Downlink MIMO in LTE-Advanced: SU-MIMO vs. MU-MIMO

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ABSTRACT

Single-user multi-antenna technologies are well upported in current standard specifications like LTE Release 8/9. Further development of the specification (LTE-Advanced) is expected to conform to the requirements for IMT-Advanced systems. One of the key enabling features of LTE-Advanced to meet IMT-Advanced downlink performance requirements is multi-user MIMO, where a transmitter serves multiple users simultaneously on the same frequency resource, primarily relying on spatial separation. In general, multi-user MIMO is beneficial for improving average user spectral efficiency. However, cell edge user spectral efficiency may be reduced if multi-user MIMO is used exclusively, due to residual inter-user interference arising from practical multi-user beamforming and reduced transmit power allocated to each user. Therefore, it should be possible to configure the UE-specific transmission mode to support dynamic switching between single-user MIMO and multi-user MIMO to balance the cell edge user spectral efficiency as well as the average cell user spectral efficiency. In this article, we study various aspects of multi-user MIMO including design philosophy, multi-user precoding, and control signaling. The associated feedback schemes, including those that facilitate dynamic switching, are discussed. Performance evaluation is conducted to demonstrate the gain of dynamically switched single-user and multi-user MIMO as opposed to traditional single-user MIMO.

INTRODUCTION

The Third Generation Partnership Project (3GPP) candidate technology for the next-generation wireless broadband network, developed in the form of Long Term Evolution (LTE) Release 10 (Rel-10), also known as LTE-Advanced, has been conferred International Mobile Telecommunications-Advanced (IMT-Advanced), or fourth generation (4G), status by the International Telecommunication Union (ITU). Compared to the legacy 3G technologies such as LTE Rel-8 and high-speed packet access (HSPA) Rel-6/7, LTE-Advanced targets the achievement of another major performance breakthrough from the current 3G system, in terms of achieving 1 Gb/s downlink (DL) and 500 Mb/s uplink (UL) throughput [1]. The DL spectral efficiency requirements of IMT-Advanced systems are specified in two performance measures: cell average spectral efficiency and cell edge user spectral efficiency. The cell average spectral efficiency indicates the overall effectiveness of a base station (evolved NodeB or eNB in LTE/LTE-Advanced) in exploiting its spectrum resource, and the cell edge user spectral efficiency is defined to be the 5th percentile of the per-user spectral efficiency, indicating the cell coverage capability.

While the recently finalized 3GPP LTE Rel-8 standard allows us to achieve 300 Mb/s for DL and 75 Mb/s for UL with the introduction of orthogonal frequency-division multiplexing (OFDM) and single-user multiple-input multiple-output (SU-MIMO) techniques, the DL spectral efficiency targets of IMT-Advanced are not satisfied by Rel-8 LTE [2]. Accordingly, meeting IMT-Advanced requirements has been a major motivation to further evolve LTE to LTE-Advanced technologies.

The study item (SI) phase of Rel-10 LTE-Advanced was initialized in March 2008 with most items finished in August 2009. The associated work item (WI) phase started immediately after the SI phase and stabilized by the middle of 2011. In September 2009, the 3GPP community submitted a complete system evaluation of LTE-Advanced key features to ITU toward meeting the IMT-Advanced performance targets. In November 2010, LTE-Advanced was accepted as IMT-Advanced (4G) technology [3].

The substantial performance improvements of LTE-Advanced against other legacy standards are achieved with advanced physical layer techniques including carrier aggregation, enhanced interference coordination techniques, and enhanced multiple-antenna schemes. Among these techniques, DL MIMO enhancements especially in terms of multi-user MIMO (MU-MIMO) is the key enabling technology for LTE-Advanced to meet the IMT-Advanced spectral efficiency targets, while other techniques provide support for new deployments. In this article, we discuss DL MIMO in LTE-Advanced, with particular focus on various aspects of MU-MIMO operation. Dynamic switching of SU-MIMO and MU-MIMO together with the feedback framework to enable these operations are also covered.

DL MIMO IN LTE/LTE-ADVANCED

SU-MIMO FRAMEWORK

SU-MIMO is one of the key technologies in LTE Rel-8. There are two major operations under SU-MIMO: transmit diversity and spatial multiplexing. Transmit diversity is an efficient way to improve the reliability of a system. Accordingly, it is used in LTE Rel-8 for control channel and data channel of cell edge mobile stations (called user equipment [UE] in LTE/LTE-Advanced), and also as a fallback mode when feedback is unreliable. On the other hand, spatial multiplexing can be used to improve UE's spectral efficiency, mainly targeted at cell center users.

