LTE-Advanced MIMO CoMP

Technology Reports

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—Ongoing Evolution of LTE toward IMT-Advanced—

MIMO and CoMP in LTE-Advanced

The standardization of LTE-Advanced, which is an enhanced version of LTE, is currently in progress at the 3GPP. LTE-Advanced will maintain backward compatibility with LTE, while realizing considerably higher spectral efficiency and cell-edge user throughput than LTE. Extensions to MIMO technology as well as CoMP technology are being studied for LTE-Advanced to accomplish these goals.

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1. Introduction

Release 8 specification on the radio interface of Universal Mobile Telecommunications System (UMTS) LTE (hereinafter referred to as "LTE Rel. 8"), was completed in 3GPP in December 2008 [1][2]. LTE Rel. 8 is a mobile radio packet access system supporting a variety of traffic with low delay and low cost, so after the standard radio interface was completed, development of commercial equipment proceeded. The LTE Rel. 9 specification, which expands on some of the functions of LTE Rel. 8, such as User Equipment (UE) location measurements, was also completed in December 2009 at the 3GPP [3][4].

In parallel with LTE Rel. 9, a Study Item (SI) on LTE-Advanced was approved in March 2008, and study of the LTE-Advanced radio interface began [5]. See reference [6] regarding the requirements for LTE-Advanced. Multiple Input Multiple Output (MIMO)*1 and Coordinated Multi-point transmission/reception (CoMP)*2 are two radio-access technologies being studied to contribute to satisfying these requirements [7]. After the SI, a Work Item (WI) for MIMO technology was approved to begin study in December 2009. Work is also proceeding on deciding the standard specification for the radio interface specification, to be completed by the end of 2010 as Rel. 10 [8][9]. For LTE-Advanced, the MIMO and CoMP technologies are seen as important technologies for meeting system performance requirements, including spectral efficiency*3 (system capacity) and cell-edge user throughput. Increasing system capacity and user throughput will help to increase user data transmission speed and reduce per-bit system costs. Also, to maintain backward compatibility

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*1 **MIMO**: A signal transmission technology that uses multiple antennas at both the transmitter and receiver to perform spatial multiplexing and improve communication quality and spectral efficiency (see *3).

*2 **CoMP**: Technology which sends and receives signals from multiple sectors or cells to a given UE. By coordinating transmission among multiple cells, interference from other cells can be reduced and the power of the desired signal can be increased.

*3 **Spectral efficiency**: The number of data bits that can be transmitted per unit time and unit frequency band.

of the LTE-Advanced system with LTE Rel. 8, it is based on LTE Rel. 8 multiple access[*4]. Accordingly, the MIMO technology in LTE-Advanced should be based on the technology adopted for LTE Rel. 8.

In this article, we describe the MIMO and CoMP technology in LTE Rel. 8 and LTE-Advanced, which is based on discussion and agreement reached at the 3GPP.

2. MIMO Technology in LTE Rel. 8

2.1 Downlink MIMO Technology

Single-User MIMO (SU-MIMO) was used for the downlink for LTE Rel. 8 to increase the peak data rate. The target data rates of over 100 Mbit/s were achieved by using a 20 MHz transmission bandwidth, 2×2 MIMO, and 64 Quadrature Amplitude Modulation (64QAM)[*5], and peak data rates of over 300 Mbit/s can be achieved using 4×4 SU-MIMO. The multi-antenna technology used for the downlink in LTE Rel. 8 is classified into the following three types.

1) Closed-loop SU-MIMO and Transmit Diversity[*6]

For closed-loop SU-MIMO transmission on the downlink, precoding is applied to the data carried on the Physical Downlink Shared Channel (PDSCH) in order to increase the received Signal to Interference plus Noise power Ratio (SINR)[*7]. This is done by setting different transmit antenna weights for each transmission layer (stream) using channel information[*8] fed back from the UE. The ideal transmit antenna weights for precoding are generated from eigenvector(s) of the covariance matrix[*9] of the channel matrix[*10], H, given by $H^H H$, where ^{H} denotes the Hermitian transpose [10]. However, methods which directly feed back estimated channel state information or precoding weights without quantization[*11] are not practical in terms of the required control signaling overhead. Thus, LTE Rel. 8 uses codebook-based precoding, in which the best precoding weights among a set of predetermined precoding matrix candidates (a codebook) is selected to maximize the total throughput on all layers after precoding, and the index of this matrix (the Precoding Matrix Indicator (PMI)) is fed back to the base station (eNode B) (**Figure 1**) [11].

