Antenna Selection in LTE: From Motivation to Specification

Neelesh B. Mehta, *Senior Member, IEEE*, Andreas F. Molisch, *Fellow, IEEE*,

Salil Kashyap, *Student Member, IEEE*

Abstract

Transmit antenna selection (TAS) technology has been adopted for the uplink by the next generation Long Term Evolution (LTE) wireless standard in order to harness the spatial diversity offered by multiple antennas at the mobile transmitter, while keeping the hardware complexity and cost of a mobile low. In TAS, the number of radio frequency (RF) chains for processing/up-conversion is smaller than the number of available antenna elements, so that at any time the signals can only be transmitted from a (dynamically optimized) subset of antenna elements. As a result, the training procedure for AS needs to be carefully engineered. In LTE, this is accomplished by reusing the wideband sounding reference signal (SRS) for the purpose of AS training. Further, new mechanisms are required to facilitate feedback from the receiver (the base station) to the transmitter about which subset is optimal and should, thus, be used by the mobile. In LTE, this is accomplished by employing a unique masking technique on the downlink control channel that eliminates the feedback overhead at the expense of a minor increase in complexity at the mobile. This paper provides an in-depth and systematic overview of all physical layer and higher layer features in the LTE standard that enable transmit AS. Also highlighted are the variety of technical and standardization challenges that drove the specification of AS in LTE, and the aspects of the LTE standard that are impacted by AS.

Index Terms

Training, Antenna selection, Long Term Evolution, Diversity methods, Reference signals, Control signaling, Next generation cellular radio standards

N. B. Mehta and S. Kashyap are with the Dept. of Electrical Communication Eng. at the Indian Institute of Science (IISc), Bangalore, India. A. F. Molisch is with the Dept. of Electrical Eng. at the University of Southern California, Los Angeles, CA, USA.

Emails: nbmehta@ece.iisc.ernet.in, andreas.molisch@ieee.org, salilkashyap@gmail.com

I. INTRODUCTION

Antenna selection (AS) provides a low-hardware-complexity solution for exploiting the spatial diversity benefits of multiple antenna technology [1], and has been considered at the transmitter and receiver. In receive AS, the receiver does not process signals received by all its N_r antennas. Instead, it dynamically selects an L_r-antenna subset comprising antennas that have the 'best' instantaneous channel conditions to the transmitter, and only processes signals received by them. This enables the receiver to employ fewer of the expensive radio frequency (RF) chains, each of which consists of a low noise amplifier, down-converter, and analog-to-digital converter. Similarly, in transmit AS (TAS), the transmitter employs fewer (L_t) RF chains than the available number of antennas N_t. Each transmit RF chain consists of a digital-to-analog converter, up-converter, filters, and power amplifier. We shall denote TAS that selects L_t antennas out of N_t antennas by $L_t/N_t \times N_r$. Similarly, $N_t \times L_r/N_r$ denotes receive AS that selects L_r antennas out of N_r antennas.

AS has the following important advantages:

1) *Diversity and spectral efficiency gains:* For an $N_t \times N_r$ multiple input multiple output (MIMO) system with N_t transmit and N_r receive antennas, AS that uses $L_t \geq 1$ RF chains at the transmitter and $L_r \geq 1$ RF chains at the receiver achieves the full diversity order of $N_t N_r$ regardless of the value of L_r and L_t. The larger the diversity order, the more robust the MIMO system is to fading. Notably, this holds even when the receiver has a noisy estimate of the channel, which affects the accuracy of both antenna selection and data demodulation [2], [3].

2) *Reduced hardware complexity and switches:* AS exploits the presence of additional antennas without increasing the number of RF chains. For this, an RF switch is required, introducing which causes power and insertion losses. However, these losses are negligible in the new RF micro-electro-mechanical systems (RF-MEMS) switches.

3) *Flexibility and general applicability:* AS can be flexibly deployed and combined with other MIMO schemes. For instance, spatial division multiplexing (SDM) for a 2×2 MIMO system, which sends out two streams simultaneously, can be extended to a $2/4 \times 2$ AS-SDM scheme without costly changes in the baseband processing module. Similarly, the Alamouti 2×1 space-time block coding (STBC) scheme can be easily extended to a

corresponding $2/4 \times 1$ scheme.

4) *Minimal feedback for TAS:* For TAS, only the index of the subset of antennas to be used needs to be fed back to the transmitter. Therefore, the feedback requirements are considerably simpler compared to other feedback-based (also called closed-loop) transmit diversity techniques. This reduced feedback burden of TAS enables it to deliver benefits even at higher mobile speeds when the channel varies quickly.

