Theory and Technology for Standard WiMAX Over Fiber in High Speed Train Systems

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***Abstract*—In this investigation, we propose and investigate the standard WiMAX access in high speed railway (HSR) using radio over fiber (RoF) link. We also discuss the theory of mobile WiMAX at a target speed of 300 km/hr in simulation. We also analyze the effect of the Doppler frequency shift over HSR. The effective transmission fiber length in the WiMAX-RoF system was limited due to the time-division-duplex (TDD) protocol in the practical WiMAX. Thus, we also demonstrate the transmission limitation and performance of the standard WiMAX access in RoF link. The performances of throughput and packet loss at different fiber lengths are also investigated and discussed. Furthermore, a WiMAX-RoF field trial is also demonstrated based on a simple two RAUs RoF architecture. It was tested and measured in the SongShan tunnel of the Taiwan high speed railway (THSR).**

***Index Terms*—High speed railway, OFDM, radio over fiber (RoF), time-division-duplex (TDD), WiMAX.**

I. INTRODUCTION

RECENTLY, people want to access the Internet at anytime, everywhere, and every situations. And the demand of users to access the high data rate broadband services is increasing rapidly [1]–[5]. Furthermore, the traveling users also want to access broadband services with a high level of quality of service (QoS) [6]–[8]. Therefore, different wireless access network technologies have been developed and deployed [9]–[13]. However, the Internet access for the passengers in high speed train ($\sim$300 km/hr) would be an interesting research with many challenging issues [14]–[16].

Although, the current cellular and satellite access technologies could provide the limited wireless services to the fast moving users, these technologies cannot be considered for the fast moving train passengers due to their inherent limitations, such as the fast time varying fading and deep frequency selective fading [17], [18]. A direct connection between a train passenger and the ground base station of the cellular network is not possible due to high penetration losses because of the Faraday cage characteristics of train. Also, there are tradeoffs among the speed of the train, available bandwidth, and handover issues [19], [20]. On the other hand, the satellite technology is not suitable for real time applications because of its inherent delay, limited bandwidth, and poor coverage in urban areas, hilly areas and tunnels.

Nowadays, WiMAX access technology for the last mile wireless network is used to provide flexible and mobile broadband service to end-user according to the standards of IEEE 802.16 and 802.16e [11], [13], [21], [22]. In the future, the competition of access technologies may result in the lower cost for both home and business customers. In accordance with the WiMAX standard, when signal access inside a long tunnel and indoor, the WiMAX signal distribution would be greatly hindered. Because of this issue, using radio-over-fiber (RoF) technology to carry the WiMAX signal could extend the cell coverage by using multiple distributed remote antenna units (RAUs). The RoF technology also provides the advantage of using cost-effective RAU, and increasing the scalability of the network [23]–[28]. In this regard, the WiMAX-RoF is an integration of wireless and optical system, which could be the powerful solution for providing high bandwidth Internet to the fast moving train passengers. Furthermore, cellular trackside solutions based on RoF have been proposed in [16], [20], which discussed only the architectural aspects and networking perspective of distributing broadband services to the train.

Moreover, in the WiMAX network, the time-division-duplex (TDD) system is favored by a majority of implementations than the frequency-division-duplex (FDD) because of its advantages [26], such as: (1) providing flexibility in choosing uplink-to-downlink data rate ratios, (2) ability to exploit channel reciprocity, (3) ability to implement in nonpaired spectrum, and (4) less complex transceiver design. However, it is worth to mention that the TDD system limits the transmission distance of WiMAX system. This is because if the transmission distance is too long, there is a large delay between the downlink and uplink data packets, resulting in the base station (BS) cannot synchronize the data and high packet loss will be observed. In the BS, the TDD switch (SW) is used for downlink/uplink switching.

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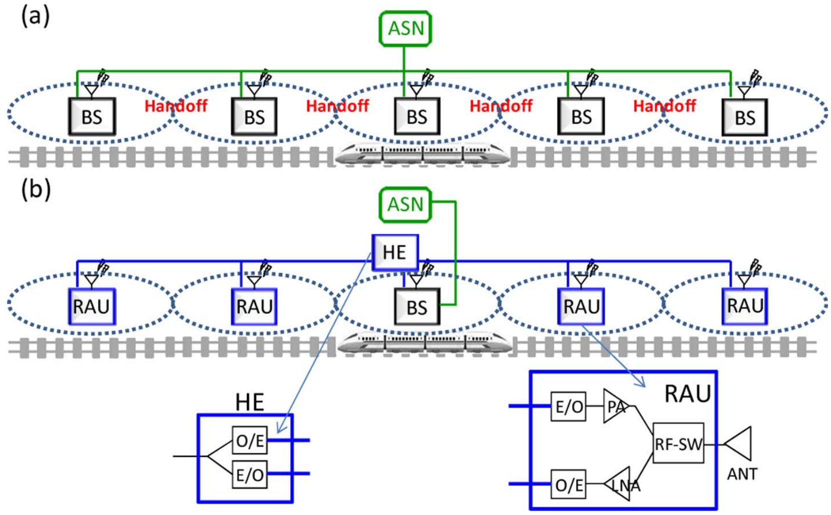

Fig. 1. (a) Conventional WiMAX access networks. (b) Proposed WiMAX over fiber connection by using HE and RAUs to extend the cell coverage. (a) WiMAX System, (b) WiMAX-ROF System.

However, the TDD SW of each RAU for uplink and downlink traffic in RoF system is difficult to perform due to the fiber delay time and high leakage power between the downlink and uplink WiMAX signals [29].

When the TDD transmission is used in WiMAX-RoF link, the TDD switch design is required at RAU for switching the downlink and uplink signals. Based on the previous studies of the TDD switch [26], [30]–[32], they were not good enough to withstand high output power form the BS. And the leakage power from the downlink may cause damage to the electronic components, such as low noise amplifier (LNA), in the uplink path. According to WiMAX standard for the TDD-based operation [20], [28], there are two time gaps of transmit/receive transition gap (TTG) and receive/transmit transition gap (RTG) between downlink-and-uplink and uplink-and-downlink, respectively. And the maximum gap time of TTG is 105 μs. However, when the WiMAX-RoF link is used, the TDD switch design in distributed RAUs should be an important issue during downlink/uplink TDD switching due to the fiber delay ($\sim$5 μs/km). In [26], to obtain the downlink/uplink signal switching in RoF system, the proposed TDD switch in each RAU should increase the gap times of TTG and RTG by media access control (MAC) protocol to overcome the fiber delay time. In addition, for the commercial WiMAX BS, it is also hard to control the two gap times. Furthermore, the total isolation of TDD switch in RAU was typically only 40 dB ([26]). It was also difficult to isolate the leakage power of downlink when the WiMAX output power was 35 dBm.

In this investigation, we propose and investigate an access architecture to provide both external broadband Internet services (ground-to-train) and internal on-demand wireless services (in-train) to high speed train passengers using WiMAX-RoF system in high speed railway (HSR). We apply the standard WiMAX signal generated from a BS in the RoF system. In this experiment, we can extend cell coverage to 16 km long by WiMAX-RoF link. In Section II, we describe the WiMAX-ROF architecture. In Section III, we analyze and discuss the background theory of standard mobile WiMAX for the applications in the HSR. In Section IV, we demonstrate the transmission limitation and performance of the standard WiMAX access in RoF link. The performances of throughput and packet loss at different fiber lengths are also investigated and discussed. A WiMAX-RoF field trial using two RAUs in RoF architecture has been tested and measured in the SongShan tunnel of the Taiwan high speed railway (THSR).