LTE Rel. 8 adopts frequency-selective precoding, in which precoding

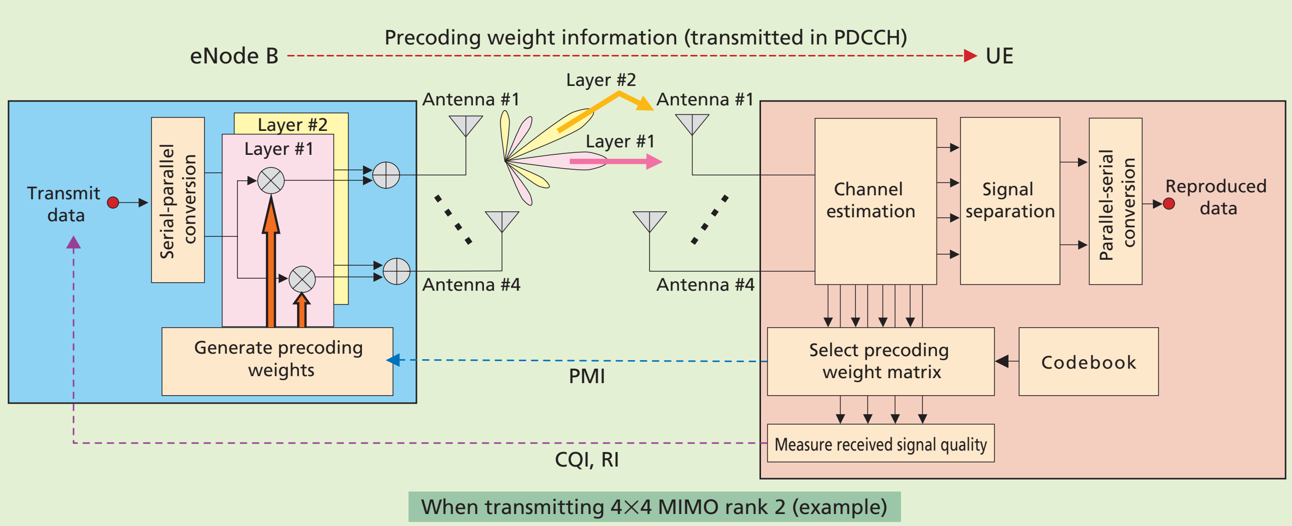

Figure 1 Closed-loop SU-MIMO transmission using code-book-based precoding

*4 **Multiple access**: Indicates methods in a radio system in which channels are assigned from among multiple vacant radio channels for communication, when multiple UE are communicating within the system.

*5 **64QAM**: A digital modulation method used in wireless communication. Data is transmitted using 64 different phase and amplitude costellations. Can transmit more data at a time (6bits) than either Quadrature Phase Shift Keying (QPSK) or 16QAM.

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

*7 **Received SINR**: The ratio of desired-signal power to the total power from interference from other users in the same cell, interference from other cells and sectors, and from noise within the received signal.

*8 **Channel information**: Parameters values representing the attenuation, phase change and delay in the received signal relative to the transmitted signal, due to traversing the radio channel between transmitter and receiver.

weights are selected independently for each sub-band of bandwidth from 360 kHz to 1.44 MHz, as well as wideband precoding, with single precoding weights that are applied to the whole transmission band [12]. The channel estimation[*12] used for demodulation and selection of the precoding weight matrix on the UE is done using a cell-specific Reference Signal (RS) transmitted from each antenna. Accordingly, the specifications require the eNode B to notify the UE of the precoding weight information used for PDSCH transmission through the Physical Downlink Control Channel (PDCCH), and the UE to use this information for demodulation.

LTE Rel. 8 also adopts rank adaptation, which adaptively controls the number of transmission layers (the rank) according to channel conditions, such as the received SINR and fading correlation[*13] between antennas (**Figure 2**). Each UE feeds back a Channel Quality Indicator (CQI), a Rank Indicator (RI) specifying the optimal rank, and the PMI described earlier, and the eNode B adaptively controls the number of layers transmitted to each UE based on this information.

