REVIEW PAPER

A Comprehensive Survey of TDD-Based Mobile Communication Systems from TD-SCDMA 3G to TD-LTE(A) 4G and 5G directions

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Abstract: TDD (Time Division Duplex) is one of the two duplex modes. TD-SCDMA (Time Division Synchronous CDMA) is the first TDD-based cellular mobile system which is commercialized in wide area and large scale and TD-SCDMA is also the first cellular mobile system which adopted smart antenna technology (also called as beamforming). As the long term evolution of TD-SCDMA, TD-LTE(A) (Time Division-Long Term Evolution, and TD-LTE Advanced) introduced OFDM (Orthogonal Frequency Division Multiplexing) and enhanced smart antenna technology together with MIMO (Multiple Input Multiple Output), which are adopted by LTE FDD (Frequency Division Duplex) either. It is indicated that TD-SCDMA and TD-LTE(A) have opened a sustainable utilization era of TDD and smart antenna technologies in the wireless mobile communication. This paper aims to present a systematic introduction to TDD-based mobile communications from TD-SCDMA to TD-LTE and beyond, with particular focuses on TDD key technologies, principles of TDD cellular mobile systems, TDD evolution path, and future TDD 5G directions. The comparisons between TDD and FDD are also included. We hope that this paper will provide a comprehensive overview of TDD technology upgrade and its standard evolution, and serve as a valuable reference for research on 5G mobile communication systems. It is believed that TDD will play more important role in 5G.

Keywords: TDD; TD-SCDMA; TD-LTE; TD-LTE-Advanced; smart antenna array; synchronization; 5G

I. INTRODUCTION

In the past 30 years, it has been witnessed a tremendous success of wireless communication in the global market. Even after decades of fast growth, the number of cellular devices is still steadily increasing, surpassing the population in some countries due to consumers' need to stay connected wirelessly. For instance, since China Mobile commercially launched TD-SCDMA 3G in 2009, statistics reveals that there have been more than 2.3 hundred million TD-SCDMA subscribers until April 2014[1].

FDD and TDD are two fundamental duplex schemes in wireless communication systems. FDD system requires two isolated bands in paired spectrum for separate downlink and uplink communications, whereas TDD system occupies a single band in unpaired spectrum and uses UL/DL subframes in time domain to support traffic in different directions. Both

This paper aims to present a systematic introduction to TDD-based mobile communications from TD-SCDMA to TD-LTE and beyond and its comparisons to FDD, with particular focuses on TDD key technologies, principles of TDD cellular mobile systems, TDD evolution path, and future TDD 5G directions.

TDD and FDD have their pros and cons and will continue to co-exist in the global cellular ecosystem.

In light of the scarcity of paired spectrum, it is expected that an increasing level of importance will be placed upon TDD which has been evidenced by the growing adoption of TDD 4G systems among global mobile operators. By Q4 of 2014, 44 commercial TD-LTE networks have been rolled out by tier one operators including Sprint, Softbank, China Mobile, China Telecom and China Unicom [2]. This number is expected to steadily increase as the majority of WiMAX networks will be upgraded to TD-LTE[3]. Unfortunately, compared to WCDMA, WiMAX, and LTE FDD, fewer papers[4-9] are available on TD-SCDMA and TD-LTE from both academia and industry. Some of existing articles focused on the introduction of TD-SCDMA system and evolution of the 4G TD-LTE system, but failed to deliver a whole picture of TDD systems. Within this survey article we therefore intend to give the readers a comprehensive overview of the TDD mobile communication systems and their technology upgrade and standard evolution threads, including the role of TDD systems in the development of mobile communications, TD-SCDMA system and key technologies, TD-LTE system and key technologies, global TDD systems deployment scenarios, and a brief discussion on future 5G systems. The authors hope that this article will provide a full picture of TDD and its development, and serve as a useful reference for researchers and industry planners.

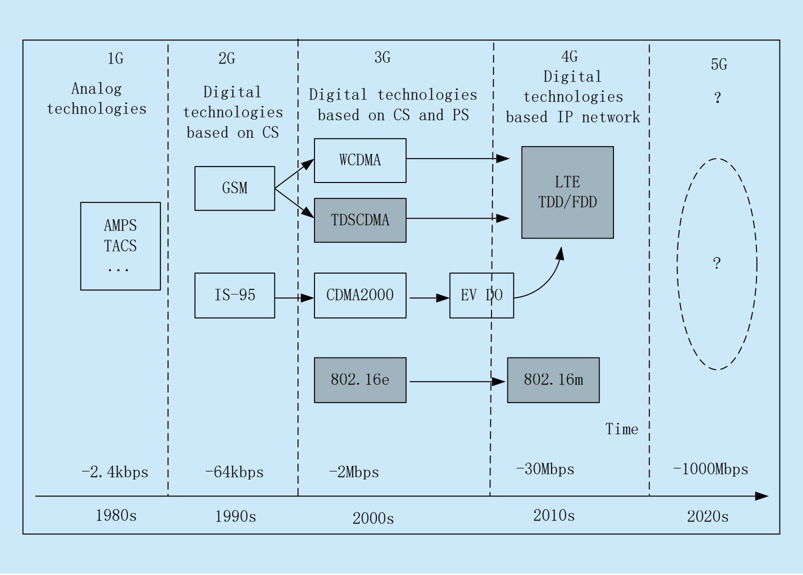

Fig.1 *Generation of mobile communication system*

Since Bell Labs proposed the concepts [10-11] of cellular mobile communication systems in 1979, mobile communications systems have evolved through 4 generations, and now the momentum of R&D of 5G mobile communication system is gradually increasing globally, as depicted in Figure 1. The typical UE throughput is increased from 2.4 kbps of the 1 G to 30 Mbps of 4G. It is expect that typical UE throughput will reach 1000 Mbps in the next generation.

The first generation mobile systems (1G) were commercially deployed in the 1980's. 1G was mainly based on Frequency Division Multiple Access (FDMA) and mainly provided voice services. As a technology in its infancy, 1G was limited in terms of small system capacity, low quality and limited services. Typical 1G system included AMPS (North American Advanced Mobile Phone System) [12] system and TACS (British Total Access Communication System) system. Due to the limitation in digital technologies, 1G was designed as an analog system and only supported FDD mode.

The second generation mobile systems (2G) were first commercially deployed in the early 1990's. The access schemes were based on TDMA (Time Division Multiple Access) or CDMA (Code Division Multiple Access). As a digital communication system, 2G demonstrated significantly improved system capacity and quality compared to 1G, and also supported low data rate services in addition to voice services. Due to these advantages, 2G system received quick market adoption and was deployed globally with tremendous commercial success. This, on the other hand, spurred cellular wireless communication technologies as a focal topic for research, investment and government strategies. Similar to 1G, 2G system also used FDD mode, with typical examples being the European GSM (Global System for Mobile Communications) [13] and North American IS-95 (IS，Interim Standard) system[14]. In Figure 1, CS stands for circuit switching and PS stands for packet switching.

Following the continuingly fast development of digital communication technologies, deployment of the TDD duplex mode in public communication systems has been rapidly increased. The earliest TDD system was used in cordless phones systems, such as European DECT[15], Bell's PACS and Japanese PHS[16] systems.

Under the coordination of ITU [17], third generation mobile systems (3G) were standardized in the early 21st century in two major standardization bodies, 3GPP[18] and 3GPP2[19]. 3G was based on CDMA technology. It supported larger bandwidth, higher system capacity and data rate, and was capable of delivering unprecedented user experience. Additionally, the services were more data oriented than voice which is significantly different from its 2G counter parts. Major 3G standards include WCDMA in Europe, CDMA2000 in north American, and TD-SCDMA in China[20]. In 2007, WiMAX (worldwide interoperability for Microwave Access, IEEE 802.16e) [21] officially became the 4th member of 3G global standards family. In 3G, TDD has gradually become a main stream duplex mode for cellular systems, such as TD-SCDMA and WiMAX.

Due to the challenge posed by WiMAX, 3GPP and 3GPP2 started LTE and UWB (Ultra Wideband) projects separately, which is that narrowband wireless mobile system evolutes towards mobile broadband. In June 2012, ITU-R formally approved LTE-A and Wireless MAN-advanced (IEEE 802.16m) as the IMT-Advanced (4G) standards. LTE-A and Wireless MAN-advanced systems support both FDD and TDD duplex modes [22-24].