Due to these advantages, AS has been adopted in next generation wireless systems such as IEEE 802.11n. In the Third Generation Partnership Project (3GPP) Long Term Evolution (LTE) standard [4], the reference antenna configuration of LTE, which is the configuration used for performance benchmarking and is a configuration that is likely to be deployed, provides an additional motivation for TAS. It assumes that the base station, which is also called eNodeB in LTE, uses two antenna elements both for transmission and reception. However, a mobile, which is also called user equipment (UE), uses two antenna elements in receive mode and only one antenna element in transmit mode. This is done in order to allay concerns related to increased hardware complexity and greater energy drain in UEs. This asymmetry in the number of transmit and receive antennas in the reference configuration makes TAS on the uplink an attractive technology for UE vendors. It enables them to develop a cheaper UE that uses only one transmit antenna at any given time and, yet, exploits the spatial diversity benefits offered by the two antennas that are physically present in the UE. Note that AS is also employed in the downlinks of IEEE 802.16e/m WiMAX and LTE. However, the use of AS in the downlink is related to multiple antenna precoding; hardware constraints are not the motivation. Table I summarizes the motivation for AS in the cellular standards.

Figure 1 compares the symbol error rate (SER) of M-ary phase shift keying (PSK) constellations for $1/2 \times 2$ AS, no-AS (1×2), Alamouti STBC, and single-stream eigen-beamforming, in which the transmitter and the receiver jointly form beams to maximize the signal-to-noise ratio. In the latter two cases, the transmitter has two RF chains and two transmit antennas. The comparison is done for a frequency-flat Rayleigh fading channel and independent and identically distributed (i.i.d.) fading across antenna elements with perfect channel estimates at the receiver. Note that the feedback overhead for eigen-beamforming is significantly larger than in all other schemes. We observe that the diversity order, which is the slope of the SER curve for large SNRs, is the same as that of eigen-beamforming and open-loop Alamouti STBC, which requires

no channel knowledge at the transmitter. This is despite AS using only one RF chain. For QPSK and an SER of 1%, AS requires only 1 dB more SNR compared to eigen-beamforming. Further, AS outperforms no-AS by 4 dB and Alamouti STBC by 1 dB.

While TAS is a seemingly simple and intuitive idea, several challenges – technical and otherwise – needed to be overcome to implement it in a standard as sophisticated as LTE. The impact on the standard can be classified into the following three different but essential categories: (i) Training, (ii) Control signaling, and (iii) Layer 3 signaling.[1] Further, *in LTE, TAS is specified to work in both the frequency division duplex (FDD) and time division duplex (TDD) modes of operation.* In the FDD mode, the UE can transmit and receive simultaneously, while in the TDD mode, the UE can either transmit or receive but cannot do both simultaneously.

The paper makes the following contributions. It provides an in-depth and systematic overview of all the hooks in the LTE standard that enable TAS. It also discusses the variety of technical and standardization challenges and solutions that were considered in the process. This will hopefully spur further research into AS and the technologies that are required to enable it in other next generation wireless standards. Another contribution of the paper is simulation results that quantify the performance gains of AS in the presence or absence of frequency-domain scheduling.

The paper is organized as follows. The key features of the physical layer of LTE are summarized in Section II. The training mechanisms for TAS are described in Section III. Control and Layer 3 signaling related to AS are discussed in Section IV. A performance evaluation of AS in Section V is followed by our conclusions in Section VI.

II. LTE UPLINK: A QUICK OVERVIEW

The LTE uplink uses SC-OFDMA, which stands for single-carrier (SC) orthogonal frequency division multiple access (OFDMA) [5]. This variant of OFDMA was chosen as it leads to a lower peak-to-average power ratio (PAPR), which allows the use of more efficient power amplifiers in the UEs. We first briefly review classic OFDM. In it, the system bandwidth is divided into many subcarriers. Data that are modulated, for example, using MPSK, are transmitted over those subcarriers in parallel. The symbol duration and the subcarrier spacing are chosen such that the signals on any two subcarriers are orthogonal to each other. A guard interval called the cyclic

---

[1]Receive AS, on the other hand, can be implemented without further modifications in the standard.

prefix (CP) is pre-pended to eliminate inter-symbol interference caused by the multipath delay dispersion in the channel. Finally, the signals from the subcarriers are added up and transmitted over the wireless channel to the receiver.

In practice, it is not necessary to physically generate multiple subcarriers and modulate signals onto them. Rather, the transmit signal is equivalently generated through an Inverse Fast Fourier Transform (IFFT) of the original data stream. At the receiver, the signal is stripped off the cyclic prefix, after which it goes through an FFT block. This is followed by a per-subcarrier equalization; it only consists of a division by a complex scalar, which is the channel transfer function at the subcarrier frequency.

Assigning symbols to specific modulation symbols on particular subcarriers can be viewed as a 'tiling' of the time-frequency plane. Note also that OFDM is a *modulation* format. If different subcarriers are assigned to (i.e., modulated with signals from) different users, we speak of OFDMA instead.