II. WiMAX-RoF Architecture

The Industrial Technology and Research Institute (ITRI) in Taiwan has developed a WiMAX access network for the THSR bullet train system to provide high bandwidths for downlink and uplink traffic. Fig. 1(a) shows the WiMAX access network using multiple BSs along the track. Each BS is connected to access service network (ASN) gateway for Internet access. For example, if five BSs are required cover the track, as shown in Fig. 1(a), four handoffs are needed as the train moves from one BS's cell coverage to the next. Handoffs are common in all wireless systems, but the combination of speeds up to 300 km/hr and the terrain makes handoffs on highly mobile connection very challenging.

Generally, the RF cell coverage in each WiMAX BS is approximately 0.5 to 5 km [28] when the BSs are deployed along the track, as shown in Fig. 1(a). However, the deployment of network coverage over mobile corridors often presents unique and significant challenges. These corridors typically traverse challenging terrain like tunnels, mountains, bridges, and various man-made obstructions as well as sparsely populated areas. There is also a high cost associated with the deployment of wireless coverage over the complete corridor, which in many cases results in marginal to poor reception over various parts of the corridor. WiMAX access architecture in high speed train also results in several problems, such as the handoff (handover), Doppler effect, and non-uniform RF power coverage. Besides, nearly 20% total track length in THSR would be through the tunnels. Therefore, the WiMAX-RoF distributed antenna system

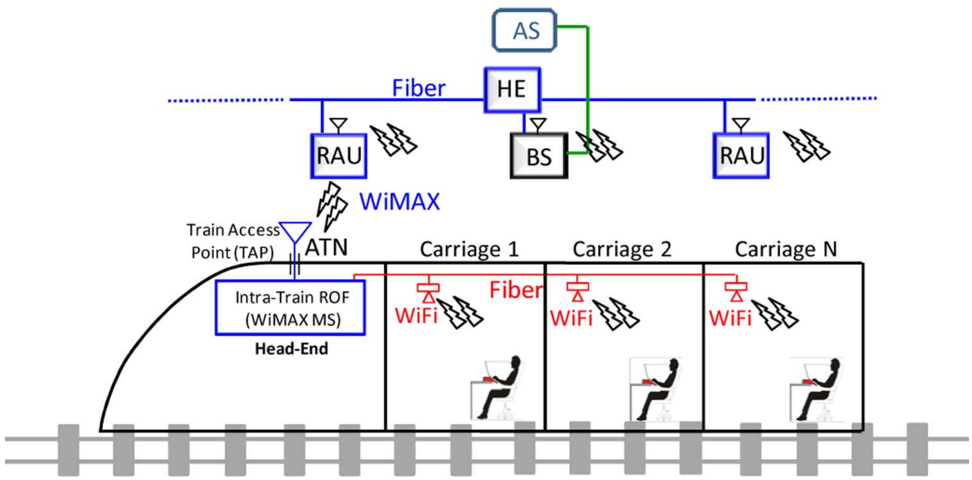

Fig. 2. The proposed RAU scheme. SW: 1 × 1 switch; PA: power amplifier; LNA: low noise amplifier; DE: delay element; C: circulator; D: detector; CS: control system; ANT: antenna.

could be proposed and developed to overcome critical issues of handoff and continuous coverage.

Hence, Fig. 1(b) presents the typical WiMAX-RoF optical link consisting of a head-end (HE) and several distributed remote antenna units (RAUs) separated by a span of optical single-mode fiber (SMF). The RoF system can also reduce the overall cost, the complexity, and deployment time. In this case, the WiMAX signal from a single BS is transmitted to the distributed RAUs optically, as seen in Fig. 1(b). Since the signals are replicated from a single BS, there are no handoffs required when the high speed train moves between one RAU and the next.

Fig. 2 shows the proposed architecture of WiMAX-RoF transmission system providing high quality broadband services to the high-speed train. For the ground-to-train connection, the downlink WiMAX signal is broadcasting from each BS through the distributed RAUs by using the proposed RoF system along the railway. The downlink WiMAX signal can be received by the train access point (TAP) for intermediate access between ground-to-train and intra-train. The TAP is considered as the gateway to the train. Finally, the Intra-train RoF network provides both external broadband internet services and internal on-demand select services (such as Movie/Video on demand, interactive gaming, on-train conferences etc.) to the individual passenger using wireless (Wi-Fi network) access to each carriage, as shown in Fig. 2.

III. WiMAX Theory

Due to the orthogonal frequency division multiplex (OFDM) WiMAX access in high speed railway (300 km/hr) used, the fast time varying and deep frequency selective fading would be the problem to face. The performance of transmission channel could be affected by two factors as follows. One was the multi-path effect, and the other was the Doppler shift. Furthermore, in the fast moving status, the inter-carrier interference (ICI) would degrade the OFDM signal. First, we will discuss the theoretical analysis on the mobility of mobile WiMAX. In general, the maximum total bandwidth (BW) of Doppler spectrum can be estimated in

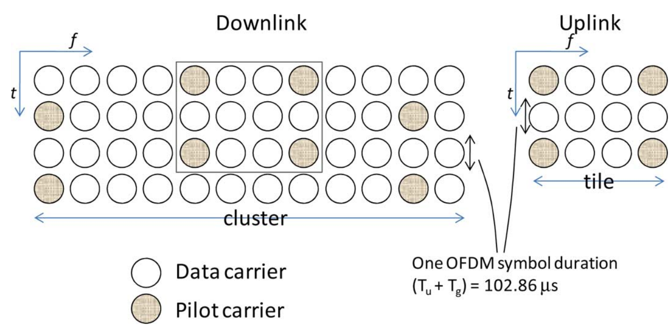

Fig. 3. Two-dimensional sampling of the channel.

4.86 kHz (±2.43 kHz) when one OFDM symbol duration time is 102.86 μs in the 2-D sampling of channel, as shows in Fig. 3.

The Doppler shift frequency is $f_D = f_c \times (v/c)$, where f_c is carry frequency, v is moving speed and c is light speed. While the WiMAX is operated at the center frequency of 2.5 GHz, this means the f_c and v are 2.5 GHz and 300 km/hr, the f_D will be equal to ∼694 Hz (< 2.43 kHz). And the subcarrier spacing $(f_{\rm SC})$ is equal to 10.9375 kHz. The normalized Doppler frequency (δ) can be also calculated, $\delta = f_D/f_{\rm SD} =$ 694 Hz/10. 9375 kHz $= 6.4\%$. As we know, the ICI would cause the degree of Doppler shift. When the δ is larger than 5%, the Doppler shift was severe. And while the δ is less than 2.5%, the Doppler shift was slight. From the calculation above, when the WiMAX is operated at 2.5 GHz band, Doppler compensation is required. However, if the WiMAX is operated at 700 MHz band, then the calculated f_D = 194 Hz and δ = 194 Hz/10.9375 kHz $= 1.77\% (< 2.5\%)$. Hence, Doppler compensation is not necessary. Other Doppler compensation scheme that can be used in the high speed train, such as using sampling procedure comprising an allocation of different time delays to the signal and the different time delays being chosen following a law adapted to compensate the determined Doppler effect [33].