2) Open-loop SU-MIMO and Transmit Diversity

Precoding with closed-loop control is effective in low mobility environments, but control delay results in less-accurate channel tracking ability in high mobility environments. The use of open-loop MIMO transmission for the PDSCH, without requiring feedback of channel information, is effective in such cases. Rank adaptation is used, as in the case of closed-loop MIMO, but rank-one transmission corresponds to open-loop transmit diversity. Specifically, Space-Frequency Block Code (SFBC)[*14] is used with two transmit antennas, and a combination of SFBC and Frequency Switched Transmit Diversity (FSTD)[*15] (hereinafter referred to as "SFBC+FSTD") is used with four transmit antennas. This is because, compared to other transmit diversity schemes such as Cyclic Delay Diversity (CDD)[*16], SFBC and SFBC+FSTD achieve higher diversity gain, irrespective of fading correlation between antennas, and achieve the lowest required received SINR. On the other hand, for PDSCH transmission with rank of two or higher, fixed precoding is used regardless of channel variations. In this case, cyclic shift[*17] is performed before applying the precoding weights, which effectively switches precoding weights in the frequency domain, thereby averaging the received SINR is over layers [9].

3) Adaptive Beamforming[*18]

Adaptive beamforming uses antenna elements with a narrow antenna spacing of about half the carrier wavelength and it has been studied for use with base stations with the antennas mounted in a high location. In this case beamforming is performed by exploiting the UE Direction of Arrival (DoA) or the channel covariance matrix estimated from the uplink, and the resulting transmit weights are not selected from a codebook. In LTE Rel. 8, a UE-specific RS is defined for channel estimation in order to support adaptive beamforming [9]. Unlike the cell-specific RS, the UE-specific RS is weighted with the same weights as the data signals sent to each UE, and hence there is no need to notify the UE of the precoding weights applied at the eNode B for demodulation at the UE. However, its effective-

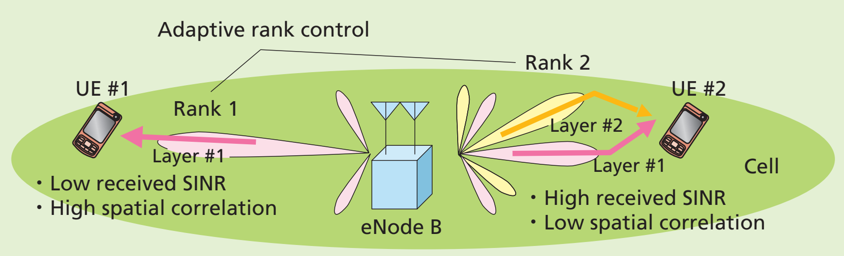

Figure 2 Rank adaptation

*9 **Covariance matrix**: A matrix whose diagonal components express the variance of each variable in a set of variables and whose other elements each express the degree of correlation between two variables with respect to their direction of change (positive/negative).

*10 **Channel matrix**: A matrix composed of the changes in amplitude and phase on the channels between each transmit and receive antenna pair.

*11 **Quantization**: In digital communications, approximation of the amplitude and phase of an analog signal using discrete, digital values. When converting to digital data, the number of levels used effects the quality of the information.

*12 **Channel estimation**: Estimation of the amount of attenuation and phase change in the received signal when a signal is transmitted over a radio channel. The estimated values obtained (the channel data) are used for separating MIMO signals and demodulation at the receiver, and to compute channel data which is fed back to the transmitter.

*13 **Fading correlation**: In this article, an index indicating the correlation of fading between different antennas used in MIMO transmission.

ness is limited in LTE Rel. 8 because only one layer per cell is supported, and it is an optional UE feature for Frequency Division Duplex (FDD)[*19].

2.2 Uplink MIMO Technology

On the uplink in LTE Rel. 8, only one-layer transmission was adopted in order to simplify the transmitter circuit configuration and reduce power consumption on the UE. This was done because the LTE Rel. 8 target peak data rate of 50 Mbit/s or more could be achieved by using a 20 MHz transmission bandwidth and 64QAM and without using SU-MIMO. However, Multi-User MIMO (MU-MIMO) can be used to increase system capacity on the LTE Rel. 8 uplink, using multiple receiver antennas on the eNode B. Specifically, the specification requires orthogonalization[*20] of the demodulation RSs from multiple UEs by assigning different cyclic shifts of a Constant Amplitude Zero Auto-Correlation (CAZAC) sequence[*21] to the demodulation RSs, so that user signals can be reliably separated at the eNode B. Demodulation RSs are used for channel estimation for the user-signal separation process [9].

