LTE | Radio Interface and Radio Network Architecture | High Data Rate/High Capacity/Low Latency

Technology Reports

Special Articles on "Xi" (Crossy) LTE Service—Toward Smart Innovation—

Overview of LTE Radio Interface and Radio Network Architecture for High Speed, High Capacity and Low Latency

On December 24, 2010, the "Xi" (Crossy)[*1] *LTE service was launched in Tokyo, Nagoya and Osaka region. Compared with FOMA, the "Xi" (Crossy) service implements radio communication that provides higher data rate, higher capacity and lower latency. "Xi" (Crossy) uses LTE that incorporates various measures with regard to radio access technology, radio network configuration and radio interface protocol technology.*

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1. Introduction

Data traffic on mobile phone networks is growing rapidly due to the enrichment of services and content associated with the increased functionality of mobile terminals (User Eguipment (UE)) and the expansion of flat-rate data services. To ensure that favorable network quality is made available for this growing data traffic, there is a growing need for the use of radio communication technology that can make effective use of limited frequency resources. Also, to provide users with easy access to a wide variety of applications on mobile phone networks, it is necessary to increase data transfer speeds and provide low-latency radio communication technology to reduce connection delays and transmission delays.

Under these circumstances, NTT DOCOMO has introduced a "Xi" (Crossy) LTE service to provide radio communication that outperforms FOMA in terms of data rate, capacity and latency. The service was initially launched in Tokyo, Nagoya and Osaka region on December 24, 2010.

As an overview of the LTE technologies that support "Xi" (Crossy), this article describes technical aspects including radio access methods, radio network configurations and radio interface protocol technology shown in **Figure 1**.

2. Overview of Radio Access Methods

LTE uses Orthogonal Frequency Division Multiple Access (OFDMA)[*2] as the radio access method for downlinks. OFDMA enables the transmission of high-quality signals in multipath[*3] mobile communication environments. By modifying the number of subcarriers[*4] that make up the OFDM signal, it is also possible to adapt to a wide variety of different channel bandwidths, and to operate flexibly in accordance with the band-

*1 **"Xi" (Crossy)**: "Xi" (read "Crossy") and its logo are trademarks of NTT DOCOMO.

*2 **OFDMA**: A radio access scheme that uses Orthogonal Frequency Division Multiplexing (OFDM). OFDM uses multiple low data rate multi-carrier signals for the parallel transmission of wideband data with a high data rate, thereby implementing high-quality transmission that is highly robust to multipath (see *3) interference (interference from delayed waves.)

*3 **Multipath**: A phenomenon that results in a radio signal transmitted by a transmitter reaching the receiver by multiple paths due to propagation phenomenon such as reflection, diffraction, etc.

width assigned to operators. Furthermore, due to the strong affinity with channel-dependent scheduling in the frequency domain and Multiple-Input Multiple-Output (MIMO)[*5] technology, these core technologies can be used to implement high data rate and high-capacity communication.

Meanwhile, Single-Carrier FDMA (SC-FDMA)[*6] is used as the uplink radio access method. One of the benefits of SC-FDMA is its ability to reduce the signal's Peak-to-Average Power Ratio (PAPR)[*7], thereby achieving power savings in the UE and a reduction in the costs associated with transmitter power amplifiers. It is also possible to apply channel-dependent scheduling in the frequency domain, and since the signals are orthogonalized between users in the same cell (intra-cell orthogonalization[*8]), fractional transmission power control (fractional TPC) can be used to modify the target received power in the vicinity of cells and at cell edges. These interference control techniques make it possible to achieve high data rate and high-capacity communication.

Figure 2 shows the radio frame structure used for LTE signal transmission [1]. This 10 ms radio frame consists of ten 1 ms sub-frames. Each sub-frame consists of two 0.5 ms slots, and each slot comprises seven symbols. By reducing the radio frame length, it is possible to reduce connection delays and control delays, thereby implementing a low-latency radio access network.

In the LTE system, channels used for transmitting and receiving data are shared by multiple users. The base station (eNodeB: evolved node B) performs scheduling to allocate users with radio resources[*9] on the shared data channel in which data is transmitted and received (**Figure 3**). The minimum