LTE Rel-8 supports a maximum of four-layer spatial multiplexing in SU-MIMO. That is, a UE unit can receive at most four different streams from an eNB in the downlink. In LTE-Advanced, the maximum number of layers supported in SU-MIMO is extended to eight to achieve a twofold increase in peak spectral efficiency. Other than the number of supported layers, the major operational difference between Rel-8 SU-MIMO and Rel-10 SU-MIMO lies in the aspect of beamforming/precoding. Rel-8 SU-MIMO was developed under the codebook-based precoding framework where transmit precoding vectors/matrices at the eNB are confined within a finite codebook. As demodulation is based on the unprecoded common reference signals (CRS), the precoder at eNB needs to be explicitly signaled to the UE in a separate physical downlink control channel (PDCCH) to enable MIMO decoding. Obviously, codebook-based precoding limits the eNB's precoding flexibility, which is particularly important for MU-MIMO that relies on beamforming to pre-mitigate the inter-user interference. To that end, non-codebook-based precoding was introduced in LTE-Advanced through the introduction of multilayer demodulation reference signals (DMRS). Because the DMRS is precoded with the same precoding vector/matrix as DL data, the effective composite channel after precoding can readily be measured with DMRS, obviating the need to explicitly signal the transmit precoder to the UE. Furthermore, the eNB may choose arbitrary precoding vectors/matrices and achieve greatly improved precoding flexibility for both SU-MIMO and MU-MIMO operations. Although non-codebook-based precoding has a relatively small performance difference from codebook-based precoding for SU-MIMO (especially with a sufficiently well designed LTE codebook), it is proven to be the key enabling feature for MU-MIMO in LTE-Advanced.

Channel state information (CSI) feedback in LTE is based on implicit feedback where UE reports a set of recommended MIMO transmission properties (RI/PMI/CQI). The same feedback scheme is applied in LTE-Advanced for both SU-MIMO/MU-MIMO. More details are provided next.

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MIMO FEEDBACK

CSI feedback allows downlink transmission to be adaptively optimized based on the instantaneous DL channel, so that closed-loop beamforming and adaptive link adaptation can be enabled to optimize the system performance. The DL reference signal used for CSI measurement is different in Rel-8 and Rel-10. In Rel-8, CSI measurement is based on CRS, which is also used for data demodulation. In contrast, CSI measurement in Rel-10 is based on a set of newly introduced CSI-RS signals, which is low-duty-cycle and low-density, and allows a higher reuse factor than Rel-8 CRS.

The feedback mechanisms of LTE Rel-8 and LTE-Advanced Rel-10 are both based on the implicit feedback framework that has been well established and tested since early 3GPP releases. In brief, UE measures the DL channel through measurement reference signals and feeds back the channel state information (CSI) in the form of recommended transmission formats. This includes:

Rank indicator (RI): number of layers recommended for SU-MIMO transmission

Precoding matrix indicator (PMI): index of the recommended SU-MIMO precoding matrix in the feedback/precoding codebook, corresponding to the RI

Channel quality indicator (CQI): indication of the channel quality corresponding to the reported RI/PMI

In LTE, CQI is defined as a set of transport block sizes, each of which translates to a maximum code rate and quadrature amplitude modulation (QAM) order that can be received by the UE at a certain block error rate (BLER). As a criterion for testing the CQI report accuracy (e.g., for 3GPP RAN4 UE performance requirement specification), when the reported code rate and QAM order is used for actual data transmission, the UE must be able to decode the data with a BLER below 10 percent.

Note that PMI and RI jointly represent the spatial directions of the MIMO channel, while CQI indicates the strength of the corresponding spatial directions. It is easy to see that the same feedback mechanism (RI/PMI/CQI) can be applicable and followed in LTE/LTE-Advanced. This is independent of the exact measurement

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reference signals (CRS in Rel-8 and CSI-RS in Rel-10) that are used for CSI feedback, as long as they reflect the un-precoded antenna signals. More important, this commonality ensures backward compatibility so that eNB and UE of different releases can operate together seamlessly.

Benefits of this implicit PMI/CQI/RI framework include those listed here.

Overhead: It is well known in the literature that codebook-based feedback is an effective means to achieve reasonably accurate CSI quantization with manageable overhead.

UE receiver transparency: UE receiver implementation (usually proprietary) is implicitly reflected in the CSI report and therefore can stay transparent. For example, UE with an advanced interference rejection combining (IRC) receiver may report a higher CQI value than other UE with a simple minimum mean square error (MMSE) receiver. UE vendors are therefore encouraged to differentiate their products through advanced receiver implementation, offering better user experiences.