In order to provide wireless internet service in a high speed train by the mobile WiMAX technique [20], we need to realize the actual products for mobile WiMAX whether can solve the

TABLE I
EXPERIMENTAL SETUPS AND OPERATING CONDITIONS FOR THE MEASUREMENTS OF PROPOSED FOUR CASES

Case	Diversity Downlink/Uplink	Channel	Speed (km/hr)
1	SISO/SISO	AWGN	0
2	SISO/SISO	Vehicular-A	300
3	SISO/SIMO	Vehicular-A Corr.=0	300
4	SISO/SIMO	Vehicular-A Corr.=0.5	300

TABLE II
MULTIPATH CHANNEL EMULATION OF ITU VEHICULAR A UNDER NON-LINE-OF-SIGHT

ITU Vehicular-A	
Relative Delay (ns)	**Relative Meam Power (dB)**
0	0
310	-1
710	-9
1090	-10
1730	-15
2510	-20

acute channel variation and complete a stable transmission quality. In this session, we performed the in-lab performance measurement for mobile WiMAX product in high speed emulated channel (300 km/hr), and compared transmission performance between several receive conditions. Besides, the experimental results are also exploited to calculate the coverage of the base station. To set up the single-input multiple-output (SIMO) system in two channels extensively, we select the 0 and 0.5 of channel correlations for the best and worst operating environment for the standard WiMAX over high speed train in the future.

In this analysis, we use the channel emulator to simulate the transmission channel on static and dynamic (fast moving) status between base station (BS) and mobile station (MS). We set the OFDM WiMAX frequency on 2.505 GHz with 1 024 subcarriers. And the symbol number ratio of downlink and uplink traffic is 29/18. According to the [34], the minimum sensitivity of receiver (Rx) can be measured when the bit error rate (BER) was less than 10^{-6}. Furthermore, we not only can observe the different power sensitivity but also can retrieve the WiMAX throughput performance. Besides, to obtain batter transmission performance in fast moving, we use QPSK modulation with 1/2 coding rate in TDD frame for the measurement.

In this study, we propose four simulation testing cases under different operating conditions, such as the channel correlation, diversity of antenna system, and moving speed, as also shown in Table I. The diversity represents transmitted and received antenna system for downlink and uplink traffic. Single-input single-output (SISO) mean the transmitted and received ports both using single antenna. And single-input multiple-output (SIMO) mean the transmitted and received ports utilizing the single- and dual-antenna, respectively. The maximum ratio combining (MRC) technology [35] meant that the multiple-receiver was used to receive the RF signal in received port.

For the setup of channel environment, we add the additive white Gaussian noise (AWGN) in case 1 to obtain the basis performance in static status to compare with the dynamic transmission status. Hence, in case 2 to 4, we employ the ITU vehicular A of channel emulations to simulate the 300 km/hr moving speed. The selection of ITU vehicular A for the proposed four testing cases, as shown in Table I, is according to the document of WiMAX Forum [33]. In addition, we use the transmission control protocol (TCP) and user flow protocol (UDP) for the

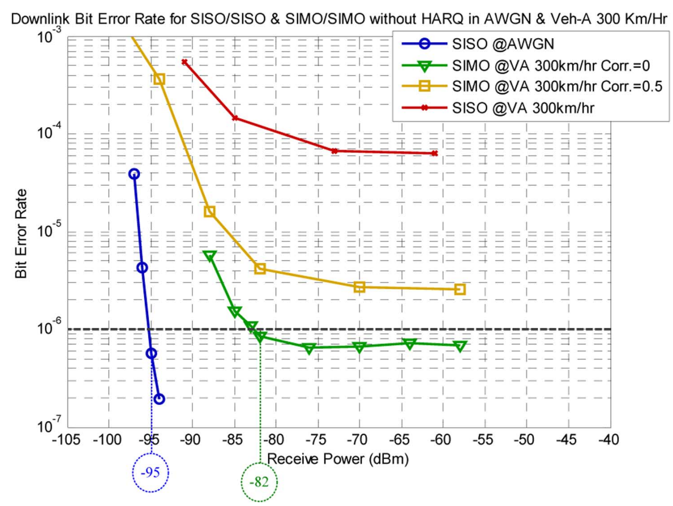

Fig. 4. BER measurements for downlink traffic in four testing cases: at back-to-back and 300 km/hr.

throughput and packet loss measurements for the connection between BS and MS.

The output powers of BS and MS are set at 35 and 26 dBm, respectively. We use the RF cables to directly connect the both BS and MS for data traffic. Between BS and MS, a RF variable attenuator (VA) is used to simulate the air path loss for the four testing case. Fig. 4 shows the BER performances for the downlink traffic. The BER of $< 10^{-6}$ can be observed only on the case 1 and 3. The sensitivities of cases 1 and 3 are measured at -95 and -82 dBm under the BER of 10^{-6}. Hence, Fig. 5 also presents the related throughput performances of downlink traffic in four testing cases. For the case 2, the throughput can not be obtained. For the case 1 and case 3, the related maximum throughputs can be retrieved around 3 and 2.6 Mb/s, respectively. As also shown in Fig. 5, the measured throughputs are 0.33 and 2.4 Mb/s, respectively, when the received power are -95 and -82 dBm under the BER of 10^{-6}. Moreover, the throughput also can retrieve around 1 Mb/s in the received power of -57 to -70 dBm, for the testing case 4.

As a result, the data traffic can be observed in 300 km/hr speed using QPSK modulation with 1/2 coding rate in the cases 3 and 4 having nearly 2.6 and 1.0 Mb/s throughputs, respectively. In the proposed channel emulations, we don't need to compensate the Doppler shift (in 2.5 GHz band frequency) in fast moving

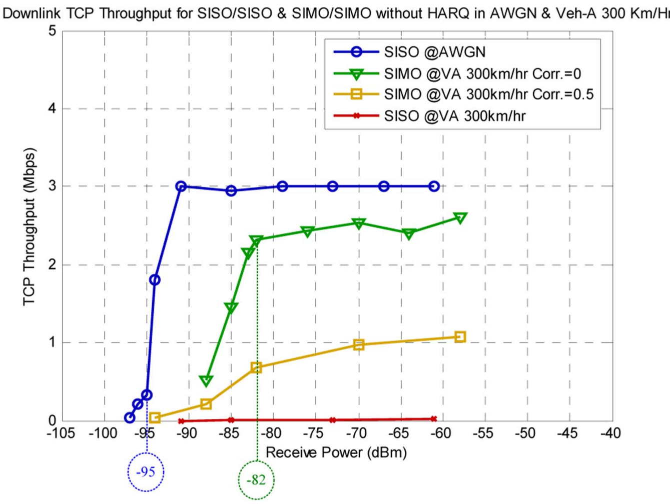

Fig. 5. Throughput measurements of downlink traffic in four testing cases: at back-to-back and 300 km/hr.