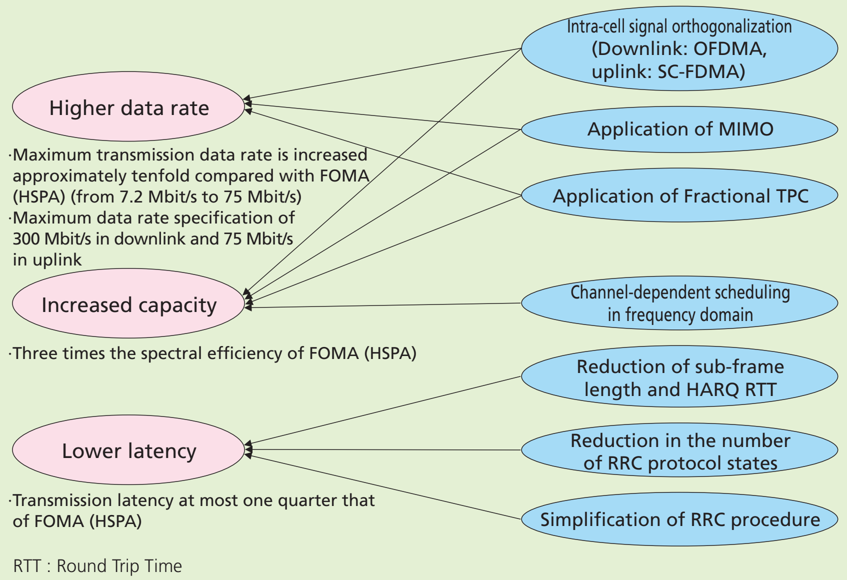

Figure 1 Features of LTE

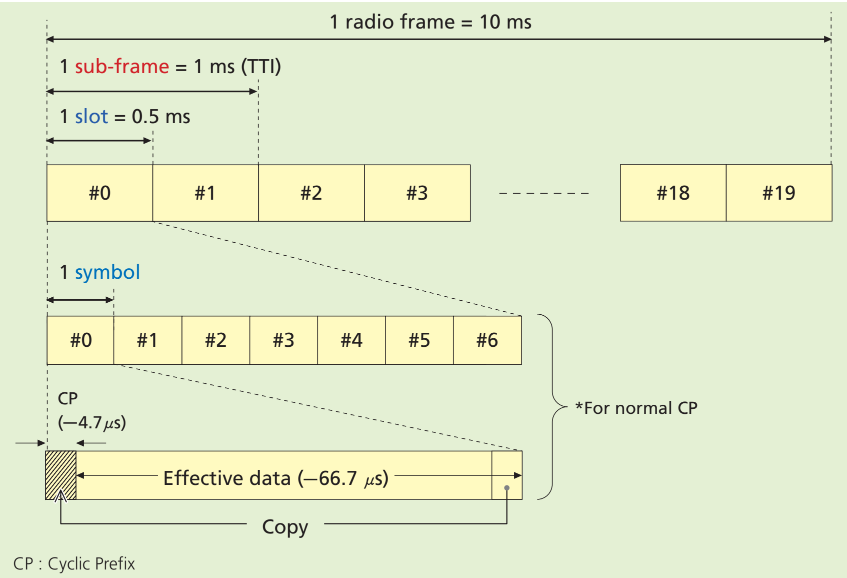

Figure 2 Radio frame configuration

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*4 **Subcarrier**: One of the individual carrier waves used to transmit a signal in multi-carrier transmission schemes such as OFDM.

*5 **MIMO**: A spatial multiplexing method where signals are transmitted using multiple transmitting antennas and received using multiple receiving antennas for increased transmission speed and transmission capacity.

*6 **SC-FDMA**: A radio access method that implements multiple access by allocating the signals for different users to different frequencies while transmitting the signals for an individual user at a single frequency.

*7 **PAPR**: The ratio of the peak transmission power of a signal to the average transmission power. A larger PAPR necessitates the use of an amplifier with lower power efficiency to avoid distortion when amplifying the signal, which is particularly problematic for the amplifiers mounted in UEs.

allocation unit of radio resources is called a Resource Block (RB), and as shown in Fig. 3, a single RB consists of 12 sub-carriers in the frequency domain, and seven symbols in the time domain. The minimum scheduling time unit is called a Transmission Time Interval (TTI), which consists of a single sub-frame, and in each sub-frame, RBs are allocated to the UE selected by the scheduling.

The LTE channel configuration can be broadly divided into two types — the physical channel and the physical signal. The physical channel transmits information from higher protocol layers, and the physical signal consists of signals that are terminated within the physical layer. **Table 1** shows an

