

On the Coexistence among WiMAX-TDD, TD-LTE, and TD-SCDMA

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Abstract

With several advantages such as flexible downlink-to-uplink(DL-to-UL) ratio and flexible spectrum usage, Time Division Duplexing(TDD) is emerging as an alternate to Frequency Division Duplexing(FDD), especially in wireless broadband systems. We already have at least four different TDD systems in the industry: Time Division-Synchronous Code Division Multiple Access(TD-SCDMA), IEEE 802.16e-TDD, IEEE 802.16m-TDD, and Time Division-Long Term Evolution(TD-LTE). A disadvantage of TDD is that tight coordination such as time synchronization between adjacent operators is required to prevent interference between the adjacent TDD systems. In this paper, we investigate coexistence scenarios among the above four well-known TDD systems and calculate spectral efficiency(SE) loss in each scenario. Our findings are that SE loss can be significant if TDD ratios of the adjacent operators are considerably different. However, as long as the TDD ratios of the adjacent operators are similar, configurations in the systems permit perfect time synchronization between the two heterogeneous TDD systems, and the resulting SE loss is zero or reasonably low. We believe that the above findings and the configurations of the TDD systems recommended to minimize SE loss will be helpful for operators who deploy TDD systems in system parameter determination and cross-operator coordination.

Key words : TDD, WiMAX, TD-LTE, TD-SCDMA, Coexistence.

1. Introduction

FDD has been used as a duplexing scheme for the majority of cellular communication systems including IS-95, cdma2000, wideband code division multiple access (WCDMA), high speed downlink packet access(HSDPA), high speed uplink packet access(HSUPA), and LTE-FDD. The only TDD-based system that has been meaningful footprint in the industry is TD-SCDMA.

Compared with FDD, TDD has several advantages such as flexible DL-to-UL ratio(i.e., TDD ratio), simpler implementation of "smart" antenna techniques, and cheaper transceiver implementation. Consequently, TDD has emerged as another duplexing scheme, especially for wireless broadband systems such as IEEE 802.16e, IEEE 802.16m, and TD-LTE.

A disadvantage of TDD is that TDD system performance is significantly degraded when DL and UL signals overlap in time. Therefore, TDD first of all requires time synchronization throughout the network within one operator to prevent performance degradation by this overlap. In addition, TDD requires a large guard band(GB) between the adjacent TDD operators and/or a high level of coordination between the adjacent TDD operators. Coordination to reduce interference between adjacent operators can be accomplished in several ways such as time

synchronization, general radio network engineering, transmit power reduction, and tighter filtering. Among them, time synchronization can be an effective coordination method to reduce interference between adjacent operators^[10].

Time synchronization between the same TDD systems (e.g., time synchronization between two adjacent IEEE 802.16e systems) is rather easy. However, if two different TDD systems are used in the adjacent spectrum, it can be more difficult to ensure time synchronization since the system parameters of the two different systems may not necessarily be the same.

There have been several studies on interference between DL and UL in TDD systems. Holma *et al.* evaluated interference between DL and UL in TDD mode of UMTS terrestrial radio access(UTRA). They also evaluated the synchronization and coordination requirements of UTRA TDD^[1]. In simulation results, Junsong *et al.* showed that the performance of dynamic TDD is unacceptable due to interference on UL in a cell caused by DL transmissions of other cells when omni-directional antennas are used at BS^[2]. Chih-He *et al.* studied the determination of DL-to-UL ratio for TDD-based IEEE 802.16e systems and proposed a scheme that adjusts DL-to-UL ratio according to the current traffic profile, wireless interference, and transport layer parameters in order to maximize the aggregate throughput of TCP

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based traffic^[3]. The following are recent studies on inter-system interference and coexistence scenarios between the different TDD systems in the adjacent spectrum. The article in [4] overviewed the coexistence studies performed in the 3rd generation partnership project(3GPP) radio access network(RAN) Working Group 4 for LTE with other mobile systems, but no specific analysis between the specific TDD systems such as TD-LTE and IEEE 802.16e-TDD was given. Yihong *et al.* analyzed coexisting interference between TD-SCDMA and WiMAX systems by system simulation^[5]. Hui Jia *et al.* presented performance loss when LTE-TDD system is deployed co-existed with TD-SCDMA system with the assumption that two systems have the similar DL-to-UL ratio^[6], and Pei Chang *et al.* investigated mutual interference between TD-SCDMA system and TD-LTE system with the minimum coupling loss(MCL) method to analyze isolation requirements^[7]. However, most results so far were obtained by simulations, and the coexistence analysis based on the specific system parameters of the different TDD systems was not fully investigated. Moreover, neither coordination among the different TDD systems to achieve time synchronization nor the impact on the SE of these systems has been discussed intensively. It should be noted that two different definitions are used for SE loss in this paper: 1) soft SE loss, which is obtained from system level simulation(SLS) and is the definition used in Section III; and 2) hard SE loss, which is calculated from system parameter analysis and is the definition used in Section V.

TDD is gaining ground, and there are already at least four different TDD systems in the industry: TD-SCDMA, IEEE 802.16e-TDD, IEEE 802.16m-TDD, and TD-LTE, which means that there is a strong possibility of having the different TDD systems in the adjacent spectrum in the future. Therefore, it is very important to investigate possible interference between the adjacent TDD systems with the specific system parameters of the above four TDD systems and to analyze the anticipated impact of coordination to achieve coexistence.

This paper is organized as follows. First, the advantageous features of TDD system are explained in detail in Section II. Secondly, the time synchronization requirement, which is one of the disadvantageous features of the TDD system, is explained in Section III. We overview the four famous TDD systems(IEEE 802.16e-TDD, IEEE 802.16m-TDD, TD-LTE, and TD-SCDMA) focusing on their frame and/or subframe structures and TDD ratios in Section IV. In Section V, the coexistence scenarios among these four TDD systems are analyzed together with their associated TDD ratios and anticipated SE loss. Finally, we conclude the paper in Section VI.

II. TDD Systems Advantages

Traditional mobile radio systems were built primarily for voice applications which are symmetric in nature. However, today's broadband internet applications are generally asymmetric, so it is very difficult to predict how this characteristic will change over time with applications such as digital broadcasting and multicasting which require even higher usage on the DL, and voice over IP(VoIP) which results in more symmetric usage. Therefore, we need a duplexing technology that can accommodate unpredictable changes in future usage models for wireless broadband access. In TDD systems, the ratio of bandwidth(BW) dedicated to DL and UL can be adjusted based on actual traffic demand. The flexibility of TDD systems can lead to a more efficient use in a valuable spectrum.