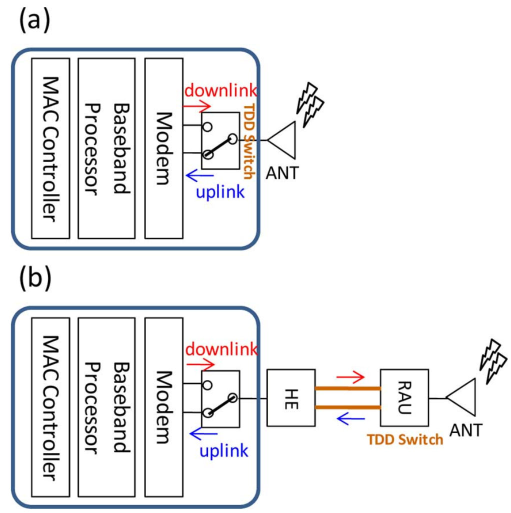

Fig. 6. (a) WiMAX TDD switching for DL and UL traffic of BS. (b) TDD switching of RAU in WiMAX BS-RoF architecture.

status based on the QPSK modulation. In addition, to achieve higher data throughput, the 16-QAM or 32-QAM modulations could be used to enhance the WiMAX access connection.

IV. Static WiMAX-RoF Experiments

To reduce the number of BS over HSR, the WiMAX signal can be used in RoF system by using the HE and distributed RAUs to extend the cell coverage for reducing the cost, as illustrated in Fig. 1(b). Here, according to WiMAX standard [20], for the TDD-based operation, there are two time gaps of TTG and RTG between downlink-and-uplink and uplink-and-downlink, respectively. The maximum time gaps of TTG and RTG are 105 and 60 μs, respectively, in standard WiMAX system. Initially, the WiMAX signal access was for uplink traffic. After ending gap time of RTG, the BS begins to transmit the downlink signal. The signal switching can be achieved by using 1×2 RF SW in BS and control by MAC within the gap time of RTG, as shown in Fig. 6(a). However, when using the WiMAX access in RoF link, as seen in Fig. 6(b), the TDD switch design of the distributed RAU must complete the downlink/uplink signal switching within the gap times of TTG and RTG. Besides, the maximum WiMAX output power emitted from BS was 35 dBm. Thus, the higher launched power to the antenna (ANT) at RAU is desirable in order to increase the emitted RF signal power in WiMAX-RoF system. Furthermore, due to the intrinsic power isolation of RF circulator, the leakage power from the downlink (DL) may cause damage to the uplink (UL) components, such as the LNA. Thus, the RF switch design in RAU must take into account the TDD signal operating and high leakage power. Hence, to overcome the TDD transmission in RoF link, a TDD switch design in RAU was also proposed and studied [26]. Reference [26] proposed a TDD switch in RAU for signal switching by adjusting the gap times of TTG and RTG in MAC to overcome the times of fiber delay and signal processing. The total isolation of its TDD switch was typically only 40 dB. It is difficult to isolate the leakage power of DL and decrease the total data rate.

As shown in Fig. 1(b), the HE and RAU modules are consisted of a pair of electrical-to-optical (E/O) and optical-to-electrical (O/E) converters for signal conversions between WiMAX electrical and optical signals. Hence, higher RF power can be launched into the ANT to improve the signal-to-noise ratio (SNR) of the WiMAX-RoF link, while preventing the leakage power may cause damage to the LNA. Thus, the proposed TDD switch in each RAU, which was used to solve the limited power isolation issue of typical high-speed RF device and the TDD operating was also proposed and discussed in [26]. Hence, higher RF power can be launched into the ANT in order to enhance the SNR, while preventing the leakage power may cause damage to the electrical components. In our proposed TDD switch of RAU [36], the downlink/uplink signal switching time was within 4 μs. For IEEE 802.16e WiMAX, the TTG frame is 105 μs, which equates to approximately 9 km round-trip over standard single mode fiber (SMF). This is the theoretical maximum transmission distance for the WiMAX RoF governed by the WiMAX protocol for waiting the acknowledgement signal. The maximum fiber length may be reduced when the switching or electrical to optical conversion delays are included.

In the experiment, the downlink WiMAX signal with the output power of 14.5 dBm was emitted from the BS. The signal then passed through a circulator, a 15 dB fixed attenuator (FA) to the HE transmitter (Tx) for E/O or O/E conversion. After the E/O conversion at the HE, optical signal was propagating through standard SMF at different lengths, and then launched into the RAU for O/E conversion. Then the converted electrical downlink signal transmitted via the RF CIR and VA into the MS. Both the BS and MS were connected to computers for signal analysis. For the UL, signal of 6.2 dBm output power was emitted from the MS and transmitted through the same optical and electrical link back to the BS. The VA in the experiment was used to simulate the atmospheric loss systematically for link between the BS and the MS. Here, we are interested to evaluate the standard WiMAX signal performance over optical fiber. Hence, we would like to remove other variables in the studies, such as antenna effect, multipath fading, etc. We also believe that for a point-to-point direct wireless link between the RAU and the MS, the main limiting factor is the air attenuation,

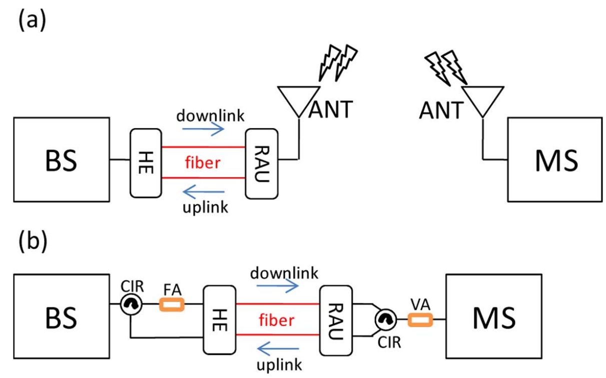

Fig. 7. (a) Typical WiMAX-RoF system. (b) The experimental setup of the proposed WiMAX RoF link architecture for characterization. FA: fixed attenuator; VA: variable attenuator; CIR: circulator.

which is regarded to be constant at a particular frequency band [28]. Hence, we believe that using RF attenuator is possible to emulate the point-to-point air attenuation. Moreover, in the HE and RAU modules, two single longitudinal mode (SLM) optical signals with output powers of 3.5 and 3.6 dBm at the 1.3 μm wavelengths are used for the uplink and downlink signal in RoF link, respectively. In the measurement, the frame length of WiMAX signal was 5 ms. And the relative power differences between overhead and payload data was about 2–3 dB. The E/O converter is a high performance analogue data transmission system, which provides great benefits to users who require a solution to electrical interference and signal attenuation problems in signal monitoring and distribution. In this study, we used two fibers with equal length to propagate the downlink and uplink signal respectively is to reduce the signal crosstalk since the the Txs in the HE and RAU are emitting optical signal at similar wavelength, and there is no optical filter before the Rxs in the HE and RAU.