Looking back at the evolution of the 4 generations of cellular mobile systems, TDD systems was deployed regionally in 2G in 1990s as the digital local loop, emerged as one of the main stream standards in 3G, and became equally important as FDD as a global communication technology in the 4G era. Looking forward, it is envisioned that TDD system will play an increasingly important role in 5G mobile communication, due to the inherent advantages of TDD mode in terms of ultra wide bandwidth, ultra high operating frequency, multi-antenna system and multi-cell co-ordination techniques. Thus, in this paper, we present to the researchers a complete systematic picture of TDD technologies through the description of TDD principles and its evolution. Table I summarized the main standards in mobile communication system, and the key players/contributors are also given out.

The organization of this paper is as follows. In section II, a comparison between TDD and FDD is provided. In section III, an overview on the standard evolution from TD-SCDMA 3G to TD-LTE-Advanced 4G is presented. We then discuss the key features of TD-SCDMA and TD-LTE(A) in section IV, and the TDD network commercialization is shown in section V. In section VI, evolution of TD-LTE-Advanced and future research areas are explored, with concluding remarks summarized in section VII.

Table I *Standards in mobile communications*

General Standards	Specific Standards	Duplex mode	Key Players/Contributors	Deployed in …
1G	AMPS	FDD	AT&T	USA
	TACS	FDD	Vodafone, Cellnet	European
2G	GSM	FDD	Ericsson, Nokia, Siemens, Alcatel	Europe, Latin America, China, USA, etc.
	CDMA (IS95)	FDD	Qualcomm	USA, Korea
3G	WCDMA	FDD	Ericsson, Nokia, NTT DoCoMo	Europe, Latin America, China, Japan, etc.
	CDMA2000 (EV-DO)	FDD	Qualcomm	USA, Korea, China, Japan
	TD-SCDMA	TDD	CATT/Datang	China
4G	LTE FDD	FDD	Ericsson, Nokia-Siemens, Alcatel-lucent, Qualcomm	Europe, USA, Korea, Japan, etc.
	TD-LTE	TDD	CATT/Datang, China mobile, Huawei, ZTE	China, USA, Korea, Japan, India, Europe, etc.

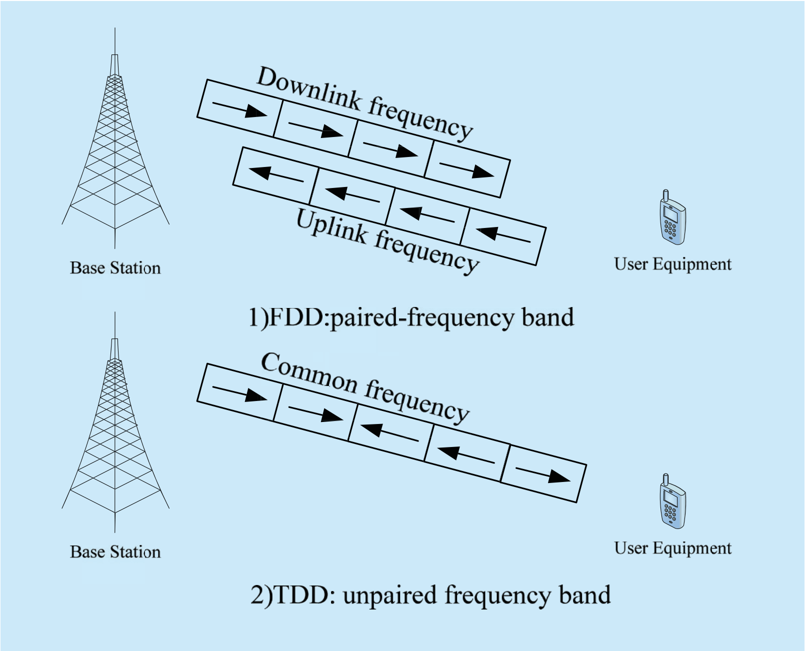

Fig.2 *FDD vs. TDD*

Table II *Comparison between TDD and FDD system*

Key Features	TDD System	FDD System
Spectrum	Unpaired	Paired
Traffic	Flexibly supported imbalanced traffic	Less flexible
Synchronization	Synchronized system	Unsynchronized system
CSI	Low overhead with channel reciprocity	Higher overhead
Interference co-ordination	Complex	Relatively complex
Service delay	Larger than FDD can meet the requirements of real-time services	small
Coverage	Relatively good	Good
Control signaling	Complex	Simple

II. Comparison of TDD and FDD

According to the timing of transmission and reception, cellular mobile communication system can be divided into two duplex modes, namely TDD and FDD, depicted in Figure 2. In TDD mode, UL and DL transmissions occur on the same frequency, where UL and DL transmissions are scheduled on different timeslots. To prevent interference between UL and DL timeslots, a guard period is required at the switching between downlink and uplink. In FDD mode, UL and DL transmissions are on different frequencies, information can be transmitted contiguously in both directions. To prevent self interference between UL and DL transmissions, certain duplex guard band is necessary.

Compared to FDD mode, TDD mode has different technical features, which are listed in Table II.

Key TDD features are described in details below:

(1) **Unpaired Spectrum**

Frequency spectrum suitable for cellular communication is an expensive finite resource and its scarcity is becoming a bottleneck for future mobile network. As FDD systems require paired spectrum, it is increasingly difficult to find large chunk of paired frequency bands essential for high network capacity. On the contrary, TDD band in unpaired spectrum is much easier to acquire, and more importantly it is relatively easy to find large chunk of unpaired TDD band. Recently, ITU is considering spectrum allocation for IMT-Advanced in 698-803MHz, 2300-2400MHz, 2500-2600MHz and 3400-3600MHz bands, where a large chunk of unpaired spectrum is expected to be allocated for TDD. The availability of large frequency spectrum is a major advantage for further development of TDD networks, compared to the spectrum challenges faced by FDD.

(2) **Asymmetry Traffic and Burst Traffic**

Flexible UL/DL resource allocation provides efficient support of imbalanced IP based traffic. In TDD, UL/DL resources can be adaptively adjusted with flexible allocation of UL/DL timeslots to cope with the UL/DL traffic asymmetries. In macro cell deployment scenario where the UL/DL traffic ratio is relatively stable, this feature is mainly applicable for different operators and different regions to support different requirements and avoid interference between UL and DL timeslots. In future heterogeneous network (HetNet) where small cells are applied to offer ultra high data rate coverage in local hotspot zones, flexible UL/DL resource allocation may adapt to dynamic asymmetric traffic variation in different small cells, resulting in more efficient spectrum utilization.

(3) **Synchronization**

In mobile systems, synchronization can be divided into system synchronization and user synchronization, the former is refer to the base station of same area should be synchronized and the later is refer to the UE's transmitting signal in one cell should reach the base station simultaneously. In order to avoid the DL-to-UL interference and to improve the performance, the TDD systems require strict system synchronization. But for FDD system, the system synchronization can bring significant gain in interference cancellation and transmission coordination, though it is not a mandatory feature. And with the development of techniques in recent, synchronization can be realized with very low cost, so synchronized system is a trend for both TDD and FDD.

(4) **Channel Reciprocity**

TDD system can obtain the channel state information (CSI) by utilizing channel reciprocity. Multi-antenna has been an important technology in wireless communication to achieve superior spectral efficiency. In TDD system, since UL and DL transmission share the same frequency bands, channel reciprocity can be utilized to obtain DL channel via the measurement on the UL signals. This enables the transmitter to efficiently collect CSI for advanced MIMO beamforming processing, without excessive feedback overhead and complicated mobile terminal processing. Such simplicity renders advanced multi-antenna technologies such as CoMP (Coordination Multipoint systems) more feasible in TDD network, e.g. in dense HetNet scenario where tight coordination among a large number of small cells crucially relies on the availability of massive DL channel information.

(5) **Interference Coordination**

As wireless network becomes ever more complex, it is important to utilize sophisticated interference coordination schemes to minimize co-channel interference for cell-edge coverage. Since TDD systems are synchronized, application of inter-cell interference coordination and multiple points coordinated techniques can be simplified. Compared to FDD system, since additional UL/DL interference should be considered, interference scenario may be more complex than it in FDD.

(6) **Service Delay**

Since the TDD is time non-contiguous, sometimes the traffic may have to wait until the UL/DL direction turn, which will increase the service delay. So the TDD system's service delay is larger than FDD usually. But it has been witnessed in TD-SCDMA and TD-LTE system that the delay requirement of real-time service can be meet.

