PERFORMANCE COMPARISONS OF ADAPTIVE ANTENNA ARRAYS WITH FIXED MULTIBEAM SYSTEMS FOR IS-136 SYSTEMS

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Abstract In this paper, we present uplink simulation results comparing four-element adaptive arrays with a six-sector antenna system and a fixed multibeam (four 30° beam with two-branch diversity per beam in each 120° sector) antenna system using an IS-136 TDMA modulation format and slot structure. The results consist of the capacity improvement (i.e., frequency reuse reduction) of these antenna systems over the baseline antenna system using the simulated bit error rate (BER) as the basis of comparison. The baseline antenna system was assumed to be a typical three-sector antenna system employing two-branch spatial diversity in each sector. Simulations were run for two different cell sizes, two Doppler spread values, and multiple reuse scenarios. The results show that substantial interference suppression gains can be obtained in an interference-dominated system using adaptive antennas. This improvement allows a reduction in the frequency reuse pattern from seven to three. In contrast a simple six-sector system is found to be limited to a frequency reuse of four. The fixed multibeam antenna can achieve similar reuse patterns but with poorer performance and requires twice as many antenna elements. It is noted that the simulation results presented here are for the uplink only, similar downlink gains must be supported in order to achieve the overall capacity improvement.

I. INTRODUCTION

The use of intelligent antenna systems to enhance system capacity in cellular wireless systems has attracted significant attention in recent years. Previous work for TDMA systems has shown that significant gains can be obtained through array processing [1, 2]. For TDMA systems, computer simulations and prototype experiments have shown that a single strong interferer can be easily nulled using a four-element adaptive array [3]. Recent work [4] has extended these results to the case of multiple interferers in the multi-cell environment which gives insight into obtainable reuse reduction. In this paper we compare the adaptive array to other advanced antenna systems including a fixed multibeam antenna and a six-sector antenna. The fixed multibeam antenna system considered is four 30° beams per 120° sector and is implemented by selecting the strongest received beam from the multiple beam antenna. Two-branch spatial diversity is assumed in each beam. We additionally consider the effect of cell size on the performance of these antenna systems.

To compare the adaptive array antenna to a fixed multibeam antenna and a six-sector antenna, we will employ a network simulation followed by a link level simulation. The network simulation calculates the statistics of the SIR (Signal-to-Interference-Ratio) for the various antenna systems using three different reuse patterns. This simulation considers the large scale channel effects of path loss and shadowing using Monte Carlo simulations. The results of the network simulation provide the statistics of SIR values and the number of dominant interferers for the simulated antenna system. These results are then used in a link level simulation.

The link simulations provide BER results for final comparisons. This simulation considers the small scale channel effects such as Rayleigh fading, noise, interference, and Doppler spread. The adaptive antenna systems are simulated as four-branch spatial diversity antenna arrays using a typical three-sector antenna for each element while we assume that two-branch spatial diversity is implemented in each beam for a three-sector (baseline), a six-sector, and the fixed multibeam antenna systems. Coverage and capacity are considered by evaluating both cell size (coverage) and frequency reuse reduction (capacity). The results show that the adaptive antenna system provides significantly better interference suppression capability than the other simulated antenna systems for similar infrastructure investment.

The remainder of this paper is organized as follows. Section II describes the adaptive algorithms used in this study as well as the system modeling assumptions. Section III presents the results of the network simulations, while link simulations and comparisons of frequency reuse reduction are given in Section IV. Conclusions are given Section V.

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II. SIMULATION ASSUMPTIONS

The overall simulation study is comprised of two distinct sets of simulations: network simulations and link simulations. The network simulation provides the high level system performance of the wireless network, while the link simulation gives the link level performance of the base station receiver. The results of the network simulation provide the statistics of SIR for the simulated antenna systems in different frequency reuse patterns. These results are then used to determine the interference environment for the BER simulation. With the combined results of these two simulations, we are able to determine the frequency reuse reduction (as compared to the baseline system) for each of three antenna systems: an adaptive array antenna, a six-sector antenna, and a fixed multibeam antenna system.

