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# Network Planning for WiMAX-R Networks

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**Abstract:** In this paper, a novel network planning process of the Mobile WiMAX for Railway (WiMAX-R) network is proposed. We first analyze the factors need considered in network planning. After introducing the WiMAX-R network architecture, the WiMAX-R network planning process is presented in detail. The process comprises application analysis, capacity prediction, network parameters configuring, coverage planning, handover planning and network simulation validation. In each step, Mobile WiMAX technical features and railway environment characters are both take into consideration. Finally, we simulated a WiMAX-R planning example based on OPNET platform. The simulation results showed that the designed WiMAX-R network can perfectly satisfy the applications' QoS requirements.

**Keywords:** IEEE 802.16e, Mobile WiMAX, Railway, Network Planning
**Categories:** C.2.1, C.2.5

## 1 Introduction

From 1960s, railway transportation began to introduce mobile communications system. After years of development, the railway mobile communication system has become an important guarantee to protect rail transportation safety. With the rapid growth of railway business, railway system requires much higher safety and reliability by context-awareness. Traditional narrowband wireless communication system cannot meet the tremendous needs. Mobile WiMAX based on the IEEE 802.16e Air Interface Standard [IEEE 802.16e, 2005] is an important 4G broadband mobile communication technology. The spectral efficiency, system capacity, communication speed, error correction and quality of service performances of Mobile WiMAX are much better than traditional system [Nair 2004]. Developing Mobile WiMAX for railway (WiMAX-R) has important practical significance. Moreover, existing work on context-awareness has provided some techniques for Mobile WiMAX, e.g., [Zhang, 2011] and [Zhang, 2011-3].

Currently, several institutions and railway operators put their research emphasis on WiMAX-R. Many related papers, reports and news rapidly emerged. In [Aguado, 2008], the authors compared the system structure, performance and opportunity of WiFi, Mobile WiMAX and LTE technology in rail market. A forward error control scheme for WiMAX-R was proposed in [Ahmad, 2008]. Paper [Masson, 2007] designed a WiMAX / WiFi high-speed data transfer scheme for trains. In [Casasempere, 2009], the performance of H.264/MPEG-4 video transferred by WiMAX-R was researched. The train control system performance based on WiMAX-R was explored in [Aguado, 2009]. In [Kumar, 2008], a seamless WiMAX-R network coverage architecture and handover algorithm was proposed. In [Haagsma, 2005], the authors developed a classification and evaluation plan for typical rail communication applications. In [Yeh, 2010], how to enable WiMAX-R support high speed mobility (higher than 200 km/h) based on Radio-over-Fiber technology was introduced. In [Zhang, 2011-2], the authors conducted experiments to evaluate the performance of speed mobility on radio.

In practical railway engineering, many experimental networks were constructed or planned. In 2004, Southern Trains, the biggest rail operator in UK, cooperated with T-Mobile, built a WiMAX-R network from London to Brighton [Saw, 2006]. In 2006, London Transport planned to realize security video surveillance based on WiMAX-R before London Olympic Games 2012 [Internet-Web, 2007]. In 2010, Azulstar constructed a 95-Miles long WiMAX-R experimental network and realized emergency rescue and remote video surveillance on trains [Internet-Web, 2010]. April 2009, Taiwan High Speed Rail carried out a series of WiMAX-R experiments between Taoyuan, Hsinchu and Tainan Science-based Industrial Park. The goal is to achieve 10Mbps downlink and 3Mbps uplink data transfer rate at 300km/h moving speed, now that the experiment has achieved good practical results [Chow, 2009].

The existing literature on Mobile WiMAX networks design and planning is not very extensive and none of the works provide a complete model on the WiMAX-R network. In this paper, we propose a novel network planning process for WiMAX-R network. After a description of the related work in this area, the paper is organized as follows. Section II describes the factors affecting the network planning. In Section III, the WiMAX-R network planning process designed on generic process is introduced. Section IV provides an extensive experimental study focusing on the performance of an actual WiMAX-R network scenario. Finally, some concluding remarks are presented in Section V.

## 2 Problem Description

For mobile communication system planning, it is very important to accurately identify which factors affect the planning process and define how to take them into account under different circumstances. The following factors affect the network planning in different ways.

### 2.1 Application Requirements

The target of the mobile network planning is to design a network construction scheme that can satisfy the applications' quality of service (QoS) requirements. Different network users and applications may have different requirements on traffic rates, latency or packet loss. These are directly related to the user experience or application performance and should be the quality performance indicator considered in the network design process.

### 2.2 Operating Frequency and Bandwidth

In a mobile communication system, a land area to be supplied with radio service is divided into regular shaped cells, which can be hexagonal, square, circular or some other irregular shapes, although hexagonal cells are conventional. Each of these cells is covered by a base station and assigned an operating frequency. The frequency can be reused in other cells, provided that the same frequencies are not reused in adjacent neighboring cells as that would cause interference. The key characteristic of a mobile network is the ability to reuse frequencies. The frequency reuse pattern is defined by the expression: (*C*, *S*, *F*). *C* is the number of cells in the network cluster and determines the inter-cellular frequency reuse. *S* represents the number of sectors in a cell and *F* demonstrates intra-cellular frequency reuse. Example of the frequency reuse case '(1, 3, 3)' is depicted in Fig.1.

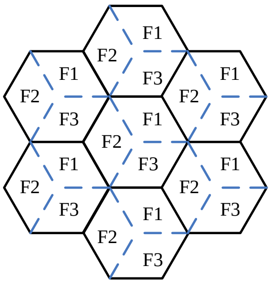

*Figure 1: Frequency Reuse Pattern (1, 3, 3)*

### 2.3 System Capacity

The number of active MS is limited by the mobile network theoretical capacity. This fact leads to a quite different network planning compared to 2G (voice-oriented system) and 3G networks (interference-limited system). Mobile WiMAX is a capacity-limited system and makes a dynamic use of bandwidth according to the throughput requirements of each service, and several time-frequency slots are allocated to fulfill their needs. This affects the network designing and planning differently.

### 2.4 Coverage Capability

A MS is covered if the received pilot signal can be demodulated correctly. Therefore, the received pilot power must be higher than the sensibility of the terminal plus the noise power. The MS checks the signal from the best signal, from the subset of active BSs. The inverse relationship between data rate and BS coverage range, together with limitations on range imposed by transmit power, may result in deployments with large numbers of BSs to cover a given area. This results in a trade-off between throughput, coverage, network cost and interference which has to be considered and balanced when planning a mobile network.

### 2.5 Mobility

In a mobile communication system, as the distributed mobile stations move from cell to cell during an ongoing continuous communication, switching from one cell frequency to a different cell frequency is done electronically without interruption and without a base station operator or manual switching. This is called the handover or handoff. Typically, a new channel is automatically selected for the mobile unit on the new base station which will serve it. The mobile unit then automatically switches from the current channel to the new channel and communication continues.