(7) **Coverage**

The TDD's time non-contiguous nature results into smaller coverage than FDD for shorter transmission duration.But in typical deployment scenarios, such as urban and sub-urban, it has been proved that TDD system can meet the macro coverage requirements, and at the same time coverage can be further improved by time domain extension techniques.

(8) **Control Signaling**

The TDD's time no-contiguous nature and the multiple configurations of UL/DL traffic cause that the HARQ process is more complex than FDD system, which also results the complexity of physical control signals.

In general, TDD system can achieve more spectrum efficiency with the traffic adaptation， beamforming，interference cancellation and so on, but the system design may be more complex with the multiple of frame configuration and interference scenarios.

III. Evolution of TDD Standards

The 1G and 2G are all based on FDD, TD-SCDMA is the first TDD-based cellular mobile system which is commercialized in wide area and large scale in 3G. After 2G mobile systems were commercially deployed, the demand for higher data rates and limited system capacity became critical challenges, and research interests started to be focused on the development of next generation mobile communication systems. In 1997, ITU globally called for 3G candidate technology proposals. In WRC-2000 conference，May 2000, ITU formally approved IMT-2000 wireless technical specification proposals, including five technologies as below:

- two TDMA based technologies: SC-TDMA and MC-TDMA,
- three CDMA based technologies: MC-CDMA (CDMA2000), DS-CDMA (WCDMA) and CDMA TDD (including LCR TDD，i.e. TD-SCDMA and HCR TDD)

Table III *TD-SCDMA standards milestones*

Time	Key Development
1998	CATT/Datang representing Chinese government formally submitted the proposal to ITU (International Telecommunication Union)
2000	ITU in WRC-2000 (World Radio Conference) formally approved TD-SCDMA as one of the third generation mobile communication systems in May 2000.
2001	3GPP (3rd Generation Partnership Project) formally accepted TD-SCDMA as a family member, symbolizing TD-SCDMA as a global standard
2001	Release of R4 version of the specification, the first release after introducing TD-SCDMA technology.
Mar 2002	Release of R5 version, introduced IP based HSDPA concept, the DL link peak user throughput reached 2.8Mbps on single carrier and 8.4Mbps in 3 carriers (5MHz).
Oct 2004	Release of R6 version, introduced HSUPA technology, the UL peak user throughput reached 5.76Mbps.
Mar 2006	Release of R7 version, HSPA technology evolved as HSPA+, introduced high order modulation and MIMO technologies.

As the result, three CDMA based technologies emerged as basis for global 3G systems, including WCDMA and TD-SCDMA standardized in 3GPP and CDMA2000 standardized in 3GPP2. On 19th October, 2007 after a long debate, ITU approved WiMAX (802.16e) as a new 3G standard.

Evolution of TD-SCDMA standards and its milestones are depicted in Figure 3.

The milestones of TD-SCDMA standardizations are further depicted in details in Table III:

In recent years, with the development of new technologies and increased demand of mobile data traffic, 3G systems continued to evolve and to meet the new requirements. There are two paths of evolution for TD-SCDMA technology and its standards [4-9]:

The first path is the enhancement based on CDMA technology in order to improve system performance with backward compatibility. TD-SCDMA system gradually evolved with enhanced features and from single carrier to multi carrier system through the path TD-SCDMA → HSDPA → HSUPA → multi carrier HSPA → HSPA+. The main goal was to introduce feature enhancements step by step to improve 3G systems performance while maintaining backward compatibility.

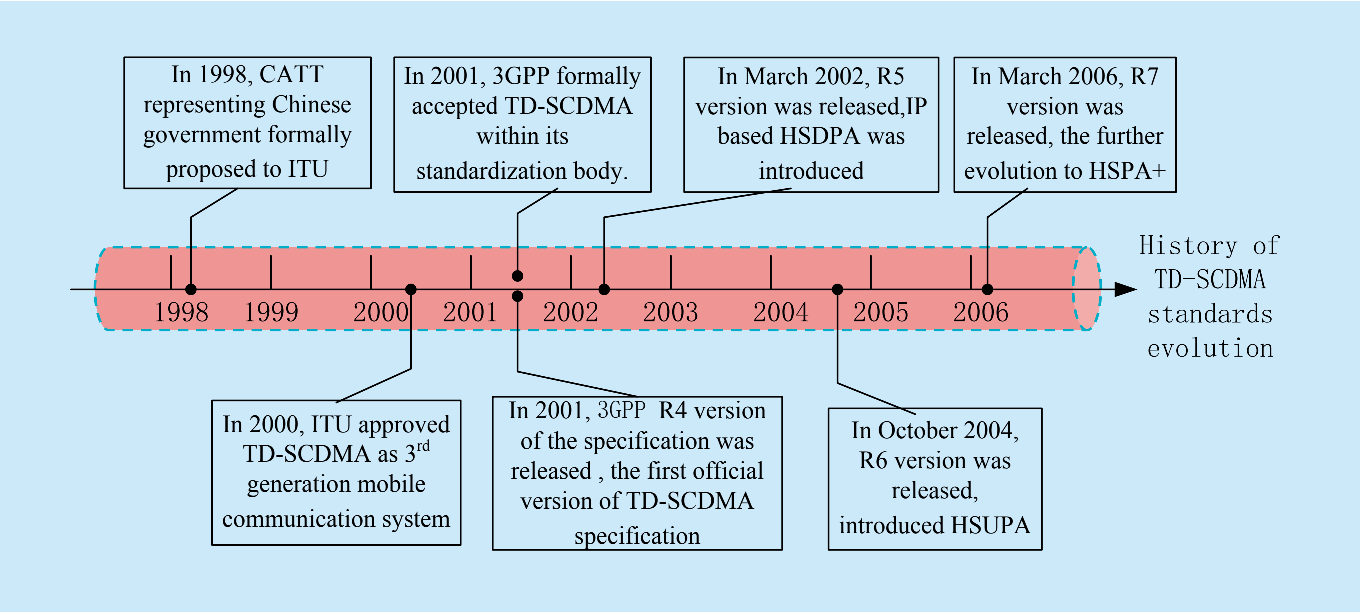

Fig.3 *TD-SCDMA standards evolution*

The second path is the long term evolution(LTE) based on OFDM technology, known as LTE. This is a completely new design without backward compatibility to 3G systems; however different releases within LTE (e.g. Rel-8 and beyond) are backward compatible. TD-LTE, as one of the two duplex modes since the first LTE Release (Rel-8), has evolved through Rel-9 to Rel-12 with continuously improved system performance.

3GPP started the standardization of LTE in March 2005 with support of both TDD and FDD modes [25]. Four releases of specification (i.e. Rel-8 – Rel-11) have been completed, each with enhanced features over the previous one. The latest release (e.g. Rel-12) is completed in 2014. LTE standard can be divided into two phases as LTE (includes Rel-8 and Rel-9) and LTE-Advanced (includes Rel-10 and beyond) [25-32]. LTE TDD and LTE-Advanced TDD modes, also known as TD-LTE and TD-LTE-Advanced, adopted experiences from TD-SCDMA system design and its key features, hence supporting smooth evolution and co-existence with TD-SCDMA system. TD-LTE/TD-LTE-Advanced are designed targeting 4G capacity, spectrum and service requirements. They target at ultra-high spectral efficiency up to 30bps/Hz with low latency, where smooth evolution and co-existence with 3G system is considered. However, no constraint on the backward compatibility is considered. Important milestones of TD-LTE standardization are summarized in Figure 4

Table IV *Key milestones of TD-LTE standard evolution*

Time	Key Developments
Nov 2004	3GPP RAN organized "Further Evolution Workshop", discussing on long term development plan for the third generation mobile communication technology.
Dec 2004	3GPP approved "Evolved UTRA/UTRAN" Study Item, the beginning of study on long term evolution of the third generation mobile communication technology
Jun 2006	3GPP approved "3G Long-Term Evolution" Work Item, development towards TD-LTE Rel-8 version of the specifications, Rel-8 is the first version of LTE specifications.
Oct. 2007	Frame structure type 2, which proposed by Datang/CATT with modification for compatible with FDD, has been accepted as TD-LTE Frame Structure, it is fundamental step to built a global TD-LTE standard.
Mar 2008	Considering the call for IMT-Advanced (4G) technical proposals by ITU-R, 3GPP approved "LTE-Advanced" Study Item
Dec 2008	First version of LTE Rel-8 specifications was completed, started working on the standardization of enhanced version Rel-9 and the study Items for Rel-10.
Nov 2010	3GPP LTE-Advanced passed ITU-R technical evaluation, accepted as candidate technology for 4G by ITU-R#5D
Mar 2011	LTE-Advanced Rel-10 standardization completed, starting standardization of enhanced version Rel-11.
Jun 2012	Rel-11 version of specification completed, starting standardization of LTE-Advanced Rel-12