In SC-OFDMA, the signals from the group of subcarriers that are assigned to a user undergo an FFT before they are modulated onto the subcarriers. Essentially, this operation attempts to undo the IFFT encountered in classic OFDM, so that the transmit signal is similar to a high-speed PSK-modulated signal on a single carrier – hence, the name. Furthermore, the characteristics of the transmit signal are similar to those of single-carrier modulation; this includes a lower PAPR, which allows the use of more efficient power amplifiers. Due to the presence of the CP, the benefits of simple equalization at the receiver are also retained.

Finally, any OFDMA or SC-OFDMA signal requires reference signals (RS), also known as pilots, for channel estimation. LTE foresees two types of pilots for the uplink transmission: (i) Sounding RS (SRS), and (ii) Demodulation RS (DMRS); these will be discussed in more detail below.

We now turn to the specifics of SC-OFDMA in LTE, which is shown in Figure 2. In the uplink, the basic unit of time for data transmission is a slot, which is 0.5 ms long. Two adjacent slots are called a subframe. An uplink frame consists of 10 subframes. The smallest transmission unit in the uplink is called a physical resource block (RB), which is one slot in duration and consists of 7 SC-OFDMA symbols. The LTE specification also allows for the use of an extended CP. In this case, each slot contains six SC-OFDMA symbols. However, the specification of AS is unchanged. We, therefore, focus on the 'normal CP' case in this paper.

In the frequency-domain, each RB is 180 kHz wide and consists of 12 subcarriers of 15 kHz bandwidth each. The assignment of RBs is for a minimum duration of 1 ms (two slots). The system bandwidth, which ranges from 1.25 MHz to 20 MHz, is divided into several RBs. Of the 14 SC-OFDMA symbols in a subframe, two symbols are reserved for DMRSs. One SC-OFDMA symbol in a subframe is used for carrying the SRS when required; otherwise, it carries data. The remaining symbols carry data. Each UE can be assigned multiple RBs for transmitting data. The exact mechanism for scheduling, which assigns different RBs to different UEs, is not specified in the standard. For example, the eNodeB may employ either a round-robin scheduler or another frequency-domain scheduler that trades off spectral efficiency with fairness differently. In any case, it is the eNodeB that schedules; it communicates its decisions to the UEs on the downlink control channel.

The standard, thus, defines two types of RSs – DMRS and SRS – which serve different purposes. The DMRS is used to determine – with high accuracy – the channel transfer function in the specific RB(s) used by a UE for data transmission; it is used for equalization at the receiver. The SRS, on the other hand, enables the eNodeB to estimate the wideband frequency-domain channel response over a large portion of the system bandwidth, and, thus, enables scheduling. Therefore, the SRS transmitted by a UE typically occupies the entire system bandwidth or a large portion of it. However, due to its wideband nature, the SRS might encounter a higher degree of interference than the DMRS. Further, to reduce the SRS overhead, only one in every six subcarriers carries a pilot symbol. Different UEs are assigned different SRS sequences to enable the eNodeB to distinguish among them.

III. TRAINING

As discussed in Section I, the receiver in the base station needs to learn the channel from each transmit antenna element to the receiver. We first discuss this training procedure in the FDD mode of operation. We then discuss the differences that arise for implementing TAS in the TDD mode.

Since the downlink and uplink are not reciprocal in the FDD mode of LTE, a periodic pilot-based training procedure is required to help the UE select its best antenna. In order to help the eNodeB receiver acquire channel state information for the purpose of antenna selection, the UE alternates transmission of the SRS from its two antennas. This is because the limited number of

transmit RF chains, which motivates TAS, imposes the fundamental constraint that the SRS can be transmitted from only one antenna at any time.

As a result, TAS occurs over two phases in LTE. In the first uplink phase, which is elaborated in this section, the UE basically alternates transmission of the SRS from its two antennas. The eNodeB then estimates the (wideband) channel response of the UE from all its antennas and then chooses the best antenna. In the second downlink phase, which is described in the next section, control signaling from the eNodeB tells the UE which antenna to use. The overall process is illustrated in Figure 3.

In order to correctly associate its channel estimates with the transmit antennas, the eNodeB needs to know a priori the antenna sounding pattern of the UE, which specifies which antenna the UE should transmit from as a function of time. Therefore, the sounding pattern is precisely defined in the standard [6, Sec. 8.2]. It depends on whether the SRS is frequency-hopping or not, which is determined by the `SRSHoppingBandwidth` parameter.

If frequency-hopping is disabled, SRS is alternately transmitted from the two antennas. When enabled, frequency-hopping can occur either as intra-frame or inter-frame hopping. In intra-frame hopping, the UE hops from one RB to another within a subframe. This means that if during the first slot of a subframe, the UE transmits in the lower edge of the bandwidth, then in the second slot it transmits in the higher edge of the bandwidth. In inter-frame hopping, the frequency allocation changes from one sub-frame to the other. The different hopping patterns are intricately prescribed in the standard to ensure that the SRSs of different users can be of different bandwidths and, yet, do not overlap in either time or frequency. The interested reader is referred to [5, Sec. 5.5.3.2] for more details. Figure 4 illustrates an example of a frequency-hopping SRS pattern along with how it is used for AS training.