3. MIMO Technology in LTE-Advanced

3.1 Downlink 8-Layer SU-MIMO Technology

The target peak spectral efficiency in LTE-Advanced is 30 bit/s/Hz. To achieve this, high-order SU-MIMO with more antennas is necessary. Accordingly, it was agreed to extend the number of layers of SU-MIMO transmission in the LTE-Advanced downlink to a maximum of 8 layers [6]. The number of transmission layers is selected by rank adaptation. The most significant issue with the radio interface in supporting up to 8 layers is the RS structure used for CQI measurements and PDSCH demodulation.

1) Channel State Information (CSI)-RS

For CQI measurements with up-to-8 antennas, new CSI-RSs are specified in addition to cell-specific RS defined in LTE Rel. 8 for up-to-four antennas. However, in order to maintain backward compatibility with LTE Rel. 8 in LTE-Advanced, LTE Rel. 8 UE must be supported in the same band as in that for LTE-Advanced. Therefore, in LTE-Advanced, interference to the PDSCH of LTE Rel. 8 UE caused by supporting CSI-RS must be minimized. To achieve this, the CSI-RS are multiplexed over a longer period compared to the cell-specific RS, once every several subframes (**Figure 3**). This is because the channel estimation accuracy[*22] for CQI measurement is low compared to that for demodulation, and the required accuracy can be obtained as long as the CSI-RS is sent about once per feedback cycle. A further reason for this is that LTE-Advanced, which offers higher data-rate services, will be developed to complement LTE Rel. 8, and is expected to be adopted mainly in low-mobility environments.

2) UE-specific RS

To allow demodulation of eight-layer SU-MIMO, the UE-specific RS were extended for SU-MIMO transmission, using a hybrid of Code Division Multiplexing (CDM)[*23] and Frequency Division Multiplexing (FDM)[*24] (**Figure 4**). The UE-specific RS pattern for each rank (number of layers) is shown in **Figure 5**. The configuration of the UE-specific RS in LTE-Advanced has also been optimized differently from those of LTE Rel.8, extending it for SU-MIMO as well as adaptive beamforming, such as by applying two-dimensional time-frequency orthogonal

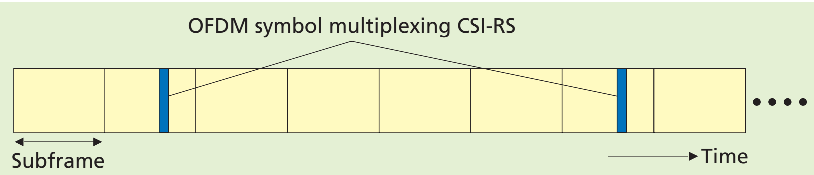

Figure 3 Example configuration multiplexing CSI-RS

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*14 **SFBC**: A type of transmit diversity technology in which Alamouti coding is used between adjacent subcarriers on two transmit antennas, and by coding between frequencies and antennas, diversity gain equivalent to maximal ratio combining can be obtained.

*15 **FSTD**: A type of transmit diversity technology, in which diversity gain can be obtained by switching between two or more antennas for each subcarrier when transmitting.

*16 **CDD**: A type of transmit diversity technology, in which differing amounts of cyclic delay is assigned to the same data signal between transmit antennas, producing frequency diversity gain while avoiding inter-symbol interference.

*17 **Cyclic shift**: For a transmitted signal, when the phase of each subcarrier is shifted by a fixed interval.

*18 **Beamforming**: A technique for increasing or decreasing the gain of antennas in a specific direction by controlling the amplitude and phase of multiple antennas to form a directional pattern of the antennas.

*19 **FDD**: A method for implementing simultaneous transmission and reception with technologies like radio, in which transmission and reception are done using different frequencies.

CDM to the multiplexing between transmission layers [7].

