ACCEPTED FROM OPEN CALL

TECHNICAL INNOVATIONS PROMOTING STANDARD EVOLUTION: FROM TD-SCDMA TO TD-LTE AND BEYOND

SHANZHI CHEN, YINGMIN WANG, WEIGUO MA, AND JUN CHEN,
STATE KEY LABORATORY OF WIRELESS MOBILE COMMUNICATIONS,
CHINA ACADEMY OF TELECOMMUNICATIONS TECHNOLOGY

The authors present the evolution strategies from TD-SCDMA to TD-LTE and TD-LTE-Advanced, including standardization progress, key technologies, performance evaluation, industry development, and commercial status.

ABSTRACT

As the scarcity of frequency resources and the increasing wireless broadband requirements become very serious problems worldwide, more and more attention has been focused on TDD technology development, which is anticipated to provide desirable solutions to these problems. This has boosted standard evolution from TD-SCDMA to TD-LTE and TD-LTE-Advanced in recent years, with a lot of innovative technologies contributed to the TDD-based cellular mobile communication world. This article mainly presents the evolution strategies from TD-SCDMA to TD-LTE and TD-LTE-Advanced, including standardization progress, key technologies, performance evaluation, industry development, and commercial status. Some new technologies and challenging work for TD-LTE beyond are discussed as well.

INTRODUCTION

Time-division synchronous code-division multiple access (TD-SCDMA) is the first time-division duplex (TDD)-based international telecommunications standard. The evolution of TD-SCDMA cellular mobile communication systems can be divided into two phases: the CDMA phase and the orthogonal frequency-division multiplexing (OFDM) phase. The CDMA phase includes the basic and enhanced versions of TD-SCDMA systems, and the OFDM phase includes the time-division Long Term Evolution (TD-LTE) and TD-LTE-Advanced versions [1, 2].

The main features and key technologies of each evolution version are summarized in Table 1. More detailed descriptions of these features and technologies are provided in the following sections.

The majority of the papers in the literature have addressed the evolution process of TD-SCDMA; there are far fewer detailed studies on innovative technologies and evolution motivation of TD-SCDMA, TD-LTE, and beyond [1–5]. This article puts more emphasis on discussion of the innovative technologies of TD-SCDMA, TD-LTE, and beyond as well as the motivations behind TD-SCDMA evolution. Moreover, current industry development and the commercial status of TD-SCDMA and TD-LTE are also presented.

INNOVATIVE TECHNOLOGIES: TD-SCDMA, TD-LTE, AND BEYOND

Before starting a detailed discussion of technologies being used or considered for TD-SCDMA evolution, it is important to understand the motivation for this evolution. So this section first provides an understanding of whence the technical requirements and solutions for TD-SCDMA evolution may come.

MOTIVATION FOR TD-SCDMA EVOLUTION

TDD and frequency-division duplex (FDD) are two basic duplex modes in wireless communication systems. In TDD mode, physical channel transmissions in the uplink (UL) and downlink (DL) alter in the time domain. However, for FDD mode, physical channel transmissions are continuous in both directions. Traditionally, FDD is suitable for continuous coverage, while TDD is suitable for the coverage of hot spots in low-speed mobile scenarios [6].

However, because of the scarcity of frequency resources and the increasing wireless broadband requirements, the lack of sufficient spectrum resources is a major problem worldwide. To resolve this, higher spectrum efficiency, higher peak rate, improved capacity and coverage, and lower latency become crucial technique requirements. Moreover, lower cost and higher power efficiency are also required. Motivated by these requirements, more and more attention has been focused on TDD technology development with respect to the following advantages of TDD over FDD.