Advantages: The wideband nature of the SRS enables joint space-frequency assignment, i.e., TAS and RB assignment for the selected antenna happen together since the eNodeB can estimate the channel responses of both the antennas over a large portion of the system bandwidth. More importantly, the use of the SRS for AS training ensures that AS can be supported with minimal changes to the standard.

Disadvantages: A given antenna transmits fewer SRSs with TAS than without TAS. As a result, the ability to track time variations in the channel decreases. The SRS is also a more co-channel interference-prone pilot. Consequently, estimation errors may cause a sub-optimal

antenna to get selected. However, the performance of coherent demodulation, which depends on the accuracy of the estimates obtained using the DMRS pilots, is not affected by this. Note also that AS is fairly robust to estimation errors [7]. Since the SRS is sent less often (every 2 to 10 ms) than the DMRS, the training delays also increase. This leads to the channel estimates, based on which the antenna is selected, to become partially outdated by the time the UE transmits data.

TDD mode: In the TDD mode, only some pre-specified subframes are used for uplink transmissions. Therefore, this affects when and how often the SRS can be transmitted [5, Tbl. 5.5.3.3-2]. However, the two antennas still alternately transmit the SRS to enable AS training.

A. Other Training Options Considered for AS

1) Use of DMRS for AS Training: Instead of alternating the transmission of the SRS from different antennas, another option that was considered during the standardization deliberations was to alternate the transmission of the DMRS between the two antennas [8].

Advantages: Since the DMRS is sent in *every slot* in which data is transmitted, the selection delays are less. The channel estimates obtained using the DMRSs are also considerably more accurate. Thus, unlike the SRS, the DMRS provides the eNodeB with a less noisy and less outdated estimate of the uplink channel, but over a narrower portion of the system bandwidth.

Disadvantages: Fewer channel estimates are available about the antenna transmitting data since some of the DMRS pilots are transmitted by the other unused antenna. This leads to less accurate channel estimates, which, in turn, affects the demodulation at the receiver. Further, joint frequency-domain scheduling and AS is not possible. Using DMRS for AS training purposes was considered to be a bigger change in the standard specification, and was not adopted.

2) Adaptive Transmission of SRS: As we saw, the transmitter can only send the pilot from one transmit antenna at a time. In order to maintain the same level of estimation accuracy, the transmitter, thus, needs to send twice as many pilots. An adaptive technique was also proposed to reduce the overhead [8]. In it, the antenna that has not been selected to transmit data sends the SRS less often than the other antenna. Doing so clearly reduces the overall SRS sounding overhead. Alternately, for the same sounding overhead, it decreases the average delay between two transmissions of the SRS from the antenna that is transmitting data. However, this option was discarded in favor of the simpler strategy of transmitting from the antennas alternately.

IV. Control and Layer 3 Signaling, and Performance Evaluation

A. Control Signaling

As mentioned, a 1-bit feedback from the eNodeB is needed to indicate to the UE which selected antenna to use for transmitting data. The data is transmitted on the Physical Uplink Shared Channel (PUSCH). The feedback is always sent by the eNodeB in the uplink scheduling grant. The grant is a control message that tells the UE which time-frequency resources are assigned to it for uplink transmission. However, no explicit control bit is allocated in LTE for this. Instead, the header of the grant (which is said to be in 'Format 0') is masked as follows. The 16 cyclic redundancy check (CRC) parity bits in the header are scrambled using modulo-2 addition by a 16-bit AS mask. UE transmit antenna 0 is indicated using the mask 0000 0000 0000 0000, and antenna 1 is indicated using the mask 1000 0000 0000 0000. The receiver uses blind decoding to determine which mask was used, and, therefore, which antenna to transmit from.

The eNodeB may also permit the UE to use open-loop TAS, wherein the UE is free to determine which antenna to transmit from. However, the standard does not specify any aspect related to open-loop TAS.

Pros and Cons: The implicit encoding avoids the use of an explicit bit for TAS. Thus, no additional overhead is introduced for UEs that do not support AS or when the eNodeB does not want to configure the UEs to use AS. Since the receiver needs to determine this bit using blind decoding, the number of blind decodes that the UE has to perform increases. Note, however, that in LTE, even a UE that does not support TAS already performs close to 40 blind decodes per frame to determine other control signaling bits.

B. Layer 3 Signaling

Layer 3 signaling is the higher layer signaling that occurs during the connection establishment phase, and enables a UE to communicate to the eNodeB whether it supports the closed-loop AS capability. In the Layer 3 message, the field `ue-TxAntennaSelectionSupported` defines whether the UE supports AS [9]. The eNodeB takes this capability into consideration when configuring and scheduling the UE. Clearly, a UE that only supports open-loop AS need not inform the eNodeB about its capability.