3.2 Downlink MU-MIMO Technology

In addition to the peak data rate, the system capacity and cell-edge user throughput must also be increased in LTE-Advanced compared to LTE Rel. 8. MU-MIMO is an important technology for satisfying these requirements [13]. With MU-MIMO and CoMP transmission (described below), various sophisticated signal processing techniques are applied at the eNode B to reduce the interference between transmission layers, including adaptive beam transmission (zero-forcing[*25], block diagonalization[*26], etc.), adaptive transmission power control[*27] and simultaneous multi-cell transmission. When these sophisticated transmission techniques are applied, the eNode B multiplexes the UE-specific RS described above with the PDSCH, allowing the UE to demodulate the PDSCH without using information about transmission technology applied by the eNode B. This increases flexibility in applying sophisticated transmission techniques on the downlink. On the other hand, PMI/CQI/RI feedback extensions are needed to apply these sophisticated transmission techniques, and this is currently being discussed actively at the 3GPP.

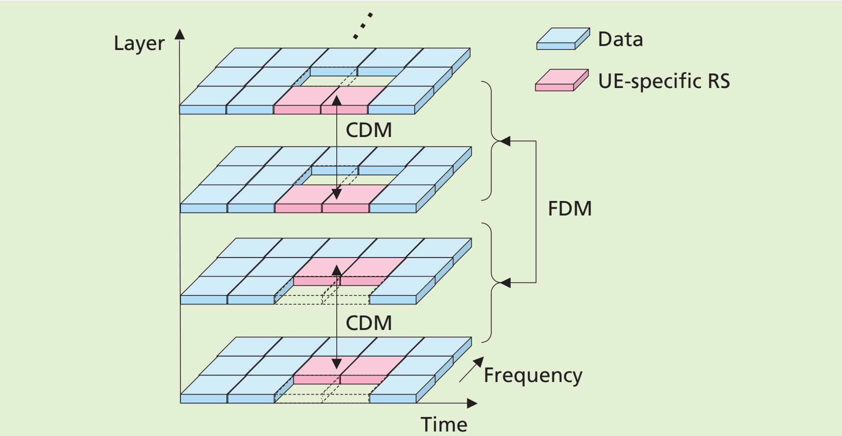

Figure 4 UE-specific RS multiplexing

3.3 Uplink SU-MIMO Technology

To reduce the difference in peak data rates achievable on the uplink and downlink for LTE Rel. 8, a high target peak spectral efficiency of 15 bit/s/Hz

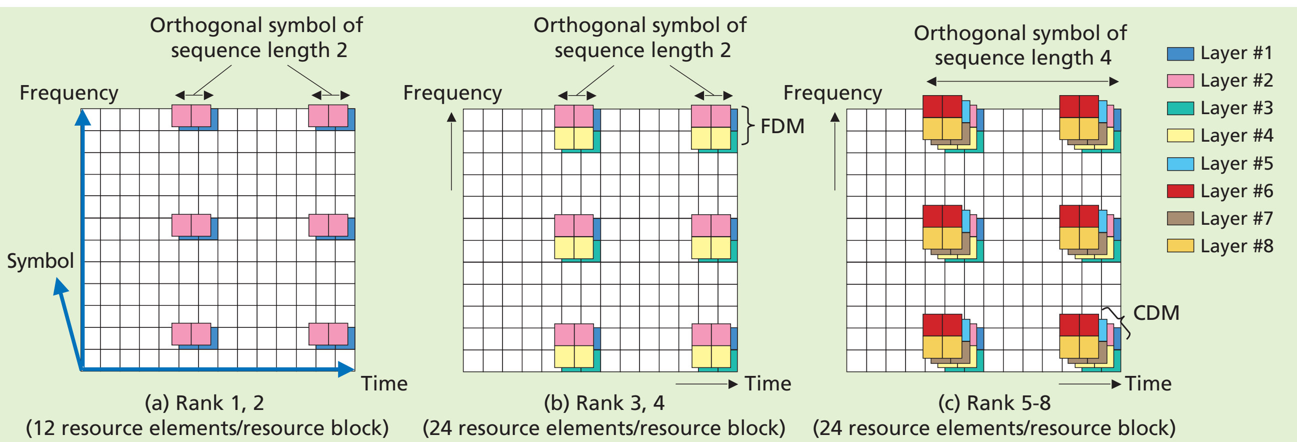

Figure 5 UE-specific RS configuration

*20 **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).