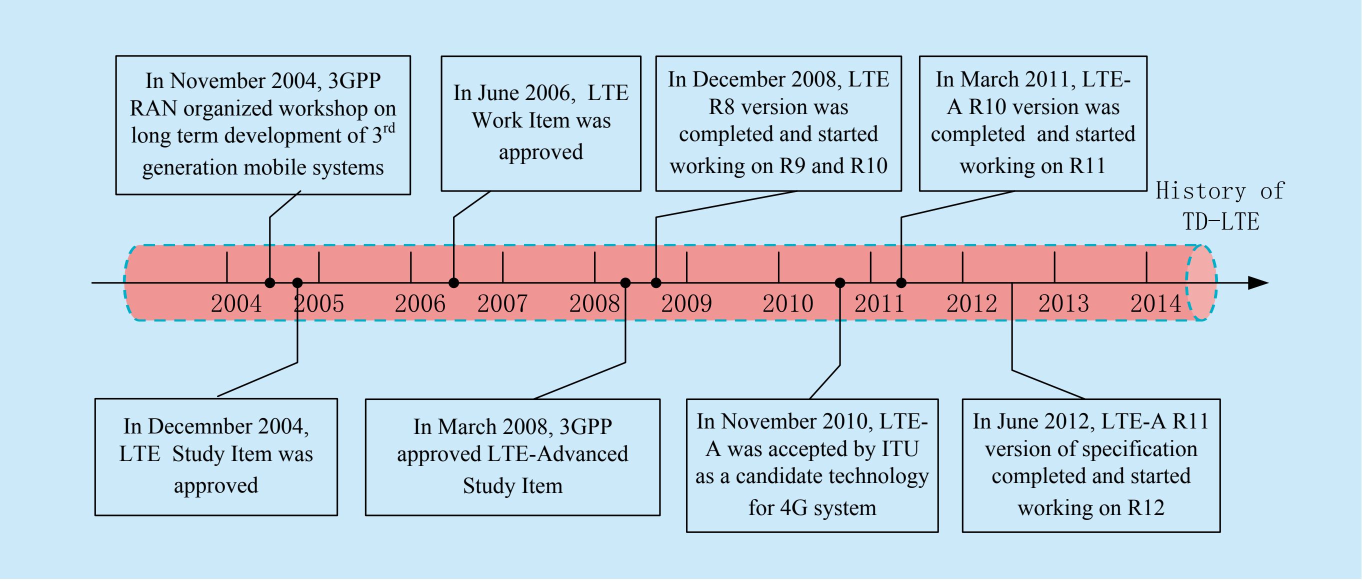

Fig.4 *TD-LTE standards evolution*

and Table IV.

In parallel with LTE development, WiMAX system was standardized by IEEE and becomes also an important technology of TDD based wireless systems. WiMAX is mainly based on TDD mode, although the support of FDD mode is also possible [33-35]. Wireless broadband access technologies rapidly developed in the 1990's. In 1999, IEEE set up the 802.16 working group to develop broadband wireless access technology standards. Since December 2001, IEEE started releasing 802.16 series of standards; the 802.16e version released in 2006 supports both fixed and mobile broadband wireless access systems and became a new member of global 3G standards in 2007. The further evolved version 802.16m was accepted as 4G candidate technology in January 2012. Unfortunately, due to the weakness of WiMAX supply chain, WiMAX will update to TD-LTE since 2011.

IV. TD-SCDMA and TD-LTE(A) Key Technologies

TD-SCDMA system is based on TDD and CDMA technologies, where fundamental components of the access technology include time division multiplexing, synchronization and code division multiple access. It's the first time that the TDD is introduced to the mobile communication system. Competitive performance of TD-SCDMA is ensured by advanced physical layer techniques including dynamic resource allocation, smart antenna, joint detection and uplink synchronization techniques [20].

Compared to 2G and 3G systems, TD-LTE features revolutionary physical layer technologies which incorporated research work in academics and technical breakthroughs in the industries in recent years. As an evolution of TD-SCDMA, TD-LTE system inherited multiple advanced physical layer features of TD-SCDMA, while introducing additional enhancements for further performance optimization. For example，the frame structure of TD-LTE was very similar to that of TD-SCDMA，smart antenna and uplink synchronization techniques are also succeed and developed. In LTE, MIMO-OFDM becomes the most important technique. TD-LTE adopted advanced MIMO techniques designed specifically for OFDM air interface, reaping the benefits of MIMO and OFDM simultaneously to meet the coverage and data rate requirement for both indoor and outdoor channels. These advanced MIMO features include single user beamforming (SU-BF) and multiuser beamforming (MU-BF). Dynamic switching between SU-MIMO and MU-MIMO is also supported in TD-LTE to achieve the optimal spectral efficiency. It can be understood that OFDM and enhanced beamforming techniques are the two most fundamental techniques in TD-LTE system. Additionally, TD-LTE system leveraged a large amount of recent research results in mobile communication system and the common aspects between TD-LTE and LTE FDD, achieving superior performance of TD-LTE.

In Rel-8 phase of TD-LTE, basic features such as multiple access technology, frame structure, multiple antenna technique and physical channel designs are specified. In Rel-9 phase, dual layer beamforming technology, positioning and MBMS (Multimedia Broadcast Multicast Service) techniques are introduced. In Rel-10 phase, to meet the ITU requirement of 4G system, carrier aggregation, MIMO enhancement, CoMP (Coordination of Multiple Point), Relay techniques are introduced. In Rel-11 phase, apart from enhancement of carrier aggregation, further enhancement of MIMO and CoMP, dynamic TDD technique is also introduced [45-50].

Due to limited paper size, only some commom features of TDD systems are introduced in this section, including TD-SCDMA and TD-LTE.

- **Frame structure** [20,26,36,37]

TDD system operates in unpaired spectrum and can efficiently utilize the available frequency bands. The frame structure should be multiple UL/DL configurable timeslots designed to support imbalanced traffic, which can easily adapt to the different requirements of data services. At the same time, the resource management, scheduling efficiency and coverage should be considered in the frame structure design.

The frame structure of TD-SCDMA system is designed considering the features mentioned above. Each radio frame is 10ms long and divided into 2 half frames of 5ms each. Every half frame consists of UL timeslots, DL timeslots and special timeslot, where special timeslot is further divided into three components, namely DwPTS(Downlink Pilot Time Slot), GP (Guard Period) and UpPTS (Uplink Pilot Time Slot), shown in figure5.

TD-LTE system frame structure is designed partly based on TD-SCDMA system frame structure [51-56]. Herein one radio frame is 10ms which is further divided into two half frames, 5ms each. Each half frame is consisted of downlink subframes, uplink subframes and a special subframe, which is made of three parts DwPTS, GP and UpPTS, as shown in the figure 6, where the GP can be configured form one OFDM symbol to 10 OFDM symbols freely to protect the interference of DL to UL.

In both TD-SCDMA and TD-LTE systems, the subframes can be flexibly configured where multiple UL/DL subframe configurations can be used, therefore the system can be flexibly deployed according to the service requirement. Absorb the experience of TD-SCDMA, the frame structure of LTE is more flexible, for example the GP length.

Flexible UL/DL configuration has also been utilized in TD-SCDMA and TD-LTE systems, however there are some limitations such as: 1) UL/DL configuration is semi-static, which impacts on the system performance; 2) the interference due to different UL/DL configurations in neighboring cells is a serious problem in macro scenarios.