C. HARQ Transmissions and AS

Automatic retransmission (ARQ) refers to the retransmission of a signal when the first transmission was not successful. In Hybrid ARQ (HARQ), the receiver combines the signals from the original transmission with that of the retransmission(s) to obtain a higher quality overall signal. Since LTE uses HARQ, its operation when AS is enabled is also specified so as to clarify whether the UE should retransmit using the same antenna or not [10]. In LTE, the following two forms of HARQ are used:

- *Adaptive HARQ:* In adaptive HARQ, the antenna indicator is always sent via CRC masking in the uplink grant to indicate which antenna to use. For example, for high Doppler spreads, the eNodeB might instruct the UE to alternate between the transmit antennas. Otherwise, the eNodeB may always select a pre-determined UE antenna for all the retransmissions.

- *Non-adaptive HARQ:* In non-adaptive HARQ, which antenna the UE should transmit from is left unspecified. For low Doppler spreads, the UE could use the same antenna as that signaled in the uplink grant, while at high Doppler spreads the UE could choose to hop between its antennas.

V. PERFORMANCE EVALUATION

We now present Monte Carlo simulation results to evaluate the benefits of AS in the presence and absence of a frequency-domain scheduler at the eNodeB. The simulation scenario is as follows. Five UEs are placed in a cell. The system bandwidth is 5 MHz. Each user is assigned one fifth of the total number of RBs. The average data SNR at the input of each of the receive antenna elements is set as 10 dB per subcarrier for all UEs. The propagation channel from each UE to the eNodeB follows a 6-path Typical Urban (TU) power delay profile, which is among the more dispersive of the standardized channel profiles. The more frequency-selective the channel, the less likely it is that the same transmit antenna will be optimal for all the RBs, and the smaller the performance gain observed for TAS. The eNodeB has two uncorrelated receive antennas and uses maximum ratio combining. The channel estimation error in the SRS SC-OFDMA symbol is modeled by means of an additive Gaussian noise in the SRS signal received by the eNodeB receiver.

Different SRS transmit power settings are considered to determine how robust AS is to estimation error. Each UE has two transmit antennas out of which one is selected on the basis of

the 1-bit feedback from the eNodeB. A UE transmits its SRS over the entire system bandwidth alternately from its two antennas. As mandated in LTE, when multiple RBs are assigned to the same UE, they are all contiguous in the frequency-domain. This simplifies the frequency-domain scheduling algorithm and enables the use of frequency-domain interpolation techniques for channel estimation.

The simulation results presented in Figure 5 show the cumulative distribution function (CDF) of the data SNR observed for each RB as a function of the channel estimation error and the number of UEs scheduled per subframe. The CDF of the data SNR is a relevant measure of performance because adaptive modulation and coding, which is an integral component of the LTE standard, fundamentally depends on the data SNR. The larger the SNR, the higher the transmit data rate. The CDF also captures more statistical information about the SNR variations than the mean SNR value.[2] The performance of AS with different SRS powers is compared to no-AS. Also shown is the performance with perfect noise-free channel estimates. Scenarios with frequency-domain scheduling and without frequency-domain scheduling are evaluated, as described below.

1) Without Frequency-Domain Scheduling: In this case, different RBs are assigned to different UEs without taking into account the channel estimates obtained from the SRS. Only the antenna is selected on the basis of these estimates. AS delivers an SNR gain of 2.2 dB at 10%ile and 1.3 dB at 50%ile (median) compared to no-AS. Furthermore, AS is quite robust to imperfect SRS channel estimates. Even when the SRS SNR is 10 dB below the data SNR, the 10%ile data SNR with AS decreases by only 0.2 dB. Intuitively, this can be explained as follows. When the SNR of the two available antennas is similar, a channel estimation error does not have a strong effect on the achievable performance, since the choice is between two almost equally good antennas. Instead, if the instantaneous SNRs of the two antennas are very different, even a noisy training sequence is sufficient to determine which antenna is the best. The impact of DMRS-based AS training, described in Sec. III-A1, in which the more accurate DMRS estimates are used for AS can also be inferred from this figure because its performance is well modeled

---

[2]To focus on the role of SRS, we do not model the impact of imperfect channel estimation using the DMRS on the data SNR. This is justifiable because the channel estimate obtained from the DMRS is considerably more accurate than that obtained from the SRS. Note that, in general, the scheduler need not assign the same number of RBs to each user. In addition to the data SNR, a system-level simulator would measure overall system throughput and delay.

by the perfect channel estimates curve. We see that using DMRS gives a median SNR gain of 0.2 dB.