1536-1284/12/$25.00 © 2012 IEEE

Release	Characteristic descriptions
R99	WCDMA + HCR-TDD, TD-SCDMA is not included yet.
R4 (LCR-TDD)	Supporting basic features of TD-SCDMA, 1.6MHz bandwidth, smart antenna, dedicated channel allocation, UL/DL peak throughput 384K/2 Mb/s.
R5 (TD-HSDPA)	Supporting downlink shared channel fast scheduling, AMC and HARQ, 16-QAM, smart antenna, DL peak throughput 2.8 Mb/s.
R6 (TD-MBMS)	Supporting broadcasting and multicasting services.
R7 (TD-HSUPA, MC-LCR-TDD)	Supporting uplink shared channel fast scheduling, AMC and HARQ, 16QAM, UL peak throughput 2.2 Mb/s. Supporting multi-carrier TD-SCDMA, the bandwidth and peak throughput to be increased roughly proportionally to the amount of carriers.
R8 (HSPA+, TD-LTE)	HSPA enhancement: supporting MIMO and 64QAM for L1, and CPC and Cell-FACH enhancement for L2/L3. TD-LTE: supporting OFDM, MIMO, and single-layer beamforming, maximum bandwidth 20 MHz, and UL/DL peak throughput of 50/200 Mb/s.
R9 (HSPA+, TD-LTE)	HSPA further enhancement. TD-LTE: supporting dual-layer beamforming.
R10 and R11 (TD-LTE-Advanced)	To meet IMT-Advanced requirements. Supporting carrier aggregation, DL MIMO 8 × 8, UL MIMO 4 × 4, type 1 relay, MU-MIMO, CoMP, etc.

Table 1. *3GPP standardization roadmap for TD-SCDMA, TD-LTE, and TD-LTE-Advanced.*

Spectrum Allocation — TDD systems typically operate on unpaired frequency bands and thus can be deployed flexibly to achieve higher spectrum efficiency and higher peak date rate and improve capacity and coverage. FDD systems typically require paired frequency bands with a large enough guard gap to separate uplink and downlink transmissions, and thus always have lower spectrum efficiency.

Resource Allocation/Reconfiguration — In TDD mode, time slot resources can be allocated/reconfigured flexibly for uplink and downlink transmissions to support asymmetric traffic. In FDD mode, frequency band resources allocated for uplink/downlink transmissions are predetermined and cannot be dynamically adjusted. Thus, such resource allocation cannot flexibly support uplink/downlink asymmetric traffics.

Uplink and Downlink Reciprocity — In TDD mode, the same frequency is used for uplink and downlink transmissions so that the channel reciprocity can be exploited by the smart antenna technology to increase throughputs for users at cell edges. In FDD mode, uplink and downlink transmissions use different frequencies, so uplink and downlink channels are usually uncorrelated. Therefore, the performance gains achieved by using the smart antenna technology are much larger for TDD mode than for FDD mode.

Guard Period/Guard Gap — In TDD mode, a guard period is used to avoid the collision between uplink and downlink transmissions with a corresponding reduction in the system capacity as a consequence. A long guard period is normally required in order to accommodate a large propagation delay. However, for FDD mode, a guard gap is required to avoid interference between uplink and downlink transmissions, leading to a waste of spectrum resources.

Transmitter and Receiver Units — A device in TDD mode needs to frequently switch between transmission and reception, so the timing characteristics of switchers and related radio frequency (RF) components are critical for system performance. However, a device in FDD mode should separate its transmitter and receiver by using a duplexer, which should meet stringent requirements for transceiver separation. These cause obvious differences in the design of RF and antenna parts for TDD and FDD modes, and thus make the transceiver units in TDD devices more cost effective and power efficient.

Although there are some basic differences between TDD and FDD, as mentioned above, the commonality between TDD and FDD needs to be considered in order to realize compatibility and simplicity of implementation.

In summary, based on TDD's inherent merits and technology advancements, TD-SCDMA evolution becomes inevitable in order to fulfill these important requirements. It is expected that TD-SCDMA, TD-LTE, and TD-LTE-Advanced will play very important roles in future cellular mobile communications.

Technical Features of TD-SCDMA and TD-LTE

During the recent TD-SCDMA evolution, a lot of innovative technologies have been contributed to the TDD-based cellular mobile communication world. Compared to FDD-based systems, TD-SCDMA systems have several inherent advantages, such as more flexible spectrum allocation, asymmetric traffic patterns more suitable for mobile Internet services, and improved capacity and coverage using advanced smart antenna (SA) technology.

TD-LTE is the long-term evolution of TD-

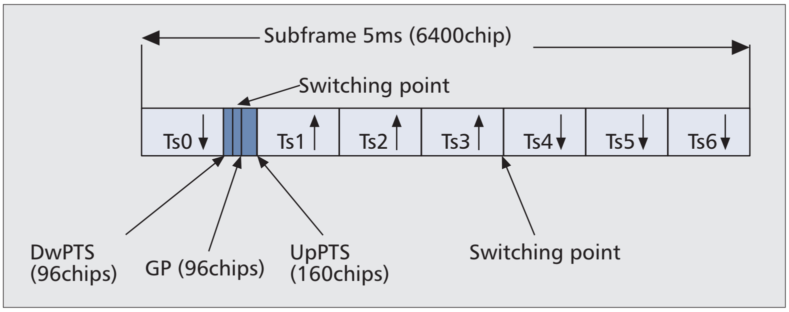

Figure 1. *TD-SCDMA subframe structure.*

SCDMA. Several fundamental technical characteristics of TD-SCDMA are preserved for TD-LTE. However, during the process of developing LTE and LTE-Advanced specifications, the maximum commonality between TDD and FDD has been emphasized in the Third Generation Partnership Project (3GPP), and realized by achieving a good balance between the commonality of basic structures and optimization of individual characteristics.

