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Abstract

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Antenna Selection Training in MIMO-OFDM/OFDMA Cellular Systems

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***Abstract*—Antenna selection allows multiple-antenna systems to achieve most of their promised diversity gain, while keeping the number of RF chains and, thus, cost/complexity low. In this paper we investigate antenna selection for fourth-generation OFDMA-based cellular communications systems, in particular, 3GPP LTE (long-term evolution) systems. We propose a training method for antenna selection that is especially suitable for OFDMA. By means of simulation, we evaluate the SNR-gain that can be achieved with our design. We find that the performance depends on the bandwidth assigned to each user, the scheduling method (round-robin or frequency-domain scheduling), and the Doppler spread. Furthermore, the signal-to-noise ratio of the training sequence plays a critical role. Typical SNR gains are around 2 dB, with larger values obtainable in certain circumstances.**

I. Introduction

Next-generation cellular communications systems, like the long-term evolution (LTE) of 3GPP (third generation partnership project), will have to provide higher spectral efficiency and reliability. There is general consensus that such systems will use OFDMA (orthogonal frequency division multiple access) for multiple access, and OFDM (orthogonal frequency division multiplexing) as the modulation format. In order to further enhance the spectral efficiency and robustness, multiple antenna elements will be used at the base station (BS) and mobile station (MS). However, it is also recognized that the complexity and cost of MSs must not be significantly higher than those of current handsets.

Antenna selection (AS) has attracted considerable attention recently as a solution that reduces the hardware complexity of multiple input multiple output (MIMO) antenna systems while still retaining their diversity advantages [1, 2]. In AS, only the signals from a limited-sized subset of the available antenna elements are adaptively chosen and processed by RF and baseband circuitry. This approach greatly reduces the cost of a transceiver, since antenna elements are typically cheap and easy to implement, while RF chains, in particular, mixers, low-noise amplifiers, and oscillators are expensive.

Considerable work has appeared in the literature on the performance of antenna selection, including capacity [3], [4], diversity [5], [6], optimal and suboptimal selection criteria and processing [6–9]. However, one critical aspect that has received relatively less attention is training, through which the channel states of all antennas are determined in order to select the best antenna. While a low hardware complexity is one of the key advantages of AS, it also imposes unique constraints on how training can be done for AS. This is because only a subset of the antennas can be activated at any instant to transmit signals (in transmit AS) or receive signals (in receive AS). The only published work we are aware of in this context is [10]; however, this paper analyzes a packet-based system in low-Doppler-spread environments, and is thus not applicable to the cellular systems that are the focus of this paper.

This paper shows how training can be done for transmit AS by handsets in 3GPP LTE systems, which are currently being standardized. We suggest the use of available and sparse wideband pilot signals, which are transmitted at regular intervals. We find that a considerable amount of noise can be tolerated on the pilot tones without influencing the effectiveness of AS. However, if the Signal-to-Noise Ratio (SNR) becomes considerably negative, the performance loss becomes significant. The paper also presents extensive simulations analyzing the impact of other system parameters on the performance. For example, we investigate the impact of the bandwidth assigned to each user, the Doppler spread, and the chosen scheduling method on the effectiveness of AS.

The paper is organized as follows. Section II briefly describes relevant aspects of the physical transmission structure of the 3GPP LTE frequency division duplex uplink. The training method for transmit AS is described in Sec. III, and various aspects of its system-level performance are studied in Sec. IV. Our conclusions follow in Sec. V.

II. Physical Frame Structure

The LTE uplink uses single-carrier OFDMA (SC-OFDMA) [11]. In the uplink, the basic unit of time for data transmission is a transmission time interval (TTI), which is 1 ms long. The smallest transmission unit in the uplink is called a resource block (RB). Each RB is 1 TTI long and consists of 14 SC-OFDMA symbols. In the frequency-domain, each RB is 180 kHz wide and consists of 12 subcarriers of 15 kHz bandwidth each. Of the 14 SC-OFDMA symbols, the 4-th and 11-th symbols are reserved for demodulation reference signals (RSs). The first SC-OFDMA symbol is (tentatively) used for carrying either the sounding RS (RS) or data. The remaining symbols always carry data. Each user can be assigned multiple RBs for transmitting data. The exact mechanism for the scheduling (i.e., assignment of RBs) is not specified. For

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example, a round robin scheduling is possible. However, the BS might also implement other, more efficient (but potentially less fair) mechanisms. For example, in frequency-domain scheduling, users are assigned the frequencies at which they instantaneously have the best transmission quality.