## 3 WiMAX-R Network Planning Process

In this section, we propose a WiMAX-R network planning process. Firstly some characters of WiMAX-R network are introduced. WiMAX-R made some modifications on Mobile WiMAX architecture, so it can adapt to the railway environment. In Fig.2, we can see that WiMAX-R network can be divided into following parts:

- Connectivity Service Network (CSN) is a set of network devices that provide IP connectivity services to the WiMAX subscribers. A CSN may comprise network elements such as routers, AAA proxy/servers, user databases and interworking gateway devices. WiMAX-R CSN can be constructed with in railway IP backbone.
- Access Service Network (ASN) provides means to connect mobile subscribers using 802.16e air link to IP backbone with session continuity. ASN comprises Base-Stations (BS) and ASN-Gateways (ASN-GW).
- Mobile Subscriber (MS) is an on-train mobile subnet contains a WiMAX Customer Presise Equipment (CPE) and multiple end devices. CPE is installed on the train roof and acts as a wireless router, which provides WiMAX-R access service for other end devices.

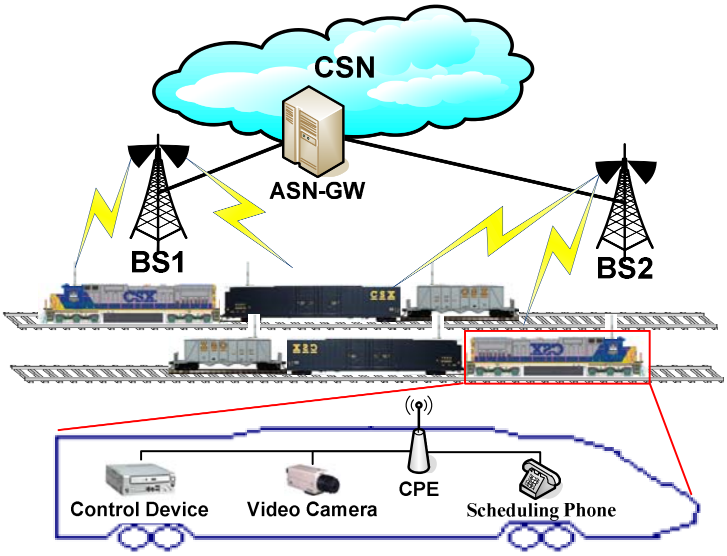

*Figure 2: WiMAX-R Network Architecture*

In the process of network planning - where a set of candidate sites are given and the number of combinations is huge - it is very unlikely that the planner can find the optimal network configuration using a manual method. Therefore, propose an automated procedure for WiMAX-R network design is the main research objective of this paper.

In order to provide excellent performance, many advanced technologies are introduced with Mobile WiMAX. These features affect the network planning process in different aspects. Referring to the network planning factors described in Section II, the WiMAX-R network planning process consists of following steps: applications analysis, capacity prediction, network parameters configuring, coverage planning, handover planning and simulation validation. In each step, we need take into consideration of the Mobile WiMAX advanced technical features and the railway environment characteristics. The process flow chart is shown in Fig.3.

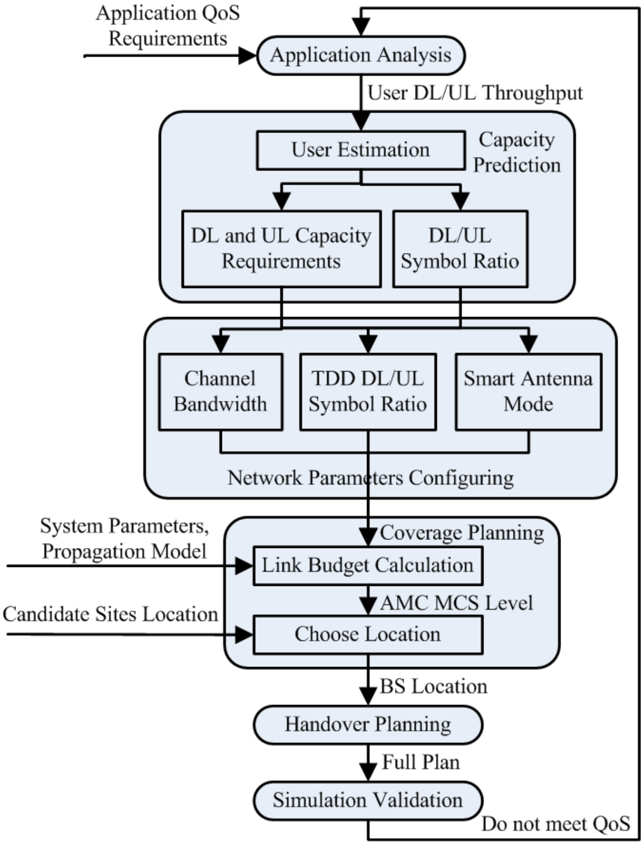

*Figure 3: WiMAX-R Network Planning Process*

### 3.1 Application Analysis

Since the application QoS parameters are targets have to be meet in network planning, our network planning process begins with analyzing the applications of railway communication systems. After many years development, there are numerous railway communication systems. Typically, they can be classified into following categories:

- Train Control System (TCS) is the most important guarantee of the train operation safety. Nowadays, the actual utilizations of TCS over the world include the European Train Control System (ETCS-2/3), the Positive Train Control System (PTCS) in North American, the Chinese Train Control System (CTCS-3/4) and the Incremental Train Control System (ITCS). Traditional railway mobile communication network (such as GSM-R) uses 9.6kbps circuit switch channel to carry TCS messages. The TCS applications are mainly signaling messages and the packet length ranges from 30 to 1000 bytes. TCS average traffic rate per user is about 2.4 kbps and requires no loss. TCS packet latency should be less than 500ms.

- Train Dispatching Telephone System (TDTS) provides voice communication ability between train schedulers, station watchers and train drivers. It supports one-button push-to-talk call, prioritized voice call, voice group call and voice broadcast call. WiMAX-R can carry TDTS via VoIP technology. The traffic rate per user depends on the voice codec. Currently, many mature voice codec such as G.711 (64kbps), G.723 (5.3 or 6.3kbps), G.726 (16~40kbps) and G.729 (8kbps) can be chosen. Typically, voice codec generates a voice frame every 20ms. Before transmitting, the frame will be encapsulated and introduce some overheads (12 bytes RTP header, 8 bytes UDP header and 20 bytes IP header). So additional 16kbps overhead should be added to each VoIP stream. For fluent and clear conversation, the packet latency and loss should be controlled less than 50ms and 10% respectively.
- Train Video Surveillance System (TVSS) provides train equipment or railway status surveillance and improves railway emergency rescue ability. Since video stream application requires much more throughput, traditional railway wireless communication system can not support it. But this is not a big problem for WiMAX-R. Like TDTS, TVSS application throughput also depends on video codec. For instance of H.264 video codec, typical traffic rate ranges from 128 kbps to 1.5 Mbps. TVSS video stream does not require low latency and can bear about 5% packet loss.