Smart antenna techniques can provide better SE and coverage in cellular deployments. TDD systems enable the simpler implementation and operation of smart antenna techniques with the reciprocal feature of DL and UL channels. While FDD systems would generally require fairly accurate channel feedback from mobile stations(MS) to the BS for DL spatial processing, BSs in TDD systems can get DL channel characteristics based on UL channel estimation thanks to channel reciprocity as long as DL and UL paths are well calibrated.

TDD is also generally more flexible for deployment because it does not require a paired spectrum. Therefore, technically it is feasible to deploy TDD systems even in FDD spectrum allocations. In addition, while there should always be a duplexing gap between DL and UL in FDD systems, TDD does not require a duplexing gap.

Other advantages of TDD systems include lower costs of hardware both on the MS and the BS. TDD systems avoid the need for expensive duplexers(or diplexers) and require less RF front-end customization for operating in different bands and different regulatory requirements. Fig. 1 shows a typical FDD radio solution and Fig. 2 shows a typical TDD radio solution, respectively. As shown in Fig. 1 and Fig. 2, significantly fewer components are used in the TDD radio solution.

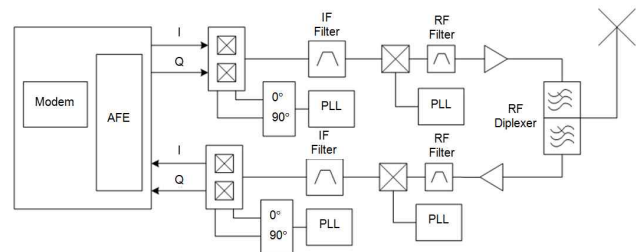


Fig. 1. Typical FDD radio solution.

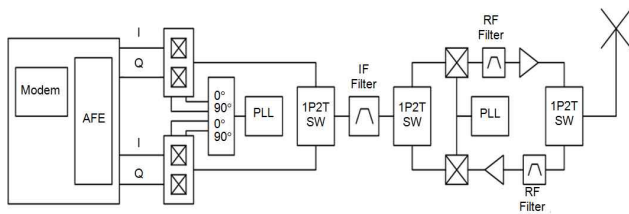


Fig. 2. Typical TDD radio solution.

III. Time Synchronization Requirement in TDD Systems

A disadvantage is that TDD system performance is significantly degraded when DL and UL signals overlap in time. Time synchronization is required across BSs within an operator to prevent performance degradation by this overlap. In other words, the DL/UL frame boundaries across TDD networks should be synchronized in order to ensure an acceptable level of co-channel interference. This synchronization means that all BSs frame start timings should be synchronized—through a global positioning system(GPS), for example. The ratio of DL and UL cannot be dynamically changed per cell but should be changed on a system-wide basis.

This requirement sometimes can be extended to adjacent channel interference(ACI) and inter-operator scenarios. Fig. 3 shows a situation in which different TDD ratios (also known as DL-to-UL ratio) are used in two channels that are adjacent to each other in frequency domain. As Fig. 3 shows, DL is interfered by the adjacent DL for the duration from t_0 to t_1 , and UL is interfered by the adjacent UL for the duration from t_2 to t_3 , which is a normal ACI scenario. However, due to the asynchronism between the two channels, UL is interfered by the adjacent DL and DL is interfered by the adjacent UL for the duration from t_1 to t_2 . Given the fact that the transmit power of BS is generally much higher than that of MS, the UL of Ch-1 can be significantly interfered by the DL of Ch-2 in this particular example.

In general, there are three ways to mitigate interference¹⁾: 1) Use the same TDD ratio in adjacent channels to fundamentally prevent interference situations from happening; 2) Use sharp filters at the transmitter side and/or at the receiver side to enhance adjacent channel leakage ratio(ACLR) performance and adjacent channel selectivity (ACS) performance, respectively; 3) Use a GB between two adjacent channels to reduce interference.

Usually, sharp filters are not sufficient to ensure an

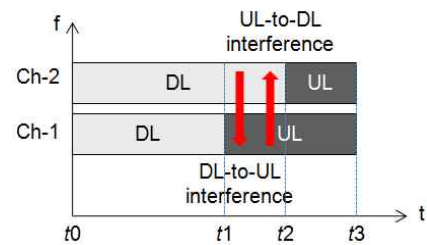


Fig. 3. Example situation in which different TDD ratios are used in two adjacent channels.

acceptable interference level if we limit the cost of the filters to the practically reasonable level in number two above. In this case, we may need to reduce DL transmit power to reduce interference, which is not desirable from a link-budget perspective. Furthermore, in general the amount of required GB in asynchronous TDD systems is unacceptably large.

Table 1 shows the required GB size between two adjacent WiMAX IEEE 802.16e-TDD systems. The results are based on the following assumptions.

- The frames of both systems start at the same time.
- If they are synchronized, both systems have the same DL-to-UL ratio(TDD ratio).
- If they are not synchronized, one system's DL-to-UL ratio is 35:12 and the other's is 26:21, which is the worst case scenario according to Table 2 in Section IV.1.
- Path-loss models are the same as those in ITU-R M.2113.
- Assuming the worst case, there is no power control in WiMAX.
- The filter characteristics at BS and MS are based on Annex. 6. IMT-2000 orthogonal frequency division multiple access(OFDMA) TDD wireless metropolitan area network(WMAN) of ITU-R M.1580-2 and ITU-R M.1581-2, respectively^{[8],[9]}.
- Co-location of two systems with MCL of 50 dB is considered to be the worst case scenario²⁾.
- A frequency reuse factor(FRF) of 1 was used in 19 cells with 3 sectors per each cell.
- The distance between two BSs is 1,500 m.
- The frequency band is 2.5 GHz and channel BW of IEEE 802.16e-TDD systems is 10 MHz.
- The active MSs per sector is 10, and they are uniformly distributed in the cell.
- Lognormals with 8 dB standard deviation for BS-MS and 4 dB for MS-MS are assumed for shadow fading.

1) There can be more ways to reduce interference other than the ones described here. Also, the combination of the three ways mentioned here can be used to reduce interference.

2) ITU-R M.2045 states that MCL of 70 dB is achievable by careful site engineering.

- Typical BS parameters are used: 36 dBm Tx power, 18 dBi antenna gain, 30 m antenna height, and 3 dB noise figure(NF).
- Typical MS parameters are used: 20 dBm Tx power, 0 dBi antenna gain, 1.5 m antenna height, and 5 dB NF.
- Both co-channel interference(CCI) from the desired system and ACI from the interfering system are considered in calculating signal-to-interference and noise ratio(SINR).
- The amount of required GB is obtained as the points where the victim system's SE loss is less than 5 % and 10 %, respectively.