Testability: Interoperability is an essential part of any multivendor ecosystem, including LTE/LTE-Advanced. The implicit feedback framework (e.g., reported RI/PMI/CQI must pass 10 percent BLER test when used for data transmission) has a proven track of testability to ensure that the CSI report is reliable.

The MU-MIMO Framework

MU-MIMO is widely considered a key technology for system capacity improvement in modern wireless networks. In contrast to SU-MIMO, where the spatial multiplexing gain is confined to a single user, MU-MIMO allows multiple users to be co-scheduled on the same time-frequency resources to exploit this gain among two or more UE units. This is particularly beneficial as high-rank SU-MIMO transmission is often limited by the number of antennas and antenna design constraints at the user end, whereas high-rank transmission using MU-MIMO is more feasible due to the scattered user distribution.

It is well known that the information theoretic optimal MU-MIMO scheme is dirty paper coding (DPC), which unfortunately is a nonlinear/non-causal beamforming scheme and therefore unrealistic in real-life applications. From a practical deployment point of view, the most critical issue for MU-MIMO in LTE is to strike a balance among MU performance gain, CSI feedback overhead, a low-complexity transceiver design, as well as an efficient scheduling methodology. Consideration of the commercial deployment of MU-MIMO includes the following aspects.

Channel model: As MU-MIMO primarily relies on spatial domain separation for user multiplexing, environments with sufficient user separation are most suitable. Fortunately, this is usually the case in commercial LTE deployments where UE units are distributed in a geographically scattered manner. In addition, the angular spread at the eNB side imposes a nontrivial impact on MU-MIMO performance. Propagation channels with a lower angular spread tend to create narrower antenna beam patterns, which are beneficial for user separation and MU-MIMO communication [4].

eNB antenna configuration: The performance of any multi-antenna scheme heavily depends on the antenna configuration. For SU-MIMO, widely spaced antennas and cross-polarized antennas reduce the spatial correlation and usually result in good SU-MIMO performance. However, wide antenna spacing is considered a serious challenge for most commercial base station designs. On the other hand, MU-MIMO is found to perform particularly well in highly correlated antenna setups (e.g., small antenna spacing, ULA array), which create narrow antenna beams critical for space-division multiple access (SDMA). Therefore, MU-MIMO is a promising candidate for practical deployment.

Cell loading & traffic type: Deployment of MU-MIMO should also be jointly considered with the cell loading and traffic types. It is well known that the asymptotic capacity of MU-MIMO broadcast channel scales as $O(\log\log(K))$where K is the number of users. A highly loaded cell with a large number of users experiencing steady DL traffic (e.g., video streaming) provides more MU-MIMO grouping possibility and is considered more appropriate for MU-MIMO transmission.

Next, details of MU-MIMO beamforming are provided in the context of Rel-8 and Rel-10, respectively.

MU-MIMO in Rel-8 LTE

A primitive MU-MIMO transmission mode (TM 6) with codebook-based precoding is defined in LTE Rel-8 where DL beamforming and demodulation rely on CRS. Similar to Rel-8 SU-MIMO, the transmit precoder/beamforming vector for each user is chosen from a fixed codebook and has to be explicitly signaled to the UE in the PDCCH for MIMO decoding. The same codebook is also used for the purpose of channel feedback.

It is obvious from codebook-based precoding that the eNB does not have the full flexibility to arbitrarily choose MU beamforming vector for intra-cell interference nullification. Therefore, the performance of this CRS-based MU-MIMO mode (TM6) is quite limited, whereas no significant gain over SU-MIMO has been demonstrated.

MU-MIMO in Rel-10 LTE-Advanced

The introduction of DMRS based precoding in Rel-10 LTE-Advanced allows the eNB to arbitrarily choose the downlink beamforming vectors/matrices. Such flexibility due to DMRS releases the MU-MIMO potential and leads to significant improved MU-MIMO performance.