In order to realize the WiMAX-RoF system, an experiment is performed. Here, Fig. 7(a) shows the simple architecture of WiMAX-RoF link connecting the HE and RAU. The HE and RAU consist of a pair of E/O and O/E converters for conversing electrical and optical signals. To characterize and analyze solely the performance of the WiMAX-RoF system and to remove the atmosphere multipath fading effects of the signal, the antenna (ANT) in the RAU and the mobile station (MS) are purposely removed. For the reported WiMAX-over-fiber system in the paper, the conventional antenna connecting to the BS via the electrical RF cable has been replaced by a pair of O/E and E/O converter and optical fiber. The detection of multipath fading signals in the conventional wireless antenna is the same as that by using the RAU. Since multipath fading issue has been considered in standard wireless WiMAX system, we believe that the multipath fading issue is not the main interest in this manuscript. And this is the reason we try to simplify the setup by focusing on the performance analysis owing to the optical fiber solely. Hence, the RAU and the MS are directly connected using high frequency electrical cables via a RF circulator (CIR) and RF variable attenuator (VA).

Thus, Fig. 7(b) presents the experimental setup of the proposed WiMAX-RoF system. In the experiment, we used a commercial standard WiMAX BS and MS, which are designed and optimized for wireless WiMAX access communications. For the RoF connection, the HE and the RAU are two pairs of OE and EO transceivers (TRxs) with the maximum input RF power was 10 dBm. In this analysis, the WiMAX-RoF link between BS and MS was connected by using TCP and UDP for the throughput and packet loss measurements. The standard WiMAX signal with 14.5 dBm output power produced by the BS was set at the center frequency of 2.545 GHz. The WiMAX was 16-quadrature amplitude modulation (QAM) orthogonal frequency division multiplexed (OFDM) signal with 3/4 code rate. Thus, Fig. 8 shows the measured output constellation diagram and frequency spectrum of WiMAX signal of BS used before injecting into HE [measured in setup of Fig. 7(b)]. Moreover, in this measurement, the bandwidths of DL and UL traffic were around 9.8 Mb/s and $\sim$3.2 Mb/s respectively, communicating in TDD mode.

In the experiment, the downlink signal from BS passed through a RF CIR, a 15 dB fixed attenuator (FA) and the HE Tx for E/O conversion, as seen in Fig. 7(b). And about 0 dBm of electrical power was launched into the HE. After the E/O conversion, optical signal was propagating through standard single mode fiber (SMF), and then launched into RAU for OE conversion. Then the downlink signal transmitted via the VA and into the MS. For the uplink, signal from MS with 6.2 dBm output power was transmitted through the same optical and electrical components of the link. The VA in this setup is used to simulate the atmospheric loss systematically for link between the BS and the MS.

In order to characterize the WiMAX signal transmission length, total throughput and packet loss in RoF system, against various fiber lengths are measured in the setup in Fig. 7(b). The RF VA of Fig. 7(b) is used to simulate the air loss of RF signal. Thus, Fig. 9(a) and (b) show the throughput at 9.8$\pm$0.5 Mb/s and packet loss for downlink traffic under the different fiber length at back to back (B2B), 1, 4, 7 and 8 km, respectively, when the emitted power form BS and MS are $-$6.5 and 6.1 dBm. Besides, for the measured results, the packet loss and carrier intensity to noise ratio (CINR) must be smaller than 10% and larger than 30 dB, respectively, to maintain the effective throughput for data traffic. Fig. 9 also presents the dynamic range of 32, 23, 34, 40 and 42 dB in the case of B2B, 1 km, 4 km, 7 km and 8 km fiber lengths, respectively. This measured results show the dynamic range will increase gradually with the fiber length increase.

Fig. 10(a) and (b) show the throughput at 3.2 ± 0.5 Mb/s and packet loss for uplink traffic under the different fiber length at back to back (B2B), 1, 4, 7 and 8 km, respectively. Besides, for the measured results, the packet loss and CINR must be also smaller than 10% and larger than 30 dB, respectively, to maintain the effective throughput for data connection. Fig. 10 also presents the dynamic range of 32, 35, 27, 38 and 36 dB in the case of B2B, 1 km, 4 km, 7 km and 8 km fiber lengths, respectively. This measured dynamic range of Fig. 10 has the irregular change as the fiber length increase gradually in uplink traffic. In this demonstration, using RF cables cannot emulate the multipath effect. However for the reported WiMAX-over-fiber system in the manuscript, the conventional antenna connecting to the base station via the electrical RF cable has been replaced by a pair of O/E-E/O converter and optical fiber.

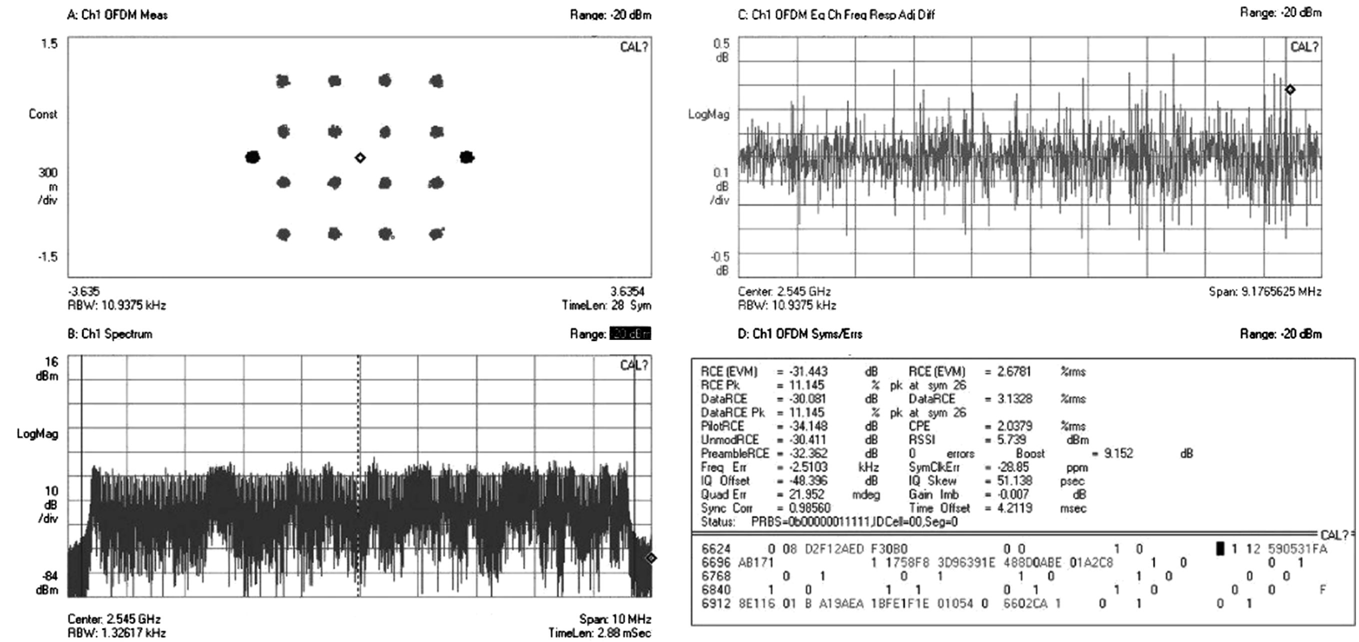

Fig. 8. Output constellation diagram and frequency spectrum of WiMAX signal before injecting into HE.