Frame Structure — TD-SCDMA transmission signals in downlink and uplink are organized into radio frames with 10 ms duration. Each radio frame is divided into two subframes of length 5 ms. Each subframe has seven normal and three specific time slots (i.e., DwPTS, GP, and UpPTS), as shown in Fig. 1. In each subframe, there are two switchpoints used for switching between uplink and downlink transmissions. The second switchpoint can be configured to support flexible time slot allocations for uplink and downlink transmissions so that both symmetric and asymmetric patterns can be supported in TD-SCDMA systems. DwPTS is used for downlink synchronization and cell search. UpPTS is used for uplink synchronization and random access. GP, between DwPTS and UpPTS, is the first switchpoint, and is used to avoid interference between uplink and downlink transmissions.

TD-LTE physical channels use a frame structure quite similar to that of TD-SCDMA, as shown in Fig. 2. Each radio frame consists of two half-frames of length 5 ms. Each half-frame is further divided into five equally sized subframes of length 1ms. Two kinds of downlink-to-uplink switch-point periodicities, 5 and 10 ms, are supported in the frame structure. In case of 5 ms downlink-to-uplink switchpoint periodicity, each half-frame consists of four normal subframes and one special subframe with three special fields (DwPTS, GP, and UpPTS), as illustrated in Fig. 2, while in case of 10 ms downlink-to-uplink switchpoint periodicity, one special subframe exists in the first half-frame only.

Multiple Antennas — Traditionally, beamforming is a spatial preprocessing scheme for single-stream transmission using closely-spaced antenna array (i.e., half wavelength), while precoding usually means a spatial pre-processing scheme for multi-stream transmission using a widely spaced antenna array.

In TD-SCDMA and its enhanced versions, the use of advanced smart antenna (SA) technology, also known as a single-stream beamforming scheme, has proven efficient for improving receiver sensibility and enlarging the coverage of TDD systems.

In TD-LTE systems, non-codebook-based transmission schemes with demodulation reference signal (DRS or DM-RS) are referred to as beamforming, while codebook-based schemes with cell-specific reference signal (CRS) are termed precoding. The single-layer beamforming scheme with the single-port DRS and the dual-layer beamforming scheme with the dual-port DM-RS are adopted by LTE R8 and R9 respectively, as illustrated in Fig. 3. Actually, both beamforming and precoding have the same preprocessing structure of antenna-array-based transmissions and thus allow for reuse of the common preprocessing algorithm.

In TD-LTE systems, the channel reciprocity between uplink and downlink can be exploited not only to acquire channel-state information (CSI) at base station (i.e., eNodeB, or eNB) side, but also to assist non-precoding matrix indicator (PMI)-based feedback mechanism at the user equipment (UE) side.

HARQ Design — In LTE systems, the basic principle of hybrid automatic repeat request (HARQ) protocols remains the same for both TDD and FDD modes because the asynchronous HARQ scheme in downlink and the synchronous HARQ scheme in uplink are supported for both FDD and TDD modes.

In FDD mode, each downlink subframe is always associated with a corresponding uplink subframe in a one-to-one manner, which implies a very simple one-to-one mapping relation between the PDSCH/PUSCH transmission and associated acknowledgment/negative acknowledgment (ACK/NACK) transmission. However, for TDD mode, the mapping relation between the PDSCH/PUSCH transmission and its associated ACK/NACK transmission always varies with the downlink-uplink allocation of TD-LTE systems, which leads to slightly complex HARQ protocols. For example, two ACK/NACK feedback mechanisms for downlink HARQ, i.e. ACK/NACK bundling and ACK/NACK multiplexing, are supported only in TD-LTE systems. The use of both ACK/NACK feedback mechanisms is well motivated by a possible need to acknowledge several PDSCH packets in a single uplink subframe for some downlink-heavy configurations in TD-LTE systems.

