Smart Antennas for the EDGE Wireless TDMA System

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Abstract

In this paper, we discuss the use of smart antennas in cellular TDMA systems. We first describe the current and proposed use of smart antennas in the second generation TDMA system ANSI-136. We then describe how smart antennas with space-time processing can be used in the third generation TDMA system EDGE to provide higher capacity and range. We also describe the use and performance of multiple (M) antennas at the terminal as well as at the base station to provide an M-fold increase in the data rate (384 kbps) of EDGE.

I. INTRODUCTION

Adaptive arrays can combat multipath fading of the desired signal and suppress interfering signals, thereby increasing both the performance and capacity of wireless systems. The use of these arrays will become increasingly important as wireless systems evolve from second generation with voice dominance to third generation, where high speed data will dominate.

In this paper we discuss the use of smart antennas in cellular TDMA systems, including the second generation TDMA system ANSI-136, with emphasis on how adaptive arrays, or smart antennas, can be used in the third generation TDMA system EDGE.

Enhanced Data Rates for Global Evolution (EDGE) is currently being standardized as an evolution of GSM in Europe and ANSI-136 in the United States. Initially, it will provide an air interface for high speed data services [1], and it will be enhanced to provide voice, real-time, and simultaneous voice and data services. EDGE reuses the GSM time slot structure, carrier bandwidth (180.05 kHz), and symbol rate (270.833 kbaud), but can provide a 3 times higher data rate (up to 384 kbps) through the use of 8-PSK modulation with partial response pulse shaping. EDGE is being introduced as an ANSI-136 overlay using a 1/3, 3/9, or 4/12 reuse pattern (instead of the 7/21 reuse pattern in current ANSI-136 systems); thus, cochannel interference severely limits the radio link performance. Adaptive array techniques, using multiple receive antennas for interference suppression (as used in ANSI-136 (see, e.g., [2,3])), can mitigate this problem.

In Section II, we give a brief overview of smart antennas. We describe their current and possible use in ANSI-136 in Section III. In Section IV, we discuss how the same smart antennas used with ANSI-136 can be used in EDGE to suppress interference and provide a 4-fold capacity increase (up to 1.5 Mbps) using multiple-input multiple-output (MIMO) techniques [4-6] with multiple handset antennas, and how these antennas can also be used to provide data rates up to 10 Mbps on the downlink. Conclusions are presented in Section V.

II. SMART ANTENNAS

Wireless communication systems are limited in performance and capacity by three major impairments. The first of these is multipath fading, which is caused by the multiple paths that the transmitted signal can take to the receive antenna [7]. The signals from these paths add with different phases, resulting in a received signal amplitude and phase that varies with antenna location, direction, and polarization, as well as with time (with movement in the environment). For example, at 2 GHz a 60 mph vehicle speed results in a 179 Hz fading rate. This increases the required average received signal power for a given bit error rate (BER).

The second impairment is delay spread, which is the

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difference in propagation delays among the multiple paths. When the delay spread exceeds about 10% of the symbol duration, significant intersymbol interference can occur, which limits the maximum data rate (see, e.g., [8]).

The third impairment is co-channel interference. Cellular systems divide the available frequency channels into channel sets, using one channel set per cell, with frequency reuse (e.g., most TDMA systems use a frequency reuse factor of 7). This results in co-channel interference, which increases as the number of channel sets decreases (i.e., as the capacity per cell increases). In TDMA systems, the co-channel interference is predominantly from one or two other users. For a given level of co-channel interference (channel sets), capacity can be increased by shrinking the cell size, but at the cost of additional base stations.

Cellular systems today generally use 120° sectorization. That is, the 360° around each base station is split into 3 sectors, with handoffs from one carrier frequency to another between the sectors. For higher performance (low cochannel interference and greater range), narrower sectors could be used, but this can result in too many handoffs and may not be effective if the angular spread (angular range of the multipath for a given user at a base station) is too large. To overcome this limitation, let us consider the use of smart antennas at the base station, which we define as a multibeam or adaptive array without handoffs between beams. These two types of smart antennas are shown in Figure 1 and are described below.

The first type of smart antenna is a multibeam antenna, which consists of multiple nonoverlapping beams covering a sector. For example, four 30° beams would cover a 120° sector. For each user, the base station selects one of the beams for transmission and reception based on the strength of the received desired signal. To select the beam, the base station needs to check every few seconds to determine the appropriate beam. An M-beam antenna provides a gain of M (for range increase) as well as reduces the number of interferers by a factor of M, although it cannot suppress interferers within the beam of the desired signal. Furthermore it can provide only limited diversity gain against multipath fading.