MU-MIMO in Rel-10 has been designed with the following considerations:

Transparency: In a transparent MU-MIMO system, the UE is unaware of whether or not it is being co-scheduled with other UEs in the same time-frequency resource. The reason for adopting a transparent MU-MIMO design in LTE-Advanced is based on the tradeoff between the practical performance and implementation complexity. In theory, a non-transparent MU-MIMO design allows advanced UE receiver implementation to exploit the information associated with the co-scheduled UEs for possibly more sophisticated intracell interference suppression. For example, if the first UE knows the MCS for the second UE, it may decode the second UE's data first and apply interference cancellation receiver to improve its own performance. A joint maximum likelihood (ML) type receiver may also be used with the knowledge of modulations of the co-scheduled UE by reusing some SU-MIMO receiver designs. On the other hand, practical restrictions in MU-MIMO deployment (e.g., resource allocation misalignment in the time/frequency domain, control signaling overhead and complexity) limit the effectiveness of a non-transparent MU-MIMO design in a real-life network. As such, a transparent MU-MIMO framework was adopted in Rel-10 LTE-Advanced to balance the performance and control signaling complexity/overhead. This is reflected in the following two aspects:

- **Transparency in control signaling:** The DL control signaling (e.g., PDCCH) for scheduled UE contains no information regarding the existence of co-scheduled UE. Therefore, a UE unit cannot tell whether it is being scheduled in SU-MIMO or MU-MIMO mode. However, vendors with advanced UE receiver design may still choose to implement advanced interference suppression schemes for better MIMO decoding performance (e.g., an IRC receiver).
- **Transparency in UE feedback:** Feedback of RI/PMI/CQI for each UE is done under the hypothesis of SU-MIMO; that is, the reported RI/PMI/CQI is calculated under the assumption of SU-MIMO transmission. Such feedback will be used for both SU-MIMO and MU-MIMO scheduling. Upon receiving the feedback from the UE, it is at the eNB's discretion whether to further process the UE's feedback to determine if the UE may benefit from MU-MIMO transmission.

These features are necessary to enable dynamic SU/MU switching in LTE, which will be further addressed in the following section.

MU-MIMO dimensioning refers to the number of UE units to be co-scheduled in MU-MIMO, as well as the number of layers each UE unit can receive. Likewise, such parameters were carefully chosen to balance the system performance and control signaling overhead. In LTE-Advanced, up to two orthogonal DMRS antenna ports are available for orthogonal layer multiplexing. Each DMRS antenna port may be further scrambled by two scrambling sequences to support non-orthogonal layer multiplexing. As a result, a maximum of four spatial layers can be effectively transmitted in MU-MIMO mode. Further increasing the MU-MIMO dimensioning, albeit possible in theory by taking advantage of spatial separation, may provide only marginal performance gains in real-life deployment. This is because the power splitting at the eNB and increased intracell interference may quickly deteriorate MU-MIMO performance.

DYNAMIC SU/MU-MIMO SWITCHING

Dynamic SU/MU-MIMO switching aims to improve system performance by allowing the network to serve UE transparently in SU- or MU-MIMO operation. The SU/MU switching aspect is important because, depending on channel and traffic conditions, some UEs may be best served with SU-MIMO, while others benefit from MU-MIMO operation. As channel and traffic conditions may vary from subframe to subframe, the dynamic switching aspect is important to optimize system performance.

Important factors that influence the suitability of SU-MIMO vs. MU-MIMO include the spatial characteristics of the MIMO channel (e.g., potential rank deficiency that could be relaxed by performing MU-MIMO) as well as the UE's typical signal-to-interference-plus-noise ratio (SINR) conditions (also termed *geometry*). In addition, channel and traffic variations are important factors (e.g., UE mobility or the burstiness of a UE unit's traffic). MU-MIMO is most suitable when UE mobility is low and traffic conditions are stable as this improves the ability to find suitable groupings of UE for MU-MIMO operation. The following subsections address the above considerations in detail.

GENERAL SYSTEM DESIGN CONSIDERATIONS

As discussed earlier, transparency of SU/MU-MIMO has been an important high-level design goal for Rel-10 LTE-Advanced. This design philosophy provides the foundation for dynamic switching between SU-MIMO and MU-MIMO in LTE-Advanced. From a system perspective, dynamic SU/MU-MIMO switching is also motivated by bursty traffic considerations. In practice, the burstiness of traffic needs to be taken into consideration as it impacts the number of UE units that are active in a given subframe. This in turn affects the ability of grouping one or multiple UE units in MU-MIMO operation. Being able to do this on a fast timescale helps to improve system performance.

FEEDBACK CONSIDERATIONS

As explained earlier, non-codebook-based precoding enables beam selection methods that perform transmit interference nulling to co-scheduled UE, thus improving MU-MIMO performance. However, it is well known that transmit interference nulling is sensitive to inaccuracies of CSI [5]. This impacts feedback considerations significantly, especially codebook granularity and the design of feedback modes. In this section, we address some of these aspects to provide an overview of Rel-10 LTE-Advanced design considerations.