As briefly mentioned in Section I, SE loss here is obtained from SLS based on the simulation assumptions described above. Therefore, the required GB size in Table 1 means that the victim system's capacity will be reduced further below 95 % or below 90 % compared with its original capacity if the GB size assigned between the adjacent systems is less than the minimum required size. It is important to see that a very big GB that is more than 10 MHz is still required even though we compromise 10 % SE loss in the victim system.

Please note that GB requirements in Table 1 do not take into account any other interference mitigation techniques such as tighter TX/RX filters for BS and MS, additional RF filtering for BS, or site engineering in the BS to BS case. If other interference mitigation techniques are used, the required GB size can be reduced. However, the results in Table 1 show that time synchronization is one of the most efficient coordination schemes to reduce interference between the adjacent systems.

Similar results can be found in [10], and it is entirely possible for time synchronized TDD systems to operate satisfactorily in adjacent frequency blocks with zero guard frequency.

Therefore, it is desirable to have the same TDD ratio on a system-wide basis across adjacent channels as well as in co-channel. However, it is true that this require-

ment forces different operators to use the same TDD ratio if the adjacent channels are owned by the different operators. This requirement may limit operators' flexibility in their respective business models.

Fig. 4 shows different interference cases per operator business models assuming all operators are using IEEE 802.16e systems. Fig. 4(a) is a case where two adjacent operators provide generic internet access services but use slightly different TDD ratios. Fig. 4(b) is a case where one operator provides generic internet access service while the adjacent operator provides VoIP service, which leads to a significantly different TDD ratio from the one used for the internet service. Finally, Fig. 4(c) is a case where one operator provides generic internet access service while the adjacent operators provide multicast broadcast service (MBS), which also leads to a significantly different TDD ratio from the one for the internet service. The amount of interference in these three cases varies significantly as shown in Fig. 4.

IV. TDD Ratios of Cellular Communication Systems

The following section reviews several TDD-based cellular communication systems and summarizes TDD ratios.

4-1 WiMAX IEEE 802.16e-TDD

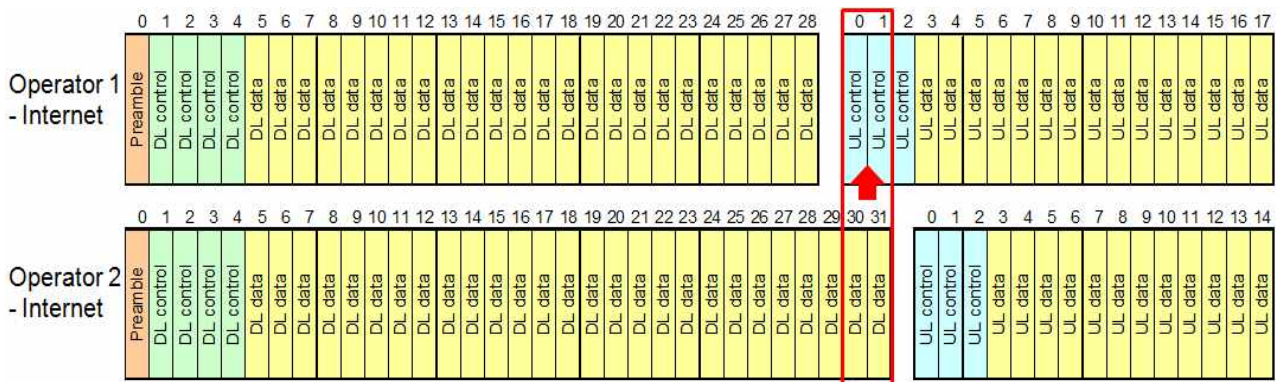
The TDD frame duration of IEEE 802.16e is 5 ms. Each frame in DL transmission begins with a preamble followed by a DL transmission period and a UL transmission period. In each frame, the transmit-to-receive time gap(TTG) shall be inserted between DL and UL, and the receive-to-transmit time gap(RTG) shall be inserted between the UL and DL at the end of each frame, respectively, to allow BS to turn around^{[11],[12]}.

The duration of the cyclic prefix(CP) is 1/8 Tb in IEEE 802.16e. By excluding the switching times(TTG and RTG), there are 47 OFDM symbols per 5 ms frame for 5 and 10 MHz BW and 42 OFDM symbols per 5 ms frame for 8.75 MHz BW³⁾. The number of different

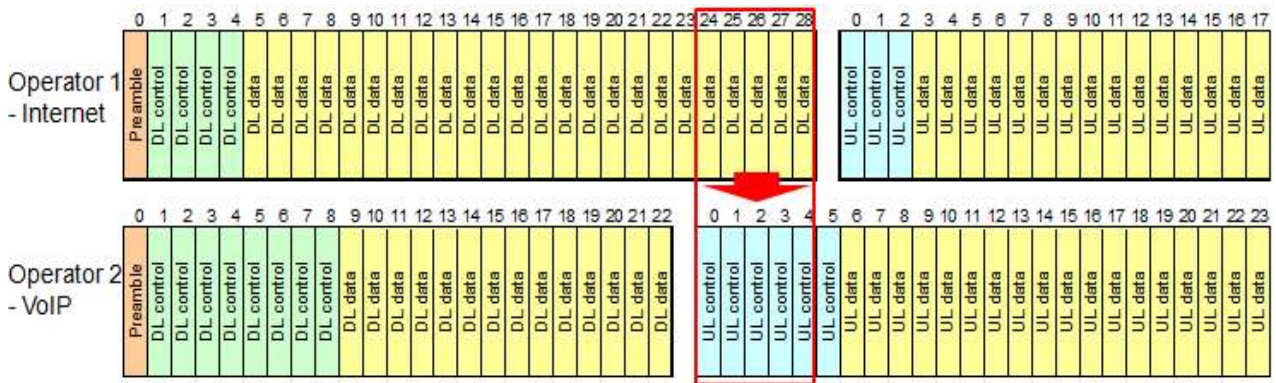
Table 1. Required GB size in time synchronized and non-synchronized adjacent 802.16e systems.