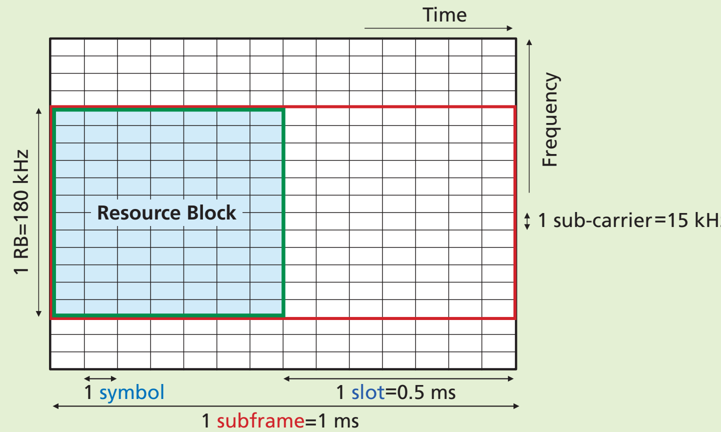

Figure 3 Sub-frame configuration and RB placement

Table 1 Overview of physical channels and physical signals

Name of physical channel/physical signal	Purpose
SS (Synchronization Signal)	Synchronization signal used for cell search. This cell's physical ID (PCI) and SS sequence have a one-to-one binding
DLRS (Downlink Reference Signal)	Used for downlink propagation path estimation, symbol timing synchronization, reception quality measurement, quality measurements for cell selection and hand-overs, etc.
PBCH (Physical Broadcast Channel)	Used to transmit the minimum amount of information (system bandwidth, system frame number, number of transmitting antennas) initially needed for reading after a UE performs a cell search
PDSCH (Physical Downlink Shared Channel)	A shared data channel for transmitting user data in the downlink, where all data is transmitted together regardless of whether it is for the C-Plane or U-Plane
PCFICH (Physical Control Format Indicator Channel)	Used to report how many symbols at the head of each sub-frame can be reserved as a region capable of transmitting downlink control information
PHICH (Physical HARQ Indicator Channel)	A channel for transmitting delivery confirmation information (ACK/NACK) to a PUSCH
PDCCH (Physical Downlink Control Channel)	Used by an eNodeB to indicate radio resource allocation information to a user selected by scheduling
PMCH (Physical Multicast Channel)	Used for the operation of MBSFN
DM RS (Demodulation Reference Signal)	Used for uplink propagation path estimation, symbol timing synchronization, reception quality measurement, etc. DM RS is multiplexed with the PUSCH and PUCCH transmitted by the UE
SRS (Sounding Reference Signal)	Used for reception quality measurements and timing adjustments that are needed for the application of channel-dependent scheduling in frequency domain. Transmission bands from broadband to narrowband are supported
PRACH (Physical Random Access Channel)	Used when a UE is establishing a connection to or resynchronizing with a cell, e.g. at an initial access or handover. May be either contention-based or non-contention-based
PUSCH (Physical Uplink Shared Channel)	A shared data channel for transmitting user data in the uplink, where all data is transmitted together regardless of whether it is for the C-Plane or U-Plane
PUCCH (Physical Uplink Control Channel)	Used to transmit ACK/NACK signals to the PDSCH, downlink reception quality and scheduling request

ACK : Acknowledgement
MBSFN : Multimedia Broadcast multicast service Single Frequency Network
NACK : Negative Acknowledgement

Downlink physical channel
Uplink physical channel

*8 **Orthogonalization**: When multiple signal series are multiplexed and transmitted in the same radio system band, the process of adjusting them so they do not interfere with each other (making them orthogonal).

*9 **Radio resources**: In this article, frequency bandwidth, transmission power, etc. available to each user.

overview of the LTE physical channel and physical signal. Also, **Figures 4** and **5** show the physical channel configurations of the downlink and uplink.

3. Key Technologies in Layer 1 and Layer 2

Including the purpose of each physical channel, the basic key technologies of the LTE physical layer (layer 1[*10]) and radio link protocol layer (layer 2[*11]) are as follows [1]-[3].

1) Cell Search

Cell search is the process whereby a UE searches for the best cell to connect to. The signal used for cell search is called a Synchronization Signal (SS), and in LTE it is transmitted in the 945 kHz band at the center of the system bandwidth. This allows cell searches to be performed in the minimum bandwidth compatible with LTE without the UE having to be aware of the channel bandwidth used by the system. An overview of the cell search procedure is shown in **Figure 6**. SS uses two types of code sequence — a primary-SS (P-SS) sequence which is mainly used for symbol timing synchronization and local ID detection, and a secondary-SS (S-SS) which is used for radio frame synchronization and cell group ID detection. By detecting a combination of these two sequences, it is possible to acquire the physical ID (Physical Cell Identity (PCI)) of the cell in question.