The Mobile WiMAX end-to-end network architecture is based on an All-IP platform, all packet technology with no legacy circuit telephony. In the Mobile WiMAX Media Access Control (MAC) layer, QoS support is provided via service flows. The QoS parameters associated with the service flow define the transmission ordering and scheduling on the air interface. Since the air interface is usually the bottleneck, the connection-oriented QoS can effectively enable the end-to-end QoS control. The service flow based QoS mechanism applies to both downlink (DL) and uplink (UL). Mobile WiMAX supports a wide range of data services and applications with varied QoS requirements. These are summarized in Table 1. The network planner can configure proper scheduling mode with the features of railway applications.

| QoS Category | Scheduling Mode | Applications |
|---|---|---|
| UGS (Unsolicited Grant Service) | BS reserves fixed bandwidth for MS. | VoIP, Circuit Emulation |
| rtPS (Real-Time Polling Service) | BS periodly polls requests from MS and allocates bandwidth dynamically. | Streaming Audio or Video |
| ertPS (Extended Real-Time Polling Service) | BS adjusts bandwidth only when MS bandwith request changes. | VoIP with Activity Detection |
| nrtPS (Non-Real-Time Polling Service) | BS provides contend bandwidth request opportunities for MS. | File Transfer (FTP) |
| BE (Best-Effort) | BS only allcates bandwidth to MS when having free resource. | Data Transfer, Web Browsing |

*Table 1: Mobile WiMAX Applications and Quality of Service*

### 3.2 Capacity Prediction

Since WiMAX-R is a capacity-limited system, in the second network designing step, planner need to estimating total system capacity requirement based on user traffic rate and user estimation. As mentioned in Section II, the user-equipment of WiMAX-R is CPE installed on the train locomotives. With the movement of trains the users is also moving along with railway. The densities of users are not even. As shown in Fig.4, in the railway station or marshaling yard area, the user density is relative high for the increasing parallel tracks and arriving trains. In the train running area, the user density is relative low.

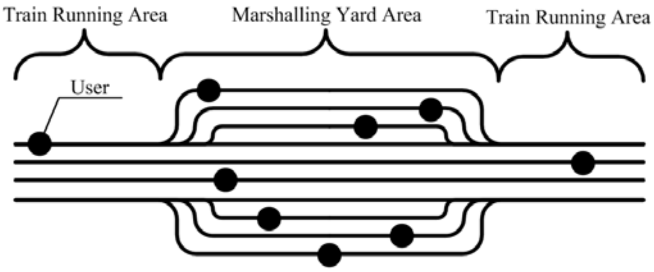

*Figure 4: Different User Densities in Different Zones*

We divide the railway into different zones, which have same user density. In the zone, follow variables are defined:

- *I*: the kinds of railway applications;
- *P(i)*: the packet delivery ratio of the *i*-th application;
- *T(i)*: the traffic rate of the *i*-th application. Since the DL and UL traffic rate is independent, T(i) should also be expressed in *TDL (i)* and *TUL (i)*;
- *D(i)*: the estimated users per kilometer of the *i*-th application in the zone, which expresses the user density;

With the information above, for each zone, network planner can predict the total DL and UL capacity requirements and the DL/UL traffic ratio with following formulas.

- DL and UL capacity density requirements: can be expressed as $CR_{DL} = \sum_{i=1}^{I} T_{DL}(i) * D(i) * P(i)$ and $CR_{UL} = \sum_{i=1}^{I} T_{UL}(i) * D(i) * P(i)$ respectively;
- DL/UL traffic ratio: can be expressed as $R = \frac{CR_{DL}}{CR_{UL}}$;

In the zone, CRDL, CRUL and R represent the requirements of the users, and the network planner should use them to configure some important network parameters.

### 3.3 Network Parameters Configuring

Mobile WiMAX is a capacity-limited system and its system capacity is subject to following 4 network parameters.

1) *Channel Bandwidth*

WiMAX-R requires linear coverage alone with the railway and its cell shape is designed like an ellipse. To reducing interference, the WiMAX-R frequency reuse mode should be configured to (*N*, *2N*, *2N*). The number of *N* depends on the frequency resources owned. Fig.5 shows each WiMAX-R BSs are constructed alone with the railway and contain 2 sectors which pointing to the 2-ends of the railway. Different sector works on different frequency and the frequency resource reuse mode is (1, 2, 2).

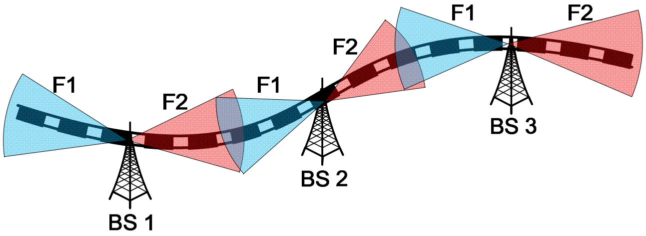

*Figure 5: WiMAX-R Coverage*

In each sector, BS works on a certain operating frequency. Mobile WiMAX air interface adopts Orthogonal Frequency Division Multiple Access (OFDMA) and can support 5, 7, 8.75, and 10 MHz channel bandwidths for licensed worldwide spectrum allocations in the 2.3 GHz, 2.5 GHz, 3.3 GHz and 3.5 GHz frequency bands. The channel is divided into many equally spaced subcarriers (10.94 kHz). For example, a 10MHz channel is divided into 1024 subcarriers some of which are used for data transmission (Data subcarriers) while others are reserved for monitoring the quality of the channel (Pilot subcarriers), for providing safety zone between the channels or for using as a reference frequency (Null subcarrier).

Subcarriers are organized into subchannels The number and exact distribution of the subcarriers that constitute a subchannel depend on the *subcarrier permutation mode* including DL FUSC (Fully Used Subcarrier), DL PUSC (Partially Used Subcarrier) and UL PUSC and additional optional permutations. Different channel bandwidth scheme have different subcarrier, subchannel numbers and can offer different sector throughput.

2) *TDD DL/UL Symbol Ratio*

The current release of Mobile WiMAX supports Time Division Duplex (TDD) operation. Fig.6 shows the OFDMA frame structure for a TDD implementation. The frame duration is 5ms and contains 48 OFDMA symbols. Each frame is divided into DL and UL sub-frames separated by 1 symbol duration Transmit/Receive Transition Gaps (TTG). The split between DL and UL sub-frames may be decided once, based on average statistic expectations of the traffic behavior. The DL/UL symbol ratio profiles supported are 35:12 (3:1), 31:15 (2:1), 29:18 (3:2) and 25:21 (1:1).

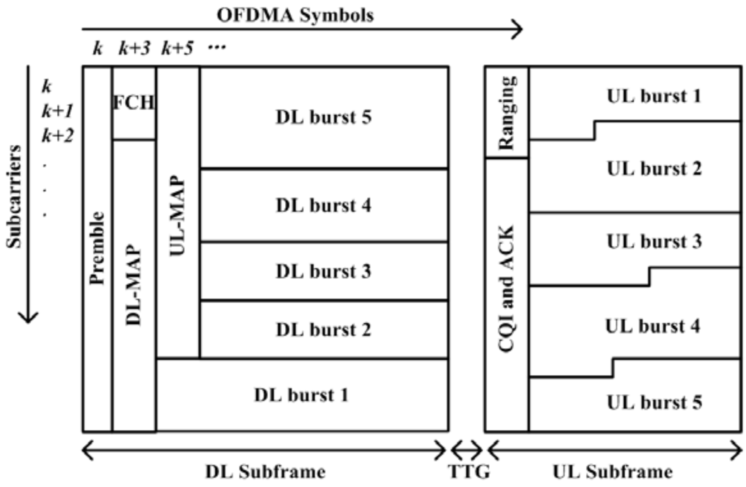

*Figure 6: TDD Frame Structure of Mobile WiMAX*

*3) Smart Antenna Mode*

Mobile WiMAX supports a full range of smart antenna technologies to enhance system performance. The smart antenna technologies supported include: Space-Time Code (STC) and Spatial Multiplexing (SM). SM improves peak throughput. With SM, multiple streams are transmitted over multiple antennas. For example, with 2x2 MIMO, SM increases the peak data rate two-fold by transmitting two data streams. However, when channel conditions are poor, the Packet Error Rate (PER) can be high and thus the coverage area where target PER is met may be limited. STC on the other hand provides large coverage regardless of the channel condition but does not improve the peak data rate. Since the performance of SM mode deceases significantly in high speed mobility and the data reliability is very important for railway communication, STC mode is always chosen in WiMAX-R network planning.