As mobile Internet access in rapidly growing and the users' demand for data throughput is ever increasing, heterogeneous deployment will be the main deployment scenario in 4G systems to support high data rate in hotspots. To support such deployment scenarios and requirements, 3GPP started studying the TDD eIMTA (enhanced Interference Management and Traffic Adaptation)[57-59] technology and develop its specification. eIMTA technology,

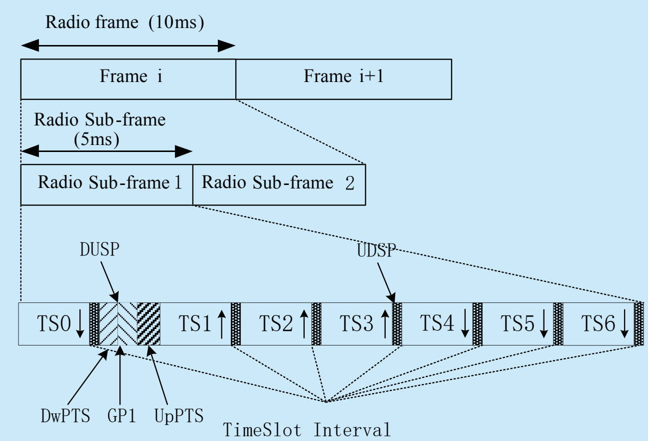

Fig.5 *TD-SCDMA frame structure*

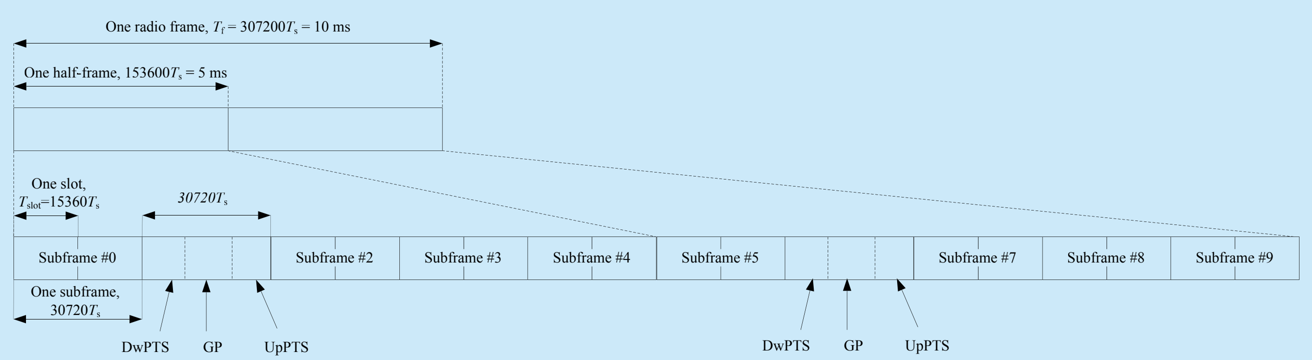

Fig.6 *TD-LTE frame structure*

especially in HetNet scenario, dynamically changes the TDD UL/DL configuration according to the dynamic change (in terms of 10ms) of traffic in lower power nodes to improve the resource utilization. In Figure 7, an example of HetNet deployment scenario is shown, where different Home eNBs (Enhanced Node of Station) use different UL/DL subframe configurations. Within the coverage of low power nodes, the number of users is usually low thus UL/DL traffic imbalance is even more pronounced, hence with dynamic TDD subframe configuration the system performance can be significantly improved. Dynamic UL/DL subframe configuration will certainly introduce interference between UL and DL subframes. Inter cell interference coordination and management, inter eNB coordination for transmission power control and resource allocation are the main areas of study in eIMTA. Dynamic UL/DL subframe configuration in TDD can significantly boost the system capacity and reduce the network energy consumption by allocating few DL subframes when the system load is low. Some simulation results are shown in reference [58], TDD UL-DL reconfiguration based on traffic condition provides significant benefits over a fixed reference TDD UL-DL configuration. In some cases, the relative gain over 100% can be achieved.

- **Smart antenna technology** [38-40]

In 2G system, the multiple antenna receiver has been used to improve the receive signal power of the base station. TD-SCDMA system is one of the first cellular mobile communication systems using smart antenna technologies, which is enhanced further in TD-LTE.

According to the channel status information of the user equipment, a strong directional signal is transmitted towards the target user applying specific beamforming weights to the transmitting antenna array. Users sharing the same frequency, timeslot and different CDMA channels can be further distinguished by different beams in the spatial domain to boost the received signal strength at the user side. Smart antenna technology can increase the coverage and system capacity by focusing the power direction and minimizing the interference. In typical scenarios of 8 transmit antennas, 6dB~9dB Beamforming gain can be achieved and cell average spectrum efficiency and cell edge spectrum efficiency can be improved by 15% and 50% respectively [72]. Smart antenna technology combined with joint detection and uplink synchronization technologies further improve system performance in highly fading scenario such as high mobility environment by effectively cancelling the interference, which have been successfully applied and tested in TD-SCDMA system. In TD-SCDMA system, many difficulty of smart antenna application is overcome, for example the size of multiple antennas and calibration of multiple antennas.

Multi-antenna technique are developed further in TD-LTE system[63-72], due to diversity gain, spatial multiplexing gain and array gain, can significantly increase the peak data rate, reliability, coverage enhancement, system capacity and mitigate interference. In different application scenarios, it can support transmission diversity, spatial multiplexing, beamforming techniques.

In TD-LTE system, smart antenna can be categorized as single layer beamforming in Rel-8 and enhanced multiple layer beamforming in Rel-9/10. In single layer beamforming, UE specific reference signal and data are applied with the same weighting vector at the transmitter. UE estimates the effective channel on the UE specific reference signal and performs coherent detection of data. eNB can utilize channel reciprocity properties to

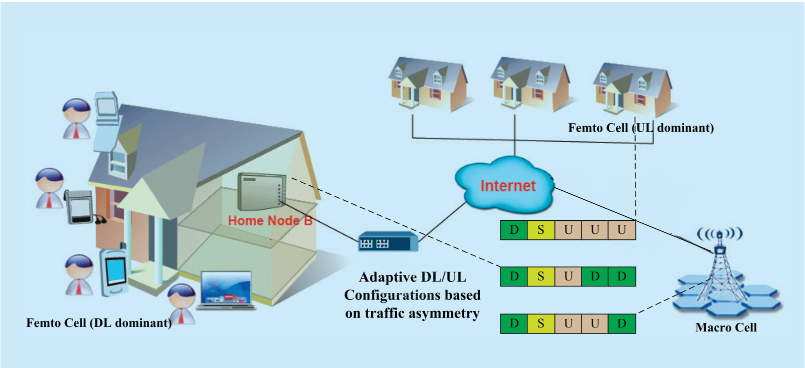

Fig.7 *Application of dynamic TDD subframe allocation*

obtain downlink channel information via measurement on uplink signals. eNB using SVD (Singular Value Decomposition) or other algorithms obtains the beamforming vector from the measured channel in uplink, and due to accuracy in the channel state information the system performance is improved. For single layer beamforming, advantages of traditional smart antenna like performance gain, coverage enhancement, better cell edge throughput and interference mitigation are maintained. In [72], DL performance of 8-antenna SRS based beamforming and 2-antenna codebook based precoding is evaluated with different inter-site distances. Correspondingly, UL performance of 1x8 SIMO(Single Input Multiple Output) and 1x2 SIMO are also evaluated. Results show that the cell edge user spectrum efficiency increase from 0.05bps/Hz up to 0.13 bps/Hz in DL and from 0.06bps/Hz up to 0.13 bps/Hz in UL with inter-site distance 500m. It can be seen that 8-antennas beamforming can greatly improve both DL and UL data channel coverage, compared with 2 antennas. For the cell average spectrum efficiency of SU-BF, the efficiency increase from 2.2bps/Hz up to 2.6 bps/Hz in DL and from 1.2bps/Hz up to 2.3 bps/Hz in UL.

To further improve the system capacity and peak throughput, on top of single layer beamforming, TD-LTE system also supports multiple layer beamforming combining the beamforming and spatial multiplexing techniques. In multi layer beamforming technique, multiple layers of data are transmitted on multiple beams to either a single user or multiple users, known as SU-BF and MU-BF as shown in figure 8. In the system design, a unified transmission mode is defined to support SU/MU-MIMO transmission supporting dynamic switching. It also supports higher order MU-MIMO technique which further optimizes the TDD system performance.

As the antenna technology and design evolve, 3D beamforming based on AAS (Adaptive Antenna System) and massive MIMO technologies have attracted much attention in the academy and industry[92-97].