The second type of smart antenna is an adaptive array, which consists of multiple antenna elements, each covering the entire sector (although they may have different polarization). For each user, the received signals are weighted and combined to suppress interference and maximize desired signal power. This is typically done by generating the weights that minimize the mean squared error (MMSE) or maximize the signal-to-interference-plus-noise ratio (SINR) in the output signal. In a line-of-sight system, this puts a main beam in the direction of the desired signal and nulls in the antenna pattern in the direction of interferers. Now, with the appropriate weights, an M-element adaptive array can suppress up to $M-1$ interfering signals, in both line-of-sight as well as multipath environments. Furthermore, in a multipath environment, the adaptive array can suppress the signal from an interfering user, even if that user is within a few inches of the desired user, and provide up to an M-fold diversity gain against multipath fading. Thus, the adaptive array has much greater interference suppression and multipath mitigation than the multibeam antenna. However, the weights must track the multipath fading, which requires weight updates at about 10 to 100 times the fading rate or 2 to 20 kHz for a mobile moving at 60 mph with a 2 GHz carrier frequency. Thus, the computational complexity of the adaptive array is much higher than that of the multibeam antenna, but this is generally still within the complexity that can be handled by typical DSP's today. Adaptive arrays are difficult to use on the downlink, however, since most cellular systems operate in a frequency division duplex mode with different uplink and downlink frequencies, and thus the receive weights will be different than that required for transmission.

In terms of the wireless impairments discussed above, the adaptive array provides both multipath mitigation as well as cochannel interference suppression. For delay spread, the adaptive array can also suppress delayed signals, but it is generally better to use the spatial processing of the array to suppress cochannel interference and use temporal processing to mitigate the intersymbol interference due to delay spread. A typical architecture for this spatial-temporal processing is to first have a linear equalizer for each antenna element, followed by a combiner and a nonlinear equalizer (e.g., a maximum likelihood sequence estimator (MLSE) or decision feedback equalizer). The linear equalizers suppress the cochannel interference and maximize the desired SINR in the combined signal, without respect to the intersymbol interference of the desired signal. The nonlinear equalizer then mitigates this intersymbol interference.

Finally, in terms of capacity increase, since an array of M antenna elements can suppress up to $M-1$ interfering signals even when the transmit antennas are closely spaced in a multipath environment, MIMO techniques can be used to increase the capacity M-fold. That is, with M

transmit and M receive antennas, M different signals can be transmitted and then separated at the receiver, for an M-fold increase in capacity with about the same total transmit power as a single transmit/receive antenna system.

III. SMART ANTENNAS IN ANSI-136

Most base stations today use 2 receive antennas and one transmit antenna per sector. Until the last few years, for the second generation TDMA system ANSI-136, the signals received by the two receive antennas were weighted and combined to maximize the desired signal-to-noise ratio, e.g., using maximal ratio combining (MRC). Recently, however, the combining technique was changed to adaptive array combining, i.e., combining that maximizes the SINR [9], and thereby suppresses interference as well as increases desired signal power. Although adaptive array combining provides the same performance as MRC in a noise-limited environment, in an interference-limited environment it increases the output SINR by about 3-4 dB at the 10% probability level. That is, adaptive array combining does not provide range increase, but does permit higher levels of interference for a most robust system. Note that this was done without changing the base station hardware - only a software change was needed. Furthermore, since with two receive antennas MRC requires about the same computational complexity as adaptive array combining, this software change does not require significant additional DSP power. Note that the symbol rate in ANSI-136 is 24.3 ksps, so that the weights must be updated every few symbols and typically updates every symbol are used. However, at this symbol rate equalization of delay spread is rarely needed, and spatial processing alone can be used most of the time - when equalization is required, it is only for delay spread over less than one symbol, and MLSE equalizers modified for spatial-temporal processing can be used [10].

To provide a similar improvement on the downlink so that frequency reuse reduction for greater capacity is possible, power control on the downlink is being considered [11-13]. Although the gain of power control in ANSI-136 is limited because of the requirement of a continuous downlink (i.e., the same transmit power must be used for all three users that share each carrier), power control may still obtain a gain in SINR similar to that on the uplink in interference-limited environments. Thus, software changes only should provide about a 3-4 dB SINR improvement which permits the frequency reuse factor to be reduced to 5 or 6 for about a 50% increase in capacity.