The downlink Physical Broadcast

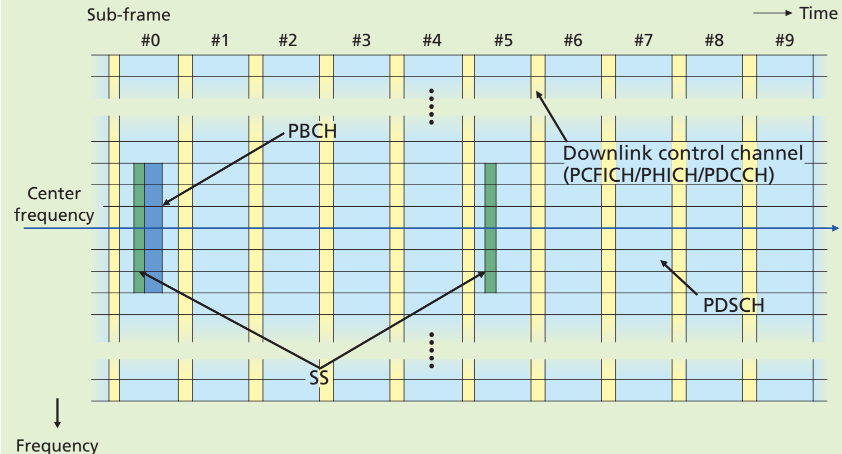

Figure 4 Downlink physical channel configuration

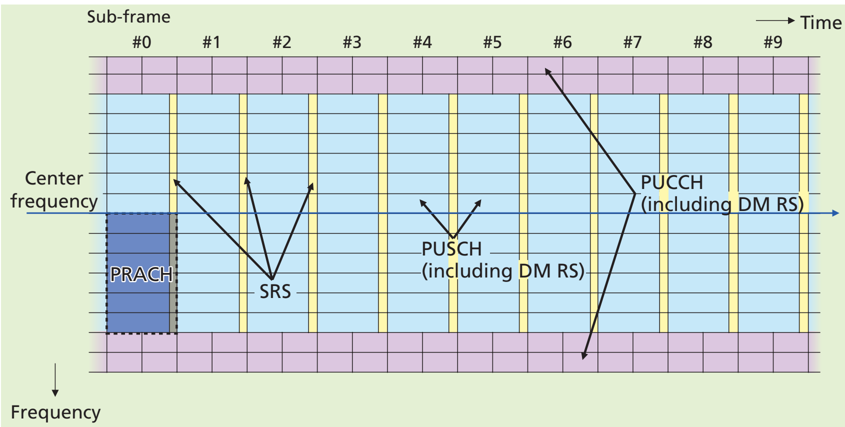

Figure 5 Uplink physical channel configuration

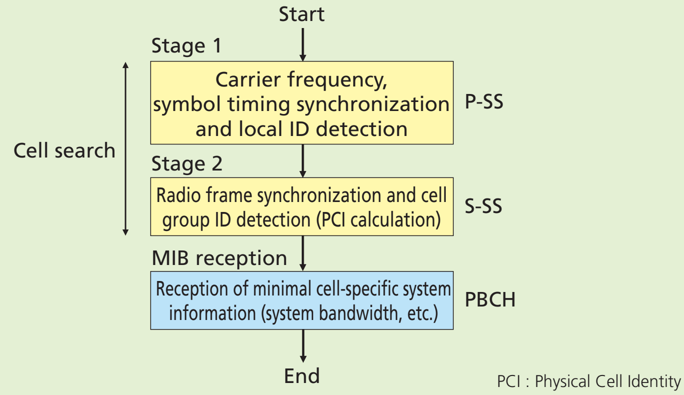

Figure 6 Cell search procedure

*10 **Layer 1**: The first layer (physical layer) in the OSI reference model.

*11 **Layer 2**: The second layer (data link layer) in the OSI reference model.

Channel (PBCH) includes only the bare minimum of information that needs to be read first by the UE after a cell search. This information is called the Master Information Block (MIB), and includes basic information such as the channel bandwidth and System Frame Number (SFN), and the number of transmitting antennas. Other system information is carried by a System Information Block (SIB) transmitted via the shared data channel (described below). Since the PBCH needs to be decoded without prior knowledge of the bandwidth, like SS, it is transmitted in the central 1.08 MHz section of the channel bandwidth. By transmitting the SS and PBCH in the center of the band in this way, it is possible to implement fast cell search in systems of any bandwidth, allowing "Xi" (Crossy) to be used for flexible cell development (using a 5 MHz channel bandwidth for outdoor areas and a 10 MHz channel bandwidth for some indoor facilities).

2) Channel-dependent Scheduling in the Frequency Domain

As mentioned above, LTE achieves a simple system configuration by using a shared data channel to transmit all data regardless of whether it belongs to the Control-Plane (C-Plane) that handles control messages or the User-Plane (U-Plane) that handles user data. The PDSCH carries not only user data such as the C-Plane and U-Plane, but also notifications including System Information Blocks (SIBs) and information such as paging[*12] messages that are generated when calls are made (Table 1).

In LTE, it is possible to perform two-dimensional channel-dependent scheduling by considering not only the time domain but also the frequency domain. In the downlink, the UE measures the reception quality of the DL RS (Downlink Reference Signal) transmitted from eNodeB, and reports the result to eNodeB as a Channel Quality Indicator (CQI). Based on this information, the eNodeB allocates RBs with good reception quality to each user to improve the spectral efficiency. Channel-dependent scheduling in the frequency domain can also be applied to the uplink in the same way, and by measuring the reception quality of the Demodulation RS (DM RS) and Sounding RS (SRS) transmitted from the UE, the eNodeB is able to allocate RBs with good reception quality to each user. DM RS is a reference signal that is multiplexed in order to demodulate the PUSCH. On the other hand, SRS is a reference signal for measuring the reception quality across the entire band. To maintain the SC-FDMA single-carrier transmissions, each UE is always allocated continuous RBs in the uplink.