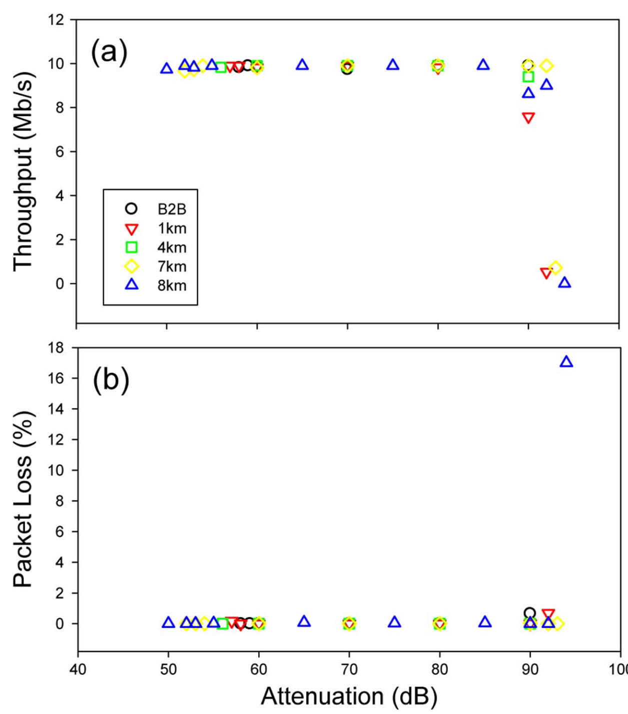

Fig. 9. Experimental measurements of (a) throughput and (b) packet loss under the different fiber lengths in downlink traffic at BTB, 1, 4, 7, and 8 km, respectively.

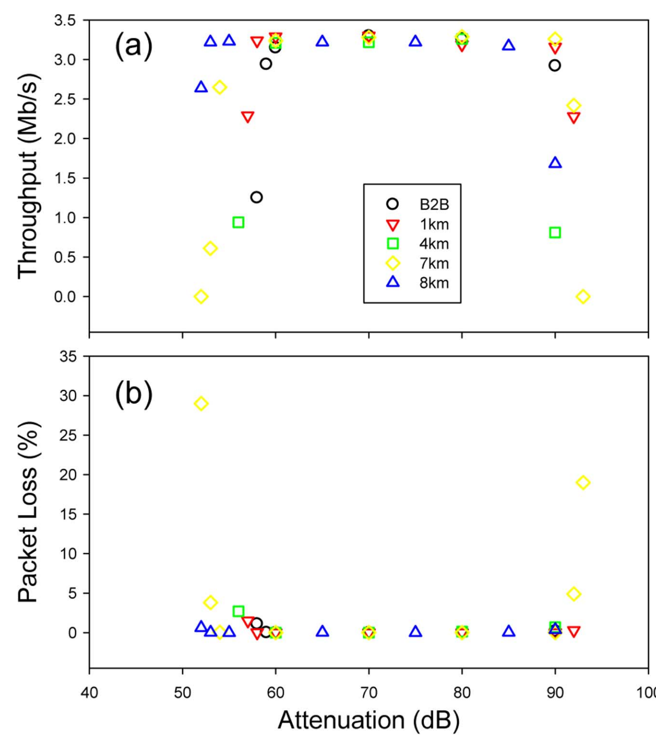

Fig. 10. Experimental measurements of (a) throughput and (b) packet loss under the different fiber lengths in upink traffic at BTB, 1, 4, 7, and 8 km, respectively.

The detection of multipath fading signals in the conventional wireless antenna is the same as that by using the RAU. Since multipath fading issue has been considered in standard wireless WiMAX system, we believe that the multipath fading issue is not the main interest in this manuscript.

Therefore, when 9 km of SMF were used in the downlink and uplink traffic, no signal can be detected due to the TDD limitation as described above. The maximum fiber length (9 km theatrically) may be reduced when the switching or electrical to optical conversion delays are included. We have measured and shown in Figs. 9 and 10 that the high packet loss starts to appear when the fiber length is 8 km. When using 9 km of standard SMF, the whole system cannot be synchronized, thus, we cannot have the measure results at 9 km SMF. Besides, while the fiber lengths change to 8 km, the downlink and uplink throughputs

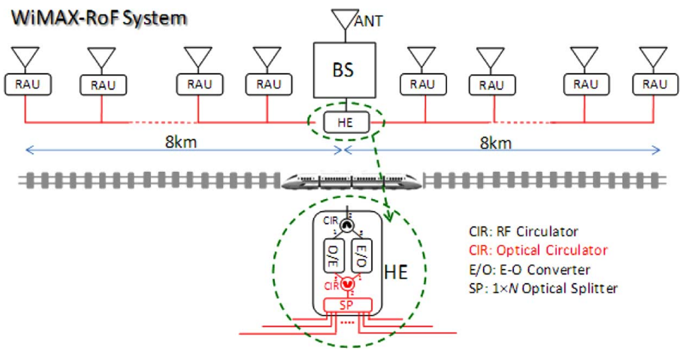

Fig. 11. Proposed WiMAX-RoF access architecture in HSR.

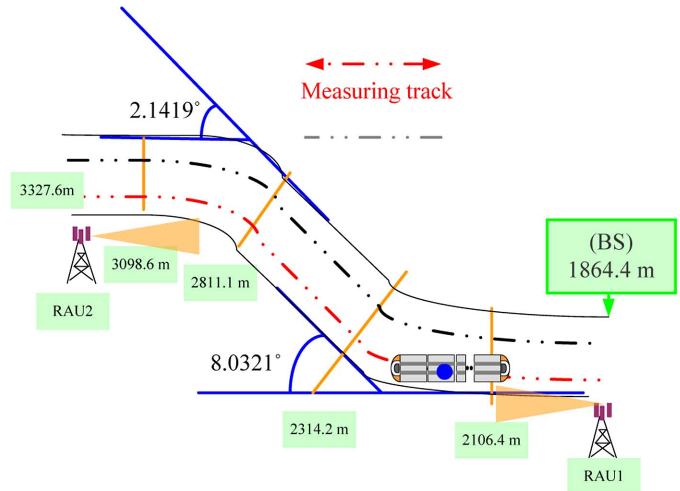

Fig. 12. WiMAX-RoF configuration for SongShan Tunnel Testing in THSR.

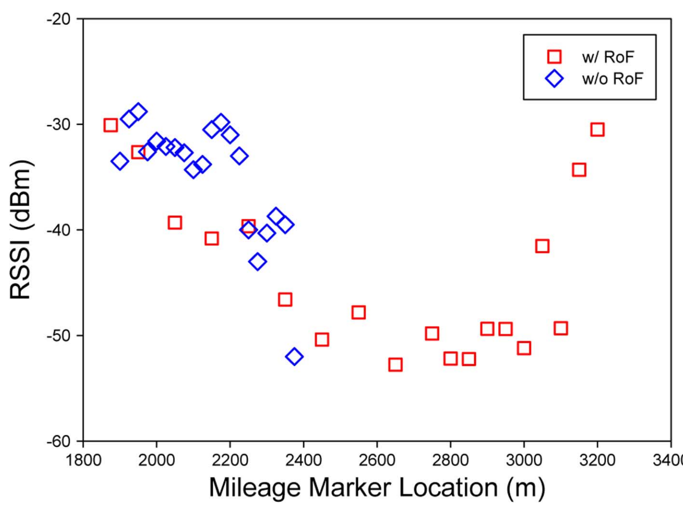

Fig. 13. RSSI measurement along the track of SongShan Tunnel without and with RoF link.

can be maintained at 9.8 and 3.25 Mb/s, respectively. For the WiMAX-ROF link, the data traffic must to be finished within the gap time, including the signal processing time, converting time and transmitting time.