Network Model

Network level simulations were run using a typical multi-cell and multi-sector system layout with various antenna configurations. In this part of the simulation, only large scale channel effects such as path loss and shadowing are considered. Three frequency reuse patterns are evaluated: seven, four, and three. In each reuse pattern, three-sector and six-sector cell layouts are implemented. For the three-sector system, there are two types of antennas used in the simulation: one is a three-sector antenna (105° beamwidth) and the other is a fixed multibeam antenna (four beams, each with a 30° beamwidth to cover one 120° sector). For the six-sector system, only a 52° beamwidth antenna is evaluated. The antenna patterns used in the simulation are generated by using the function $\frac{\sin\theta}{\theta}$, where θ is the azimuthal angle. This implies that the antenna sidelobes are taken into account.

Spatial diversity is implemented in each beam, however the statistics of SIR values and the number of dominant interferers are independent of the number of receive branches. Therefore, we need to simulate only one receive antenna branch at the base station for the network simulations. Since in a practical switched multibeam implementation it is difficult to track a fast fading signal, in the simulation we assume the fixed multibeam system switches beams based on the long-term average received power.

The network simulation is a Monte Carlo simulation. In each simulation run, co-channel interferers are placed in sectors based on the reuse pattern and randomly placed (with a uniform area distribution) within the sectors. In each Monte Carlo network simulation, we calculate the SIR values for each of the simulated antenna systems. The received power with the effects of path loss and shadowing at a antenna can be calculated as

$$\mathrm{S}_0 = \frac{\gamma_0 \sum_{l=1}^{L} G(\alpha_{0,l})}{D_0^{\rho}} \tag{1}$$

for the received power of the desired signal, and

$$\mathrm{I}_n = \frac{\gamma_n \sum_{l=1}^{L} G(\alpha_{n,l})}{D_n^{\rho}} \tag{2}$$

for the received power of the nth interfering signal, and SIR is defined as

$$\mathrm{SIR} = \frac{S_0}{\sum_{n=1}^{K} I_n} \tag{3}$$

where L is the number of arriving paths, $G(\alpha_l)$ is the antenna response at the l^{th} path arrival angle α, K is the number of interferers in the system, ρ is the path loss exponent(4) and γ is a log-normal random variable which represents the shadowing (6dB). D_n is the distance from the n^{th} interferer to the base station of desired user. The results of the network simulation are then used to determine the SIR level which is exceeded 90% of the time for each reuse pattern. The discussion of the network simulation results is given in Section III.

Receiver Model

The second part of the simulation is the link level BER simulation. The number of interferers used in the simulation is based on results from the network simulation which tracks the number of dominant components in the interference seen at the base station. The noise level is determined by the average received SNR at each base station antenna, which increases as the mobile station is moved closer to the base station. That is, a high average SNR can be obtained in the system by reducing the cell size (reducing coverage). Therefore, the smaller the cell size is, the larger the average SNR value is.

The received baseband equivalent input signal with K interferers from M antenna elements is sampled once per symbol and represented in complex vector notation as

$$\mathbf{y}[k] = \mathbf{x}_0 s_0[k] + \sum_{i=1}^{K} \mathbf{x}_i s_i[k] + \mathbf{n}[k] \tag{4}$$

where $\mathbf{y}[k]$, $\mathbf{x}[k]$, $\mathbf{n}[k]$ are $M \times 1$ complex column vectors, $s_0[k]$ is the differentially encoded signal, $\mathbf{x}_0[k]$ is the channel vector of the signal of interest at sampling epoch k, $s_i[k]$, $i = 1,2,\ldots,K$ are interfering signals,

$\mathbf{x}_i[k]$ are the channel vectors of the interferers and $\mathbf{n}[k]$ is a vector of noise samples taken from a temporally and spatially white complex Gaussian process. The channels of the desired signal and interferers are generated by a vector channel model and temporal variation is based on the Doppler spread, which typically ranges from 0 to 180 Hz for the PCS band. Boldface type is used to represent vector quantities. The three-sector (baseline system), six-sector, and fixed multibeam antenna systems use maximal ratio combining of differentially detected $\pi/4$-DQPSK on two spatially separated antennas. That is

$$z[k] = \mathbf{y}^\dagger[k]\mathbf{y}[k-1] \tag{5}$$

where $z[k]$ is the decision statistic. Detection of the data is slightly different with the adaptive array since combining is done prior to differential decoding. The array output $z[k]$ is the weighted sum of the element outputs

$$z[k] = \mathbf{w}^\dagger[k]\mathbf{y}[k] \tag{6}$$

where $\mathbf{w}$ is the vector of complex array weights and the superscript $\dagger$ denotes transpose and conjugate. Unlike the case of MRC, differential decoding is performed after combining, thus the decoded symbol is estimated as

$$\hat{s}_{0,I}[k] = \operatorname{sgn}\Big[\operatorname{Re}\{z[k]^* z[k-1]\}\Big] \tag{7}$$

$$\hat{s}_{0,Q}[k] = \operatorname{sgn}\Big[\operatorname{Im}\{z[k]^* z[k-1]\}\Big] \tag{8}$$