	Interference path	GB required to limit SE loss of victim system by 5 %	GB required to limit SE loss of victim system by 10 %
Time synchronized	BS to MS	0	0
	MS to BS	0	0
Time non-synchronized	MS to MS	4 MHz	0
	BS to BS	>10 MHz	>10 MHz

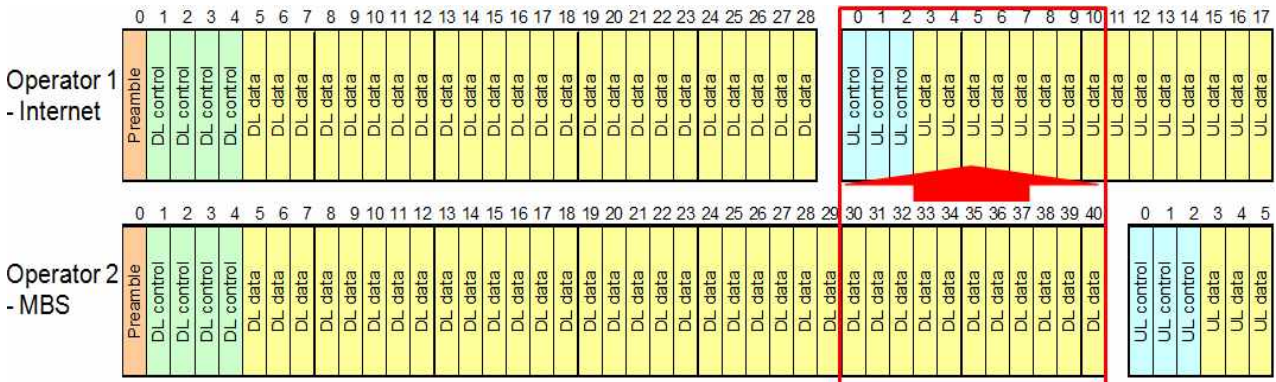
3) For 5 and 10 MHz BW, TTG duration is 105.71 μ s, RTG duration is 60 μ s, and OFDM symbol duration is 102.86 μ s, respectively. For 8.75 MHz BW, TTG duration is 87.2 μ s, RTG duration is 74.4 μ s, and OFDM symbol duration is 115.2 μ s, respectively.



(a) Case where two adjacent operators provide generic internet access services with slightly different TDD ratios



(b) Case where one operator provides generic internet access service while the adjacent operator provides VoIP service



(c) Case where one operator provides generic internet access service while the adjacent operators provide MBS

Fig. 4. Examples of inter-operator TDD interference cases in IEEE 802.16e.

TDD ratios defined by WiMAX Forum is shown in Table 2^[15]. For example, if we use (29, 18) TDD ratio for the 10 MHz WiMAX system, the first 2.98 ms(=29×102.86 μs) of a frame is used for DL transmission followed by TTG with 105.71 μs duration, UL transmission with 1.85 ms(=18×102.86 μs) duration, and RTG with 60 μs duration.

4-2 WiMAX IEEE 802.16m-TDD

In TDD mode of IEEE 802.16m, a 5 ms frame is divided into 8 subframes together with TTG and RTG. One

Table 2. Number of OFDM symbols for DL and UL in IEEE 802.16e-TDD.

	Values (DL, UL)
Number of OFDM symbols in DL and UL for 5 and 10 MHz BW	(35,12), (34,13), (33,14), (32,15), (31,16), (30,17), (29,18), (28,19), (27,20), (26,21)
Number of OFDM symbols in DL and UL for 8.75 MHz BW	(30,12), (29,13), (28,14), (27,15), (26,16), (25,17), (24,18)

subframe can be comprised of either 5, 6, 7, or 9 OFDM symbols depending on the advanced air interface(AAI)

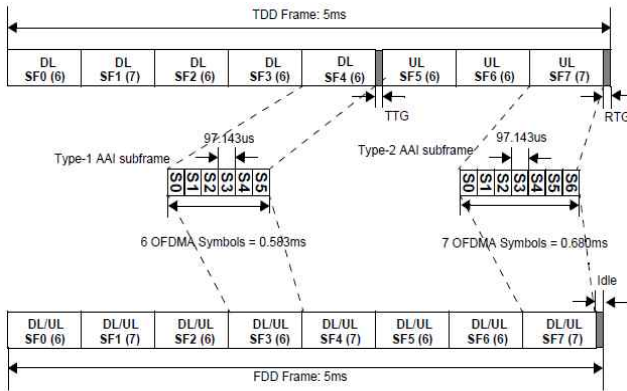


Fig. 5. IEEE 802.16m TDD frame structure for 5, 10, and 20 MHz channel BWs(CP=1/16 Tb).

subframe types. In a TDD frame with DL-to-UL ratio of D:U, the first contiguous D AAI subframes and the remaining U AAI subframes are assigned for DL and UL, respectively, where D+U=8 for 5, 10 and 20 MHz channel BWs, and D+U=7 for 8.75 MHz channel BW. The ratio of D:U shall be selected from one of the following values: 8:0, 6:2, 5:3, 4:4, or 3:5 for 5, 10 and 20 MHz channel BWs, and 5:2, 4:3, or 3:4 for 8.75 MHz channel BW. Fig. 5 illustrates an example TDD frame structure for 5, 10, and 20 MHz channel BWs with a CP of 1/16 Tb. Assuming OFDMA symbol duration of 97.143 μ s and a CP length of 1/16 Tb, the length of type-1 and type-2 AAI subframes are 0.583 ms and 0.680 ms, respectively. TTG and RTG are 82.853 μ s and 60 μ s, respectively^[13].

4-3 3GPP TD-LTE

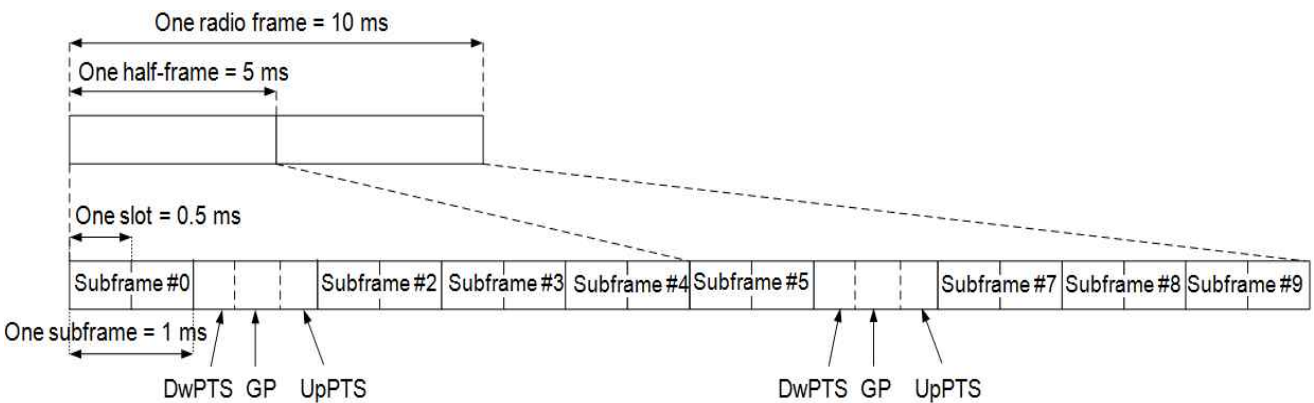


Fig. 6. LTE frame structure type 2(for 5 ms switch-point periodicity).