*4) Modulation and Coding Scheme*

Adaptive Modulation and Coding (AMC) is introduced with Mobile WiMAX to enhance coverage and capacity. The AMC technology makes MS and BS can dynamically adjust Modulation and Coding Scheme (MCS) based on receiving Signal-to-Interference and Noise Ratio (SINR). Support for QPSK, 16QAM and 64QAM are mandatory in the DL with Mobile WiMAX. In the UL, 64QAM is optional. As shown in Fig.7, AMC makes the capacity of BS various in different area (cell edge has the lowest capacity).

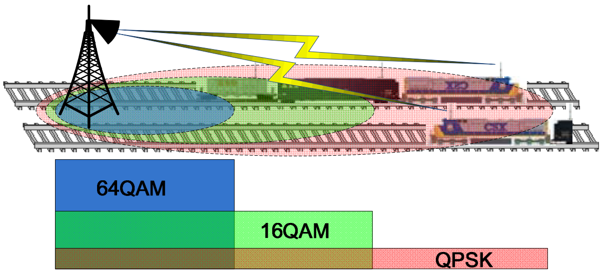

*Figure 7: WiMAX-R BS Capacity affected by AMC*

In order fulfill the requirements of $CR_{DL}$, $CR_{UL}$ and $R$, WiMAX-R network planner should configure the former 4 network parameters. The smart antenna mode is always configured as STC and the TDD DL/UL symbol ratio profile should be chosen with the value of $R$. Then, network planner can compute the BS capacities under the conditions of different channel bandwidth and MCS. Table 2 shows the WiMAX-R BS capacities under the conditions of 5MHz and 10MHz channel bandwidth, PUSC subchannelization, DL/UL symbols equals to 25:21 (the frame overhead to account for Preamble, MAP, and UL Control Channel is 3 OFDMA symbols in the DL and 2 in the UL). Proper channel bandwidth and MCS profile should be chosen to meet $CR_{DL}$ and $CR_{UL}$.

| **Parameter** | | **DL** | **UL** | **DL** | **UL** |
|---|---|---|---|---|---|
| Channel Bandwidth | | 5 MHz | | 10 MHz | |
| FFT Size | | 512 | | 1024 | |
| Null Subcarriers | | 92 | 104 | 184 | 184 |
| Pilot Subcarriers | | 60 | 136 | 120 | 280 |
| Data Subcarriers | | 360 | 272 | 720 | 560 |
| Subchannels | | 15 | 17 | 30 | 35 |
| Symbol Period | | 102.9ms | | | |
| Frame Duration | | 5ms | | | |
| Symbols/Frame | | 47 + 1 (TTG) | | | |
| DL/UL Ratio | | 25:21 (22:19 Data symbols) | | | |
| Smart Antenna Mode | | STC | | | |
| **Mod.** | **Code Rate** | **5 MHz Channel** | | **10 MHz Channel** | |
| | | **DL Rate** | **UL Rate** | **DL Rate** | **UL Rate** |
| QPSK | 1/2 | 1.584 | 1.034 | 3.168 | 2.128 |
| | 3/4 | 2.376 | 1.551 | 4.752 | 3.192 |
| 16QAM | 1/2 | 3.168 | 2.067 | 6.336 | 4.256 |
| | 3/4 | 4.752 | 3.101 | 9.504 | 6.384 |
| 64QAM | 1/2 | 4.752 | ---- | 9.504 | ---- |
| | 2/3 | 6.339 | ---- | 12.678 | ---- |
| | 3/4 | 7.128 | ---- | 14.256 | ---- |
| | 5/6 | 7.919 | ---- | 15.839 | ---- |

**Note**: Data Rate = (Data Subcarriers)*(Data Symbols)*(Bits per Symbol)*(Code Rate)/Frame Duration

*Table 2: Mobile WiMAX BS Capacities (Mbps)*

### 3.4 Coverage Planning

With the information of the network parameters, network planner can calculate the BS coverage capabilities with different MCS in DL and UL respectively and furthermore determine the BS coverage radius. These are achieved by the DL and UL link budget. Before the calculation, we summarize all required system parameters in Table 3.

| **Parameters** | **Values** |
|---|---|
| Operating Frequency | 2500 MHz |
| System Channel Bandwidth | 10 MHz |
| DL:UL Symbol Ratio | 25:21 |
| DL:UL Data Symbol Ratio | 22:19 |
| Frequency Reuse Pattern | (1, 2, 2) |
| BS Height | 30 meters |
| MS Height | 4 meters |
| BS Antenna Gain | 18 dBi |
| MS Antenna Gain | 7 dBi |
| BS Maximum Power Amplifier Power | 10.0 Watts (40 dBm) |
| MS Maximum Power Amplifier Power | 2.0 Watts (33 dBm) |
| # of BS Tx/Rx Antennas | 2Tx，2Rx |
| # of MS Tx/Rx Antennas | 1Tx，2Rx |
| BS Noise Figure | 4 dB |
| MS Noise Figure | 7 dB |

*Table 3: WiMAX-R System Parameters*

A link budget is the accounting of all of the gains and losses from the transmitter, through the medium to the receiver. It accounts for the attenuation of the transmitted signal due to propagation, as well as the antenna gains and miscellaneous losses. Randomly varying channel gains such as fading are taken into account by adding some margin depending on the anticipated severity of its effects. The results of WiMAX-R link budget are Maximum Allowed Path Loss (MAPL) of the different kinds of railway applications. It is notable that link budgets of DL and UL are different.

- In DL, BS always spread all of it’s transmit power on all operating frequency spectrum. The DL link budget is not concern with traffic rate. Table 4 shows the DL link budget with the typical MCS. Due to space limitations, we do not show the MCS case of 64QAM.