Base stations may also be upgraded from a 2 to a 4 element adaptive array for the uplink in combination with a 4-beam multibeam antenna on the downlink. This combination provides similar gains on the uplink and downlink, extending the range (with about a 4 dB increase in gain [14]), and/or doubling the capacity by permitting the frequency reuse factor to be reduced to 4 or 3. Although this requires hardware as well as software upgrades, which can be expensive, in typical cellular systems a large portion of the gain of 4-antenna base stations can be achieved with limited deployment (on the order of 10 - 30%) of these base stations. The deployment of these base stations not only increases capacity, but also permits spectrum to be cleared for the deployment of the third generation TDMA system EDGE.

IV. SMART ANTENNAS IN EDGE

EDGE is being introduced as an enhancement to GSM and as an overlay for ANSI-136 using a 1/3, 3/9, or 4/12 reuse pattern (instead of the 7/21 reuse pattern in current ANSI-136 systems); thus, cochannel interference severely limits the radio link performance, and adaptive array techniques are even more needed than in ANSI-136. As an overlay system, it is desirable to use the same base station antenna hardware as in ANSI-136. Thus, we need to consider adaptive array techniques for EDGE with both 2 receive antenna and 4 receive/transmit antenna base stations.

IV.A. Interference Suppression

The EDGE system (see, e.g., [1]) uses a TDMA format with a burst length of 576.92 μs, with each burst containing 116 payload symbols and 26 training symbols as a midamble. Because the burst length is short enough, the spatial-temporal equalizer weights need only be calculated once per burst rather than every symbol as in ANSI-136. However, because the symbol duration is much shorter, temporal equalization of delay spread is nearly always required, and the spatial-temporal equalizer needs to cover delay spread for the desired and interfering signals up to 5 symbols. With 8-PSK modulation, equalization using MLSE is too computationally complex for today's DSP's, and reduced complexity techniques are required.

Figure 2 shows a block diagram of a receiver that we have considered for spatial-temporal processing in EDGE [15]. It is similar to the original EDGE receiver described in [1] which provided only temporal equalization, except for an additional receiving branch. The figure shows two receive antennas, although four antennas could also be used. The front-end filters of the diversity receiver perform MMSE cochannel interference suppression, while leaving the intersymbol interference to be mitigated by the subsequent equalizer. This equalizer is a delayed decision feedback sequence estimator (DDFSE), consisting of a reduced-state Viterbi (MLSE) processor and a feedback filter. This equalizer provides soft output to the channel decoder after deinterleaving.

Figure 3 shows the block error rate of the DDFSE versus the signal-to-interference-power ratio with a single interferer. An interference-limited environment is assumed with the signal-to-noise ratio equal to 40 dB. Results are shown for two standard GSM environments - Typical Urban and Hilly Terrain. The figure compares the performance of a single antenna (branch) receiver to that of two antenna receiver with MMSE combining. The results show that in both environments adaptive array processing provides significant interference suppression - at a 10^{-1} block error rate, the adaptive array can operate with a 20 dB stronger interferer. Of course, in a typical cellular system, there is not just one interferer, and thus the gains will be lower. However, the gains with four receive antennas will be higher. Furthermore, dual handset antennas would be required to obtain similar gains on the downlink, although the multibeam transmit antenna will also provide significant interference reduction.

IV.B. MIMO-EDGE

With base stations using four transmit/receive antennas, it may be possible to use multiple antenna terminals to obtain MIMO capacity increases. Theoretically, with four transmit/receive antennas at the terminal and independent fading between all antennas, an increase in capacity of 3.77 times is possible with the same transmit power (i.e., up to 1.45 Mbps in EDGE). With EDGE, this could be accomplished by transmitting a different EDGE signal out of each antenna with equal power and then using spatial-temporal processing to separate the four EDGE signals at the receiver. Note that no changes to the EDGE standard would be required (except that each EDGE signal must have a different training sequence), and MIMO terminals/base stations could be gradually introduced into standard EDGE systems since systems with and without MIMO can operate together.

For MIMO type capacity increases to be achieved in practice two issues must be resolved. First, a suitable spatial-temporal equalization technique with weight adaptation must be developed which separates and detects four equal-power signals at a block error rate on the order of 10^{-1} when the SINR is 7-12 dB (typical for frequency reuse of 1 to 3). One potential technique is the DDFSE of Section IV.A. For MIMO, we consider using the DDFSE with successive interference cancellation. In this case, with four receive antennas, we first determine the MMSE of each of the four output signals after the DDFSE (e.g., using the training sequences), and detect the signal with the lowest MMSE. Then this detected signal is subtracted from the received signals and the above process repeated for the next signal. The entire process is repeated until all signals are detected. Note that the selection process results in improved performance for the first selected signal as compared to a randomly-selected signal, and subsequently-detected signals, although their MMSE's are higher with all interferers present, have increasing diversity with fewer interferers for improved performance. The results in Section IV.A are promising in that they show that with two equal-power signals (SIR = 0 dB) a randomly-selected signal can be detected with a 10^{-1} block error rate in a Typical Urban environment with a 40 dB signal-to-noise ratio. Although performance with successive interference cancellation should be better, and improved weight-generation techniques have been developed [16], further research is needed for operation with four antennas and Hilly Terrain environments.