For a user selected by the eNodeB in scheduling, the radio resource allocation is indicated by the Physical Downlink Control Channel (PDCCH). The PDCCH carries scheduling information called DL scheduling information in the downlink and a UL scheduling grant in the uplink. This control information includes the allocated RB's position, modulation method and data size (size of Transport Block (TB)[*13]), and command information for transmitter power control. The PDCCH also includes the Cell-Radio Network Temporary Identifier (C-RNTI) of the destination UE, and the UE allocates the radio resources if it finds that the C-RNTI is addressed to it.

3) Random Access

When a UE is making a call or engaging in a hand-over, a random access procedure is used if a connection with an eNodeB is established or is resynchronization is performed. In random access, the channel used for initially sending the preamble[*14] is called the Physical Random Access Channel (PRACH). For example, **Figure 7** shows an overview of how random access works when making a call. The UE sends a preamble selected at random from the multiple preambles available within the cell. When the eNodeB detects the preamble, it replies by sending a RACH response. When the UE receives a RACH response, it sends a Radio Resource Control (RRC)[*15] connection request signal as message 3. After the eNodeB has received message 3, it transmits message 4, which comprises an RRC connection setup mes-

*12 **Paging**: A method and signal for calling a visiting UE that is on standby when a call is received.

*13 **TB**: A basic unit used when processing data transmissions and the like.

*14 **Preamble**: The signal sent by a UE when performing random access control such as during initial connection.

*15 **RRC**: Layer 3 (see *31) protocol for controlling radio resources.

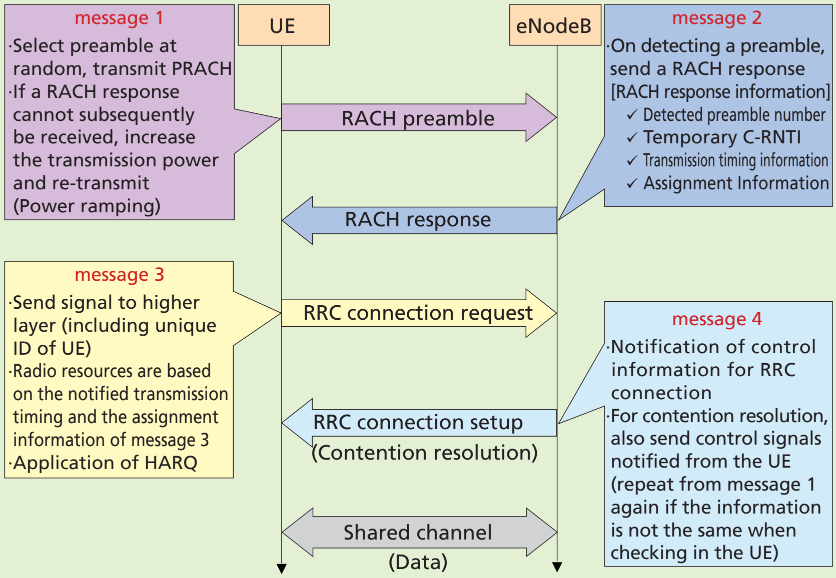

Figure 7 Random access overview

sage including cell setup information for establishing the connection. When a UE receives a message 4 containing its own UE ID, it terminates the random access process and establishes the connection. On the other hand, if its own UE ID is not included, the random access is aborted and the process is repeated by sending a preamble.

4) MIMO

In the downlink, it is possible to employ MIMO technology using multiple transmitting and receiving antennas. Transmissions from up to four antennas are supported, which is expected to lead to a significant improvement in peak data rate. According to the rank indicator reported from the UE, rank adaptation is used to switch between transmit diversity[*16] and multi-codeword transmission[*17] [4].

5) Fractional TPC

Since SC-FDMA makes it possible to orthogonalize signals between UEs in the frequency domain as mentioned above, it is immune to the same-cell (same-sector) interference that affects CDMA. This means fractional TPC can be used to control the target value of the received level of transmission power control for each individual UE [4]. In fractional TPC, the target values of UEs close to the eNodeB can be set higher for increased throughput,[*18] and the target values of UEs close to the cell edge can be set lower to reduce interference with other cells. This makes it possible to improve the system's overall throughput.

4. Radio Network Configuration

The main features of an LTE radio network architecture include the fact it only supports packet switched domains, and the fact that it uses a flat architecture with distributed control.