As a result of the dynamic and transparent nature of SU/MU-MIMO switching, a common feedback framework is used in Rel-10 LTE-Advanced for both SU and MU-MIMO operation. In particular, the RI/PMI/CQI feedback framework is fundamentally tailored to SU-MIMO operation since no information about co-scheduled UE is available. It is up to the eNB to extrapolate the SU-MIMO-based feedback to

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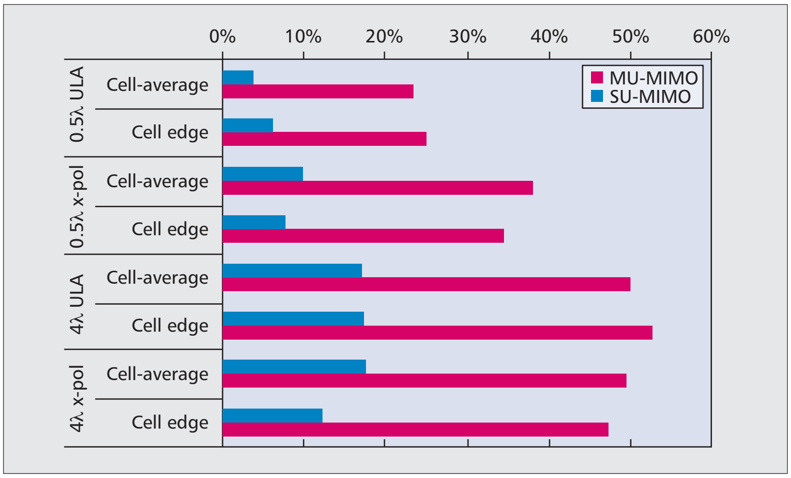

Figure 1. *Performance gap of ideal CSI feedback vs. practical feedback based on LTE-A codebooks.*

perform MU-MIMO UE grouping, MU-MIMO precoding, MU-CQI prediction, and user scheduling [6]. The extrapolation of the MU-CQI is especially important as the intracell interference resulting from co-scheduled UE needs to be factored into the rate prediction for each UE, and this information is also crucial for SU/MU-MIMO scheduling [7]. As pointed out earlier, when extrapolating the CQI that was reported by the UE under an SU-MIMO assumption, it is important to take into account the interference from co-scheduled UE as well as the power splitting that occurs as a result of serving multiple UE units on the same time/frequency resource.

MU-MIMO benefits from a finer codebook granularity as this helps to improve the performance of transmit interference nulling. Figure 1 illustrates this by showing the relative performance gain associated with having perfect CSI at the eNB vs. the practical feedback reporting that was specified in LTE-Advanced for a 4-Tx-antenna configuration [5]. A higher gain in Fig. 1 therefore suggests a larger sensitivity to inaccurate CSI feedback. The figure shows this comparison for various antenna configurations, including uniform linear arrays (ULAs) and cross-polarized (X-pol) configurations with narrow (0.5λ) and wide (4λ) antenna spacing, respectively.

From the figure, we observe that the performance gap between ideal and realistic feedback is much more pronounced for MU-MIMO compared to SU-MIMO, which illustrates the increased sensitivity of MU-MIMO with respect to CSI accuracy. This is due to the fact that more accurate CSI feedback helps to improve the accuracy with which interference nulling can be performed at the eNB and to better predict the MU-CQIs, which are crucial for multi-user scheduling [7]. While Fig. 1 sheds light on the benefits that may be achieved with improved CSI feedback accuracy, in practice a tradeoff between improving downlink performance and increasing uplink overhead needs to be struck. In Rel-10, increasing the granularity of the feedback codebooks was discussed but no agreement on a specific enhancement scheme could be reached. Some further enhancements may be targeted in future releases, as discussed later.

Another important aspect is the design of feedback reporting modes as this also impacts the CSI accuracy that can be obtained at the eNodeB. Fundamentally, feedback reporting is categorized depending on whether information is carried on the UL control or data channels. While the control channel's capacity for carrying CSI information is quite limited, the data channel has the potential to accommodate larger payload sizes. This capacity difference has given rise to two fundamental classes of feedback reporting. First, so-called *periodic* feedback modes utilize the control channel to provide a basic CSI reporting that, once configured, provides CSI reports according to a fixed timeline. Second, the eNB may request *aperiodic* CSI reports with larger payload that utilize the UL data channels and can be requested as needed. In practice, structuring the feedback reporting in this way enables the eNB to maintain coarse knowledge of a UE unit's channel conditions through periodic reporting while having the ability to request more accurate CSI reports when needed (e.g., when a large burst of data arrives for a specific UE unit).