2) With Frequency-Domain Scheduling: Frequency-domain scheduling aims to assign each UE to the RBs that offers the best channel quality. The eNodeB uses the channel estimate obtained from the SRS to determine which user to assign to each set of five contiguous RBs and also which transmit antenna the assigned user should use. The data transmission rate of each RB and a given transmit antenna is calculated using the channel estimate derived from the SRS using the Shannon capacity formula. The antenna chosen is the one that leads to the highest rate summed over all RBs being considered for assignment to a UE. Once a UE is selected for transmitting a fixed number of contiguous RBs, it is not selected again in the same subframe.

We again see from the figure that even when the SRS SNR is 10 dB below the data SNR, the data SNR with AS decreases only marginally. Further, AS yields a 10%ile SNR gain of 1.9 dB and a median SNR gain of 1.1 dB over no-AS. Now, even the performance of no-AS depends on the SRS pilot SNR, albeit marginally. Note also that frequency-domain scheduling improves the data SNR, as a result of which the CDF shifts to the right.

VI. SUMMARY AND DISCUSSION

Antenna selection and its variants enable the use of multiple antennas at the transmitter and receiver and reap their diversity benefits without increasing the requirements for RF hardware of the devices. Training for Transmit AS in the LTE standard is accomplished using the wideband SRS. The antennas in the UE alternately transmit the SRS, which enables the eNodeB to estimate their channel responses over a large portion of the system bandwidth and select the best transmit antenna. It also enables joint space-frequency resource allocation and optimization. The feedback from the eNodeB is sent in an implicit manner using a zero-overhead CRC header masking technique. Ensuring that AS has minimal impact on the overall specification and does not create additional overhead for UEs that do not support it was a key consideration in adopting this scheme. We also saw that joint AS and scheduling is robust to the larger channel estimation errors that the SRS is expected to encounter. Altogether, AS is a promising technology that has been adopted by LTE for both the FDD and TDD modes of operation in order to reap the benefits of having multiple antennas in UEs, but at a lower hardware cost.

REFERENCES

[1] A. F. Molisch and M. Z. Win, "MIMO systems with antenna selection," *IEEE Microwave Mag.*, vol. 5, pp. 46–56, Mar. 2004.

[2] A. B. Narasimhamurthy and C. Tepedelenlioglu, "Antenna selection for MIMO-OFDM systems with channel estimation error," *IEEE Trans. Veh. Technol.*, vol. 58, pp. 2269–2278, Jun. 2009.

[3] V. Kristem, N. B. Mehta, and A. F. Molisch, "Optimal receive antenna selection in time-varying fading channels with practical training constraints," *IEEE Trans. Commun.*, vol. 58, pp. 2023–2034, Jul. 2010.

[4] S. Sesia, I. Toufik, and M. Baker, *LTE – The UMTS Long Term Evolution, From Theory to Practice*. John Wiley and Sons, 2009.

[5] "Technical specification group radio access network; evolved universal terrestrial radio access (E-UTRA); physical channels and modulation (release 8)," Tech. Rep. 36.211 (v8.2.0), 3rd Generation Partnership Project (3GPP), 2008.

[6] "Technical specification group radio access network; evolved universal terrestrial radio access (E-UTRA); physical layer procedures (release 8)," Tech. Rep. 36.213 (v8.2.0), 3rd Generation Partnership Project (3GPP), 2008.

[7] V. Kristem, N. B. Mehta, and A. F. Molisch, "A novel, balanced, and energy-efficient training method for receive antenna selection," *IEEE Trans. Wireless Commun.*, vol. 9, pp. 2742–2753, Sep. 2010.

[8] Mitsubishi Electric and NTT DoCoMo, "Low cost training for transmit antenna selection on the uplink," Tech. Rep. R1-062941, 3GPP RAN1#46bis, Oct. 2006.

[9] "Technical specification group radio access network; evolved universal terrestrial radio access (E-UTRA); user equipment (UE) radio access capabilities (release 8)," Tech. Rep. 36.306 (v8.3.0), 3rd Generation Partnership Project (3GPP), 2008.

[10] "Technical specification group radio access network; evolved universal terrestrial radio access (E-UTRA); multiplexing and channel coding (release 8)," Tech. Rep. 36.212 (v8.2.0), 3rd Generation Partnership Project (3GPP), 2008.

Neelesh B. Mehta is an Associate Professor in the Dept. of Electrical Communication Eng., Indian Institute of Science, Bangalore, India. Prior to joining IISc, he has held research positions in USA at AT&T Laboratories, Broadcom Corp., and Mitsubishi Electric Research Laboratories (MERL). He was also actively involved in standardization in 3GPP RAN1 during 2003-07. He has co-authored 30+ IEEE journal papers and is a co-inventor in 20 issued US patents.

Andreas F. Molisch is Professor of Electrical Engineering at the University of Southern California. His research interests include MIMO, cooperative communications, wireless propagation channels, ultrawide-band (UWB) communications and localization, and new wireless architectures. He is a Fellow of the IEEE, Fellow of the IET, and Member of the Austrian Academy of Sciences, as well as recipient of numerous awards.