By using the commercial BS and MS, the emitted RF power by the MS is automatically controlled by the BS. The automatic power control in the MS is to extend the life of battery in the MS. Therefore, Fig. 10 would obtain the irregular change when the fiber transmission was in different distance. In the experiment, when the attenuation between the BS and MS is decreased, the BS detects a higher power from the MS. Then it will order the MS to reduce the emitted RF power. Because of this, the throughput decreases when the attenuation decrease. The above results illustrate that the maximum RoF link is not more than 9 km SMF transmission based on the present WiMAX standard. This implies that if the total length of the WiMAX-RoF is 8 km, the distance between the MS and the RAU should be very close, otherwise synchronization cannot be achieved between the BS and MS due to the TDD mode access.

In WiMAX RoF system, the fiber transmission would induce a 40 μs delay in an 8 km fiber length by one way. Besides, the signal conversion and TDD switching in HE and RAU modules also need processing time to transmit RF signal. Thus, as mentioned before, the WiMAX-RoF system could result in the fiber transmission distance in 8 km long. This also implies that there is a trade-off in distances between the RAU-BS (fiber) and RAU-MS (air). As the target of WiMAX is to provide wireless connections between ANT and MS within 5 km cell coverage, the present WiMAX protocol developed for wireless connection can have limitation when applied to the WiMAX RoF system. Because of this, TDD framing protocol should be modified or frequency division duplex (FDD) should be used in order to make the full use of the benefits offered by RoF and WiMAX systems.

As mentioned above, we know that the WiMAX-RoF system can extend the cell coverage to 8 km in both right-side and left-side using single WiMAX BS in HSR, as shown in Fig. 11. Hence, the total extend coverage can reach 16 km long by RoF connection.

Next, we will experiment and analyze the WiMAX signal in a tunnel of the THSR. Fig. 12 shows the experimental configuration for the SongShan tunnel testing in the THSR. The WiMAX signal from the BS was split to two independent HE-RAU RoF links. The differential distance between RAU_1 and RAU_2 was approximately 1.6 km. And the fiber length of HE-RAU_1 and HE-RAU_2 is 2 km long. The BS is placed at 1864.4 m (our internal reference location) connecting a HE and the two RAUs. RAU_1 and RAU_2 are located at 1864.4 and 3327.6 m respectively. For the railway RoF architecture, a triangle power distribution was setup using directional antennas transmitting in the same direction along the track, as seen in Fig. 12. A MS was put on a test vehicle and moved slowly at 15 km/hr along the length of the track, as seen in Fig. 12. Based on the calculation described in Section II, we can estimate the maximum speed of the test vehicle is $\sim$110 km/hr at 2.5 GHz frequency band without Doppler effect. The receive signal strength indicator (RSSI) and throughput measurements were performed in static conditions at various positions along the track of SongShan tunnel. Here, Fig. 13 shows the RSSI performances along the track of SongShan Tunnel without and with RoF link. When a BS locates at the position of 1864.4 m without RoF link, the RSSI only can be observed within 2400 m due to the larger curved way in the tunnel. While the two RAUs are used in this measurement, the RSSI can be obtained in the positions between 1900 and 3300 m.

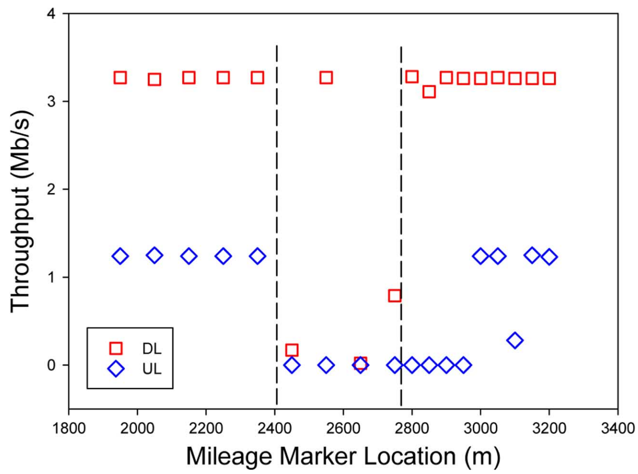

Fig. 14. Throughput measurement in downlink and uplink traffic along the track of SongShan Tunnel.

Thus, the RoF link not only can extend the RF coverage, but also can solve the curved way in tunnel. Besides, Fig. 14 also shows the related throughputs of downlink and uplink traffic around 3.3 and 1.2 Mb/s, respectively, using RoF technology with two RAUs in the same measuring track. As illustrated in Fig. 14, between 2400 and 2700 m, we retrieve the worst throughputs due to the curved environment of tunnel.

V. Conclusion

In summary, the performance of WiMAX-RoF has been characterized and analyzed, showing that the RoF transmission in the TDD framing in the connection using standard WiMAX signal. According to the WiMAX-RoF link, the RF coverage could be extended using a single BS over HSR. The performances of throughput and packet loss at different fiber link lengths have been also investigated and analyzed. Thus, the use of WiMAX-RoF may be expected to eliminate handovers. A WiMAX-RoF field trial using a simple architecture of two RAUs in RoF link was setup and performed in the SongShan tunnel in THSR. Additional static and fast moving trials are planned to further analyze and characterize the performance of the WiMAX-RoF link. In the future, we will plan and culminate with a field trial on the commercial THSR in 300 km/hr moving speed based on standard WiMAX.

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References

[1] S. Lee and M. Kang, “Optical switching based on position-tracking algorithm to realize moving cells in RoF network,” in *Proc. ICACT’08*, 2008, vol. 3, pp. 2170–2173.

[2] J. Song, X. Li, and Z. Zhong, “A multi-service bit and power allocation in WiMAX networks,” in *Proc. ICCSN’09*, 2009, pp. 395–398.

[3] L. Yu, X. Huang, F. You, and W. Zhang, “MSTG: A multi-service traffic generator for testing next generation wireless broadband communication systems,” in *Proc. NWSCTC’09*, 2009, vol. 1, pp. 580–583.

[4] R. Chaparadza, “A composition language for programmable traffic flow monitoring in multi-service self-managing networks,” in *Proc. DRCN’07*, 2007, pp. 1–8.

[5] F. A. Cruz-Perez, J. L. Vazquez-Avila, and L. Ortigoza-Guerrero, “Recurrent formulas for the multiple fractional channel reservation strategy in multi-service mobile cellular networks,” *IEEE Commun. Lett.*, vol. 8, no. 10, pp. 629–631, Oct. 2004.

[6] Y. Chung, M. H. Park, and E. H. Paik, “A QoS negotiable service framework for multimedia services connected through subscriber networks,” in *Proc. ISCE’06*, 2006, pp. 1–4.

[7] Y. Ito and S. Tasaka, “QRPp1-1: User-level QoS assessment of a multipoint-to-multipoint TV conferencing application over IP networks,” in *Proc. IEEE GLOBECOM’06*, 2006, pp. 1–6.