From the antenna array point of view, the spatial properties of the transmitting signal can be decomposed into horizontal and vertical spaces. In traditional antenna array, UE specific beamforming is only possible in horizontal domain and cannot flexibly adapt the beam directions in vertical domain, thus restricting the system performance. With the AAS, UE specific beamforming in horizontal as well as vertical domain is possible to further improve the system performance. As the AAS technology is developing, 3GPP has started studying AAS and 3D MIMO/3D beamforming in LTE Rel-12.

- **Interference coordination**

In mobile cellar system, the interference is the bottle neck to improve system. The techniques to reduce interference, such as interference cancellation or interference coordination, play a key role in 3GPP's standard.

3G systems are based on wideband CDMA technology. There exist heavy multi-path interference and multi-user interference in the system. Traditionally, single user detection utilizes correlation properties of the CDMA codes to retrieve the desired signal and reject the interference; however with the traditional method it is only possible to remove the interference in ideal scenario. In non-ideal scenarios, the interference cannot be removed and will increase the BLER which subsequently negatively impacts on the system performance. Joint detection[37,41-43] in TD-SCDMA system utilizes all received signals including interference and desired signals and their a priori information to retrieve useful signal. It has robust interference rejection capability, reduced impact of near-far effect, and at the

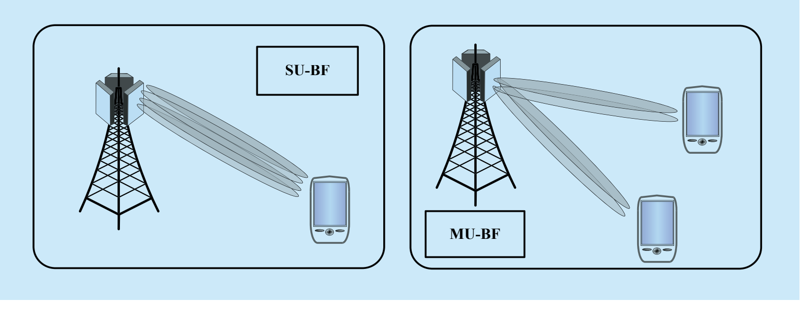

Fig.8 *Single user/multi user beamforming*

same time requirement on power control can also be relaxed.

Since 4G systems are based on OFDM technology, the interference of inter-cell impacts the performance more seriously. And in TD-LTE, in order to maximize the frequency resource utilization generally single frequency network is deployed. Reducing inter cell interference to improve the cell edge performance is a critical issue in single frequency network.

Inter cell coordination techniques can be based on semi-static or dynamic coordination. Semi-static coordination techniques include ICIC (Inter-Cell Interference Coordination), eICIC (enhance ICIC) and the dynamic coordination technique is the CoMP (Coordination of Multiple Point) [73-81].

In ICIC technique eNBs exchange information via X2 interface such as the transmission power, cell load, resource allocation, interference level. eNBs utilize these information to coordinate the resources and power allocation for cell center UEs and cell edge UEs in order to boost the performance of cell edge UEs.

eICIC is the enhancement of ICIC which is even more efficient in boosting cell edge UEs' performance in HetNet scenarios. In HetNet scenario, a power offset for handover margin is introduced between macro eNB and lower power eNB such that the coverage of low power eNB is enlarged and many UEs are attached to it, thus maximum offloading to low power eNB is achieved. In such a scenario, the UEs at the cell edge of low power eNBs are severely interfered by macro cell down link transmission, so eICIC introduced ABS (Almost Blank Subframe) for macro cell downlink subframe to decrease the interference to the UEs connected to low power eNBs. In the ABS subframes, macro eNB almost does not transmit any control and data signal so that low power eNBs can schedule the cell edge UEs. Although, macro eNB does not transmit data in some subframes, sacrificing some resources, however the low power eNBs can significantly improve their performance, therefore from the overall system perspective the performance gain is obvious.

To support ICIC, eICIC and interference mitigation techniques, network synchronization is necessary. As TDD network is well synchronized there are obvious advantages in supporting these techniques.

The concept of CoMP[73-79] is that the transmission points located in geographically different locations cooperate to transmit to or jointly receive data from an UE, which is adopted in LTE Rel-11. The transmission points involved in cooperated transmission could be different eNBs or the remote RF heads. Downlink CoMP supports 4 transmission modes: 1) dynamic transmission point switching, which dynamically select the best transmission point to transmit data to the target UE among the cooperated transmission points. 2) joint transmission, wherein multiple transmission points jointly transmit data to the target UE. 3) coordinated scheduling/beamforming, by sharing the scheduling or beamforming information among the coordinated transmission point to reduce the interference. 4) dynamic transmission point blanking, by selecting the best transmission point to transmit the data to the target UE, and blanking/muting potential high interference transmission point, as shown in figure 9. Uplink CoMP is the reception of data from the same UE from multiple reception points at the network to enhance the performance. In TDD system, the system performance can be significantly improved with reduced complexity and feedback overhead by utilizing channel reciprocity properties.

- **synchronization technique** [44]

As described in section 2, TDD system is a synchronized system to avoid the DL-to-UL interference.

TD-SCDMA is synchronized system. In Uplink, it requires the signals from different user at different locations in the cell scheduled in the same timeslot to arrive at base station simultaneously. In TD-SCDMA system, with uplink synchronization technique multi-user signals in uplink are orthogonal at the receiver, which is beneficial in reducing multi-user interference thus increasing number of usable CDMA channels and subsequently improving

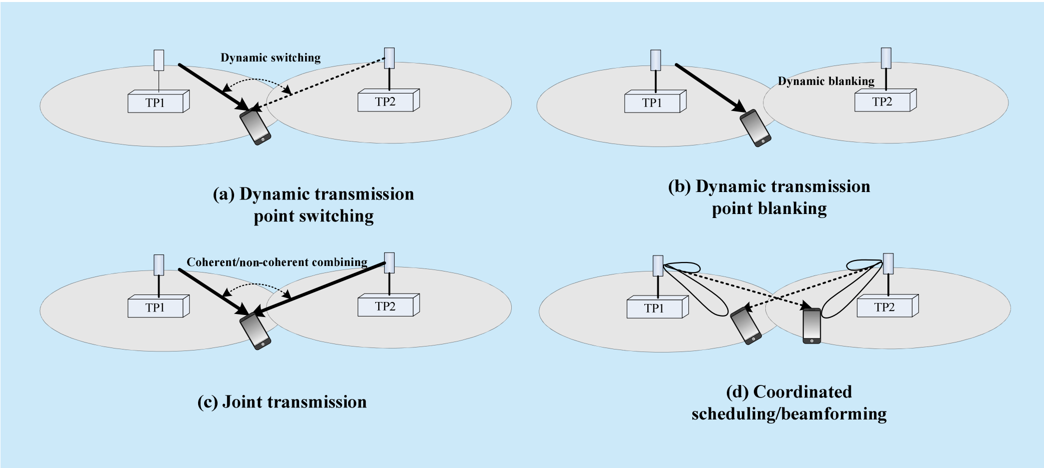

Fig.9 *CoMP transmission schemes*

the spectral efficiency. On the other hand, uplink synchronization technique significantly simplifies the data processing mechanism, and reduces the baseband complexity.

Similar to the TD-SCDMA system, TD-LTE system also has stringent requirement on synchronization, including synchronization among the base stations and uplink synchronization among the UEs. Base station synchronization can be obtained via GPS or over-the-air (OTA) synchronization technology. For macro base stations, when the cell radius is smaller than 3Km the synchronization error is required to be less than 3 micro seconds, when the cell radius is larger than 3Km the synchronization error is required to be less than 10 micro seconds, and the synchronization requirement between macro cell eNB and Home eNB is less than 3 micro seconds or 1.33 micro seconds plus the propagation delay over the air. UEs acquire time and frequency synchronization with eNB in downlink via receiving synchronization signals, and uplink synchronization of the UEs is maintained by eNB through timing advance (TA) control after detecting uplink random access channels.

The tight synchronization in TD-LTE system not only reduces the system interference, it is also the basis for new technologies such as inter cell interference coordination, MBMS [60] and CoMP [57,61] techniques. If inter cell synchronization is well maintained, interference can be mitigated with resource coordination and coordinated transmission. For MBMS services, as the transmitted signals from multiple eNBs are well synchronized, the UE can simultaneously receive signals from multiple eNBs and combine together to obtained macro diversity gain thus improving the coverage and performance. Coordinated multiple points transmission/reception and positioning technique also require better inter cell synchronization.