*21 **CAZAC sequence**: A type of orthogonal spreading sequence, using cyclic shifts, which has excellent characteristics for autocorrelation and cross-correlation, has fixed amplitude in both time and frequency domains, and has small PAPR (see *28).

*22 **Channel estimation accuracy**: The accuracy of estimating the variation of amplitude and phase in the channel by using RS, which are multiplexed with the data for each packet frame.

*23 **CDM**: When transmitting multiple signal sequences on the same radio system band, multiplexing them using spreading series' that are mutually orthogonal.

*24 **FDM**: When transmitting multiple signal sequences on the same radio system band, multiplexing them using frequencies that are mutually orthogonal.

*25 **Zero-forcing**: When using precoding and beam forming on the transmitter, a method which uses the ordinary inverse of the channel matrix to generate weighting coefficients such that the interference between users is completely zeroed.

was specified for the LTE-Advanced uplink. To achieve this, support for SU-MIMO with up to four transmission antennas was agreed upon. In particular, the two-transmission-antenna SU-MIMO function is required to satisfy the peak spectral efficiency requirements of IMT-Advanced.

For the Physical Uplink Shared Channel (PUSCH), it was agreed to apply SU-MIMO with closed-loop control using multiple antennas on the UE, as well as codebook-based precoding and rank adaptation, as used on the downlink. The eNode B selects the precoding weight from a codebook to maximize achievable performance (e.g., received SINR or user throughput after precoding) based on the sounding RS, which is used for measuring the quality of the channel transmitted by the UE. The eNode B notifies the UE of the selected precoding weight together with the resource allocation information used by the PDCCH. The precoding for rank one contributes to antenna gain, which is effective in increasing cell-edge user throughput. However, considering control-information overhead and increases in Peak-to-Average Power Ratio (PAPR)[*28], frequency-selective precoding is not very effective in increasing system throughput, so only wideband precoding has been adopted. Also, for rank two or higher, when four transmission antennas are used, the codebook has been designed not to increase the PAPR [7]. The demodulation RS, which is used for channel estimation, is weighted with the same precoding weight as is used for the user data signal transmission. Basically, orthogonalization is achieved by applying a different cyclic shift to each layer, but orthogonalizing the code region using block spread[*29] together with this method is adopted [14].

3.4 Uplink Transmit Diversity Technology

Closed-loop transmit diversity is applied to PUSCH as described above for SU-MIMO. Application of transmit diversity to the Physical Uplink Control Channel (PUCCH) is also being studied. For sending retransmission request Acknowledgment (ACK) and Negative ACK (NAK) signals as well as scheduling request signals, application of Spatial Orthogonal-Resource Transmit Diversity (SORTD)[15] using differing resource blocks per antenna or an orthogonalizing code sequence (cyclic shift, block spread sequence) has been agreed upon (**Figure 6**). However, with LTE-Advanced, the cell design[*30] must be done so that LTE Rel. 8 UE get the required quality at cell-edges, so applying transmit diversity to the control channels cannot contribute to increasing the coverage area[*31], but only to reducing the transmission power required [16].

4. CoMP Technology

4.1 Coordinated Multi-point Transmission/Reception

The implementation of intra-cell/inter-cell orthogonalization on the uplink and downlink in LTE Rel. 8 contributed to meeting the requirements of capacity and cell-edge user throughput. On the downlink, simultaneously connected UE are orthogonalized in the frequency domain. On the other hand, they are orthogonalized on the uplink, in the frequency domain as well as the code domain, using cyclic shift and block spreading. It is possible to apply fractional frequency reuse[*32] to control

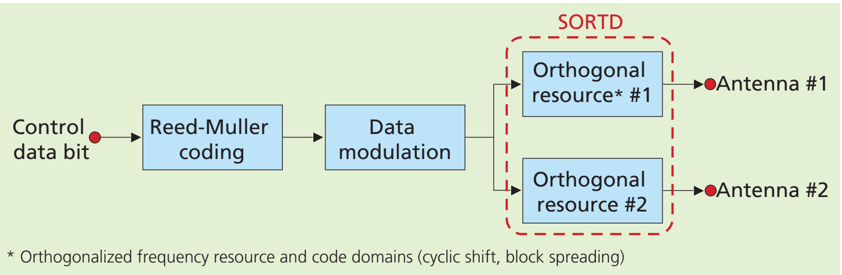

Figure 6 Transmit diversity for the PUCCH

*26 **Block diagonalization**: When using precoding and beam forming on the transmitter, a method which uses singular value analysis of the channel matrix to generate weighting coefficients such that the interference between users is completely zeroed.