Since it is specialized only for packet switched networks, there is no need to provide an interface to connect with circuit switched networks, and the radio network configuration can be simplified. For the LTE to provide voice services, which are the principal services of conventional circuit switched networks, the VoIP protocol is used.

4.1 Architecture

The LTE radio access network is configured solely with eNodeB base stations, each of which is connected by an S1 interface to the Evolved Packet Core (EPC) core network accommodating the LTE (**Figure 8**). Specifically, the C-Plane is connected to the Mobility Management Entity (MME)[*19] via an S1-MME interface, and the U-Plane is connected to the Serving Gateway (S-GW)[*20] via an S1-U interface. Neighboring eNodeB base stations are connected via an X2 interface. The EPC node configuration and core network technologies are discussed in references [5] and [6].

Each eNodeB performs Radio Resource Management (RRM) tasks

*16 **Transmit diversity**: Technology which utilizes the differences in channel fluctuation between transmission antenna channels to obtain diversity gain.

*17 **Multi-codeword transmission**: A method whereby each signal stream is independently transmitted by parallel encoding and data modulation when using MIMO to transmit signals by spatial multiplexing of multiple signal streams.

*18 **Throughput**: Effective amount of data transmitted without error per unit time.

*19 **MME**: A logical node accommodating a base station (eNodeB) and providing mobility management and other functions.

*20 **S-GW**: The area packet gateway accommodating the 3GPP access system.

such as call admission control, hand-over control and bearer[*21] management, and all forms of radio control including scheduling the shared data channel mentioned above, and terminates all the radio interface protocols used for communication with the UE (**Figure 9**).

This architecture reduces not only the processing for each packet in the radio access network but also the number of control signals, compared with the current FOMA system where a Radio Network Controller (RNC)[*22] is provided as a higher node for each NodeB. This contributes significantly to the reduction of packet delays and control delays associated with call connection, hand-overs and the like.

As radio processing and control tasks are terminated by the eNodeB, hard hand-overs[*23] are utilized in LTE. During a hard hand-over, the transmission of user data is temporarily interrupted, but only for a few tens of milliseconds.

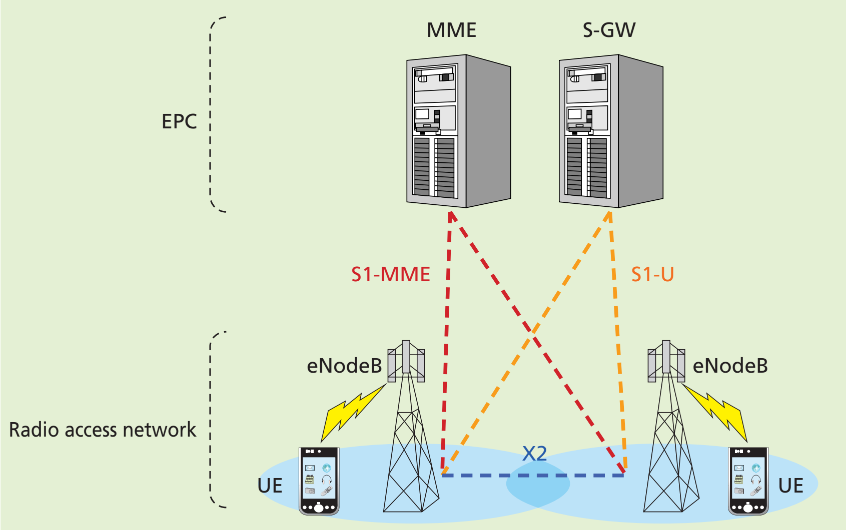

Figure 8 LTE radio access network architecture

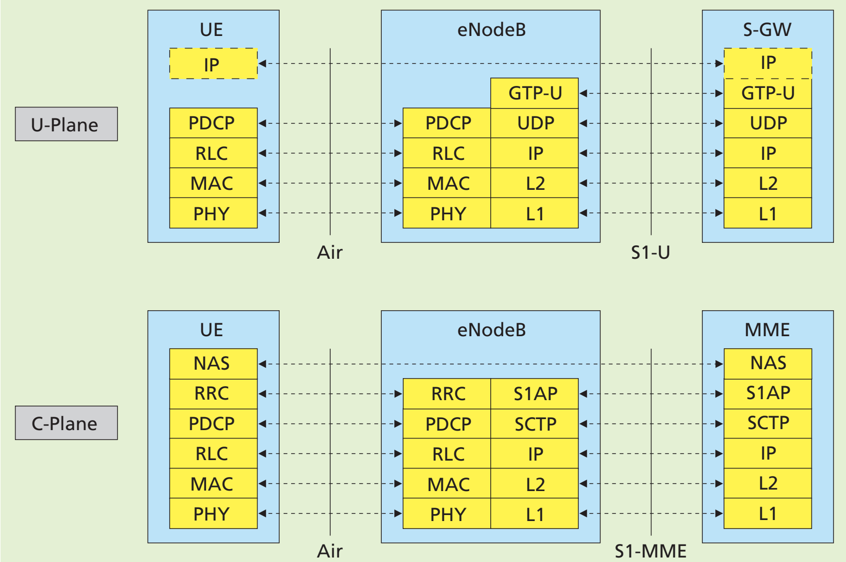

Figure 9 LTE protocol configuration

4.2 Transmission line protocol

1) S1 Interface

In the S1-MME interface, the following functions are performed by the S1 Application Protocol (S1AP).