- In UL, the subchannel number allocated to MS is changing with MCS and required traffic rate. This makes the MS’s operating bandwidth also changes. So the UL link budget is concern with the application traffic rate. Table 5 shows the TVSS application (512 kbps) UL link budget with the typical MCS. Due to space limitations, we do not show the UL link budgets for TCS and TDTS.

| | **Unit** | | | | | **Comments** |
|---|---|---|---|---|---|---|
| **BS Parameters** | | | | | | |
| MCS | | QPSK 1/2 | QPSK 3/4 | 16QAM 1/2 | 16QAM 3/4 | |
| Max Tx Power | dBm | 40.0 | 40.0 | 40.0 | 40.0 | A |
| Cyclic Combining Gain | dB | 3.0 | 3.0 | 3.0 | 3.0 | B |
| Tx Antenna Gain | dBi | 18 | 18 | 18 | 18 | C |
| Cable Loss | dB | 1.0 | 1.0 | 1.0 | 1.0 | D |
| EIRP | dBm | 62 | 62 | 62 | 62 | E=A+B+C-D |
| Number of Occupied Subcarriers | | 840 | 840 | 840 | 840 | F |
| Power per Occupied Subcarrier | dBm | 32.8 | 32.8 | 32.8 | 32.8 | G=E-10*$log_{10}$(F) |
| **MS Parameters** | | | | | | |
| Rx Antenna Gain | dBi | 7.0 | 7.0 | 7.0 | 7.0 | H |
| 2 Rx Antenna Diversity Gain | dB | 3.0 | 3.0 | 3.0 | 3.0 | I |
| Rx Noise Figure | dB | 7.0 | 7.0 | 7.0 | 7.0 | J |
| Cable Loss | dB | 0 | 0 | 0 | 0 | K |
| **Margins** | | | | | | |
| Shadow Fade Margin | dB | 5.56 | 5.56 | 5.56 | 5.56 | L |
| Fast Fading Margin (120km/h) | dB | 8.72 | 8.72 | 8.72 | 8.72 | M |
| Interference Margin (1,2,2) | dB | 0.39 | 0.39 | 0.39 | 0.39 | N |
| Penetration Loss | dB | 0 | 0 | 0 | 0 | O |
| Total Margin | dB | 14.67 | 14.67 | 14.67 | 14.67 | P=L+M+N+O |
| **Mobile Rx Sensitivity** | | | | | | |
| Thermal Noise | dBm/Hz | -174 | -174 | -174 | -174 | Q |
| Subcarrier Spacing | Hz | 10940 | 10940 | 10940 | 10940 | R |
| Thermal Noise per Subcarrier | dBm | -133.6 | -133.6 | -133.6 | -133.6 | S=Q+10*log10 (R) |
| SINR Required | dB | 4 | 7.5 | 8.5 | 13.5 | T |
| Rx Sensitivity (per subcarrier) | dBm | -122.6 | -119.1 | -118.1 | -111.1 | U=T+J+S |
| System Gain | dB | 165.37 | 161.87 | 160.87 | 155.87 | V=G-(U-H-I) |
| **MAPL** | dB | 150.70 | 147.20 | 146.20 | 141.20 | W=V-P |

*Table 4: WiMAX-R DL Link Budget*

| | **Unit** | | | | | **Comments** |
|---|---|---|---|---|---|---|
| Traffic Rate | bps | 512000 | | | | A |
| MCS | | QPSK 1/2 | QPSK 3/4 | 16QAM 1/2 | 16QAM 3/4 | |
| Modulation Efficiency | | 1 | 2 | 3 | 5 | B |
| Total UL Subchannels | | 35 | 35 | 35 | 35 | C |
| Total UL Subcarriers | | 840 | 840 | 840 | 840 | D |
| Subcarriers per Subchannel | | 24 | 24 | 24 | 24 | E=D/C |
| UL Data Subcarriers | | 560 | 560 | 560 | 560 | F |
| Data Subcarriers per Subchannel | | 16 | 16 | 16 | 16 | G=F/C |
| UL Data Symbols per Frame | | 19 | 19 | 19 | 19 | H |
| Frame Duration | sec | 0.005 | 0.005 | 0.005 | 0.005 | I |
| Subchannels Allocated | | 9 | 5 | 3 | 2 | J=(A*I)/(B*G*H) |
| **MS Parameters** | | | | | | |
| Max Tx Power | dBm | 27.0 | 27.0 | 27.0 | 27.0 | K |
| Tx Antenna Gain | dBi | 7.0 | 7.0 | 7.0 | 7.0 | L |
| Cable Loss | dB | 0 | 0 | 0 | 0 | M |
| EIRP | dBm | 34.0 | 34.0 | 34.0 | 34.0 | N=K+L+M |
| Subcarriers Allocated | | 216 | 120 | 72 | 48 | O=E*J |
| Subcarrier Tx Power | dBm | 10.7 | 13.2 | 15.4 | 17.2 | P=N-10*$log_{10}$(O) |
| **BS Parameters** | | | | | | |
| Rx Antenna Gain | dBi | 18 | 18 | 18 | 18 | Q |
| 2 Rx Antenna Diversity Gain | dB | 3.0 | 3.0 | 3.0 | 3.0 | R |
| Rx Noise Figure | dB | 4.0 | 4.0 | 4.0 | 4.0 | S |
| Cable Loss | dB | 1.0 | 1.0 | 1.0 | 1.0 | T |
| **Margins** | | | | | | |
| Shadow Fade Margin | dB | 5.56 | 5.56 | 5.56 | 5.56 | U |
| Fast Fading Margin (120km/h) | dB | 8.72 | 8.72 | 8.72 | 8.72 | V |
| Interference Margin (1, 2, 2) | dB | 1.40 | 1.40 | 1.40 | 1.40 | W |
| Penetration Loss | dB | 0.0 | 0.0 | 0.0 | 0.0 | X |
| Total Margin | dB | 15.68 | 15.68 | 15.68 | 15.68 | Y=U+V+W+X |
| **Mobile Rx Sensitivity** | | | | | | |
| Thermal Noise | dBm/Hz | -174.0 | -174.0 | -174.0 | -174.0 | Z |
| Subcarrier Spacing | Hz | 10940 | 10940 | 10940 | 10940 | Z1 |
| Thermal Noise per Subcarrier | dBm | -133.6 | -133.6 | -133.6 | -133.6 | Z2=Z+10*log10(Z1) |
| SINR Required | dB | 3.6 | 8 | 10.5 | 13.5 | Z3 |
| Rx Sensitivity (per subcarrier) | dBm | -126.1 | -121.6 | -119.1 | -116.1 | Z4=Z3+S+Z2 |
| System Gain | dB | 157.67 | 155.03 | 153.32 | 152.54 | Z5=P-(Z4-Q-R) |
| **MAPL** | **dB** | 141.99 | 139.35 | 137.64 | 136.86 | **Z6=Z5-Y** |

*Table 5: WiMAX-R UL Link Budget (TVSS, 512 kbps)*

Combining of the preceding analysis, we show the complete MAPL values with the different MCSs and different railway applications in Table 6.

| **MCS** | **Code Rate** | **DL** | **UL** | | |
|---|---|---|---|---|---|
| | | | **TCS** | **TDTS** | **TVSS** |
| QPSK | 1/2 | 150.70 | 151.53 | 148.52 | 141.99 |
| | 3/4 | 147.20 | 147.13 | 144.12 | 139.35 |
| 16QAM | 1/2 | 146.20 | 144.63 | 144.63 | 137.64 |
| | 3/4 | 141.20 | 141.63 | 141.63 | 136.86 |
| 64QAM | 1/2 | 139.20 | ---- | ---- | ---- |
| | 2/3 | 138.20 | ---- | ---- | ---- |
| | 3/4 | 135.70 | ---- | ---- | ---- |
| | 5/6 | 133.20 | ---- | ---- | ---- |