Array Processing Algorithm

The adaptive weights are calculated based on the MMSE (Minimum Mean Square Error) criterion, also known as the Wiener-Hopf solution. The weights can be shown to be

$$\mathbf{w}[k] = \mathbf{R}_{yy}^{-1}[k]\mathbf{r}_{yd}[k] \tag{9}$$

where $\mathbf{R}_{yy} = E\{\mathbf{y}[k]\mathbf{y}^\dagger[k]\}$ is the covariance matrix of the received signal and $\mathbf{r}_{yd}[k] = E\{\mathbf{y}[k]\mathbf{s}^*[k]\}$ can be shown to be equivalent to the desired signal's channel vector $\mathbf{x}_0$.

From an implementation point of view, these weights can be obtained adaptively using the LMS (Least Mean Square) algorithm or DMI (Direct Matrix Inversion). In this study, we use DMI with Diagonal Loading to calculate the optimum weights [5]. With this technique, the array weights are constructed as

$$\mathbf{w}[k] = \left[(1-\beta)\hat{\mathbf{R}}_{yy}[k] + \beta\mathbf{I}\sigma^2\right]^{-1}\hat{\mathbf{r}}_{yd}[k] \tag{10}$$

where β is the diagonal loading factor, $\hat{\mathbf{R}}_{yy}[k]$ is the estimated covariance matrix, and $\hat{\mathbf{r}}_{yd}[k]$ is essentially the estimated channel vector.The diagonal loading factor can be adjusted so that the adaptive weights give the best performance [5]. Additionally, to save memory and to have better tracking capability, the moving average is implemented as a single pole filter. Thus

$$\hat{\mathbf{R}}_{yy}[k] = \alpha\hat{\mathbf{R}}_{yy}[k-1] + (1-\alpha)\mathbf{y}[k]\mathbf{y}^\dagger[k] \tag{11}$$

$$\hat{\mathbf{r}}_{yd}[k] = \alpha\hat{\mathbf{r}}_{yd}[k-1] + (1-\alpha)\mathbf{y}[k]\hat{s}_0^*[k] \tag{12}$$

where α is the forgetting factor ($0 \leq \alpha \leq 1$) which determines the time constant of the update, and $\hat{s}_0[k]$ is the estimated reference signal[1].

III. NETWORK SIMULATION RESULTS

SIR statistics and the cumulative distribution function (CDF) were created for each of the simulated antenna systems using 10,000 Monte Carlo runs for each system and reuse pattern. We use the 90^{th} percentile of SIR as a criterion to compare the performance of the systems. The results show that the 90^{th} percentile of SIR values, $\text{SIR}_{90\%}$, ($\text{CDF}=10^{-1}$) for a three-sector antenna system are approximately 17dB for reuse seven, 12dB for reuse four, and 9dB for reuse three. In other words 90% of the time the SIR seen in the three sector system with a reuse of seven will be 17dB or better. For a six-sector antenna system, the $\text{SIR}_{90\%}$ is approximately 20dB for reuse seven, 16dB for reuse four, and 12dB for reuse three. The results also show that the $\text{SIR}_{90\%}$ values of a fixed multibeam antenna system are approximately 24dB for reuse seven, 19dB for reuse four, and 15dB for reuse three. As expected, a six-sector antenna and the fixed multibeam antenna system provide a better performance than a three-sector antenna system. This is because these antennas use a narrower antenna beamwidth with higher antenna gain to increase the received signal power and to reduce the co-channel interference from other cells.

A summary of the 90^{th} percentile of SIR values for the simulated antenna systems using different reuse patterns is given in Table 1. Additionally, these simulations provided statistics on the nature of the interference. Specifically, we tracked the number of dominant interferers when $\text{SIR} < \text{SIR}_{90\%}$. Space does not permit showing those results, but suffice it to say that the interference was predominantly made up of three or fewer interferers.