Frame structure type 2 of LTE, which is shown in Fig. 6, is applicable to TD-LTE^[16]. One radio frame has 10 ms duration and is comprised of 10 subframes.

There are 7 different DL-UL configurations defined in LTE as shown in Table 3⁴⁾. In addition, the durations of downlink pilot time slot(DwPTS), guard period(GP), and uplink pilot time slot(UpPTS) in a special subframe are configurable as shown in Table 4. For example, if we use DL-UL configuration 2 in Table 3 and special subframe configuration 2 in Table 4, DL transmission continues for 3.71 ms followed by GP with 214.06 μ s duration and UL transmission with 1.07 ms duration in each 5 ms time period.

4-4 3GPP TD-SCDMA

3GPP UTRA TDD low chip rate(LCR), which is operated with 1.28 Mcps in 1.6 MHz BW, is known as TD-SCDMA in the industry. One frame has 10 ms duration and is divided into 2 subframes of 5 ms duration. The frame structure for each subframe in a 10 ms frame length is the same. Fig. 7 shows the structure of 5 ms subframe, which is comprised of 7 time slots, DwPTS, GP, and UpPTS⁵⁾. The number of time slots used for DL and UL, respectively, is configurable with the constraint that the first time slot is always allocated to DL and the second time slot(the slot right after UpPTS) is always allocated to UL. For example, if we use 4 time slots(time slot #4, #5, #6, and #0) for DL and 3 time slots(time slot #1, #2, and #3) for UL as shown in Fig. 7, DL transmission(4 time slots plus DwPTS) continues for 2.78 ms followed by GP with 75 μ s duration and

4) In Table 3, D denotes DL subframe, U denotes UL subframe, and S denotes special subframe where the DL-UL switch takes place.
 5) Single slot duration is 675 μ s, DwPTS duration is 75 μ s, GP duration is 75 μ s, and UpPTS duration is 125 μ s, respectively.

Table 3. DL-UL configurations of TD-LTE.

DL-UL configuration	DL-UL switch-point periodicity	Subframe number									
		0	1	2	3	4	5	6	7	8	9
0	5 ms	D	S	U	U	U	D	S	U	U	U
1	5 ms	D	S	U	U	D	D	S	U	U	D
2	5 ms	D	S	U	D	D	D	S	U	D	D
3	10 ms	D	S	U	U	U	D	D	D	D	D
4	10 ms	D	S	U	U	D	D	D	D	D	D
5	10 ms	D	S	U	D	D	D	D	D	D	D
6	5 ms	D	S	U	U	U	D	S	U	U	D

Table 4. Configuration of special subframe(lengths of DwPTS/GP/UpPTS) of TD-LTE with normal cyclic in both DL and UL⁶⁾.

Special subframe configuration	DwPTS [μ s]	GP [μ s]	UpPTS [μ s]
0	213.93	714.71	71.35
1	643.23	285.42	71.35
2	714.58	214.06	71.35
3	785.94	142.71	71.35
4	857.29	71.35	71.35
5	214.58	642.71	142.71
6	643.23	214.06	142.71
7	714.58	142.71	142.71
8	785.94	71.35	142.71

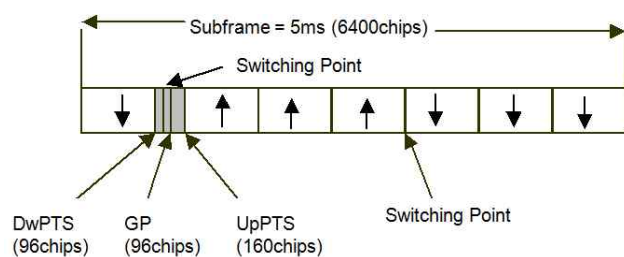


Fig. 7. Structure of the subframe for 1.28 Mcps TDD option in UTRA.

UL transmission(UpPTS plus 3 time slots) with 2.15 ms duration^[17].

V. Coexistence

6) Please note that the durations of DwPTS, GP, and UpPTS are different with different cyclic prefix length. The full table is available in [16].

5-1 Between WiMAX IEEE 802.16e-TDD and 3GPP TD-SCDMA

As we saw in Section 4-1 and 4-4, respectively, it is unfortunately impossible to make IEEE 802.16e and TD-SCDMA perfectly aligned in time domain in terms of DL transmission and UL transmission timing. However, it is true that the closer the timing alignment between the two systems is, the less interference is expected. In that regard, Table 5 illustrates the closest possible TDD ratios of IEEE 802.16e referenced to 6 possible TDD ratios of TD-SCDMA and anticipated SE loss to achieve time synchronization.

In Case 1.1, TD-SCDMA puts most of the resource to DL(6 out of 7 time slots). There is no such configuration defined in WiMAX Forum Release 1.0 system profile as presented in Table 2, and the closest TDD ratio to 6:1 in TD-SCDMA is (35,12) in IEEE 802.16e-TDD. With these configurations, there can be significant interference from TD-SCDMA DL to 802.16e UL since TD-SCDMA DL duration ends at 4.13 ms while 802.16e UL starts at 3.71 ms, i.e., the initial 0.42 ms(=4.13-3.71) duration of 802.16e UL are interfered by TD-SCDMA DL when the DL duration start timing of the two systems are aligned. In order to achieve perfect time synchronization, the last time slot of TD-SCDMA DL should not be used, which results in SE loss of 14 % (=1/7) in the system.

As briefly mentioned in Section I, SE loss throughout this Section V is *hard* SE loss, which is calculated based on system parameter analysis while SE loss in Section III was obtained from SLS. Based on the standards, most WiMAX systems put UL control channels such as channel quality indicator channel(CQICH), HARQ acknow-

Table 5. Time synchronization results between IEEE 802.16e-TDD and TD-SCDMA.