Another important design consideration for feedback reporting is the frequency granularity of the reports. As explained earlier, LTE utilizes the implicit RI/PMI/CQI framework in which PMI and/or CQI may be reported either wideband or on a subband-specific level (the RI is always reported wideband). Clearly, as for the feedback granularity, this directly affects the downlink performance vs. uplink overhead tradeoff. In fact, for a typical 10 MHz LTE/LTE-Advanced deployment, there would be nine subbands according to the specification. Therefore, whether or not to report PMI/CQI on a per-subband basis needs to be weighed judiciously as the uplink feedback overhead naturally scales linearly with the number of subbands. At the same time, the aforementioned aperiodic feedback modes help alleviate the payload increase as per-subband reports may only be sent on a per-request basis.

The potential performance gains of subband-level CSI reporting are shown in Fig. 2, which compares subband-CQI, wideband-PMI and subband PMI/CQI feedback with a basic scheme that only performs wideband PMI/CQI feedback in aperiodic feedback modes for a 4-Tx ULA antenna configuration [8].

From the figure, it can be seen that subband CQI reports have the potential to significantly improve system performance (i.e., 10–20 percent) by allowing frequency-selective MU scheduling whereas the additional gains associated with subband PMI reporting are relatively limited. Accordingly, a feedback reporting mode for wideband PMI/subband CQI was defined (which is referred to as PUSCH 3-1 in the specification), while no aperiodic reporting mode for subband PMI/CQI feedback was specified.

In addition to the above aperiodic reporting modes, there is also a periodic feedback reporting mode that allows for subband CQI feedback. In periodic reporting mode (e.g., PUCCH mode 2-1), the subband-specific information is multiplexed over multiple time instances due to the limitation of the payload restriction on each subframe, while the subband-specific information of all subbands is carried in the same subframe in an aperiodic reporting mode (e.g., PUSCH mode 3-1). The difference between these two subband-specific reporting modes can be seen more clearly in Fig. 3, where a single PUCCH 2-1 feedback corresponding to multiple subbands is sent over multiple subframes, while the entire PUSCH 3-1 aperiodic report is sent in a single subframe.

Control Signaling Considerations

To support Rel-10 MIMO enhancements, a new transmission mode is introduced that enables 8 × 8 MIMO transmission as well as SU/MU-MIMO dynamic switching. The new transmission mode is accompanied with a new format for conveying downlink control information (DCI). In Rel-10, independent downlink DCI grants are sent to UE in MU operation mode. This may lead to a control channel limitation if MU is used extensively; however, such design allows flexible UE grouping.

SU/MU Beamforming and Switching

Several exemplary SU/MU beamforming and scheduling algorithms are provided in this section for illustration purposes. It should be noted that the exact solutions are proprietary and implementation-specific, and thus may vary between different eNB vendors.

SU Beamforming and Scheduling — SU-MIMO beamforming can be based on the CSI feedback (RI/PMI/CQI) where the eNB uses the UE reported rank (RI) and precoding vectors (PMI) for SU-MIMO transmission. Alternatively, eNB may derive the beamforming vectors based on MIMO channel characteristics obtained with other standard transparent measurements. For example, in scenarios where channel reciprocity is valid (e.g., in time-division duplex [TDD] where DL and UL transmissions occur in the same bandwidth), the eNB may derive DL MIMO beamforming based on the UL MIMO channel measurement. In this case, the UE transmits a specified pilot also known as a sounding reference signal (SRS) based on which the eNB can estimate the channel. It should be noted, however, that even in this case, CQI feedback by the UE is necessary to convey the interference conditions at the UE. These can clearly not be inferred from uplink transmissions.

The CQI feedback can be used for link adaptation purpose to calculate the expected throughput for each user. It is important to note that in line with the previous discussions, the UE feeds back CQI under an SU-MIMO assumption. It is up to the eNB to extrapolate this CQI value appropriately when evaluating anticipated MU-MIMO performance. As part of making scheduling decisions, the eNB then compares the throughput of all users and schedules the time-frequency unit (e.g., resource block) to the optimal user with the highest expected throughput. Other quality of service (QoS) criteria (e.g., proportional fairness) could be taken into account in the scheduling process to balance the cell average and cell edge performance.