Salil Kashyap received his Bachelor of Technology degree in Electronics and Communication Engineering from NERIST, Itanagar in 2007 and Master of Technology degree in Digital Signal Processing from the Indian Institute of Technology (IIT), Guwahati in 2009. He is currently pursuing his Ph.D. in the Electrical Communication Engineering Department at the Indian Institute of Science (IISc), Bangalore. His research interests broadly include performance analysis of antenna selection and resource allocation algorithms in MIMO-OFDM systems.

TABLE I

TRANSMIT AS IN CELLULAR STANDARDS

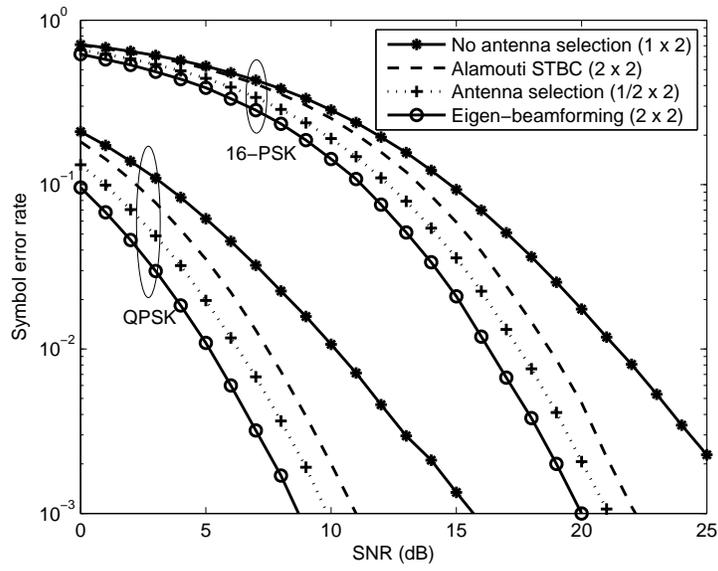|	AS standardization and motivation	
Standard	**Downlink**	**Uplink**
IEEE 802.16e/m	For precoding purposes	–
3GPP LTE	For precoding purposes	Motivated by hardware constraints

Fig. 1. Symbol error rate comparison of antenna selection, no antenna selection, eigen-beamforming, and open loop Alamouti space-time block code for QPSK and 16-PSK constellations
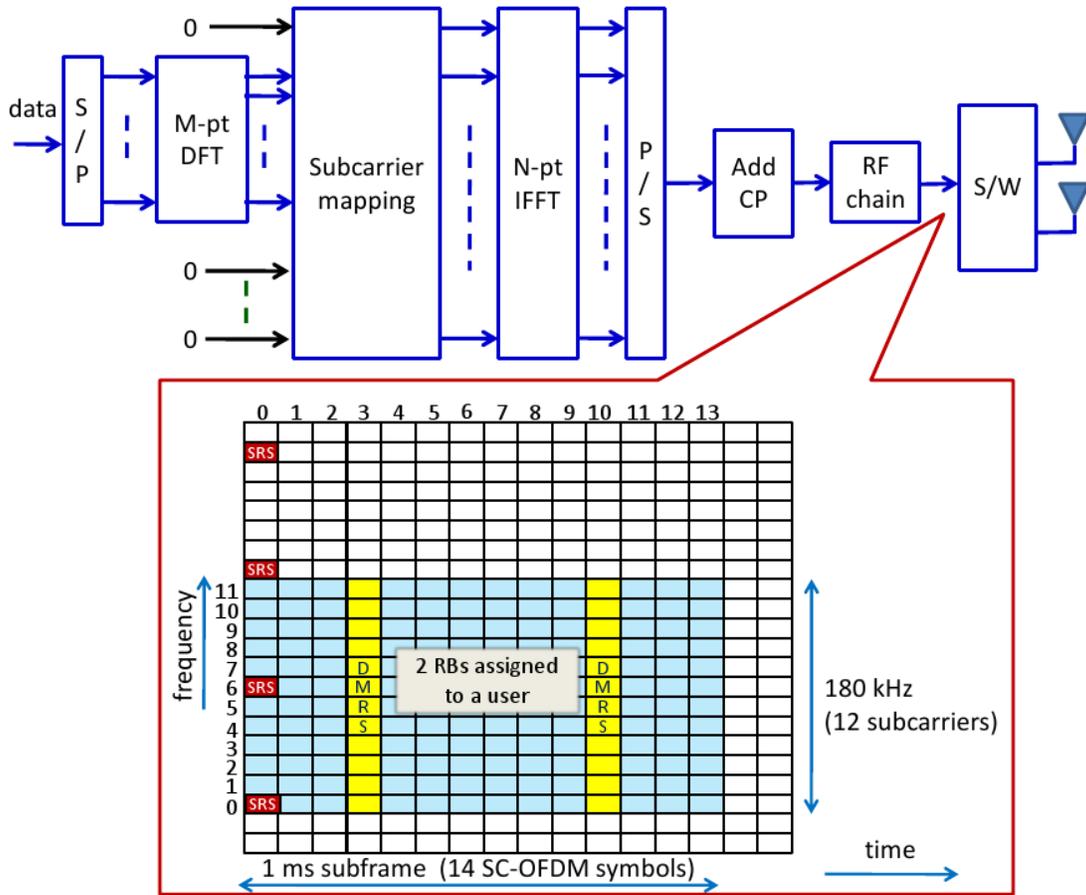
Fig. 2. SC-FDMA transmit chain, transmit antenna selection, and uplink frame structure of LTE
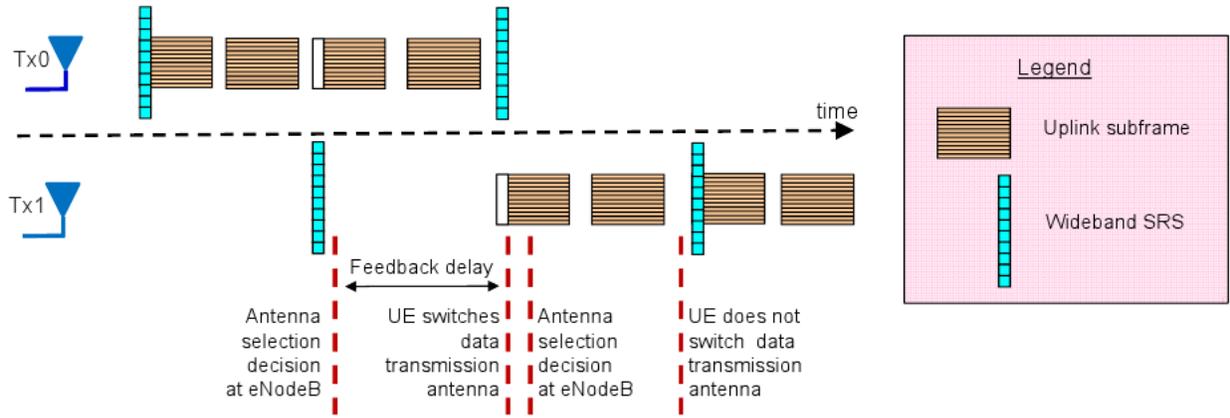
Fig. 3. Uplink transmit antenna selection training using SRS. The SRS, which is shown as a longer vertical bar given its larger bandwidth, is transmitted alternately from two antennas, Tx 0 and Tx 1. This enables the eNodeB to estimate the channels from the two antennas to it, and to perform RB allocation and AS