Case	TD-SCDMA			IEEE 802.16e-TDD			Anticipated SE loss	
	TDD ratio	DL end timing [ms]	UL start timing [ms]	TDD ratio	DL end timing [ms]	UL start timing [ms]	TD-SCDMA	16e-TDD
1.1	6:1	4.13	4.20	(35,12)	3.60	3.71	14 %	0 %
1.2	5:2	3.45	3.53	(33,14)	3.39	3.50	0 %	0, 2, 4 %
1.3	4:3	2.78	2.85	(27,20)	2.78	2.88	0 %	0, 2, 4 %
1.4	3:4	2.10	2.18	(26,21)	2.67	2.78	0 %	11 %
1.5	2:5	1.43	1.50	(26,21)	2.67	2.78	0 %	26 %
1.6	1:6	0.75	0.83	(26,21)	2.67	2.78	0 %	38 %

ledgement channel(ACKCH), and ranging channel in the first part of its UL transmission period. Performance degradation is much more significant when control channels are disrupted by interference compared to the case where data channels are disrupted by interference. Given the fact that, if there is no time synchronization, an unreasonably big GB is still required even with 10 % capacity loss(i.e., 10 % soft SE loss) in SLS for data channels in Section III, it is better not to use the latter part of the DL transmission period in the interfering system to achieve time synchronization and to eventually ensure more stable operations for both systems. Therefore, here we prevent the last time slot of TD-SCDMA DL from being used, and that is why SE loss associated with dropping the time slot(s)(or symbol(s)) is regarded as *hard* SE loss.

In Cases 1.2 and 1.3, which are suitable to serve general internet traffic, there are configurations that can achieve perfect time synchronization between two systems without dropping any time slots or symbols in the systems. However, even in these cases, there can be some SE loss in the WiMAX side since the UL slot structure of WiMAX requires the number of UL symbols to be in multiples of 3. Therefore, even though we allocate 14 or 20 symbols to UL, only 12 or 18 symbols are used for general data delivery, which results in a SE loss of 4 % (=2/47, 2 UL symbols are not used). When the last UL symbol is used to deliver the sounding signal in the WiMAX system, SE loss can be reduced to 2 % (=1/47) since one of two unused symbols can be used for sounding signal delivery.

For the remaining Cases 1.4, 1.5, and 1.6 where TD-SCDMA focuses heavily on UL, the situation is similar to Case 1.1. In these cases, there is no adequately close TDD-ratio defined in the WiMAX system profile to achieve time synchronization with TD-SCDMA. The difference is that WiMAX can be the interferer and TD-SCDMA can be the victim system in these cases, so se-

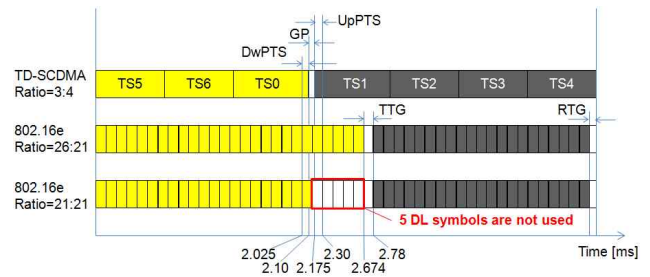


Fig. 8. Illustration of Case 1.4 in Table 5.

veral DL symbols of WiMAX systems should be dropped to achieve perfect time synchronization. Therefore, the anticipated SE losses in the WiMAX side are 11 % (=5/47, 5 DL symbols are dropped instead of being used), 26 % (=12/47), and 38 % (=18/47), respectively. Fig. 8 illustrates Case 1.4 and a situation in which the last 5 DL symbols are dropped in WiMAX to prevent interference from WiMAX to TD-SCDMA.

5-2 Between WiMAX IEEE 802.16e-TDD and 3GPP TD-LTE

In this section, the coexistence scenario between WiMAX IEEE 802.16e-TDD and 3GPP TD-LTE is investigated. Although there are 10 different TDD ratios defined for 802.16e as in Table 2, the focus is on four TDD ratios in which the multiples of 3 symbols are allocated to UL to maximize the utilization of UL symbols with the 3-symbol slot structure of 802.16e. Table 6 illustrates the closest possible TDD ratios of 3GPP TD-LTE referenced to the four selected TDD ratios of IEEE 802.16e-TDD and anticipated SE loss to achieve time synchronization.

Since the selected four TDD ratios of 802.16e-TDD appear suitable to provide general internet service with the optimum allocation of the total resource into DL and UL, respectively, there are also configurations defined in

Table 6. Time synchronization results between IEEE 802.16e-TDD and TD-LTE.

Case	IEEE 802.16e-TDD			TD-LTE				Anticipated SE loss	
	TDD ratio	DL end timing [ms]	UL start timing [ms]	DL-UL config	Special subframe config	DL end timing [ms]	UL start timing [ms]	16e-TDD [%]	TD-LTE [%]
2.1	(35,12)	3.60	3.71	2	6	3.64	3.86	0	0
2.2	(32,15)	3.29	3.40	2	5	3.21	3.86	0	0
2.3	(29,18)	2.98	3.09	1	4	2.86	2.93	2	0
2.4	(26,21)	2.67	2.78	1	6	2.64	2.86	0	0

TD-LTE to achieve perfect time synchronization between the two systems without losing too much SE.

As shown in Table 6, there is no SE loss for 802.16e-TDD or for TD-LTE in Cases 2.1, 2.2, and 2.4. In Case 2.3, there is only 2 % SE loss in 802.16e-TDD since the last DL symbol of 16e cannot be used.

Unlike WiMAX systems, LTE systems do not put UL control channel, physical uplink control channel(PUCCH), in the first part of its subframe in UL. Instead, LTE systems spread PUCCH to the entire 14 symbols in a subframe. However, it is still true that the first symbol of PUCCH can be significantly disrupted by the last DL symbol of the WiMAX system if this symbol is used in the above case. Therefore, similar to the explanation in Section 5-1, it is better not to use the last DL symbol of the WiMAX system to achieve time synchronization, and SE loss here associated with dropping the last symbol is also regarded as *hard* SE loss.

Generally, it can be said that it is not painful for operators to make time synchronization between 802.16e-TDD and TD-LTE if the both systems are used to provide general internal services.

Please note that there are seven different DL-UL configurations in TD-LTE as defined in Table 3. However, the first three configurations(0, 1, and 2) are considered to be in the coexistence scenario since the DL-UL switch-point periodicity of all the other technologies(TD-SCDMA, 802.16e-TDD, and 802.16m-TDD) is 5 ms.

5-3 Between WiMAX IEEE 802.16m-TDD and 3GPP TD-LTE

Table 7 illustrates the closest possible TDD ratios of 3GPP TD-LTE referenced to the 8 possible TDD ratios of IEEE 802.16m-TDD and anticipated SE loss to achieve time synchronization.

In Case 3.1, 802.16m-TDD puts all resources to DL, and there is no such configuration in TD-LTE, which perfectly matches this TDD ratio. Therefore, there is significant overlap between the DL transmission portion of 802.16m-TDD and the UL transmission portion of TD-LTE, which is about 0.93 ms(=4.86–3.93). If we want to prevent this overlap, the last 10 symbols of the DL transmission portion of 802.16m-TDD should not be used, and this results in SE loss of 20 %=(10/50)⁷).