- Management of the S1 interface itself
- Paging delivery to UEs
- Transmission of Non Access Stratum (NAS)[*24] messages between MMEs and UEs
- Management of bearers to be set up for the UE

S1AP messages are transmitted by Stream Control Transmission Protocol (SCTP)[*25]/IP. The S1-U interface is used for transmitting user IP packets between an eNodeB and S-GW. This interface uses the UDP layer on top of IP transport, and the GTP-U (General Packet Radio Service (GPRS) Tunneling Protocol for U-Plane) layer to pro-

*21 **Bearer**: A logical packet transmission path set up at an S-GW, eNodeB, UE, or the like.
*22 **RNC**: A device that performs radio circuit control and migration control in the W-CDMA method defined on 3GPP.
*23 **Hard hand-over**: A hand-over control method whereby a UE migrates to a new cell after stopping communication in its current cell.
*24 **NAS**: A functional layer between the UE and core network.
*25 **SCTP**: A transport layer protocol created to transmit telephone network protocols over IP.

vide UE and bearer identification.

2) X2 Interface

In the C-Plane of the X2 interface, an X2 Application Protocol (X2AP)[*26] layer is defined. During hand-overs between eNodeB base stations, the source and target eNodeB base stations can use X2 messages in order to directly exchange hand-over request and response messages. Furthermore, the user IP packets of downlinks buffered in the eNodeB are transferred via the U-Plane of the X2 interface from the source eNodeB base station to the target eNodeB base station, thereby avoiding packet losses in the radio access network during hand-overs.

The lower layer configuration of the X2AP layer is the same as that of the S1AP layer, and the U-Plane protocol configuration of the X2 interface is the same as that of the S1-U interface.

5. Radio Interface Protocols

The LTE radio interface protocol is terminated between eNodeB and UE (Fig. 9). The U-Plane is configured from the abovementioned Layer 1 PHY[*27] protocol, and a Layer 2 comprising the Medium Access Control (MAC)[*28], Radio Link Control (RLC)[*29], and Packet Data Convergence Protocol (PDCP)[*30] protocols. The C-Plane is configured from the same protocols as the U-Plane and from the Layer 3[*31] RRC protocol.

The PHY parts of Layer 1 are as described in Chapters 2 and 3. Here, we describe an overview of Layer 2 and Layer 3.

5.1 Layer 2

Figure 10 shows the Layer 2 architecture on the transmitting side.

1) PDCP

A PDCP entity is configured in the PDCP sublayer for each bearer. On the transmitting side, user IP packets are header compressed and ciphered for user data bearers (Data Radio Bearers (DRBs)), and RRC messages are ciphered and integrity protected for control message bearers (Signaling Radio Bearers (SRBs)), and are transferred to the RLC sublayer as a PDCP Protocol Data Unit (PDU)[*32]. On the receiving side, the corresponding header decompression, deciphering and integrity checking[*33] are performed.

During a hand-over, packet loss is avoided by retransmitting unacknowledged user data at the transmitting side, and duplicate detection and reordering are performed at the receiving side.

2) RLC

The RLC sublayer also has RLC entities configured per bearer. The RLC has three modes — Acknowledged Mode (AM), Unacknowledged Mode (UM) and the Transparent Mode (TM) in which the RLC itself is transparent. The transmitting side of RLC-AM/UM adaptively segments and concatenates PDCP PDUs to generate RLC PDUs of suitable length for the TB size of each TTI, and transfers them to the MAC sublayer. At the receiving side, the corresponding PDCP PDU reassembly is performed.

