by the wireless station should be 20dBm higher than the required sensitivity. That means the power received by the wireless station should be higher than -62dBm.

3.10.3 Modelling of the CBTC Channel with Leaky Waveguide.

The fading channel with the leaky waveguide can be approximated as a linear model according to the polynomial fitting results [11].

Some classic channel models have been proposed for different environments, such as the Okumura–Hata model, the COST 231 model, and the Motley–Keenan Model. Due to the specificity of the CBTC application, there is not a channel model with leaky waveguide in CBTC systems. Since the channel with leaky waveguide is linear, similar to the expression of the Okumura–Hata model [11] is considered for the CBTC channel with leaky waveguide as follows:

$$\mathrm{PL(d)} = \mathrm{PL(0)} + nd + X_{ss} \tag{3.12}$$

Where PL(0) is the difference between the power leaked from the beginning of the leaky waveguide and the input power, n is the path-loss exponent whose unit is dB/m, is the location of the receiving antenna relative to the beginning of the leaky waveguide, and X_{ss} is the small-scale fading that is a random variable. PL(0) depends on the dimensions of the leaky waveguide and the slots. There are two key parameters n and X_{ss} which is approximately determined [11] in subsequent headings respectively.

3.10.4 Path-Loss Exponent.

According to the slopes of fitting lines, we can get the average value of the path-loss exponent as follows:

$$n = \frac{1}{t} \sum_{m}^{t} n_m \tag{3.13}$$

where t is the total number of measurements, and n_m is the slope of the fitting line of the *mth* measurement. The average value of the path-loss exponent is 0.0136 dB/m [11].

The consecutive slot radiation is represented by separate successive equivalent magnetic dipoles. Since the length of waveguide is so large, transmission loss should not be ignored and it is calculated as fallows.

$$\alpha = \frac{20}{ln10}\frac{1}{b^{3/2}} \sqrt{2\pi\varepsilon_0\rho_{wg}} \; \frac{\left(\frac{f_c}{f}\right)^2 + \frac{b}{2a}\left(\frac{f}{f_c}\right)^2}{\left[1-\left(\frac{f_c}{f}\right)^2\right]^{1/2}} \tag{3.14}$$

Where ε_0 is the dielectric constant of vacuum (the value is 8.854×10^{-12}F/m), $\rho_{wg}$is the resistivity of the material of leaky waveguide (the value is 2.9×10^{-8} Ω.m), a and b are the dimensions of leaky waveguide, and f_c is the cut-off frequency of the leaky waveguide. Transmission loss α of the leaky waveguide is 0.0139dB/m [11] which is almost equal to *n*. Hence, we can use the transmission loss as the path-loss exponent of the radio channel with leaky waveguide.

3.10.5 Small scale fading.

Small-scale fading shows how much the signal level can vary on the basis of the large-scale fading. A number of different distributions have been proposed for small-scale amplitude fading in indoor and outdoor environments, including Rice, Rayleigh, Nakagami, Weibull, and Log-normal distributions. In order to determine the distribution of the small-scale fading of the channel with leaky waveguide, effects of the large-scale fading is not considered. Out of all distributions, Log-normal model is the best parametric fit to the distribution of the small-scale fading amplitudes [11].

CHAPTER 4

CORRELATION AND ANALYSIS

In the previous chapter, Communication Based Train Control system has been discussed in detail. Train to ground communication and vice-versa at 2.4 GHz using IEEE 802.11 b/g protocol is very vital part of the system in view of safety and availability of system. Train borne and Way side equipment's with WLAN as a backbone, are responsible for successful communication. Way side equipment's as an Access points (APs) are consecutively placed at specific distance, depends on physical structure of metro alignment, along the track. Since the distance between APs and highly directive train borne antenna is more, also due to the other communication in the same band causing fading and interference respectively. Fading and interference may cause the large signal variation at receiving end, therefore to avoid large signal variation at receiving end, Rectangular leaky waveguide was proposed. Rectangular Leaky waveguide with one end connected to APs, used for vital communication, placed along the track very near to train borne antenna so that effect of fading and interference can be minimized. Communication within the same AP not only ensure the availability of system, it is because when train moves from one AP region to another AP region called Handover or Handoff, data packet may be lost. For maximizing the data throughput when train in transition, proper Handoff algorithm must be chosen. Selection of Handoff algorithm depends on how the equipment's are placed on wayside and its coverage area. Here two different types of algorithm will be discussed and after analysis of both algorithms, correlation with proposed CBTC system with Rectangular Leaky Waveguide will be done.