Other than this extreme case, there is no or very little SE loss in these two systems as long as two systems are using a time synched configuration. As we see in Cases 3.3.1 and 3.3.2 in Table 7, there can be multiple configurations to make time synchronization between the adjacent systems with potentially different SE loss. In the above cases, the configuration in Case 3.3.1 looks better than the one in Case 3.3.2 since the former results in less SE loss than does the latter.

In addition, an operator configurable delay or offset between the beginning of an IEEE 802.16m-TDD frame and a TD-LTE frame can be applied in some configurations to minimize the time allocated to idle symbols or idle subframes as described in [14]. This delay is applicable to Case 3.3.2. If the frame start timings of IEEE 802.16m and TD-LTE are the same, the last two DL symbols of TD-LTE should not be used to prevent interference from TD-LTE DL to IEEE 802.16m UL, which results in SE loss of 3 %=(2/70)⁸). However, only the last single DL symbol(instead of two) of TD-LTE can be allocated to idle symbol⁹) if TD-LTE frame starts 60 μs earlier than IEEE 802.16m since the last 60 μs duration of UL transmission of IEEE 802.16m is not actually UL transmission but RTG. In any case, the assumption of the same frame start timing would suffice to analyze the coexistence scenarios and their impact in most cases.

7) As shown in Fig. 5, the total number of OFDMA symbols per 5 ms frame in 802.16m-TDD is 50(=6+7+6+6+6+6+7).

8) 70=14(symbols/subframe)×5(subframes/5 ms).

9) In this case, SE loss is 1%(=1/70).

Table 7. Time synchronization results between IEEE 802.16m-TDD and TD-LTE.

Case	IEEE 802.16m-TDD			TD-LTE				Anticipated SE loss	
	TDD ratio	DL end timing [ms]	UL start timing [ms]	DL-UL config	Special subframe config	DL end timing [ms]	UL start timing [ms]	16m-TDD [%]	TD-LTE [%]
3.1	(8,0)	4.86	5.00	2	4	3.86	3.93	20	0
3.2	(6,2)	3.59	3.68	2	6	3.64	3.86	0	0
3.3.1	(5,3)	3.01	3.09	1	4	2.86	2.93	2	0
3.3.2	(5,3)	3.01	3.09	2	5	3.21	3.86	0	3
3.4	(4,4)	2.43	2.51	1	5	2.21	2.86	0	0
3.5	(3,5)	1.85	1.93	0	4	1.86	1.93	0	0

5-4 Between 3GPP TD-SCDMA and 3GPP TD-LTE

As 3GPP TD-LTE is the natural evolution path from 3GPP TD-SCDMA, we can find configurations in both systems to achieve the perfect time synchronization without significant SE loss in most cases. Table 8 summarizes the closest possible TDD ratios of TD-LTE referenced to 6 possible TDD ratios of TD-SCDMA and anticipated SE loss to achieve time synchronization. Please refer to Tables 3 and 4 in Section 4-3 for the exact TDD ratio calculated based upon DL-UL configurations and special subframe configurations. For example, DL-UL configuration 2 and special subframe configuration 5 in Case 4.2 means that there are 3 subframes allocated to DL, 1 subframe to UL, and 1 to a special subframe in each 5 ms DL-UL switch-point period, and $214.58 \mu\text{s}$ is allocated to DwPTS, $642.71 \mu\text{s}$ to GP, and $142.71 \mu\text{s}$ to UpPTS within a special subframe.

In Case 4.1, TD-SCDMA puts most of the resource to DL, and there is no such configuration in TD-LTE, which perfectly matches this TDD ratio. If we use the closest TDD ratio of TD-LTE as in Case 4.1 of Table 8, the latter $0.2 \text{ ms}(=4.13 - 3.93)$ of DL transmission of TD-SCDMA overlaps with the initial part of UL transmission of TD-LTE. Unlike in Case 1.1, it is not necessary to drop one whole time slot of TD-SCDMA because the burst format of one time slot is comprised of two data symbols durations in which each data symbol duration spans $275 \mu\text{s}$ as shown in Fig. 9. Time synchronization is achieved by allocating only one data symbol duration to idle within one time slot, so SE loss can be 7 % (and not 14 %) in this case.

Cases 4.2, 4.3, and 4.5 show that there is no need to drop time slot(s) or symbol(s) to achieve perfect time synchronization since the current configuration already guarantees no interference between two adjacent systems.

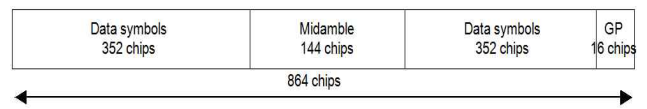


Fig. 9. Traffic burst format of one time slot in TD-SCDMA.

In Case 4.4, DL of TD-LTE slightly overlaps with the initial part of UL of TD-SCDMA, and we can achieve perfect time synchronization by dropping one DL symbol¹⁰⁾ of TD-LTE, which results in 1 % (=1/70) SE loss in TD-LTE system.

In Case 4.6 in which TD-SCDMA focuses heavily on UL, six DL symbols of TD-LTE should not be used to prevent interference from TD-LTE DL to TD-SCDMA UL, which results in 9 % (=6/70) SE loss in TD-LTE system.

Finally, Fig. 10 summarizes the anticipated SE loss of each case in all four coexistence scenarios considered in this Section. Fig. 10 shows cases with proper configurations without any SE loss except the coexistence scenario between WiMAX IEEE 802.16e-TDD and 3GPP TD-SCDMA.

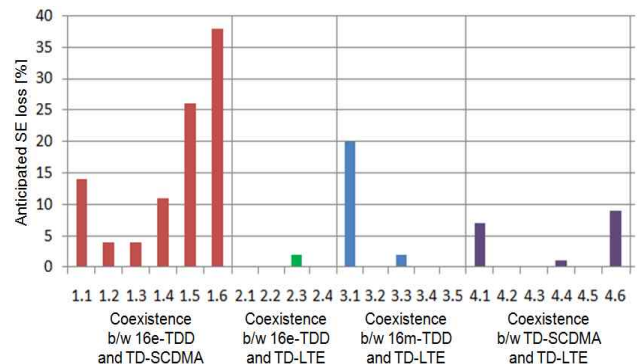


Fig. 10. Summary of anticipated SE loss in all four coexistence scenarios.

10) Symbol duration in TD-LTE with normal cyclic prefix is $71.35 \mu\text{s}$.