The second issue is the mobile channel characteristics to support MIMO-EDGE. That is, is the multipath environment rich enough to support the technique with four antennas, since the theoretical result of a capacity increase of 3.77-fold is for independent fading between all antennas? Results for indoor systems [17], showed that this environment supports far more than a four-fold increase, but outdoors, fading correlation coefficients of 0.5 are common on base station antennas. However, outdoor MIMO channel testing using two widely-spaced (10 wavelengths) dual-polarized antennas with four antennas on a terminal, showed that the measured capacity is nearly identical to that with independent fading [18].

Finally, we note that MIMO techniques can be used in combination with space-time coding [19] for potentially greater performance, although in some cases it may be more advantageous in terms of capacity or robustness to use the multiple antennas for space-time coding or interference suppression alone.

IV.C. Wideband OFDM-MIMO

Finally, to achieve even higher data rates, wideband OFDM techniques have been proposed to operate in combination with EDGE [20]. (Note that at higher data rates in a cellular environment, the extent of the delay spread makes spatial-temporal processing with single carrier operation much more computationally complex than with OFDM.) Since it is expected that most users will require higher data rates on the downlink than on the uplink, wideband OFDM would be used on the downlink only (e.g., to provide 10 Mbps in a 5 MHz bandwidth with QPSK modulation), with EDGE used for the uplink. As before, we could also use MIMO techniques with a four receive antenna terminal and a four transmit antenna base station to achieve up to a 3.77-fold increase in capacity. For example, with only a 1.25 MHz bandwidth and QPSK modulation, OFDM-MIMO has the potential to provide up to 10 Mbps. It is interesting to note that, since with OFDM temporal processing is not needed and, unlike EDGE, the training sequence length can be optimized, developing receiver processing techniques for adequate performance may be less challenging for OFDM-MIMO than for MIMO-EDGE.

V. CONCLUSIONS

In this paper, we have described smart antennas and their potential use in ANSI-136 and EDGE. We showed that using the same base station antennas in EDGE as in ANSI-136, substantial interference suppression can be achieved. Furthermore, with four-antenna terminals using MIMO techniques data rates up to 1.45 Mbps may be possible in EDGE systems and up to 10 Mbps with OFDM-MIMO. Thus, smart antennas offer the opportunity for much higher data rates in cellular systems.

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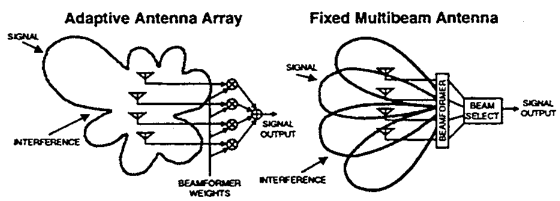

FIGURE 1
Smart antenna types.

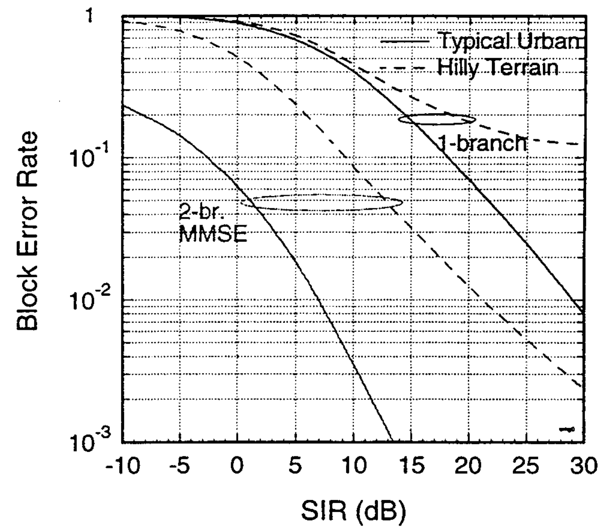

FIGURE 3
The SIR performance of the DDFSE.

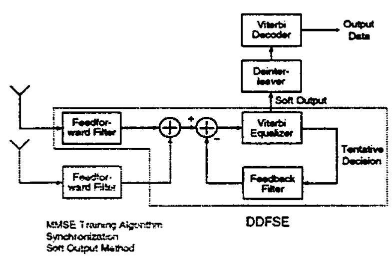

FIGURE 2
DDFSE receiver structure.