4.1 FREQUENCY COMBINATION HANDOFF ALGORITHM

4.1.1 Basic principles.

With the technologies of smart antenna (SA) and direct sequence spread spectrum (DSSS), a train can feel the existence of other APs within the range of an AP at the same time and add all discovered APs to neighbour graph [12]. By adding and deleting the sides of neighbour graph, the neighbour graph will approximate the practical moving graph. Thus, a train can know about the related real-time information of APs all around. For frequency combination handoff algorithm, a train must detect all the frequencies of the group in the process of handoff starting. Except the first AP, other APs can detect four APs simultaneously. The position and frequency of wayside APs have been prescribed in frequency combination handoff algorithm.

The position of wayside AP requires that the distance between a train and wayside AP is zero when the train is running at some speed. It is certain that new frequencies can be found around each AP as the layout of wayside APs is known. If APs in the whole networks work normally, the train in fact has already scanned three frequencies in the group up front from the first AP to the next. Accordingly, if a new frequency can be detected in the next AP, the handoff will start. The new frequency is known and the train will scan the channel actively, so the time delay caused by handoff will be little normally. As the position of each AP is also the point of handoff, the moment of handoff can be seized accurately. The data in the networks after the handoff time can adopt a certain control mechanism to eliminate the package loss for a smooth handoff.

4.1.2 Specific steps of frequency combination handoff algorithm.

STEP 1: In the initial position, the system will be reset and initialized after a train is electrified for the first time. The train then detects the surroundings to license and correlate the first detected AP and joins in the AP sets to yield a neighbour graph. The detected APs will be added to the neighbour graph, the sides of which are based on the length calculated by propagation delay. Meanwhile, the on-board computer with a counter counts +1.

STEP 2: When the train is running on the track, the remainder three channels will be detected. If a new frequency is found and demodulated correctly, the corresponding AP will be added to the created neighbour graph, the sides of which are based on the length calculated by propagation delay and the counter is +1. Flow chart of this algorithm is shown in Figure 4.1.