The standard thus defines two types of RSs. The *demodulation RS* is used to determine – with high accuracy – the channel transfer function in the specific RB(s) used by an MS for data transmission. A second type of RS, the *sounding RS*, is intended to enable efficient scheduling. The BS (called eNodeB in the LTE standard) uses it to estimate the frequency-domain channel response over the entire system bandwidth, e.g., over 1.25, 2.5, 5, or 10 MHz. Therefore, the sounding RS transmitted by each user typically occupies the entire system bandwidth. However, given that all users' sounding RSs occupy the entire system bandwidth, the sounding RS necessarily encounters a higher degree of interference than the demodulation RS, which does not overlap in time or frequency for different users that are assigned different RBs. This leads to poorer system bandwidth-wide channel estimates.

Different users are assigned different sounding RS sequences to enable the eNodeB to distinguish among them. It is noteworthy that for a sounding RS, it is not necessary to transmit a signal on every available subcarrier or in every TTI. A sparse RS, which uses only, say, every 6-th subcarrier, provides sufficient information for scheduling.

Transmit AS is now a "working assumption" in the 3GPP LTE standard and the details about its operation are currently being determined and specified. Only a simple form of AS, in which one out of two antennas is selected, is currently being considered given that the baseline (reference) assumption is that the eNodeB has 2 transmit and receive antennas and the MS has 1 transmit and 2 receive antennas. Such an approach delivers most of the diversity benefits, while keeping the complexity low.

III. Antenna Selection Training Method

Several AS training schemes have been proposed that use either the data demodulation RS or the sounding RS to enable the eNodeB to estimate the channel states of both antennas, and feed it back to the MS [12]. Using the RSs specified in the standard has the advantage of minimizing the number of changes required to enable AS in LTE and eases its implementation. A major question is whether the demodulation RS or the sounding RS should be used for AS training. This choice presents interesting trade-offs in a multi-user cellular system.

- Using the demodulation RS enables the channel states of all the antennas to be estimated quickly. However, it leads to poorer channel estimation for data demodulation at higher MS speeds since some of the demodulation RSs are used for AS. More importantly, use of demodulation RSs allows for the best antenna to be chosen *only after the RBs have been assigned a priori.*
- In contrast, using the sounding RS for AS facilitates joint frequency-domain scheduling and AS, i.e., joint space-frequency resource allocation, since the system bandwidth-wide channel response of both the antennas can be determined. On the downside, using the sounding RS for AS is a slower option, as sounding RSs are transmitted less often. Overall, however, the benefits of using the sounding RSs outweigh the drawbacks.

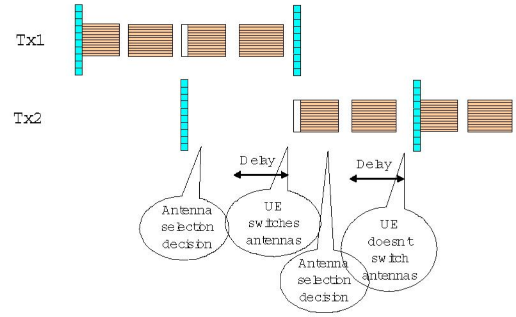

Fig. 1. Uplink transmit antenna selection training using sounding reference signals

In this paper, we propose and evaluate a method to use the sounding RS for closed-loop AS, and provide simulation results that study interactions between AS, frequency-domain resource allocation, number of MSs in the system, and scheduling [13].

The training scheme is illustrated in Fig. 1. The sounding RS, which is shown as a longer vertical bar given its wider bandwidth, is transmitted alternately from two antennas, Tx 1 and Tx 2. This enables the eNodeB to estimate the channels from the two antennas to it, and to perform RB allocation and AS. For example, in the figure, the sounding RS is transmitted every 2 TTIs, and the MS starts transmitting from TTI 1. Then, the sounding RSs of TTIs 1, 5, 9, ... are transmitted from the first antenna and the sounding RSs of TTIs 3, 7 11, ... are transmitted from the second antenna. In general, how often the sounding RS is sent by each MS is configurable, and is determined by the eNodeB.

IV. Simulation Results

A. Simulation Assumptions

In order to evaluate the effectiveness of AS under various scheduling algorithms, we perform Monte-Carlo simulations with the following settings: $N_u = 25$, 5, or 2 MSs are placed in a cell. The system follows the LTE specifications as outlined in Sec. II, and has a bandwidth of $B = 10$ MHz. The average data SNR at the input of each of the receive antenna elements is set as 10 dB (per subcarrier) for all users.[1] The propagation channel from each MS to the BS exhibits a 6-path Typical Urban (TU) power delay profile [14], which is among the more dispersive or frequency-selective of typically simulated channel profiles. Using such a profile leads to conservative performance gains because the more frequency-selective the channel, the less likely it is that the same transmit antenna will be optimal for all the RBs. However, the hardware advantages that motivate AS in the first place also mandate that an MS must use the same transmit antenna for all the RBs assigned to it. The eNodeB has 2 uncorrelated receive antennas and does maximum ratio combining. The angular power spectrum at the MS has a Gaussian

[1] For simplicity, we do not model the impact of imperfect channel estimation of the demodulation RS on data SNR.

shape with an angular spread of 58^o, and the transmit antennas at the MS are spaced half a wavelenth apart.