*Table 6: WiMAX-R MAPL (dBm)*

With MAPL, network planner can calculate the coverage capabilities with the wireless propagation model. Different models have been developed to meet the needs of realizing the propagation behaviour in different conditions. Typical for radio propagation models consist of Hata-Okumura Model, COST 231 Walfisch-Ikegami Model, Urban Dominant Path Model and SUI Model. In order to approach to the railway mobile environment, we choose ITU-Vehicular propagation model. The model can be expressed as:

$$\begin{aligned} Pathloss = 40*(1-0.004*h_{bs})*\log_{10} d \\ -18*\log_{10} h_{bs} + 21*\log_{10} f + 80 \end{aligned} \tag{1}$$

- $h_{bs}$: height of the BS, unit is meter;
- $d$: distance between BS and MS, unit is kilometer;
- $f$: working frequency, unit is MHz;

After substituting $h_{bs}$=30 and $f$=2500, we can get:

$$Pathloss = 124.77 + 35.2*\log_{10} d \tag{2}$$

Replacing the *Pathloss* with the MAPL in Table 6, we can get the maximum communication distance *d*, which presents the coverage capability. The results are shown in the Table 7.

| **MCS** | **Code Rate** | **DL** | **UL** | | |
|---|---|---|---|---|---|
| | | | **TCS** | **TDTS** | **TVSS** |
| QPSK | 1/2 | 5.45 | 5.76 | 4.73 | 3.08 |
| | 3/4 | 4.34 | 4.32 | 4.15 | 2.60 |
| 16QAM | 1/2 | 4.06 | 3.67 | 3.67 | 2.32 |
| | 3/4 | 2.93 | 3.01 | 3.01 | 2.21 |
| 64QAM | 1/2 | 2.57 | ---- | ---- | ---- |
| | 2/3 | 2.41 | ---- | ---- | ---- |
| | 3/4 | 2.04 | ---- | ---- | ---- |
| | 5/6 | 1.74 | ---- | ---- | ---- |

*Table 7: WiMAX-R Coverage Capability (km)*

The main issue of coverage planning is to find an appropriate solution to the BS location from a given set of candidate sites. With the given system parameters, BS capacity (Table 2) and coverage capacity (Table 7) are the two main constrains need to be considered. Each BS location and its coverage radius should fulfill:

- The lowest MCS of BS capacity can support the total DL/UL traffic rate in its coverage;
- The coverage of each BS should coherent with neighbor BSs to achieve seamless coverage on the whole railway;

Defining $C(k)$ (k∈[QPSK1/2, 64QAM5/6]) as the coverage capability of the certain MCS in Table 2 and $S(k)$ as the corresponding system capacity in Table 7, the valid coverage distance of the certain MCS can be expressed as $R(k)=C(k)-C(k+1)$, which is shown in Table 8.

| **MCS** | **Code Rate** | **DL** | **UL** | | |
|---|---|---|---|---|---|
| | | | **TCS** | **TDTS** | **TVSS** |
| QPSK | 1/2 | 1.11 | 1.44 | 0.58 | 0.48 |
| | 3/4 | 0.28 | 0.65 | 0.48 | 0.28 |
| 16QAM | 1/2 | 1.13 | 0.66 | 0.66 | 0.11 |
| | 3/4 | 0.36 | 3.01 | 3.01 | 2.21 |
| 64QAM | 1/2 | 0.16 | ---- | ---- | ---- |
| | 2/3 | 0.37 | ---- | ---- | ---- |
| | 3/4 | 0.3 | ---- | ---- | ---- |
| | 5/6 | 1.74 | ---- | ---- | ---- |

*Table 8: WiMAX-R Valid Coverage Distance (km)*

For each BS location chosen, if the lowest MCS level is $K$, the following equation should be complied in DL and UL respectively. The equation means the total network resource occupancy of each MCS should not exceed 100%.

$$\sum_{i=1}^{I}\sum_{k=K}^{64QAM5/6}\frac{T_{DL}(i)*D(i)*P(i)*R(k)}{S_{DL}(k)}<1 \tag{3}$$

$$\sum_{i=1}^{I}\sum_{k=K}^{16QAM3/4}\frac{T_{UL}(i)*D(i)*P(i)*R(k)}{S_{UL}(k)}<1 \tag{4}$$

With the equation, the lowest MCS level can be found in DL and UL. Furthermore, the DL and UL coverage radius of the BS can be deduced, the lower one is the BS coverage radius in the zone. With the BS coverage radius, network planner can finally determine the BS locations from the candidate sites.

### 3.5 Handover Planning

Handover is a critical issue for mobile applications. Mobile WiMAX supports seamless handover to enable the MS to switch from one BS to another at vehicular speeds without interrupting the connection. Mobile WiMAX supports Layer-2 and Layer-3 handover. Layer-2 handover is occurred between the BSs attached to the same ASN-GW. The Mobile WiMAX has developed several techniques for optimizing hard handover. These improvements have been developed with the goal of keeping Layer-2 handover delays to less than 150ms. Layer-3 handover is occurred between the BSs attached to different ASN-GW. Besides to exchanging Layer-2 handover messages, Layer-3 handover needs to exchange Mobile IP (MIP) messages. Layer-3 handover brings more handover delay than Layer-2 handover and may cause application pause in fast moving.

For the WiMAX-R network, the main target of handover planning is to achieve fast, stable and high efficient handover. With the BS location chosen in the former step, WiMAX-R network planner can optimize handover performance when designing the BS and ASN-GW connection scheme. Typically, one ASN-GW can manage about one hundred BS, in train high speed running areas, the BSs should be connected to the same ASN-GW, so that the faster Layer-2 handover can be performed. In train low speed running areas, stations or marshaling yards, the BSs can be connected to different ASN-GW.

### 3.6 Network Simulation Validation

After the former steps, we have finished the network planning process and got the network construction scheme. Since the total plan has lots of parameters, we need validate the scheme via network simulation. The main work of network simulation is modeling the network protocol logic in computer software platform, setting up the network topology and parameters and finally simulating the network performance results needed.

Choose an accurate simulation tool is the validation to ensure the quality of network simulation. At present, the mainly used network simulation tools include OPNET, QualNet, NS2 and OMNet++. The most advanced and widely used tool is OPNET, which supplied rich standard library models and supported the network simulation from simple LANs to complex world WANs. The newest OPNET Modeler 16.0 [OPNET, 2009] already integrates Mobile WiMAX model (802.16e). The model provides equipment of ASN-GW, BS, MS and supports advanced wireless communication features including OFDMA, TDD, AMC, STC and handover.

## 4 WiMAX-R Network Planning Instance

In order to verify the WiMAX-R network planning process, in this section we demonstrate an example and test it based on OPNET simulation tool.