*27 **Adaptive transmission power control**: When performing MU-MIMO or CoMP, adaptively controlling the transmission power of each antenna and cell based on the channel state when transmitting the signal.

*28 **PAPR**: As the ratio of maximum power to average power, an index expressing the peak magnitude of the transmit waveform. If this value is large, the amplifier power back-off has to be large to avoid nonlinear distortion, which is particularly problematic for mobile terminals.

*29 **Block spread**: Spreading done using an orthogonal spreading code across multiple transmission symbols in the same transmission signal sequence.

*30 **Cell design**: The area handled by a single base station is called a cell, and cell design refers to the process of designing how the desired service area is to be covered using multiple cells.

*31 **Coverage area**: The area over which a single base station can communicate with UE (cell diameter). As coverage is increased, the number of base stations required decreases.

interference between cells semi-statically, but this is done based on randomization in LTE Rel. 8. Because of this, we are planning to study CoMP technology, which performs signal processing for coordinated transmission and reception by multiple cells to one or more UE, as a technology for Rel. 11 and later in order to extend the intra-cell/inter-cell orthogonalization in LTE Rel. 8 to operate between cells [17].

4.2 Independent eNode B and Remote Base Station Configurations

There are two ways to implement CoMP technology: autonomous distributed control based on an independent eNode B configuration, or centralized control based on Remote Radio Equipment (RRE) (**Figure 7**) [17]. With an independent eNode B configuration, signaling over wired transmission paths is used between eNode B to coordinate among cells. Signaling over wired transmission paths can be done with a regular cell configuration, but signaling delay and overhead become issues, and ways to increase signaling speed or perform high-speed signaling via UE need study. With RRE configurations, multiple RREs are connected via an optical fiber carrying a baseband[*33] signal between cells and the central eNode B, which performs the baseband signal processing and control, so the radio resources between the cells can be controlled at the central eNode B. In other words, signaling delay and overhead between eNode B, which are issues in independent eNode B configurations, are small in this case, and control of high speed radio resources between cells is relatively easy. However, high-capacity optical fiber is required, and as the number of RRE increases, the processing load on the central eNode B increases, so there are limits on how this can be applied. For these reasons, it is important to use both distributed control based on independent eNode B configurations and centralized control based on RRE configurations as appropriate, and both are being studied in preparation for LTE-Advanced.

4.3 Downlink Coordinated Multi-point Transmission

Downlink coordinated multi-point transmission can be divided into two categories: Coordinated Scheduling/Coordinated Beamforming (CS/CB), and joint processing (**Figure 8**) [18][19]. With CS/CB, a given subframe is transmitted from one cell to a given UE, as shown in Fig. 8 (a), and coordinated beamforming and scheduling is done between cells to reduce the interference caused to other cells. On the other hand, for joint processing, as shown in Fig. 8 (b-1) and (b-2), joint transmission by multiple cells to a given UE, in which they transmit at the same time using the same time and frequency radio resources, and dynamic