Technical Features of TD-LTE-Advanced

In order to meet ITU IMT-Advanced (4G) requirements, 3GPP proposed several key technologies, such as CA, relay, MIMO enhancement, Het-Net, and CoMP for LTE-Advanced systems. Moreover, the backward compatibility with LTE is also required as a design requirement of LTE-Advanced systems.

Carrier Aggregation — ITU requires that IMT-Advanced systems should support system bandwidth no less than 40MHz. But as current spectrum allocation schemes have been approved, it is hard to find another single fre-

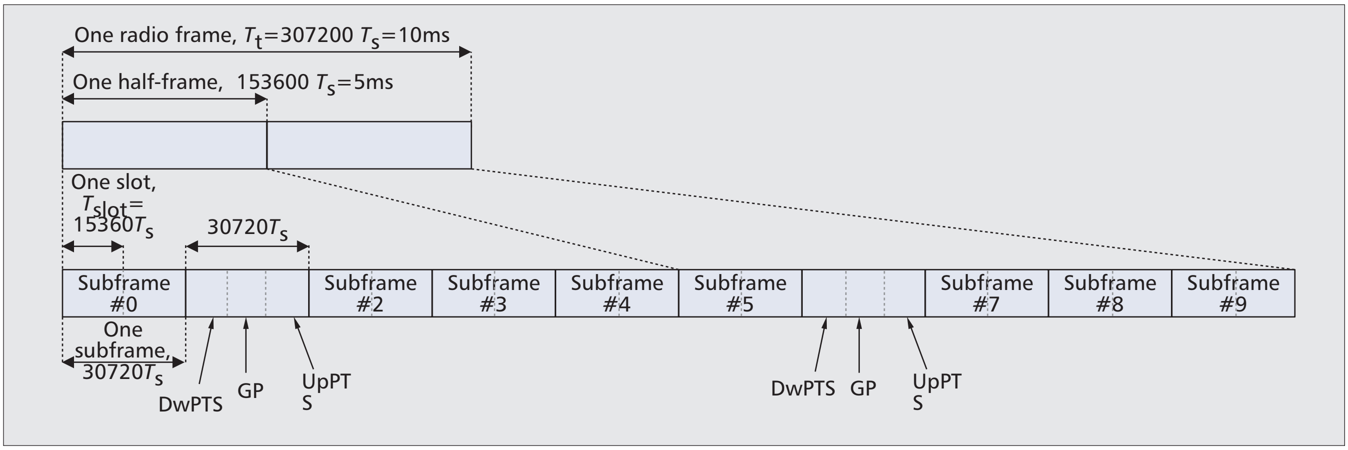

Figure 2. *TD-LTE frame structure (for 5ms switch-point periodicity).*

quency band to fulfill this requirement. In order to support wider transmission bandwidths, carrier aggregation (i.e., multiple component carriers to be aggregated) is adopted in LTE-Advanced systems. In typical TDD deployment scenarios, the same amount of component carriers with the same bandwidth in uplink and downlink is required so that a flexible design for carrier aggregation can easily be achieved.

Relaying — Relaying functionality is supported in LTE-Advanced systems to improve coverage and cell edge throughput. A new inband relay, called type 1 relay, is defined in LTE-Advanced specifications. There is a new link, called the backhaul link, between a relaying node (RN) and its donor eNB. The design of the backhaul link for TDD mode is quite different from that of FDD mode, typically including:
- Backhaul/access resource allocation
- Backhaul subframe allocation
- Backhaul HARQ timing
- eNB and RN frame timing/synchronization
- Transmission schemes

MIMO Enhancement — Multi-antenna transmission technologies are adopted in TD-LTE systems with limitations in the antenna configuration up to 4 × 4 in downlink and 1 × 1 in uplink. In TD-LTE-Advanced systems, there are further improvements to TD-LTE performance by introducing MIMO enhancements in downlink and uplink. The multi-antenna configuration is extended up to 8 × 8 in downlink and up to 4 × 4 in uplink. Hence, transmission diversity and spatial multiplexing can preferably be exploited by the use of multiple-input multiple-output (MIMO) enhancements to improve coverage or peak data rate.

Heterogeneous Network — Generally, low-rate services such as voice show a uniform distribution over the whole coverage area, while high-rate services concentrate in some hotspots, such as offices, schools, and apartment buildings. In order to solve the deployment problems in these complex scenarios and save deployment cost for operators, 3GPP proposed heterogeneous networks (Het-Nets) consisting of low power BS and macro BS. In Het-Nets, the macro BS usually supports medium-/low-rate services in large coverage areas, while the low-power BS mainly supports high-rate services in hotspots. A low-power BS can also be used in a coverage hole of a macro BS.