Table 8. Time synchronization results between 3GPP TD-SCDMA and 3GPP TD-LTE.

Case	TD-SCDMA			TD-LTE				Anticipated SE loss	
	TDD ratio	DL end timing [ms]	UL start timing [ms]	DL-UL config	Special subframe config	DL end timing [ms]	UL start timing [ms]	TD-SCDMA [%]	TD-LTE [%]
4.1	6:1	4.13	4.20	2	4	3.86	3.93	7	0
4.2	5:2	3.45	3.53	2	5	3.21	3.86	0	0
4.3	4:3	2.78	2.85	1	8	2.79	2.86	0	0
4.4	3:4	2.10	2.18	1	5	2.21	2.86	0	1
4.5	2:5	1.43	1.50	0	5	1.21	1.86	0	0
4.6	1:6	0.75	0.83	0	5	1.21	1.86	0	9

VI. Conclusions

FDD has been used as a duplexing scheme for the majority of cellular communication systems. TDD has several advantages such as flexible DL-to-UL ratio, flexible spectrum usage(i.e., no paired-band required), simpler implementation of smart antenna techniques, and cheaper transceiver implementation. Therefore, TDD has emerged as another duplexing scheme especially for wireless broadband systems. We have now at least four different TDD systems in the industry: TD-SCDMA, IEEE 802.16e-TDD, IEEE 802.16m-TDD, and TD-LTE.

A disadvantage of TDD is that tight coordination such as time synchronization between adjacent operators is required to prevent interference between adjacent TDD systems. Time synchronization between adjacent TDD systems is not straightforward when the adjacent TDD systems are different(e.g., IEEE 802.16e-TDD and TD-LTE). Since TDD now is gaining more ground in the industry, there is a strong possibility of having different TDD systems in the adjacent spectrum in the future. In this paper, we investigated the coexistence scenarios among the above four well-known TDD systems and calculate SE loss in each scenario.

It has been shown that SE loss can be significant if TDD ratios of adjacent operators are considerably different(e.g. 7~38 % depending on the difference in TDD ratios). However, as long as TDD ratios of adjacent operators are similar, configurations exist in all four TDD systems by which we can achieve perfect time synchronization between two heterogeneous TDD systems, and the resulting SE loss is reasonably low(e.g., 0~2 % depending on how close the TDD ratios of two adjacent systems are). Our analysis has verified the importance of time synchronization as a coordination scheme among TDD systems for four well-known TDD systems. It is highly recommended that adjacent operators use configura-

tions that make the closest TDD ratios as much as possible in order to both reduce interference between two systems and eventually reduce SE loss of respective systems. We believe that the selected four TDD systems are the most promising in the provision of wireless broadband services in the foreseeable future. The coexistence scenarios analyzed in this paper cover almost all the scenarios that can actually happen in the industry. Therefore, we believe that the above findings and the recommended configurations of the selected TDD systems to minimize SE loss will be helpful for operators who deploy the four TDD systems in their system parameter determination and cross-operator coordination. Thus, it will be feasible to operate heterogeneous TDD systems in the adjacent spectrum in the same geoboundary.

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References

- [1] H. Holma, S. Heikkinen, O. Lehtinen, and A. Toskala, "Interference considerations for the time division duplex mode of the UMTS terrestrial radio access", *IEEE Journal Selected Areas in Commun.*, vol. 18, issue 8, pp. 1386-1393, Aug. 2000.
- [2] Junsong Li, S. Farahvash, M. Kavehrad, and R. Valenzuela, "Dynamic TDD and fixed cellular networks", *IEEE Communications Letters*, vol. 4, issue 7, pp. 218-220, Jul. 2000.
- [3] Chih-He Chiang, Wanjiun Liao, Tehuang Liu, Iam Chan, and Hsi-Lu Chao, "Adaptive downlink and

- uplink channel split ratio determination for TCP-based best effort traffic in TDD-based WiMAX networks", *IEEE Journal Selected Areas in Commun.*, vol. 27, issue 2, pp. 182-190, Feb. 2009.
- [4] Man Hung Ng, Shen-De Lin, Jimmy Li, and Said Tatesh, "Coexistence studies for 3GPP LTE with other mobile systems", *IEEE Commun. Mag.*, vol. 47, issue 4, pp. 60-65, Apr. 2009.
- [5] Yihong Hu, Guochu Shou, Zongjue Qian, and Yajie Xue, "The co-existing interference analysis between TD-SCDMA and WiMAX", in *Proceeding of IEEE World Congress on Computer Science and Information Engineering*, pp. 329-333, 2009.
- [6] Hui Jia, Qingyu Miao, Changchuan Yin, Huarui Wu, and Yan Ma, "Performance analysis of coexistence between LTE-TDD and TD-SCDMA", in *Proceeding of IEEE ICCTA2009*, pp. 303-307, 2009.
- [7] Pei Chang, Yongyu Chang, Jing Zhou, and Dacheng Yang, "Interference analysis of TD-LTE and TD-SCDMA system coexistence", in *Proceeding of IEEE Second International Conference on Networks Security, Wireless Communications and Trusted Computing*, pp. 77-80, 2010.
- [8] Recommendation ITU-R M.1580-2, Generic unwanted emission characteristics of base stations using the terrestrial radio interfaces of IMT-2000, 2002-2005-2007.
- [9] Recommendation ITU-R M.1581-2, Generic unwanted emission characteristics of mobile stations using the terrestrial radio interfaces of IMT-2000, 2002-2003-2007.
- [10] WiMAX forum, TDD-TDD interference analysis involving synchronized WiMAX systems, Sep. 2009.
- [11] IEEE Std 802.16e-2005, IEEE standard for local and metropolitan area networks, Part 16: Air interface for fixed and mobile broadband wireless access systems, Feb. 2006.
- [12] IEEE Std 802.16-2009, IEEE standard for local and metropolitan area networks, Part 16: Air interface for broadband wireless access systems, May 2009.
- [13] IEEE P802.16m-09/D6, Draft amendment to IEEE standard for local and metropolitan area networks, Part 16: Air interface for fixed and mobile broadband wireless access systems, May 2010.
- [14] IEEE 802.16m-09/0034r2, IEEE 802.16m system description document(SDD), Sep. 2009.
- [15] WiMAX forum, WiMAX forum™ mobile system profile: Release 1 - IMT-2000 edition, Jul. 2009.
- [16] 3GPP TS 36.211, Evolved Universal Terrestrial Radio Access(E-UTRA); Physical Channels and Modulation, V9.1.0, Mar. 2010.
- [17] 3GPP TS 25.221, Physical channels and mapping of transport channels onto physical channels(TDD), V9.2.0, Jun. 2010.

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