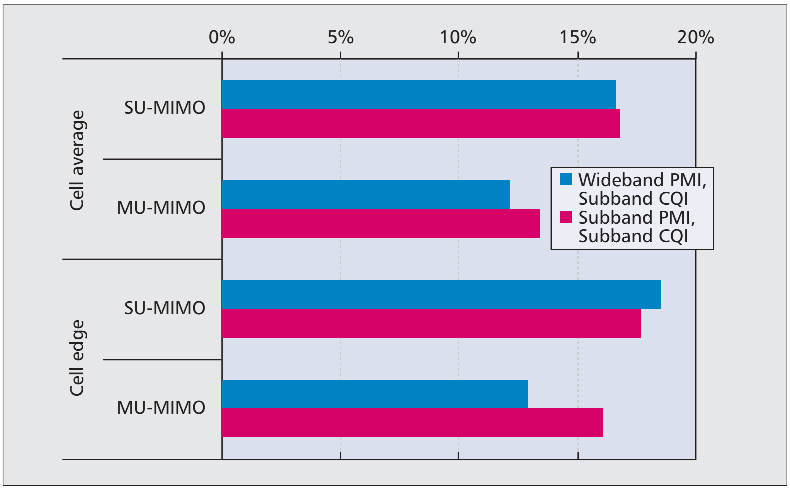

Figure 2. *Performance gains of subband CQI and/or PMI feedback compared to wideband-only feedback.*

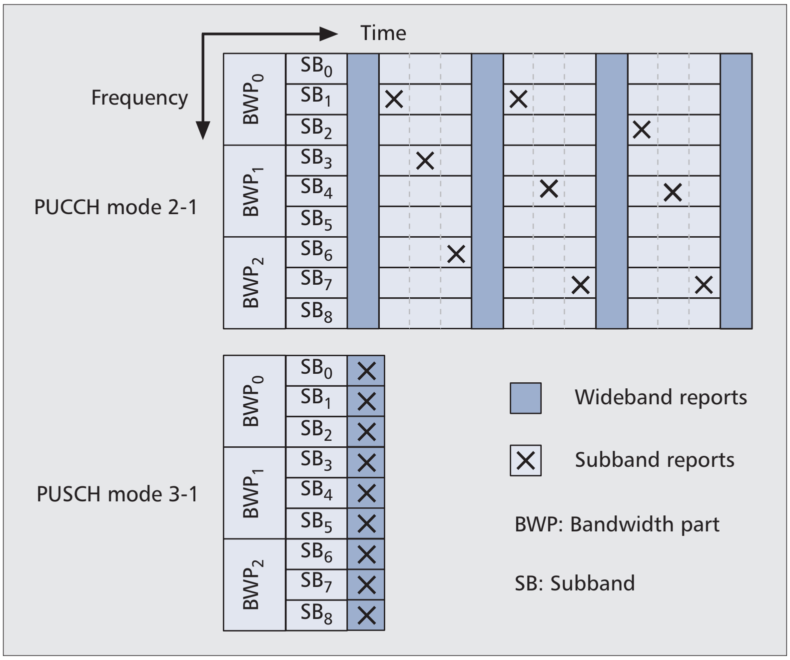

Figure 3. *PUCCH Mode 2-1 Versus PUSCH Mode 3-1.*

MU-MIMO Beamforming and Scheduling — Various MU-MIMO beamforming algorithms including block diagonalization (BD), maximum signal-to-leakage-ratio (SLR), and zero-forcing (ZF) beamforming have been extensively studied in the past decade. However, many existing studies in academia are based on the idealistic assumption of perfect CSI at the transmitter. For practical MU-MIMO deployment in LTE-Advanced, schemes based on realistic CSI feedback are required.

For the jth users, the RI/PMI report reflects the quantization of the SU-MIMO channel projected into the subspace defined by the feedback codebook, and the CQI report denotes the energy of the projection with intercell interference and noise taken into account.

ZF beamforming [10]: For a hypothetical group of users, the aggregated MU channel can be constructed by concatenating each user's PMI report.

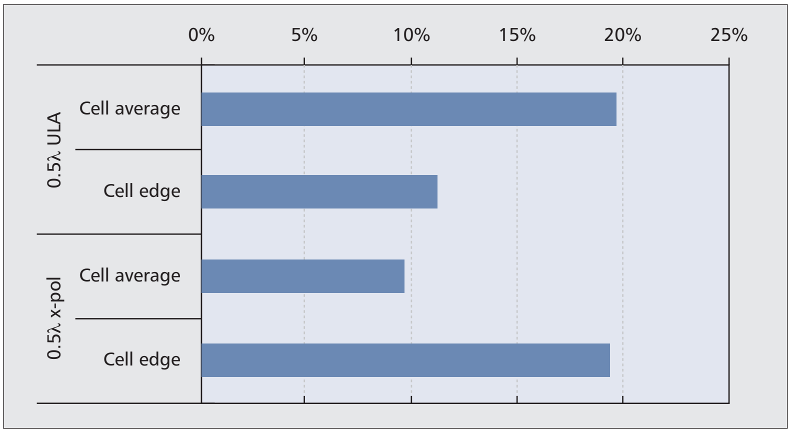

Figure 4. *Performance gains of dynamic SU/MU-MIMO over SU-MIMO operation.*

Maximum SLR beamforming [10]: The beamforming vector for UE 1, when paired with UE 2, is derived as the generalized eigenvector of UE 1's transmit covariance matrix times the inverse of the second user's covariance matrix. Each user's transmit covariance matrix can be approximated by its CQI and PMI feedback.