Some other key technologies, such as the CA (Carrier Aggregation) and relay, also play important roles in both TDD and FDD mode LTE(A). Due to the limit space, they will not be introduced here.

V. TDD Network Commercialization

Technologies cannot be developed without commercial driving. In the last 20+ years, TDD based wireless communication systems have developed from TD-SCDMA 3G system to TD-LTE 4G system and become an important part of the wireless communication industry. In this section, the commercialization of TDD wireless mobile communication systems is introduced.

5.1 TD-SCDMA 3G commercialization

In 2002, the TD-SCDMA Industry Alliance (TDIA) was founded in China by Datang, Huawei, ZTE and Lenovo. Within a decade it has grown from early 7 members to 90 members, covering every aspects of the industrial chain with more than 200 local and international vendors in the supply chain.

In 2007, a large scale pre-commercial TD-SCDMA network was deployed, and two years later China Mobile commercially launched the network operation. After six phases of expansions and deployments, the TD-SCDMA network keeps growing and the network coverage has been gradually extended from metropolitan cities to rural areas. Until August 2013, more than 390,000 TD-SCDMA base stations have been deployed and the number of installed base stations has reached 450,000 by mid 2014. Network quality has improved significantly and the TD-SCDMA subscribers have been increasing and reaching 215 million by March 2014 which is more than 50% of 3G users in China. Major handset vendors include both domestic companies such as ZTE, Huawei, Coolpad, Lenovo, as well as international vendors such as Samsung, LG, Motorola and HTC.

5.2 TD-LTE 4G network commercialization

Although TD-SCDMA 3G system is mainly deployed in China, major global players are involved from the very beginning of standardization and development of TD-LTE 4G system as a truly global technology. Most importantly, the basic features are common between TD-LTE and LTE FDD. From the specification point of view more than 90% of the content is same for TD-LTE and LTE FDD which is very important for common development of the equipments and dual mode coexistence.

- TD-LTE in China:

Since 2009, guided and regulated by MIIT (Ministry of Industry and Information Technology of China), operators and vendors are actively involved in trial and commercialization of TD-LTE technology. After 5 years of trial, TD-LTE technology has been stringently and heavily tested based on commercial oriented deployment, and a complete industrial ecosystem was formulated in china.

In July 2012, China Mobile began to deploy a large scale TD-LTE trial network. In the continuous coverage of TD-LTE of single frequency network deployment, the average downlink data rate achieved 30~40Mbps and the peak data rate exceeded 100Mbps. The call success rate was higher than 99% whereas call drop rate was less than 1%, having reached the quality of mature 2/3G network. Considering future network evolution and development of new services, advanced technologies such as carrier aggregation, multi-layer transmission, and voice over TD-LTE were also tested. In the case of the aggregation test using two carries, a peak data rate exceeding 200Mbps and an average data rate of 70Mbps were achieved in the downlink.

On Dec. 4th,2013, the MIIT of China formally issued three TD-LTE 4G licenses to China Mobile, China Telecom and China Unicom, indicating the formal beginning of the commercial deployments of TD-LTE in China. China Mobile has built the world's largest 4G network. By the end of 2014, TD-LTE base station reached 700,000, Domestic subscriber reached 80 million. China Mobile has a plan for 2015 that TD-LTE base station reaches 1 million, total 4G customer reaches 250 million.

- Global development perspective:

The TD-LTE industry has been robustly developing globally. As of May 2013, 104 TD-LTE worldwide licenses have been issued, which cover more than 3 billion population. As the end of 2014, 48 commercial TD-LTE networks have been launched in 30 countries. More than 40 operators are scheduled to launch commercial TD-LTE services in 2014-2015. According to global surveys[2], the market penetration rate is 37% and 63% for TD LTE and LTE-FDD, respectively. In terms of baseband chipset and UE development, 14 chipset vendors have successfully delivered TD-LTE chipset solutions, and approximately 644 types of TD-LTE terminals are available worldwide as of January 2015.

- Establishment of GTI [98]:

On 15th February 2011, during the mobile world congress in Barcelona, operators around world including China Mobile, Bharti, SoftBank, Vodafone and Clearwire jointly launched a Global TD-LTE Initiative, known as GTI, to promote TD-LTE system. GTI is an open platform aiming to bring major global operators together to make TD-LTE standard a leading technology for the next generation mobile broadband network.

5.3 WiMAX upgrade to TD-LTE(A)

In September 2011, the world's largest WiMAX operator, Sprint andClearwire announced their plan to upgrade their network to TD-LTE. Following the trend, 477 WiMAX networks in 150 countries will be upgraded to TD-LTE [99]. To accelerate the progress of convergence with TD-LTE and migration to TD-LTE for WiMAX and WiMAX Advanced, a Jointly Announce Strategic Collaboration was formed between WiMAX Forum and Global TD-LTE Initiative on Feb 25 2014 during the Mobile World Congress in Barcelona, Spain [100]. The unification of global 4G TDD standard will further promote the development of the TD-LTE market.

VI. TD-LTE-Advanced Evolution and TDD's Role in the Future 5G System

6.1 TD-LTE-Advanced evolution

Since LTE-Advanced is accepted as the 4G standard by ITU in WRC-12, LTE-Advanced evolution is being further researched on 3GPP, to satisfy increasing requirements and to work toward future fifth generation (5G) standard.

Key features discussed in TD-LTE-Advanced evolution are 3D-BF (3 Dimension BeamForming), D2D (Device to Device), small cell, etc.

- 3D-BF

The Rel-8 MIMO and subsequent MIMO enhancements in Rel-10 and Rel-11 were designed to support antenna configurations at the eNodeB that are capable of adaptation in azimuth only. Recently there has been a significant interest in enhancing system performance through the use of antenna systems having a two-dimensional array structure that provides adaptive control over both the elevation dimension and the azimuth dimension, which is also called FD-MIMO (Full Dimension MIMO).

As the number of transmitting antenna elements increases, the spatial channel of different users tend to be spatially orthogonal so the noise and neighboring cell interference becomes negligible, which allows power allocation to each user can be minimal and thus increasing the system capacity significantly. In FD-MIMO cases, the number of antennas may be very large, such as 64, 128 or 256. In such cases, for FDD, traditional channel estimation and channel state information feedback mechanisms become very complicated, where the pilot signals overhead, feedback overhead and pilot signal interference will be more difficult. However, utilizing channel reciprocity in TDD system, the system will be more efficient and less complex.

- D2D

With the proliferation of devices equipped with a cellular modem, device to device direct discovery offers itself as a potential feature that may significantly enhance the capabilities of LTE as a universal connectivity technology. Furthermore proximity-based applications and services represent a recent and enormous social-technological trend. The introduction of a device to device direct discovery capability in LTE would allow the 3GPP industry to intercept this important trend. It has been decided that the D2D UE will work on TDD mode in 3GPP. If the D2D UE works in FDD mode, the cost will increase since both transmitter and receiver chains are needed in the downlink-uplink paired frequency.

- Small cell

With the fast-advancing of mobile Internet, mobile data traffic increases dramatically. This trend has produced tremendous pressures on the capacity and deployment strategies of mobile networks. While it is increasingly difficult