Some kinds of low-power BSs include:

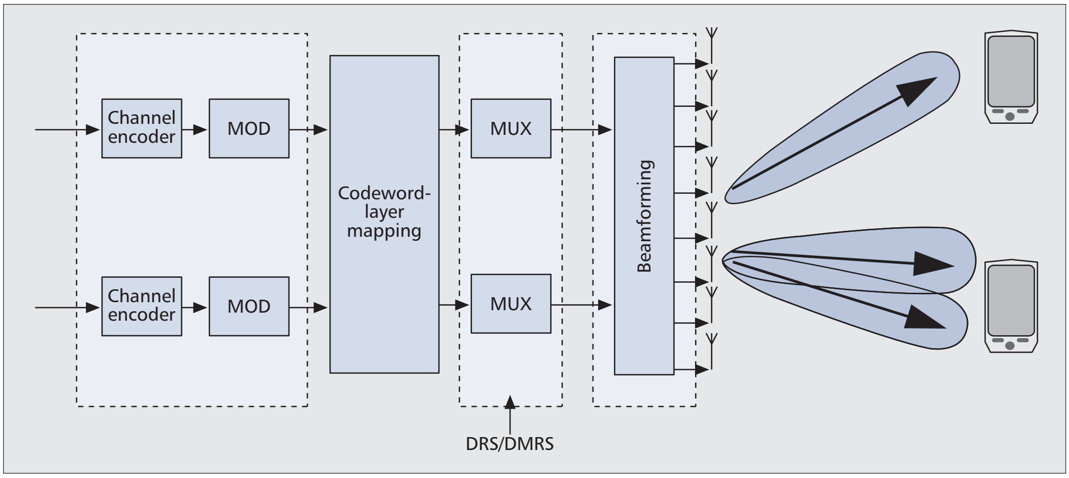

Figure 3. *Beamforming transmission schemes (single-stream/single-layer/dual-layer).*

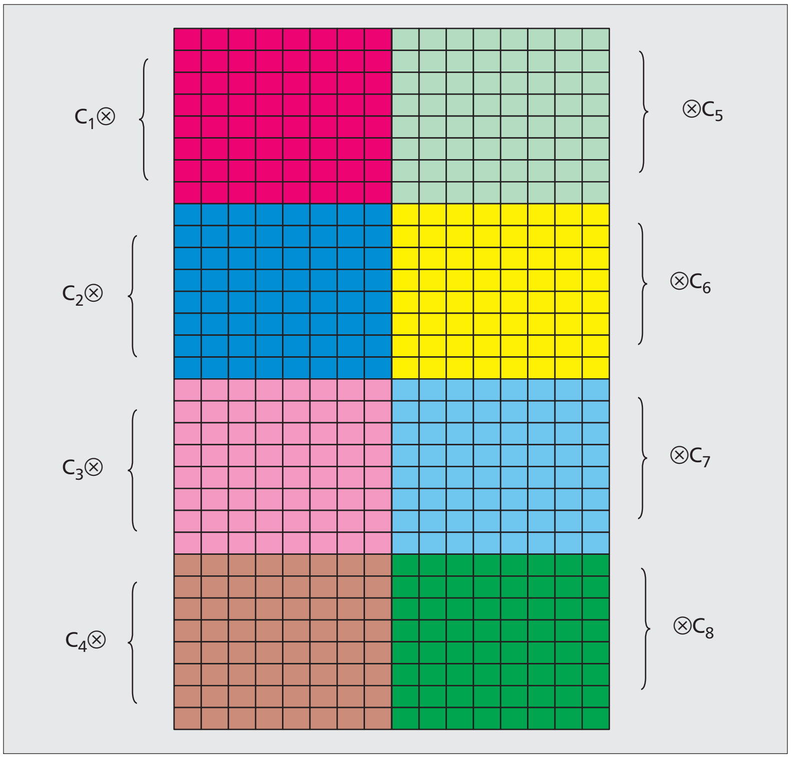

Figure 4. *Illustration of BR-OFDMA signal generation.*

- Femto BS, sometimes also called home BS, to be used in indoor scenarios, such as home and office
- Pico BS to be used in public hotspots, such as a market, subway, or plaza
- Relay BS that enables a wireless connection to macro BS through backhaul

CoMP — Coordinated multipoint (CoMP) transmission/reception technologies, such as joint processing (JP) or coordinated scheduling/beamforming (CS/CB), are considered as further extensions to traditional single-cell MIMO technologies [7]. In case of CS/CB, signals are transmitted from serving cells and user scheduling/beamforming decisions are made through coordination among cells in the CoMP cooperating set. In case of JP, a signal that intended for a single UE is simultaneously transmitted from multiple transmission points to improve the received signal quality.