[8] X. Li, E. Chuah, J. Y. Tham, and K. H. Goh, “An optimal smooth QoS adaptation strategy for QoS differentiated scalable media streaming,” in *Proc. IEEE Int. Conf. Multimedia Expo’08*, 2008, pp. 429–432.

[9] H. T. Lin, Y. Y. Lin, W. R. Chang, and R. S. Cheng, “An integrated WiMAX/WiFi architecture with QoS consistency over broadband wireless networks,” in *Proc. IEEE CCNC’06*, 2009, pp. 1–7.

[10] R. Giuliano and F. Mazzenga, “On the coexistence of power-controlled ultrawide-band systems with UMTS, GPS, DCS1800, and fixed wireless systems,” *IEEE Trans. Veh. Technol.*, vol. 54, no. 1, pp. 62–81, Jan. 2005.

[11] D. Niyato and E. Hossain, “Wireless broadband access: WiMAX and beyond—Integration of WiMAX and WiFi: Optimal pricing for bandwidth sharing,” *IEEE Commun. Mag.*, vol. 45, no. 5, pp. 140–465, May 2007.

[12] A. Ansari, S. Dutta, and M. Tseytlin, “S-WiMAX: Adaptation of IEEE 802.16e for mobile satellite services-[WiMAX update],” *IEEE Commun. Mag.*, vol. 47, no. 6, pp. 150–155, Jun. 2009.

[13] M. N. Khan and S. Ghauri, “The WiMAX 802.16e physical layer model,” in *Proc. IET Int. Conf. Wireless, Mobile Multimedia Networks’08*, 2008, pp. 117–120.

[14] J. Irvine, D. Robertson, and J. Dunlop, “The MOSTRAIN (mobile services for high speed trains) system demonstrator,” in *Proc. IEEE Int. Symp. Pers. Indoor Mobile Radio Commun.*, 1998, vol. 2, no. 8–11, pp. 1004–1008.

[15] F. D. Greve, B. Lannoo, L. Peters, T. V. Leeuwen, F. V. Quickenborne, D. Colle, F. D. Turck, I. Moerman, M. Pickavet, B. Dhoedt, and P. Demeester, “FAMOUS: A network architecture for delivering multimedia services to fast moving users,” *Wireless Pers. Commun.*, vol. 33, pp. 281–304, 2005.

[16] B. Lannoo, D. Colle, M. Pickavet, and P. Demeester, “Radio-over-fiber-based solution to provide broadband internet access to train passengers,” *IEEE Commun. Mag.*, vol. 45, no. 2, pp. 56–62, Feb. 2007.

[17] P. Cent, G. E. Bottomley, and T. Croft, “Jakes fading model revisited,” *Electron. Lett.*, vol. 29, pp. 1162–1163, 1993.

[18] B. Sklar, “Rayleigh fading channels in mobile digital communication systems,” *IEEE Commun. Mag.*, vol. 35, no. 7, pp. 102–109, Jul. 1997.

[19] Q. A. Zeng and D. P. Agrawal, “Modeling and efficient handling of handoffs in integrated wireless mobile networks,” *IEEE Trans. Veh. Technol.*, vol. 51, pp. 1469–1478, 2002.

[20] *Draft IEEE Standard for Local and Metropolitan Area Networks, Part 16: Air Interface for Fixed and Mobile Broadband Wireless Access Systems*, IEEE Std 802.16e/D12.

[21] R. Alemany, J. Perez, R. Llorente, V. Polo, and J. Marti, “Coexistence of WiMAX 802.16d and MB-OFDM UWB in radio over multi-mode fiber indoor systems,” in *Proc. MWP/APMP’08*, 2008, pp. 74–77.

[22] M. Usami, “Strategy for KDDI’s next generation network,” in *Proc. ICTON’08*, 2008, vol. 2, pp. 182–189.

[23] A. J. Seeds, “Radio over fiber systems,” in *Proc. LEOS’08*, 2008, pp. 848–849.

[24] J. Yu, Z. Jia, T. Wang, and G. K. Chang, “A novel radio-over-fiber configuration using optical phase modulator to generate an optical mm-wave and centralized lightwave for uplink connection,” *IEEE Photon. Technol. Lett.*, vol. 19, no. 3, pp. 140–142, Feb. 2007.

[25] M. Sauer, A. Kobyakov, and J. George, “Radio over fiber for picocellular network architectures,” *J. Lightw. Technol.*, vol. 25, no. 11, pp. 3301–3320, Nov. 2007.

[26] H. Kim, J. H. Cho, S. Kim, K. U. Song, H. Lee, J. Lee, B. Kim, Y. Oh, J. Lee, and S. Hwang, "Radio-over-fiber system for TDD-based OFDMA wireless communication systems," *J. Lightw. Technol.*, vol. 25, no. 11, pp. 3419–3427, Nov. 2007.

[27] J. Yu, M. F. Huang, Z. Jia, T. Wang, and G. K. Chang, "A novel scheme to generate single-sideband millimeter-wave signals by using low-frequency local oscillator signal," *IEEE Photon. Technol. Lett.*, vol. 20, no. 7, pp. 478–480, Apr. 2008.

[28] J. G. Andrews, A. Ghosh, and R. Muhamed*, Fundamentals of WiMAX*. Englewood Cliffs, NJ: Prentice-Hall, 2007.

[29] M. Presi, K. Prince, A. Chiuchiarelli, I. Cerutti, G. Contestabile, I. T. Monroy, and E. Ciaramella, "Adaptive system for OFDMA WiMAX radio-over-fiber links using a directly modulated R-SOA and optical filtering," in *Proc. OFC'09*, 2009, Paper JWA74.

[30] G. Dutta, D. , and Das, "Performance study of an optical backbone MAC interconnecting WiMAX base stations over a city/county area," in *Proc. WOCC'08*, 2008, pp. 1–6.

[31] K. Nishimori, K. Y. Cho, Y. Takatori, and T. Hori, "Automatic calibration method using transmitting signals of an adaptive array for TDD systems," *IEEE Trans. Veh. Technol.*, vol. 50, no. 6, pp. 1636–1640, Nov. 2001.

[32] J. P. R. Pereira, "A cost model for broadband access networks: FTTx versus WiMAX," in *Proc. 2nd Int. Conf. Access Networks Workshops*, 2007, pp. 1–8.

[33] T.-R. Banniza, K. Wunstel, and R. Klotsche, "Doppler Effect Compensation for Radio Transmission," 2007, EP 1806854 A1.

[34] in *Mobile Radio Conference Tests Amendment: Wave 2 Tests*, Jul. 2007, WiMAX Forum.

[35] A. A. Hutter, J. S. Hammerschmidt, and E. de Carvalho, "Effects of fading correlation on multiple antenna reception mobile OFDM systems," in *Proc. VTC Fall 2000*, 2000, vol. 6, pp. 2744–2749.

[36] C. H. Yeh, C. W. Chow, C. H. Wang, F. Y. Shih, Y. F. Wu, Y. L. Liu, and S. Chi, "Understanding standard OFDM WiMAX signal access in radio over fiber system," *Progr. Electromagn. Res. C*, vol. 10, pp. 201–214, 2009.

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