Also, in RLC-AM, based on acknowledgement (STATUS PDU) signals from the receiving side, the trans-

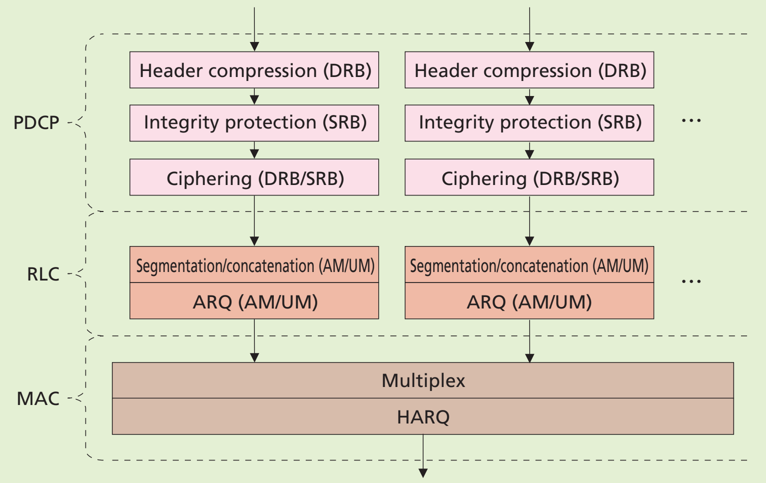

Figure 10 Layer 2 architecture on the transmitting side

*26 **X2AP**: A protocol that implements control in an X2 interface.

*27 **PHY**: The physical layer, which performs radio signal transmission processes such as modulating radio frequency carriers and modulating encoded data.

*28 **MAC**: A sub-MIMO layer in Layer 2 of the radio interface in LTE that provides protocols for allocating radio resources, mapping data to TBs, and performing HARQ (see *34) retransmission control.

*29 **RLC**: One of the sublayers in Layer 2 of the radio interface in LTE that provides protocols for retransmission control, duplicate detection, reordering and the like.

*30 **PDCP**: One of the sublayers in Layer 2 of the radio interface in LTE that provides protocols for ciphering, integrity protection, header compression and the like.

*31 **Layer 3**: The third layer (IP layer) in the OSI reference model. In this article, refers to the RRC protocol.

*32 **PDU**: Unit of data processed by a protocol layer/sublayer.

mitting side performs Automatic Repeat Request (ARQ) control to retransmit RLC PDUs, thereby compensating Hybrid ARQ (HARQ)[*34] residual errors in the MAC sublayer. The RLC-AM/UM receiving side also performs duplicate detection and reordering.

3) MAC

The MAC sublayer performs scheduling of shared channel resources. In the downlink, the eNodeB scheduler decides on the particular UE and the particular SRB/DRB of the UE from which to multiplex RLC PDUs onto the TB that it transmits. In the uplink, the eNodeB scheduler decides on which UE to allocate PUSCH resources to, and the UE decides on the particular SRB/DRB from which to multiplex RLC PDUs onto the TB. The MAC entities on the transmitting and receiving sides transmit TBs by using HARQ, and the receiving side extracts the RLC PDU from the TB and transfers it to the RLC entity.

The following control processes are also performed in the MAC sublayer.

- Random access
- Synchronization of uplink transmission timing to preserve the orthogonality of signals between UEs in the uplink
- Feedback of UE information needed by the uplink scheduler (buffer status and transmission power status)
- Discontinuous reception while establishing an RRC connection for UE battery saving

5.2 Layer 3

1) RRC

The RRC supports procedures and messages needed for the following processes.

- Delivery of system notification
- Delivery of emergency earthquake alerts
- Paging delivery
- NAS message transmission
- RRC connection management
- Radio bearer management
- Radio security configuration
- Measurement and reporting configuration
- Hand-over control
- RRC connection re-establishment control

Features to realize smooth introduction of LTE are also supported by providing the following inter-working functions with the existing FOMA system:

- Hand-overs between LTE and FOMA systems
- Circuit Switched (CS) fallback to FOMA system when a UE accesses incoming or outgoing circuit-switched services while visiting LTE [7]
- Designation of a prioritized standby system (LTE or FOMA) for each UE

There are only two RRC states for a UE in LTE: RRC_IDLE during standby and RRC_CONNECTED when a radio connection is established. This is simpler than the FOMA system which has multiple sub-states for when a wireless connection is established.

2) Connection Setup Procedure

In the LTE, connection setup sequence, the NAS message is piggybacked onto the RRC message so as to reduce the number of messages at the air interface and to reduce the connection setup delay.

6. Conclusion

In this article, we have described an overview of the LTE radio interface and radio network architecture that support “Xi” (Crossy). With the high-speed, high-capacity low-latency radio communication technology implemented by LTE, it should be possible to develop a more advanced mobile broadband environment and to accelerate the evolution of mobile telephony services and networks. It should be noted that the LTE technologies discussed in this article are based on the LTE Release 8 specification, for which standardization by the 3GPP was completed in the spring of 2009. To further enhance the functionality of LTE, the 3GPP completed the LTE Release 9 specification in October 2010, and with

*33 **Integrity check**: Checking data for tampering.

*34 **HARQ**: A technique that compensates for errors in received signals through a combination of error-correcting codes and retransmission.

the aim of making further improvements in system performance, we are now working on the detailed specification of LTE-Advanced (LTE Release 10 and beyond). For details, see references [8] and [9].

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