Although CoMP is not supported yet in LTE R10, the study and evaluation of COMP are still going on within LTE R11. Some evaluation results show that CoMP can improve the average spectrum efficiency and particularly the cell-edge spectrum efficiency in high and low load scenarios [8].

Potential Technical Features of TD-LTE Beyond

By introducing several new technologies as mentioned above, TD-SCDMA, TD-LTE, and TD-LTE-Advanced have achieved remarkable optimization in system performances, such as throughput, spectrum efficiency, mobility, coverage, etc.

However, as the global energy and environment crises become serious challenges, energy saving and emission reduction should be carefully treated by the communications industry. Motivated by this goal, a green communication network, which can save energy, reduce emission, and make effective use of network and spectrum resources, should be the focus of future TD-SCDMA evolution. Some new technologies, such as Het-Nets and beamforming mentioned above, can be employed to resolve these problems under suitable conditions. Moreover, other more advanced technologies, described below, although not included in the IMT-Advanced standardization yet, may be considered as potential technical features of TD-LTE beyond that might be able to meet this goal.

Block Repeated OFDMA — In this part, a new multiple access technology called block repeated orthogonal frequency-division multiple access (BR-OFDMA) is presented [3]. The basic principle of BR-OFDMA is block-wise repeating of an OFDM modulated resource block with a repeat code. Each repeated block is multiplied by a specific weighting factor of the repeating code and then mapped to the corresponding time-frequency resources. The same time-frequency resources can be allocated simultaneously to multiple users who use different repeating codes. Figure 4 illustrates the basic principle of BR-OFDMA signal generation, where an OFDM modulated resource block is repeated eight times.

BR-OFDMA technology is a solution to interference problems in network deployment scenarios. When users in neighbor cells use the same time-frequency resources, the interference between the transmissions from these users can be mitigated by using BR-OFDMA at transmitter sides and joint detection at receiver sides. BR-OFDMA can be exploited not only to provide robustness against interference, but also to increase the capacity or coverage of TDD evolution systems.

Direct Device-to-Device Communications — Direct device-to-device (D2D) communications, or local peer-to-peer (P2P) communications, can be used to establish an ad hoc or a mesh network without backhaul. D2D communications underlying a cellular network normally use the same frequency resources as the cellular network, and can provide local services without serious interference impact on the primary cellular network [9]. The advantages of D2D communications are manifold, for example, higher total throughput, lower energy consumption, and more robustness to infrastructure failures.

In case of direct D2D communications, all UE devices receive and transmit signals on the same frequencies. Obviously, TDD mode is the best choice for D2D communications because its uplink and downlink transmissions also operate on the same frequencies.

Cooperative Communications and Network Coding — Spatial diversity is very effective against fading in wireless networks. However, in some scenarios, equipping a wireless node with multiple antennas may be infeasible. Consequently, the spatial

TDD evolution systems	Bandwidth (MHz)	Peak data rate (Mb/s)		Spectrum efficiency (b/s/Hz)		Voice capacity (users)
		UL	DL	UL	DL	
Single carrier	1.6	0.384	2.0	0.48	0.48	23
TD-SCDMA						
TD-HSPA	5.0	6.6	8.4	—	—	—
TD-HSPA+	5.0	6.6	25.2	0.75	1.10	116
TD-LTE	20	> 50	> 200	1.78	1.96	920
TD-LTE-Advanced	100	> 1000	> 2000	2.74	3.35	—

Table 2. *System performance in downlink and uplink.*

Cognitive radio relies on software defined radio, spectrum awareness, and dynamic spectrum access, and has the potential to utilize a large amount of unused spectrum in an intelligent way, adapting to rapid variations in environments.

diversity gain will be decreased. Fortunately, the use of cooperative communications can be supported at the user level to achieve spatial diversity gains provided by multiple antennas of several cooperative nodes. Thus, the overall system performance, including power efficiency and communication reliability, can be improved. Additionally, the use of network coding would be beneficial for cooperative networks to increase spectral efficiency and reduce power consumption [9].