IV. LINK SIMULATION RESULTS

For link level simulations, two types of antenna combining techniques were used in the simulation as de-

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[1] The reference signal is known during training and estimated afterwards. Please see [3] for details concerning IS-136 slot structure.

scribed in section II: adaptive combining and MRC combining. The number of interferers added into the simulation was based on the network simulation results and ranged from 1 to 3 interferers. Figures 1-2 show the results for two-element MRC combining and four-element adaptive combining simulations. In general, the results show that adaptive combining performed much better than MRC combining, as expected. The four-element adaptive system had the advantage of greater receive diversity (for better fading performance) as well as the adaptive processing to reduce interference. Since MRC combining antenna systems are relatively unaffected by the number of interfering sources, we only show the MRC performance with one dominant interfering source. Figure 2 shows that when the Doppler frequency was increased to 180Hz (i.e., high mobility), the performance of the adaptive array antenna system was substantially affected while the performance of MRC combining was insensitive to the effects of high mobility. This is due to the tracking error in adaptive combining resulting from the fast channel variation.

Results also show that the number of dominant interferers can have a profound impact on performance at low values of SIR. This can be explained as follows. While a four-element array has sufficient degrees of freedom to null 1-3 interferers, fading requires diversity reception. As the number of interferers increases, diversity must be exchanged for interference cancellation. At high values of SIR this is not necessary, and thus there is little loss in diversity gain. Additionally, we find that the degradation is less pronounced at high Doppler since the loss in tracking ability dominates performance. Figure 3 compares the performance of four-element adaptive array combining with four-element MRC combining. This allows us to isolate the improvement due to the adaptive algorithm from the gain due to added diversity.

Using Table 1 along with Figures 1-3 we can determine the achievable reuse patterns for each of the systems. The baseline system is a three sector antenna employing two-branch spatial diversity and MRC combining. From Figures 1-2 we see that a two-branch MRC receiver requires 14-17dB SIR to achieve 1% BER depending on SNR (cell size). Table 1 shows that for a reuse pattern of seven, the $\mathrm{SIR}_{90\%}$ seen in a three sector system is 17dB. Thus, the antenna system can support a reuse pattern of seven. However, lowering the reuse to four results in a $\mathrm{SIR}_{90\%}$=11.7dB which would not provide the required BER. Similarly, if we increase the number of sectors to six, $\mathrm{SIR}_{90\%}$=16.1dB for a reuse pattern of four and $\mathrm{SIR}_{90\%}$=12.3dB for a reuse of three. Thus, a six-sector system employing two-branch diversity and MRC can support a reuse of four with a small amount of degradation, but a reuse of three is not achievable. Using the same procedure we see that a four-element adaptive array can achieve a reuse as low as three. Similarly, the fixed multibeam system can also reduce the reuse pattern to three with degradation compared to the adaptive array and it requires twice as many antenna elements per cell as the adaptive array (24 versus 12). The performance of each antenna system relative to the required SIR for a given reuse pattern is given in Table 2. Note that a positive number means that the antenna system can support the reuse pattern with extra margin, (i.e., 1% BER will be supported more than 90% of the time) while a negative number means that the reuse pattern can possibly be supported but with slight degradation (< 2dB). If the reuse pattern cannot be supported, we have indicated this condition with (x) in the table.

V. CONCLUSIONS

The simulation results show that the four-element adaptive array provides superior performance to the six-sector system with the same amount of RF hardware (12 receivers/cell). The fixed multibeam system can achieve similar reuse patterns as the four-element adaptive array, but less performance margin and requires twice the hardware (24 receivers/cell). Additionally, the adaptive array system provides much better trunking efficiency than the six-sector system since it uses only three sectors per cell. Thus, if a comparable downlink solution is paired with the four-element array, a significant capacity increase can be achieved over the baseline system by using a reuse pattern of three or four.

VI. REFERENCES

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$SIR_{90\%}$ per antenna element (branch) (dB)			
Antenna Systems	Frequency Reuse		
	7	4	3
Three-Sector	17	11.7	9.2
Six-Sector	20.3	16.1	12.3
Fixed Multibeam	24.1	19.3	15.3

Table 1: SIR Statistics for Simulated Antenna Systems with Different Reuse Patterns.