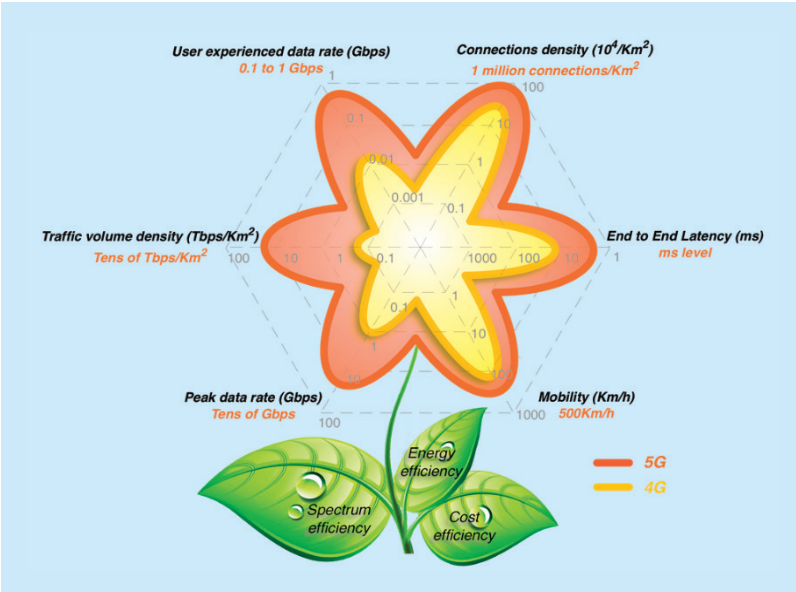

Fig.10 *Key capabilities of 5G*

Table V *Value requirements about key capabilities of 5G*

Key Capability	Value Requirement
User experienced data rate	0.1~1 Gbps
Connection density	1 million connections per square kilometer
End-to-end latency	millisecond level
Traffic volume density	tens of Gbps per square kilometer
Mobility	higher than 500Km per hour
Peak data rate	tens of Gbps
spectrum efficiency	5 to 15 times improvement
energy efficiency	100 times improvement
cost efficiency	100 times improvement

and expensive for macro networks to provide cost-effective and flexible capacity expansion by cell splitting, the small cell is now becoming a very attractive solution, especially for non-uniform traffic distribution. Statistics show that a significant and yet increasing portion of voice and data traffic happens at hotspots and indoor, where propagation, mobility and interference profiles differ substantially from traditional macro networks. Therefore, how to utilize these characteristics to provide optimized solutions for indoor and hotspot deployments to meet demands on higher bandwidth, higher performance, lower cost and adaptation to various backhauls, is becoming an important issue for further evolution of LTE. Small cell is more likely to be deployed with large bandwidth, so it is more easily to find blank spectrum in TDD mode.

Still, more topics are being discussed actively in 3GPP at present stage Rel-13, and will continue until Rel-16. With these features, TD-LTE-Advanced will still act as a key part in the future 5G.

6.2 Requirements and enabling technologies of 5G

Several organizations of standing are working to define "5G." The European Commission (EC) has funded projects like METIS[101] and 5GNow[102] under the Seventh Framework Program (FP7) and further has launched organization 5GPPP[103]. China has established the IMT-2020(5G) Promotion Group[105] and also 863 5G projects. Korea has established 5G Forum[106] and Japan has established 2020 and Beyond Ad-hoc group[107]. In addition, ITU-R WP5D has approved work items about IMT.VISION and IMT.TRENDS[108], to study future market and technology trends and potential technologies.

At present stage, the requirements of 5G is nearly in consensus among multiple organizations, mainly including 1000 times traffic increase, 10 times peak data rate, 10 times spectrum efficiency, millisecond level delay[104,105], etc. Chinese IMT-2020(5G) promotion group pronounced its expectation on 5G with the famous "blooming flower" [105] as shown in Figure 10. For the 5G flower, the petals and leaves rely on each other. The petals represent the six key capabilities in terms of performance and can fulfill the diverse requirements of future services and scenarios. The top of each petal means the maximum value of the corresponding capability. The leaves represent the three key capabilities in terms of efficiency and can guarantee the sustainable development of 5G. Exact value requirements about these key capabilities are further explained in detail in Table V.

To satisfy above requirements, at the moment a lot of enabling technologies are suggested by researchers from industries, mainly including ultra dense network, massive MIMO, novel multiple access, advanced coding and modulation, enhanced multiple carrier, high frequency communication, low latency & high reliability communication, device to device, machine to machine, flexible duplex, full duplex, unlicensed access and licensed share access, wireless backhaul, network control function orchestration, network capability openness, C-RAN evolution, multiple RATs resources coordinate, mobile content delivery network, etc[105]. Also, researchers from universities and institutes are continuing their research on novel technologies. It can be seen that these enabling technologies and also other future potential novel technologies will take important effects in 5G.

6.3 TDD's role in the future 5G system

TD-LTE-Advanced has been taking important roles in 4G standard and industry. Facing with 5G requirements and enabling technologies, TDD family will continue to take very important role due to its advantages on unsymmetrical frequency use and symmetrical propagation characteristics, making 5G more flexible in system design and network deployment.

To satisfy the requirements of high traffic volume and high data rate, more frequency is regarded as a necessary. However, the frequency below 6GHz is so scarcity that it's rather difficult to get broadband frequency allocation. Mm-wave communication[109] and dynamic frequency sharing are considered as two efficient ways to solve the broadband frequency allocation problem. Compared with FDD, TDD has evident advantages in getting broadband frequency allocation, because it uses the same frequency band for uplink and downlink. Therefore, enabling technologies like mm-wave communication, unlicensed access and licensed sharing access will be applied more easily in TDD mode.

To satisfy the requirements of high traffic density and high connection density, ultra high density networking is a commonly recognized resolution. For example, LTE-Hi[110] is a system proposed by China for hotspot and indoor coverage using high frequency, with high quality performance and high volume. Based on TDD mode, LTE-Hi takes dynamic slot allocation between uplink and downlink for adjacent cells, adapting the variation of cell traffic. Compared with FDD, TDD mode is more suitable for ultra high dense network.

To satisfy the requirements of high spectrum efficiency, massive MIMO is considered as the most enabling technology with expectation on 5~10 times enhancement for 5G relative to 4G system. Compared with FDD, TDD can provide symmetrical channel and CSI which is very useful for beamforming. Therefore, massive MIMO technology will take more efficient effect and lower cost in TDD mode.

In addition, a lot of other technologies, such as relay, device to device, coordination of multiple points, enhanced inter-cell interference cancellation, etc., can be more easily realized with high performance in TDD mode compared with in FDD mode.

Furthermore, information security is getting more and more important for mobile communication. TDD systems are demonstrated to have significant advantages in physical-layer transmission security. For example, the security key can be derived by the CSI, which can be obtained at both transmitter and receiver simultaneously with the channel reciprocity in TDD systems. Thus the security key will be very difficult to be decoded in TDD systems.

As a conclusion, TDD will take more important role in 5G compared with its functions in former generations, speeding up the development of 5G.

VII. CONCLUSION

This paper presented a comprehensive and systematic overview on the development of TDD technology. The TD-SCDMA 3G standard and the TD-LTE/TD-LTE-Advanced 4G standard and their key features were discussed in details, and the trend of next generation technology (5G) was also briefly studied.

Much more research and commercial opportunities exist thanks to the nature advantage of TDD. These opportunities will further dive TDD into a platform of future radio technologies. We hope that this paper will give a whole picture of TDD technology development and serve as a useful reference for 5G technology research.

ACKNOWLEDGMENT

We would like to thank Prof. Dake LIU from BIT, and Mr. Jian ZHAO, Ms. Shaoli Kang from CATT for their valuable advices and comments. This work was supported in part by the National Natural Science Foundation of China for Distinguished Young Scholar, Grant Number: 61425012.

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Abbreviations

1G	The first generation mobile systems
2G	The second generation mobile systems
3G	The third generation mobile systems
4G	The fourth generation mobile systems
5G	The fifth generation mobile systems
AAS	Adaptive Antenna System
AMPS	North American Advanced Mobile Phone System
BF	Beamforming
CATT	China Academy of Telecommunications Technology
CDMA	Code Division Multiple Access
CoMP	Coordination of Multiple Point
CSI	Channel State Information
D2D	Device to Device
DwPTS	Downlink Pilot Time Slot
eICIC	enhance ICIC
eIMTA	enhanced Interference Management and Traffic Adaptation
eNBs	enhanced Nodes of Base station
FDD	Frequency Division Duplex
FDMA	Frequency Division Multiple Access
FD-MIMO	Full Dimension MIMO
GP	Guard Period
GSM	Global System for Mobile Communications
GTI	Global TD-LTE Initiative
HetNet	Heterogeneous Network
ICIC	Inter-Cell Interference Coordination
LTE	Long Term Evolution
MBMS	Multimedia Broadcast Multicast Service
MIIT	Ministry of Industry and Information Technology of China

MU-	MultiUser
OFDM	Orthogonal Frequency Division Multiplexing
SIMO	Single Input Multiple Output
SU-	Single User
SVD	Singular Value Decomposition
TACS	British Total Access Communication System
TDD	Time Division Duplex
TD-	Time Division-
TDIA	the TD-SCDMA Industry Alliance
TD-LTE-A	TD-LTE Advanced
TD-SCDMA	Time division-Synchronous CDMA
TDMA	Time Division Multiple Access
UpPTS	Uplink Pilot Time Slot
WiMAX	Worldwide interoperability for Microwave Access

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