Cognitive Radio — Cognitive radio (CR) relies on software defined radio (SDR), spectrum awareness, and dynamic spectrum access, and has the potential to utilize a large amount of unused spectrum in an intelligent way, adapting to rapid variations in environments [10]. It is expected that CR would provide not only advanced services at a reasonable cost, but also existing services in a power-efficient way.

CR technology is more beneficial for TDD evolution systems than FDD systems for several reasons. First, CR in TDD mode has more efficient spectrum utilization because it allows asymmetric downlink/uplink resource allocation on a single frequency band to optimize the dynamic spectrum assignment. Second, CR in TDD mode is more flexible because it can easily find a single frequency band in white spaces suitable for downlink and uplink transmissions. Finally, CR in TDD mode is more robust because there is less interference to other incumbent users; thus, the connection interruption caused by the spectrum emigration may seldom happen.

Performance of TD-SCDMA Evolution

This section mainly provides performance evaluation for TD-SCDMA evolution. Five evolution systems with the following features and parameters are studied:

- Single carrier TD-SCDMA with 1.6 MHz bandwidth and smart antenna
- TD-HSPA (HSDPA and HSUPA) with 3 carriers, 5 MHz bandwidth, and smart antenna
- TD-HSPA+ using 2 layer MIMO, 64-QAM, CPC for VoIP, 3 carriers, and 5 MHz bandwidth
- TD-LTE using dual-layer beamforming for downlink, SIMO for uplink, and 20 MHz bandwidth
- TD-LTE-Advanced using MU-MIMO with up to 4 paired users for downlink, MU-MIMO with the antenna configuration 2 × 8 for uplink, and 20 MHz bandwidth

Since users hope to experience high quality of services in terms of user throughput or peak data rate, but operators want to support as many users as possible in their networks, the number of active users (voice capacity) and peak data rate are thus chosen as important performance measures from operator and user perspectives. Moreover, spectrum efficiency is always used as a common measure of system performance. The evaluation is based on static simulations, and spectrum efficiency and peak data rate are evaluated in uplink and downlink separately.

The evaluation results, as shown in Table 2, demonstrate significant performance improvements achieved by introducing a series of new features and advanced technologies to TD-SCDMA evolution systems. For example, single carrier TD-SCDMA achieves a DL spectrum efficiency of 0.48 b/s/Hz, as compared to 1.1 b/s/Hz for TD-HSPA+, 1.96 b/s/Hz for TD-LTE, and 3.35 b/s/Hz for TD-LTE-Advanced. These results show very large gains in DL spectrum efficiency with more than a factor 2× for TD-HSPA+, a factor 4× for TD-LTE, and a factor 7× for TD-LTE-Advanced compared to single carrier TD-SCDMA. Similar performance gains are also reached for peak data rates in uplink and downlink and voice capacity, which indicate the high potential of TD-SCDMA evolution systems to improve user quality, capacity, and coverage.

Industry Development of TD-SCDMA and TD-LTE

TD-SCDMA Industry alliance (TDIA) was founded in 2002. There are 85 members that cover every part of TD-SCDMA industrial chains, such as vendors of radio access system, terminal, chip, antenna and test instrumentation, service providers, and operators. More than 200 vendors, institutes, and design houses join TD-

Many new features and innovative technologies are proposed and applied as the enhancements or complements to TDD evolution systems in order to fulfill subscriber's requirements, which provide an explicitly smooth evolution path for TD-SCDMA.

SCDMA supply chains and provide various products. Through the end of September 2011, the number of TD-SCDMA subscribers in China had reached 43 million. China Mobile recently announced that it is expanding its TD-SCDMA networks, with a total of 300,000 base stations to be built before the end of 2012.

TD-SCDMA has attracted more and more operators in Latin America, Africa, and Southeast Asia. NetAfrique deployed TD-SCDMA networks in the Republic of Ghana and developed thousands of subscribers in 2009.

TD-LTE has received considerable attention around world and shown astonishingly fast development in recent years. A solid international TD-LTE supply chain is forming with strong participants of 11 network equipment suppliers, 14 UE chip vendors, and 8 instrument developers. All the participants are now taking part in the TD-LTE test initiated by the Long Term Evolution/System Architecture Evolution Trial Initiative (LSTI). In June 2011, large-scale trial networks with more than 1000 macro eNBs were rolled out by China Mobile in six large cities in China in order to verify network capacity, service quality, and various applications in real environments.