The channel estimation error in the sounding RS SC-OFDMA symbol is modeled by means of Gaussian channel estimation noise at the eNodeB receiver with a power that varies between 10 dB and -10 dB (per subcarrier). A 10 dB sounding RS SNR corresponds to almost perfect channel estimation for frequency-domain scheduling and antenna selection (except for delays associated with sounding and feedback). On the other hand, a -10 dB sounding RS SNR corresponds to an extremely noisy channel estimate that effectively leads to random AS as well as random frequency assignment. Each MS has 2 transmit antennas out of which one is selected based on a 1-bit feedback from the eNodeB. The feedback delay is assumed to be 1 TTI.

The eNodeB assigns RBs based on its noisy estimates of the system bandwidth-wide channel responses of all the UEs, as per Sec. III. The multiple RBs, when assigned to an MS, are assumed to be contiguous, as this simplifies the frquency-domain scheduling algorithm and also enables better channel estimation using frequency-domain interpolation techniques. For the selection, the capacity of each RB is calculated using the channel estimate derived from the sounding RS, assuming that it is perfect. Based on these capacity estimates, we choose the antennas for the users and evaluate the data SNRs they encounter as the performance measure. When multiple RBs are assigned to an MS, the antenna chosen is the one that leads to the highest capacity over all RBs being considered for an MS.

The simulation results presented below show the Cumulative Distribution Function (CDF) of the SNR (of data) observed for each RB as a function of the channel estimation error and the number of MSs scheduled per TTI. This is done for both the round-robin scheduler, which is fair but inefficient, and the frequency-domain scheduler, which can potentially sacrifice fairness for throughput when the users have asymmetric channels on average. Plotting the CDF of the SNR is useful as SNR is a fundamental performance measure on which adaptive modulation and coding and HARQ (hybrid automatic repeat request) retransmissions will depend.

B. Antenna selection with round-robin scheduling

The round-robin scheduler assigns different RBs to different MSs without taking into account their instantaneous channel states. Its performance with AS when the entire bandwidth is allocated to 25, 5 and 2 MSs in each TTI is shown in Figures 2, 3, and 4, respectively.

As more contiguous RBs are assigned to an MS, the relative performance gain from AS decreases. However, except for the extreme cases in which the entire 10 MHz bandwidth is assigned to just 1 or 2 MSs per TTI, AS delivers a gain of 1.7 dB at 1%ile and 1.3 dB at 10%ile of the system-level SNR CDF when 10 MSs are scheduled per TTI. Furthermore, AS is extremely robust to imperfect channel estimation. Even at a sounding RS SNR of -2 dB, AS suffers from a performance degradation that is less than 0.5 dB.

An intuitive explanation of this effect is the following: 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. If the instantaneous SNR of the two antennas is very different, even a quite noisy training sequence is often sufficient to determine which antenna is best.

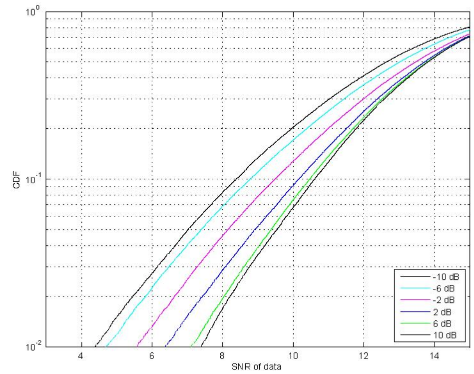

Fig. 2. Entire bandwidth assigned to 25 MSs (f_d = 5 Hz, round-robin scheduling, sounding RS sent every TTI)

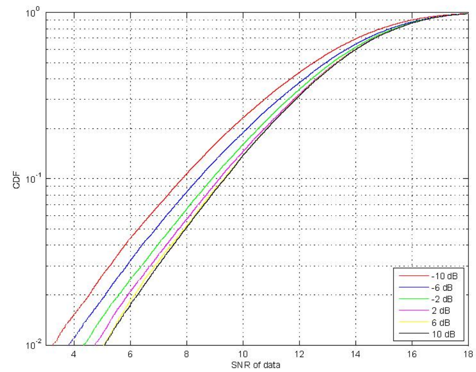

Fig. 3. Entire bandwidth assigned to 5 MSs (f_d = 10 Hz, round-robin scheduling, sounding RS sent every 2 TTI)