Antenna Systems	Frequency Reuse		
	7	4	3
SNR=10dB, Doppler Freq.=20 Hz			
Baseline	0dB	(×)[2]	(×)
Adaptive Array[5]	+17dB[3]	+11.7dB	+9.2dB
Six-Sector	+3.3dB	−1dB[4]	(×)
Fixed Multibeam	+7.1dB	+2.3dB	−1.7dB
SNR=10dB, Doppler Freq.=180 Hz			
Adaptive Array[5]	+10.7dB	+5.4dB	+2.9dB
Six-Sector	+3.3dB	−1dB	(×)
Fixed Multibeam	+7.1dB	+2.3dB	−1.7dB
SNR=15dB, Doppler Freq.=20 Hz			
Adaptive Array[5]	>17.dB	>11.7dB	>9.2dB
Six-Sector	+6.3dB	+2.1dB	(×)
Fixed Multibeam	+10.1dB	+5.3dB	+1.3dB
SNR=15dB, Doppler Freq.=180 Hz			
Adaptive Array[5]	+12dB	+6.7dB	+4.2dB
Six-Sector	+6.3dB	−2.1dB	(×)
Fixed Multibeam	+10.1dB	+5.3dB	+1.3dB

Table 2: SIR Performance Relative to Required SIR for Examined Antenna and Different Reuse Patterns

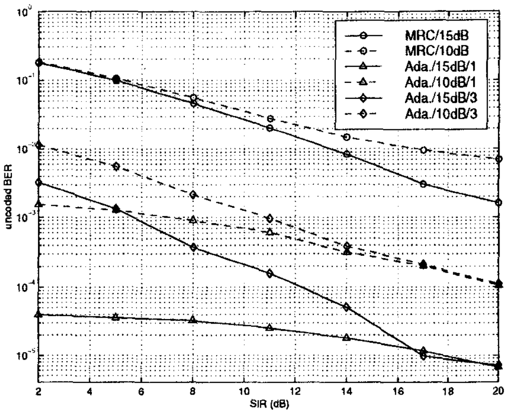

Figure 1: Performance of Two-Element MRC with One Interferer and Four-Element Adaptive Array with One and Three Interferers versus SIR for Doppler Spread of 20Hz and 10dB and 15dB per Branch.

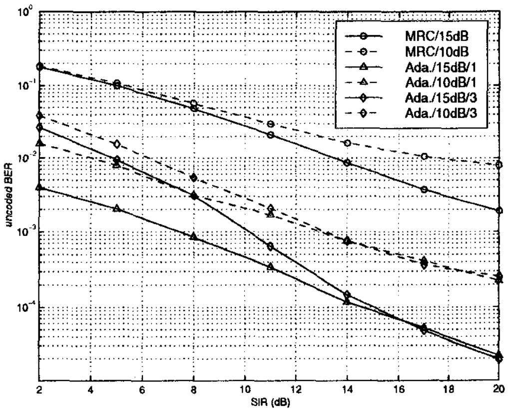

Figure 2: Performance of Two-Element MRC with One Interferer and Four-Element Adaptive with One and Three Interferers versus SIR and Doppler Spread of 180Hz and 10dB and 15dB per Branch.

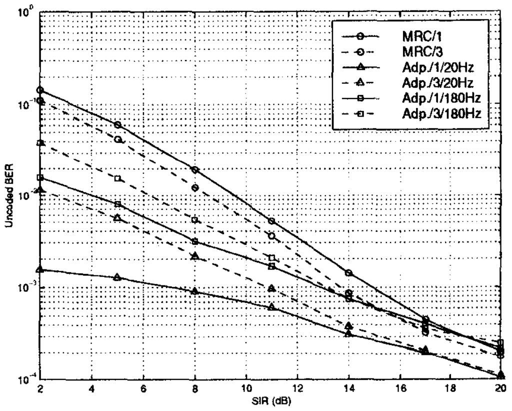

Figure 3: Performance of Four-Element MRC and Four-Element Adaptive Array versus SIR for Multiple Interferers with Baseline 10dB per Branch at Doppler of 20 and 180Hz.

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[2] (×) signifies that the reuse is unachievable.

[3] (+) signifies gain.

[4] (−) signifies degradation.

[5] the performance of four branch adaptive array with three interferers.