### 4.1 Planning Process

#### *1) Application Analysis*

The designed network should provide service for all railway applications mentioned in Section III.A. According to the analysis of railway communication systems, we can find out the WiMAX-R applications’ QoS parameters as shown in Table 9.

| **Application** | **TCS** | **TDTS** | **TVSS** |
|---|---|---|---|
| *Communication Direction* | DL and UL | DL and UL | DL or UL |
| *Traffic Rate (kbps)* | 9.6 | 80 | 512 |
| *Delay Allowed (ms)* | 500 | 50 | 1000 |
| *Packet Delivery Ratio* | 1.0 | 0.9 | 0.95 |
| *Scheduling Mode* | UGS | ertPS | rtPS |
| *Priority* | High | Medium | Low |

*Table 9: WiMAX-R Applications QoS Parameters*

2) *Capacity Prediction*

The railway zone is 100km long and the user estimation arguments are listed in Table 10. Easily to calculate that $CR_{DL}$ and $CR_{UL}$ are both 1789.8kbps and $R$ equals to 1.0.

| **Application** | **TCS** | **TDTS** | **TVSS** | |
|---|---|---|---|---|
| *Communication Direction* | DL and UL | DL and UL | DL | UL |
| *User Density (Users/km)* | 8.0 | 4.0 | 1.0 | 1.0 |

*Table 10: User Density Estimation Parameters*

3) *Network Parameters Configuring*

With the values of $CR_{DL}$, $CR_{UL}$ and $R$, we configure the network parameters as following table and the BS capacities are same as in Table 2.

| **Parameters** | **Values** |
|---|---|
| *Channel Bandwidth* | 10MHz |
| *TDD DL/UL Symbol Ratio* | 1:1 |
| *Smart Antenna Mode* | STC |

*Table 11: User Density Estimation Parameters*

4) *Coverage Planning*

With the equation (3) and (4), the lowest MCS levels found are QPSKL 1/2 both in DL and UL. Searching Table 8, we find out the BS coverage radius can reach 3.08 km. So we set the distance between BSs as 6.16 km.

5) *Handover Planning*

Since the distance between the BSs is about 6km, we plan 16 two-sectors BSs in the 100km long zone. Two ASN-GWs are planned and each 8 BSs are attached to one ASN-GW.

### 4.2 Simulation Scenario

Fig.8 shows a part of the OPNET simulation network topology, which contains 2 parallel railways and trains can run on both directions. The MSs are trains at speeds of 100km/h. Each train contains a subnet, that one CPE provides WiMAX-R access service for the TCS, TDTS and TVSS client. In ASN, 16 BSs are configured alone with the railway and attached to two ASN-GWs. In CSN, an IP cloud provides IP connections for TCS, TDTS, TVSS servers and two ASN-GWs. The simulation duration is 3600 seconds. All reported results are averaged over 10 different runs based on different random seed to account for stochastic elements.

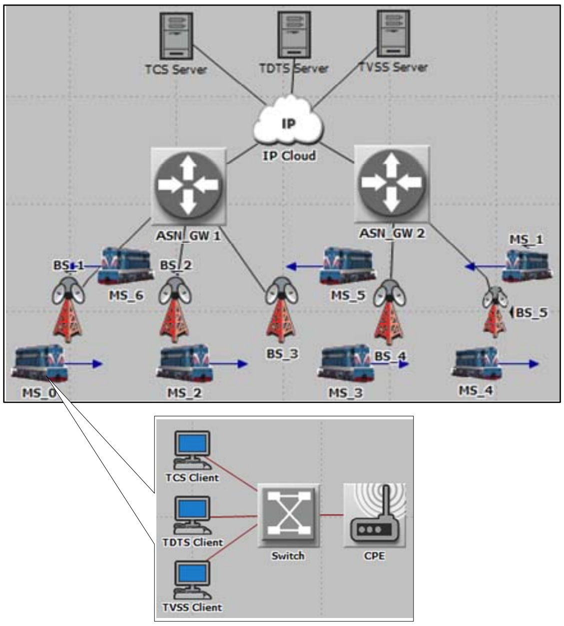

*Figure 8: WiMAX-R Simulation Scenario in OPNET*

### 4.3 Simulation Results Analysis

*1) Pathloss and SINR*

Fig.9 shows the pathloss simulation result. We can observe that the pathloss varies from 127dB to 152dB with the movement of the train. This is consistent with the ITU-Vehicular pathloss formula. Fig.10 shows the DL and UL SINR for MS_0. The most values of UL SINR are controlled in the area larger than 3.6dB, which is the decoding threshold for the QPSK 1/2. The minimum value of DL SINR is about 10dB, which is higher than the QPSK 1/2 decoding threshold value (4dB) in link budget. This is because we configure the coverage radius based on the uplink QPSK 1/2 decoding threshold. In this case, DL has more surplus capacity.

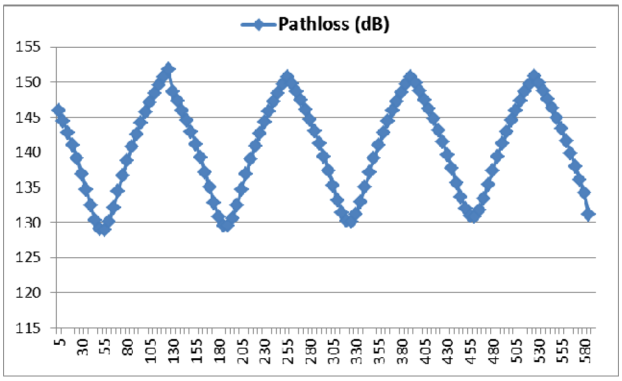

*Figure 9: Pathloss Simulation Result (dB)*

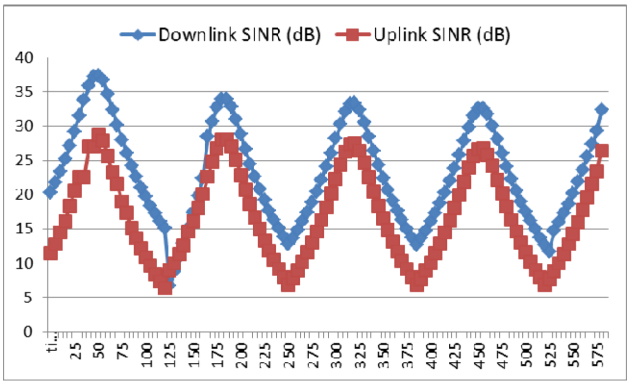

*Figure 10: DL and UL SINR Simulation Results (dB)*

### *2) DL and UL Throughput*

Fig.11 shows the DL and UL throughput simulation results of the CPE on one train (MS_0). We can find that the DL throughput ranges from 4.5Mbps to 14Mbps and UL throughput ranges from 2.1Mbps to 6.2Mbps, which are correspond to the values in Table 2.

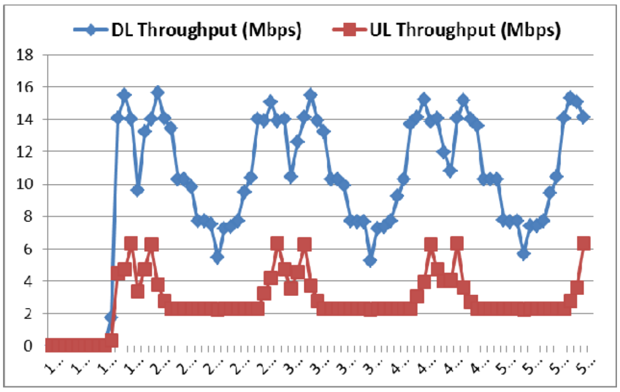

Figure 11: DL and UL Throughput Simulation Results (Mbps)

### 3) Handover Delay

Fig.12 shows the handover delay simulation result. We can see that most of values are lower than 100ms, which are caused by Layer-2 handover. Only one handover delay value is higher than 350ms, this is because of Layer-3 handover between two ASN-GWs.