Optimal SU/MU scheduling requires exhaustive search of all possible user combinations for the optimal SU/MU selection on each frequency resource [7]. This is prohibitively complicated for practical deployment. Low-complexity greedy scheduling algorithms (e.g., [9]) might be used to alleviate the scheduling complexity.

The system-level performance comparison between SU-MIMO and SU/MU-MIMO in Rel-10 LTE-Advanced is shown in Fig. 4 for a 4-Tx X-pol and ULA antenna configuration under aperiodic subband CSI feedback (PUSCH mode 3-1).

The system-level evaluation results suggest that dynamic SU/MU-MIMO provides 9.7 percent cell average gain and 19.4 percent cell edge gain over SU-MIMO in LTE-Advanced for 0.5λ antenna spacing 4-Tx X-pol; and 19.7 percent cell average gain and 11.2 percent cell edge gain for 0.5 λ antenna spacing 4-Tx ULA. Both results suggest that dynamic SU/MU-MIMO systems provide significant performance gains over SU-MIMO systems.

The presented results are obtained assuming large angular spread of 15°. In MIMO channel with smaller angular spread, the gain of MU-MIMO over SU-MIMO is expected to be more significant as narrow antenna beams benefit user separation.

Future Outlook

CSI Accuracy and Feedback Channel Enhancements

Rel-10 LTE-Advanced made significant progress in defining DMRS based dynamic SU/MU-MIMO achieving significant gains over Rel-8 MU-MIMO and Rel-10 SU-MIMO. For future studies, improved CSI accuracy, CSI granularity in frequency or uplink feedback channel enhancements can be further explored. Specifically, improved granularity in frequency may enable nonlinear precoding schemes but at the same time also represents higher overhead. Another possibility with smaller overhead is based on compressed channel information like channel covariance, which captures channel direction information averaged over multiple subbands. This scheme can provide further gains for MU [10]. Channel covariance could be obtained through uplink reference symbols in TDD or by explicit feedback of CSI in frequency-division duplex (FDD). However, there are significant challenges in standardization to support increased feedback overhead and to develop corresponding testing methodologies.

Another aspect of CSI is the CQI experienced by UE in the presence of MU transmission. As discussed, MU-CQI can be approximately predicted by the eNB based on the SU-CQI report. However, new CQI definitions capturing some average CQI degradation with MU hypothesis may also be considered as part of feedback enhancements.

New Deployments and Scenarios

New deployments are needed to address the future needs of 4G networks like high data rate support for clustered users. As a result, there is a shift in paradigm for MIMO from increasing the number of antennas at a single cell site to distributing multiple antennas over a cell area. Furthermore, such distributed antennas may be in different power levels, and also in different antenna configurations. These add an interesting aspect and require scalable designs as well as interference management as part of MIMO improvements. Geographically separated antennas implemented as remote radio heads can be controlled by a centrally located baseband unit using high-speed standardized fiber interfaces. Such low-latency fiber interfaces ensure good synchronization across antennas and make the transmission from distributed antennas as a natural extension of MIMO. Accordingly, cell boundaries are reduced, and users can be served by joint transmissions from the closest subset of antennas. Conventional definitions of SU and MU operations may have to be revisited as in general two UE units may receive transmissions from overlapping sets of antennas. Furthermore, for system optimization additional parameters like power allocations may have to be optimized along with the precoding and user allocation in MU operations in these scenarios.

Conclusion

An overview of DL-MIMO, especially the enhanced support of SU/MU-MIMO in LTE-Advanced, is presented in this article. As one of the enabling technologies for LTE-Advanced to meet IMT-Advanced targets, SU/MU-MIMO is designed carefully to balance the performance gains and control overhead. Precoding schemes for SU- and MU-MIMO are also introduced, and a performance evaluation of SU/MU-MIMO is also conducted. System-level evaluation suggests that SU/MU-MIMO provides significant gains over SU-MIMO. Potential improvements of SU/MU-MIMO for future releases of LTE-Advanced systems are discussed.

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