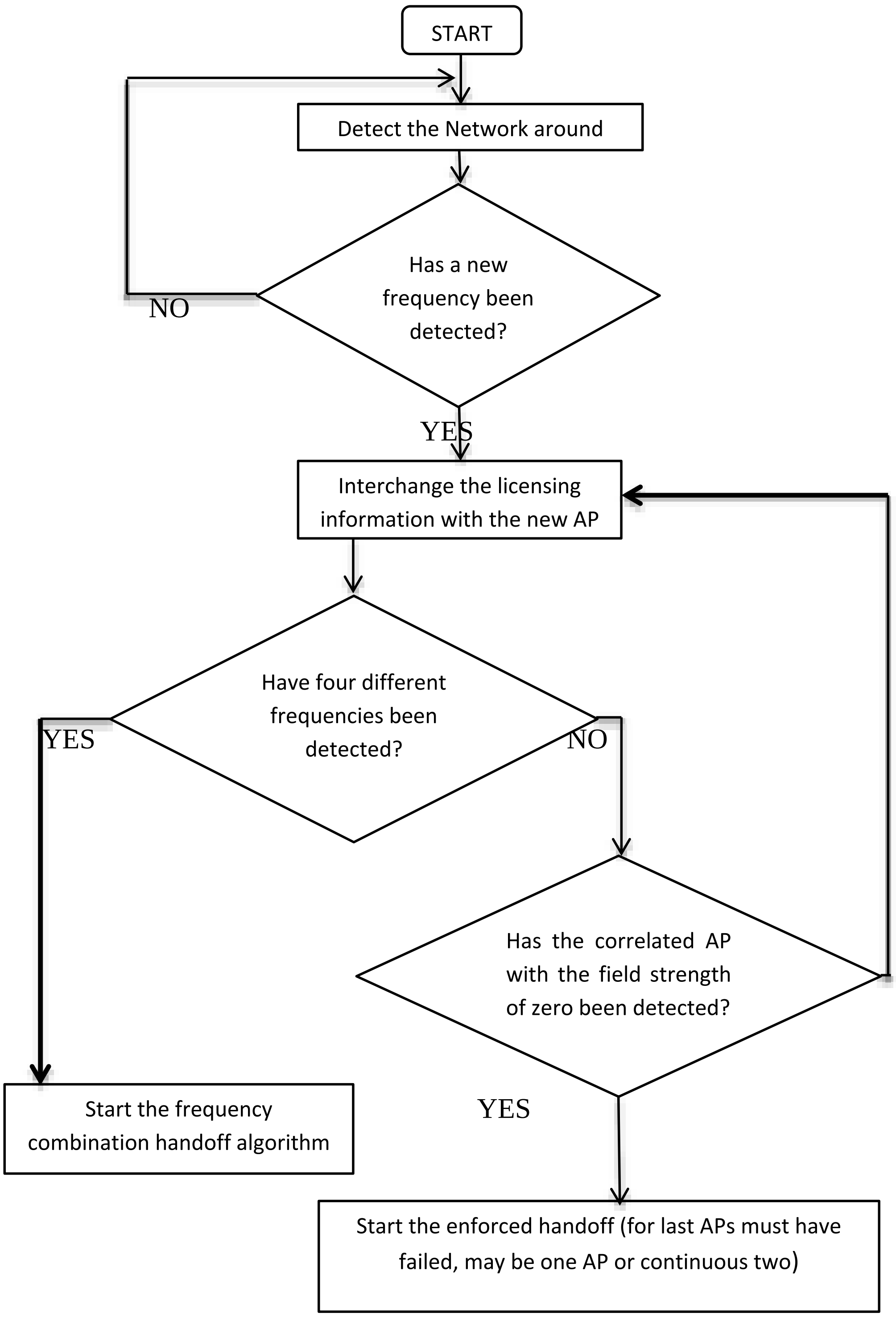

Figure 4.1: A whole process of frequency combination handoff.

STEP 3: If the counter is 4 and the conditions of handoff is satisfied, the process of handoff will be started up and the counter is set for 3. If a new AP can be found in the position of the current correlated AP with the filed intensity of zero, which manifests that the last AP goes wrong, the enforced handoff process will be start up to correlate the AP and the counter is set for 1. If a new AP cannot be found in the position of the current correlated AP with the filed strength of zero and the information of APs can be found in the list of neighbour graph using query, which accounts for two APs go wrong, the enforced handoff process will also be start up to compulsively correlate the only AP and the counter is set for 1. The condition of satisfying the enforced handoff process is to find the field intensity of the current correlated AP is zero. The purpose of implementing the enforced handoff process is to find the target AP.

STEP 4: Repeat the steps from step 2 to step 4.

4.2 LOCATION BASED HANDOVER SCHEME

4.2.1 Basic Principles.

The train transmits the location information within resolution of 5-10m, after calculating with the help of speed sensors and Doppler radar together with the transponder to the wayside device by the wireless communication system. Because the location of the train can be got in real time, a location based handover algorithm is presented [13] to reduce the happening of erroneous and Ping-Pong handover caused by the random effects of the wireless channel.

4.2.2 Specific steps of Location Based handover algorithm.

STEP 1: The mobile station in the train will send the Probe Request Frame periodically.

STEP 2: APs who receive the frame will send back a Probe Response Frame. By demodulating the received signal, the mobile station will judge whether the next AP to switch over is in the right working state.

STEP 3: The mobile station can acquire frequency and time synchronization with the next AP in this process.

STEP 4: Beginning of the handover process when the train has reached the handover location.