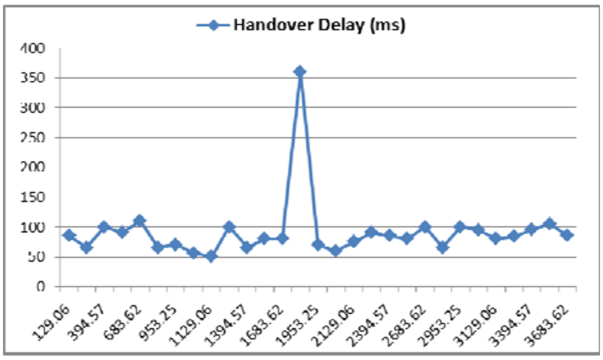

Figure 12: Handover Delay Simulation Result (ms)

### 4) Application QoS

Fig.13 and 14 show the simulation results of end-to-end delay and packet delivery ratio. The maximum end-to-end delays are 42ms, 16ms and 354ms and the packet delivery ratios are 1.0, 0.97 and 0.94 of TCS, TDTS and TVSS respectively. We can see that the performances are all meet the QoS requirements in Table 9.

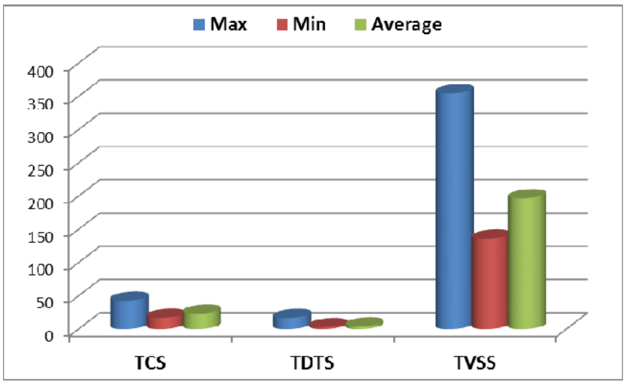

*Figure 13: End-to-End Delay Simulation Result (ms)*

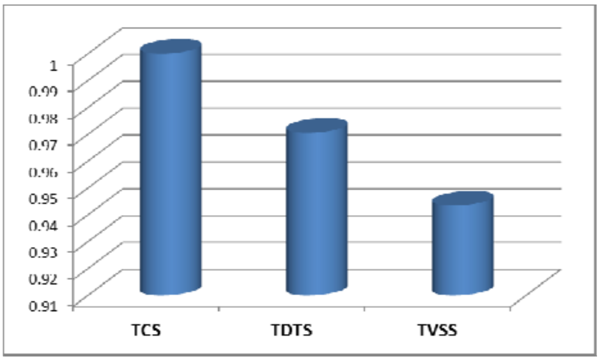

*Figure 14: Packet Delivery Ratio Simulation Result*

## 5 Conclusions

In this paper, we proposed a network planning process for WiMAX-R network. The process is consist of a series of steps analysis and calculations, including WiMAX-R network architecture analysis, railway communication applications QoS parameters analysis, DL/UL link budget calculation, BS coverage calculation, capacity planning and network simulation validation. In simulation experiment we have shown that WiMAX-R network designed by our planning process provided good performances that can perfectly satisfy the QoS requirements for all of the railway communication applications.

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## References

[Aguado, 2009] Aguado M., Jacob E., Berbineau M., Astorga J., Toledo N.: Simulation framework for performance evaluation of broadband communication architectures for next generation railway communication services, Intelligent Transport Systems Telecommunications2009, Page(s): 453-457, 2009

[Aguado, 2008] Aguado M., Onandi O., Agustin P.S., Higuero M., Taquet E.J.: WiMax on Rails, Vehicular Technology Magazine IEEE, Volume: 3 , Issue: 3 Page(s): 47 – 56, 2008

[Ahmad, 2008] Ahmad I., Habibi D.: A proactive forward error control scheme for mobile WiMAX communication, ICCS 2008. Page(s):1647–1649, 2008

[Casasempere, 2009] Casasempere J., Sanchez P., Villameriel T., Del Ser J.: Performance evaluation of H.264/MPEG-4 Scalable Video Coding over IEEE 802.16e networks, Broadband Multimedia Systems and Broadcasting, 2009. BMSB '09, Page(s): 1-6, 2009

[Chow, 2009] Chow B., Li Y. M., Sauer M., Ng'Oma A., Tseng M.C. Yeh C.H.: Radio-over-Fiber Distributed Antenna System for WiMAX Bullet Train Field Trial, Mobile WiMAX Symposium, 2009. IEEE, Page(s): 98-101, 2009.

[Haagsma, 2005] Haagsma J.J., Haylock R.D.: Technology assessment for single stage and multi-stage mobile applications, Mobile Business 2005, Page(s): 452-456, 2005

[IEEE 802.16e, 2005] IEEE Standard for Local and Metropolitan Area Networks [S], IEEE Standard 802.16e, 2005

[Internet-Web, 2007] Internet World Wide Web: London Transport to trial new tech”, http://www.cio.co.uk/news/1519/london-transport-to-trial-new-tech/

[Internet-Web, 2010] Internet World Wide Web: Azulstar Debuts WiMAX on 95-Mile New Mexico RailRunner Train System”, http://www.marketwire.com/press-release/Azulstar-Debuts-WiMAX-on-95-Mile-New-Mexico-RailRunner-Train-System-1165496.htm

[Kumar, 2008] Kumar K.R., Angolkar P., Das D., Ramalingam R.: SWiFT: A Novel Architecture for Seamless Wireless Internet for Fast Trains, Vehicular Technology Conference2008. Page(s): 3011-3015, 2008

[Masson, 2007] Masson E., Chennaoui M., Berbineau M., Dumortier H.: Performance of High Data Rate Transmission Scheme developed for train communications, Telecommunications, 2007. ITST '07. 7th International Conference on ITS, Page(s): 1-6, 2007

[Nair 2004] Nair G.，Chou J.，Madejski T., IEEE 802.16 medium access control and service provisioning. Intel Technology Journal[J]，Volume 8，Issue 3 2004

[OPNET, 2009] OPNET Technology Inc: Modeler User Guide[S]. OPNET Document, 2009

[Saw, 2006] Saw J.: A Mobile Operator's Experience on Delivering Broadband Connectivity on Trains, Wireless Broadband Conference 2006, Page(s):17-27, 2006

[Yeh, 2010] Yeh C., Chow C., Liu Y., Wen S., Chen S., Sheu C., Tseng M., Lin J., Hsu D., Chi

S.: Theory and Technology for Standard WiMAX Over Fiber in High Speed Train Systems, Lightwave Technology, Journal of IEEE/OSA, Volume: PP , Issue: 99 Page(s): 1-1, 2010

[Zhang, 2011] Zhang D, Chen M., Huang H., Guo M.: Decentralized Context Inconsistency Checking in Pervasive Computing Environments, Journal of Supercomputing, 2011.

[Zhang, 2011-2] Zhang D, Zhou J., Guo M., Cao J.: TASA: Tag-Free Activity Sensing Using RFID Tag Arrays, IEEE Transactions on Parallel and Distributed Systems (TPDS), vol. 22, Page(s): 558 – 570, April, 2011.

[Zhang, 2011-3] Zhang D, Huang H., Lai C., Liang X., Guo M.: Survey on Context-awareness in Ubiquitous Media, Multimedia Tools and Applications, 2011.