Besides China Mobile, Aircel, Clearwire, Yota, Svyazinvest, and Bharti have announced deployments of TD-LTE in the future. Recently, SoftBank has begun to deploy TD-LTE commercial networks in Japan. Three main operators in Europe are also engaged in TD-LTE test and evaluation now.

Conclusion

TD-SCDMA has been regarded as an important milestone for the Chinese telecommunication industry in the 3G era. Now TD-SCDMA is evolving toward 4G standards (i.e., TD-LTE and beyond, which have attracted worldwide attentions among RD institutes, universities and industry organizations. Ericsson, Qualcomm, Motorola, and Nokia are also involved in the development of TDD technologies and have made many contributions. Many new features and innovative technologies are proposed and applied as the enhancements or complements to TDD evolution systems in order to fulfill subscriber's requirements, which provide an explicitly smooth evolution path for TD-SCDMA.

References

[1] G.Y. Liu *et al.*, "Evolution Map from TD-SCDMA to FuTURE B3G TDD," *IEEE Commun. Mag.*, vol. 44, no. 3, Mar. 2006, pp. 54–61.

[2] M.G. Peng and W.B. Wang, "Technologies and Standards for TD-SCDMA Evolutions to IMT-Advanced," *IEEE Commun. Mag.*, vol. 47, no. 12, Dec. 2009, pp. 50–58.

[3] M.G. Peng, W.B. Wang, and H.H. Chen, "TD-SCDMA Evolution," *IEEE Vehic. Tech. Mag.*, vol. 5, no. 2, June 2010, pp. 28–41.

[4] G.Y. Liu, J. H. Zhang, and P. Zhang, "Further Vision on TD-SCDMA Evolution," *APCC '05*, Oct. 2005, pp. 143–47.

[5] R. Esmailzadeh, M. Nakagawa, and A. Jones, "TDD-CDMA for the 4th Generation of Wireless Communications," *IEEE Wireless Commun.*, vol. 10, no. 4, Aug. 2003, pp. 8–15.

[6] T.S. Rappaport, *Wireless Communications: Principles and Practice*, IEEE Press, 1996.

[7] M. Sawahashi *et al.*, "Coordinated Multipoint Transmission/Reception Techniques for LTE-Advanced," *IEEE Wireless Commun.*, vol. 17, no. 3, June 2010, pp. 26–34.

[8] CATT, "Simulation Results for the CoMP Phase 1 Evaluations," 3GPP TSG-RAN1 Mtg. 65, R1-111365, Barcelona, Spain, May 2011.

[9] A. Osseiran *et al.*, "Advances in Device-to-Device Communications and Network Coding for IMT-Advanced," *ICT-MobileSummit 2009*, Santander, Spain, June 2009.

[10] S. Haykin, "Cognitive Radio: Brain-Empowered Wireless Communications," *IEEE JSAC*, vol. 23, no. 2, 2005, pp. 201–20.

Biographies

Shanzhi Chen [SM'04] (chensz@datanggroup.cn) received his Ph.D. degree from Beijing University of Posts and Telecommunications (BUPT), China, in 1997. He joined Datang Telecom Technology & Industry Group in 1994, and has served as CTO since 2008. He is a member of the steering expert group on information technology of the 863 Program of China. His current research interests include mobile communication technology, and network convergence and evolution.

Yingmin Wang received his Ph.D. degree in signal and information system from Xidian University, Xi'an, China. Since 2010 he has served as chief scientist, Datang Telecom Technology & Industry Group. He is currently leading the Datang Wireless Mobile Innovation Center. His current research interests include digital communication signal processing and wireless networks. He has applied for more than 150 patents in wireless communications, and published several papers.

Weiguo Ma received his B.Sc. degree in electrical engineering and Ph.D. degree in signal and information systems from Beijing Institute of Technology in 1993 and 1998, respectively. He is a professor at the State Key Laboratory of Wireless Telecommunications. He chaired several research projects from the National Hi-Tech R&D 863 Program of China as well as from the industry. His current research is focusing on prototype verification of key evolution technology of TD-LTE and beyond.

Jun Chen received his Ph.D. degree in information and communication engineering from Xidian University in 2000. He is an advanced technology research engineer at Datang Telecom Technology & Industry Group. His research interests include radio transmission technologies of 4G systems, wireless relay systems, MIMO, and channel coding.