STEP 5: Repeat step 2 to step 4.

Because the mobile station has known the information of the next AP and been synchronized with it both in frequency and time domain, the mobile station doesn't need to send the Probe Request signal when beginning the handover process. So in the proposed handover algorithm the scanning stage is not needed and the handover interruption latency can be reduced.

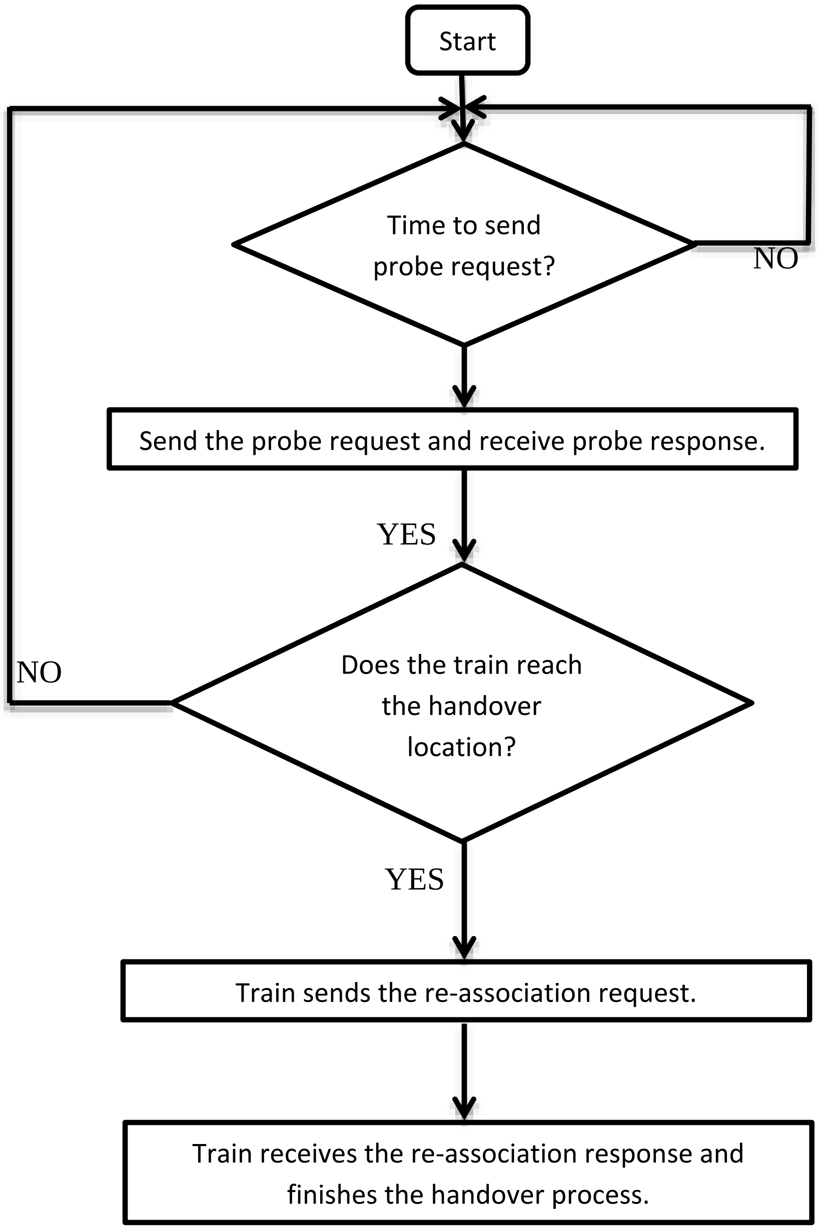

Figure 4.2: Location based handover process.

4.2.3 Analysis and Correlation.

Frequency combination based and location based handover scheme have been discussed in detail. In both proposed algorithm different principle have been adopted. Since CBTC System with Rectangular Leaky Waveguide is research area in this course work therefore its analysis and correlation with proposed algorithms must be done which is furnished below in Table 4.1.