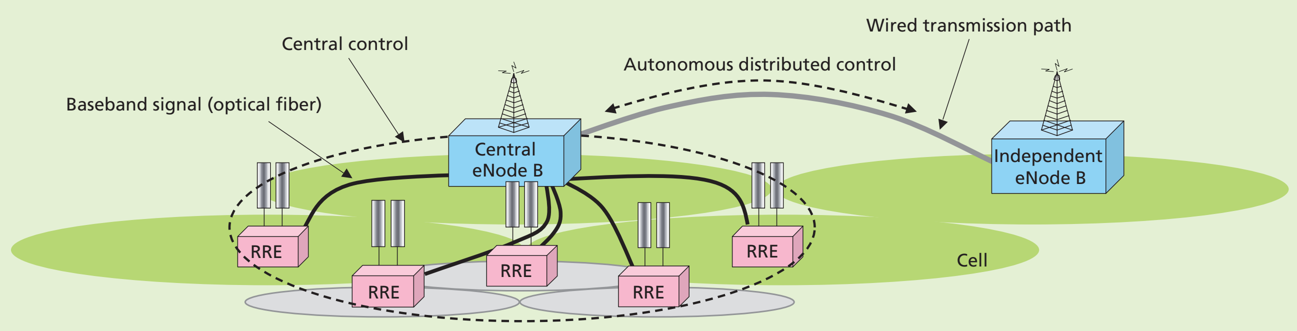

Figure 7 Independent eNode B configuration and RRE configuration

*32 **Fractional frequency reuse**: A control method which assigns different frequency ranges for cell-edge UE.

*33 **Baseband**: The bandwidth of the data signal before and after being converted to the radio frequency band on the transmitter and receiver for radio communication. Normally this is a low bandwidth.

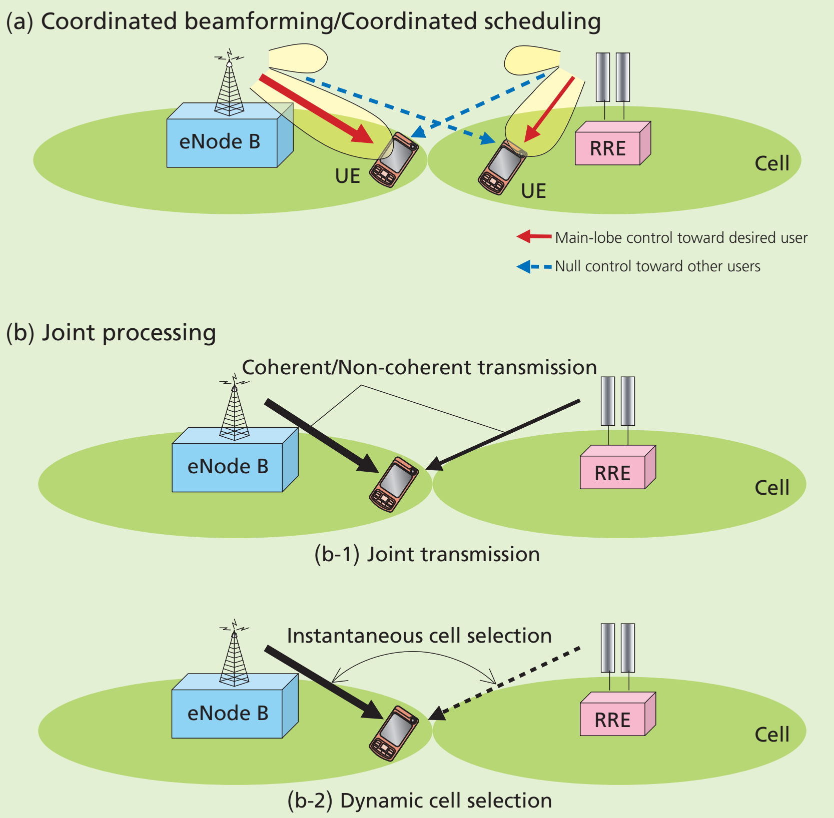

Figure 8 Downlink CoMP transmission

cell selection, in which cells can be selected at any time in consideration of interference, are being studied. For joint transmission, two methods are being studied: non-coherent transmission, which uses soft-combining reception of the OFDM signal; and coherent transmission, which does precoding between cells and uses in-phase combining at the receiver.

4.4 Uplink Multi-cell Reception

With uplink multi-cell reception, the signal from a UE is received by multiple cells and combined. In contrast to the downlink, the UE does not need to be aware of whether multi-cell reception is occurring, so it should have little impact on the radio interface specifications.

5. Conclusion

In this article, we have given an overview of MIMO and CoMP technologies being applied in LTE and LTE-Advanced. The standard specifications for LTE are complete in Rel. 8, and standardization of LTE-Advanced is currently advancing in the form of Rel. 10 and beyond at the 3GPP.

In the future, a detailed study of RS and control signaling will be done to complete the standard specification for Rel. 10 MIMO technology, and a study of technical implementation issues, such as antenna configuration and scheduling methods, needs to be done for implementation. We will also continue study towards introducing CoMP technology into LTE-Advanced, including application environments and effectiveness.

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