C. Antenna selection with frequency-domain scheduling

The frequency-domain scheduling aims to assign each user to the RBs that offers the best channel quality. We use a suboptimum, though still efficient scheduling algorithm that works as follows: once an MS is selected for transmitting a fixed number of contiguous RBs, it is not selected again in the same TTI. The above limitation makes the scheduling algorithm tractable

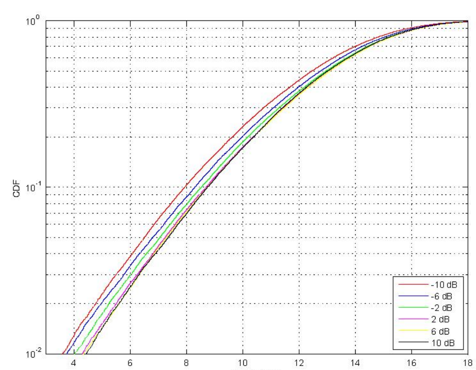

Fig. 4. Entire bandwidth assigned to 2 MSs (f_d = 10 Hz, round-robin scheduling, sounding RS sent every 2 TTI)

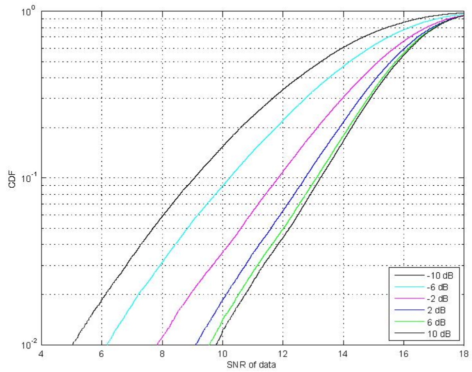

Fig. 5. Entire bandwidth assigned to 25 MSs ($f_d = 5$ Hz, frequency-domain scheduling, sounding RS sent every 2 TTI)

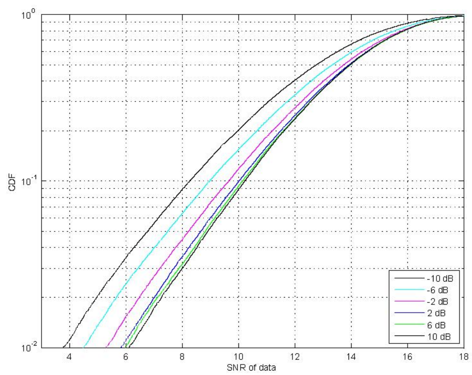

Fig. 6. Entire bandwidth assigned to 5 MSs ($f_d = 10$ Hz, frequency-domain scheduling, sounding RS sent every 2 TTI)

in the presence of AS, which imposes the rigid constraint that an MS can transmit at any time with only antenna. A total of 5 MSs are simulated in the system.

AS with frequency-domain scheduling when the entire bandwidth is allocated to 25, 5 and 2 MSs is shown in Figures 5, 6, and 7, respectively, for different values of the souding RS SNR. As mentioned, a sounding RS of -10 dB corresponds to random AS (or, equivalently, the single transmit antenna case). We again see that AS incurs a negligibile performance penalty so long as the sounding RS SNR is greater than -2 dB. We expect the frequency-domain scheduler to outperform the round-robin scheduler, because the former selects the users with the best channels, while the latter always schedules the users according to a fixed pattern, even if they have very bad channels. Comparing Figs. 5–7 with Figs. 2–4 shows that the frequency-domain scheduler indeed performs better by 1–2 dB.

V. Conclusions

We proposed and evaluated a practical training method that uses the wideband sounding reference signal for antenna selection in MIMO-OFDM/OFDMA systems, specifically, 3GPP LTE systems. The method realizes the diversity advantages of multiple antenna systems while keeping the hardware complexity of handsets under control. Doing so also enables joint space-frequency resource allocation and optimization. The simulation results showed that joint antenna selection and scheduling is extremely robust to the higher channel estimation error that the

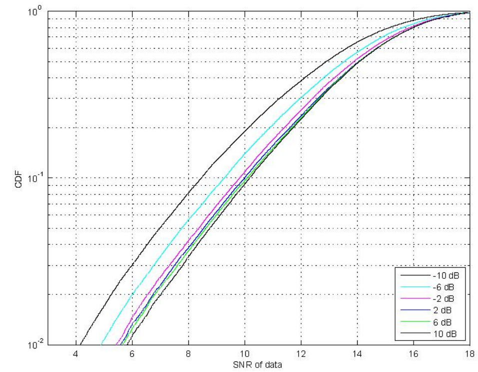

Fig. 7. Entire bandwidth assigned to 2 MSs ($f_d = 10$ Hz, frequency-domain scheduling, sounding RS sent every TTI)

wideband sounding reference signal is expected to encounter. Future research includes developing techniques that reduce the total number of times the sounding reference signal needs to be transmitted by a mobile station from both its antennas without compromising on performance.

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