Parameters in CBTC System with Leaky Waveguide.	**Frequency combination handoff algorithm.**	**Location Based handover algorithm.**
1. Handover time.	Time delay due to Scanning, Authentication, and Re-association are considered.	Time delay due to Authentication and Re-association are considered, scanning process not needed.
2. Infrastructure.	Since at least three APs coverage area must exist in coverage area of individual APs therefore to ensure the minimum requirement, Leaky Waveguides connected to consecutive APs must be placed in overlap manner.	Since location information about APs must be known to the Train borne equipment for handoff therefore to ensure the minimum requirement, Leaky waveguides connected to APs can be placed along the track with small overlap area at the end.
3. Maintenance and cost.	Complex infrastructure required therefore more and frequent maintenance needed and overall cost will be more.	Simple infrastructure require thus easy to maintain and Less costly.

Table 4.1: Comparison between Algorithms.

Frequency Combination and Location based algorithm have been compared in association with proposed CBTC system in above Table No 4.1. As per analysis it is concluded that delay due to Handover time is less in Location Based algorithm because of scanning process not needed. To meet the minimum requirement for both proposed algorithm, more complex infrastructure required in Frequency Based Algorithm, thus for maintenance more man power needed. After considering all parameters it shows that overall cost would be more if Frequency Based Algorithm is chosen.

CHAPTER 5

CONCLUSION AND FUTURE WORK

5.1 CONCLUSION

In this research work, Communication Based Train Control system and its associated subsystems has been discussed and analysed in all aspect with view of Rectangular Leaky Waveguide. Train Borne equipment, Wayside equipment and Wireless Local Area Network are the vital equipment's, its logical interfacing to each other have been analysed. Frequency band 2.4GHz, 900MHz and 5.8 GHz are three worldwide known Industrial Scientific Medical (ISM) Bands are licensed free which are generally used in CBTC system, each having different requirement and characteristics has been analysed in detail. IEEE 802.11 is a protocol dedicated for WLAN has been studied in detail from research point of view. IEEE 802.11 b/g WLAN protocol operates at 2.4 GHz is used for CBTC system has been chosen for this research work.

Safety, availability and maintainability are the most important aspect for Communication Based Train Control system. Standard IEEE 1482.1 for Rail Transit Vehicle Event Recorders, IEEE 1474.1 CBTC Performance and Functional Requirements, IEEE 1474.2 for User Interface Requirements in CBTC Systems, IEEE 1474.3 for CBTC System Design and Functional Allocations, IEEE 1474.3 for Functional Testing of a CBTC System has been covered up and analysed.

Operation of Communication Based Train Control system is based on real-time application therefore all subsystems must be available all time. Availability of all subsystem is ensured by maintaining the redundancy at all level. Furthermore, it is found that, the communication between Train borne equipment and way side equipment is most sensitive part of the CBTC system. Since all communication between Train borne equipment's and wayside equipment's done on 2.4 GHz band, in this band many others Portable Radio devices, Wi-Fi networks also operates causes the large variation in received signal. This variation has been analysed in different environments. Effect of fading in variation of received signal is also analysed.

Proposed Leaky Rectangular Waveguide which operates between 2GHz to 6 GHz to mitigate the effect of fading and interference has been covered up. It is found from proposed practical environment based on Leaky Rectangular Waveguide that the large variation in received signal can be reduced. It is also found that Handover at transition point can be improved.

When Train moves from one Access Point (APs) to another access point, all control must be handover properly. Many Handover scheme have been developed and proposed, Frequency Combination and Location Based hand over scheme are analysed and compared in view of Effect of Leaky Rectangular Waveguide on the performance of CBTC system. After comparative analysis, it is found that, in case of Location Based Handover scheme Handover time is less, simple arrangement of leaky waveguide required, less maintenance activity needed and overall cost will be less than Frequency combination handover scheme.

5.2 FUTURE SCOPE OF PRESENT WORK

- Validation of comparative analysis in this research work on practical platform.
- Mathematical modelling of Leaky Rectangular Waveguide based on Location Based Handover scheme.

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