Fig. 4. Transmit antenna sounding patterns for a frequency-hopping SRS for multiple UEs. The indices of 0 and 1 correspond to transmissions by transmit antennas 0 and 1, respectively. Different colors correspond to different UEs
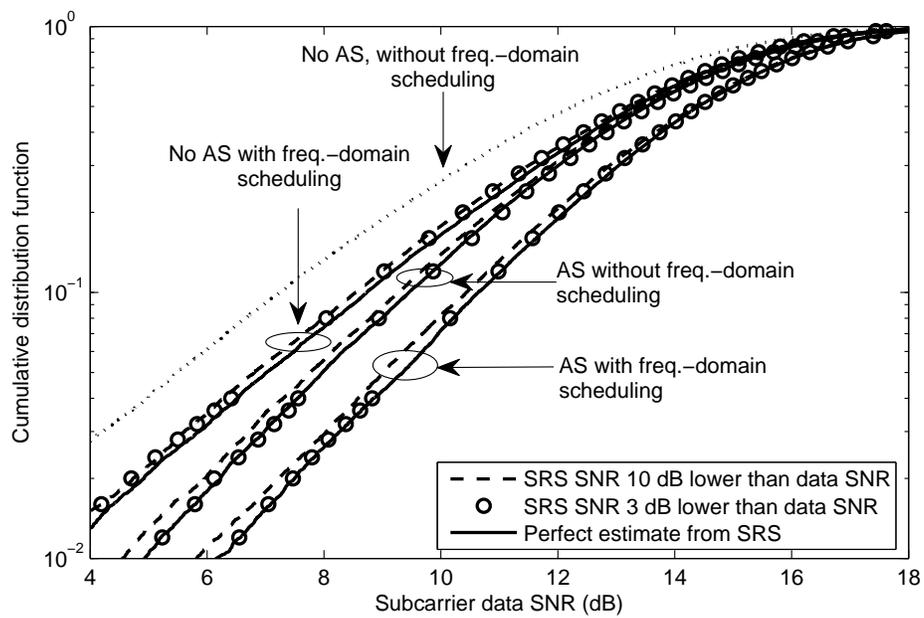
Fig. 5.   Performance of antenna selection when SRS is used for training: With and without frequency-domain scheduling