

Low Complexity Hybrid Smart Antenna with Directional Elements over Frequency-Selective Fading Channel

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Abstract—In this paper, a low complexity hybrid smart antenna system with directional elements and reduced-size digital beamformer is proposed to combat the inter-symbol interference (ISI) problem over frequency-selective fading channels. The conventional smart antenna systems with omni-directional elements utilize the full-size digital beamformer to suppress interference and obtain the optimum performance. However, the proposed hybrid smart antenna system with directional elements can split the linear receive array into two subarrays. One subarray contains the elements with no ISI, which can be processed with a simple maximum ratio combiner (MRC). The second subarray includes the elements with the ISI interference, which require the use of a reduced-size optimum beamformer for interference suppression. Finally, the outputs of the two subarrays are combined for optimal detection of the transmitted signals. Simulation results confirm that the proposed low complexity hybrid smart antenna system can provide robust performance under the multipath fading channel with ISI, and outperform the conventional smart antenna systems due to the use of directional antennas and utilization of multipath diversity gain.

Keywords—Hybrid smart antenna, inter-symbol interference, digital beamforming, maximum ratio combiner

I. INTRODUCTION

In wireless communication systems, smart antennas can be used to improve coverage, link quality, data rate, and system capacity [1]. Smart antenna systems achieve better performance by incorporating optimum algorithms to detect the signal-of-interest (SOI) and suppress interferences, e.g., multipath signals. In general, the multipath signals arrive at the receiver with different angles of arrival (AOA) and time of arrival (TOA) in a frequency-selective fading channel [2]. Multipath with different TOA will induce inter-symbol interference (ISI) and degrade the system performance. Smart antenna systems with omni-directional elements exploit the different AOAs and combat the effects of ISI. By using the extra degrees of freedom offered by an antenna array, a smart antenna system can form multiple beams, one for each multipath component, to spatially remove the ISI from the SOI. Next, the maximum ratio combining (MRC) technique [3] can be used to combine the outputs corresponding to

individual beams in order to recover the SOI coming through different paths and detect the desired signals. For a conventional smart antenna system, this operation requires a very large computational power since the number of antenna array elements needed is very large.

To overcome this computational complexity problem, the hybrid smart antenna system with directional elements for optimal multipath combining has been proposed for flat fading channels [4]-[6]. In this paper, the hybrid smart antenna system will be extended to cover frequency-selective fading channels as a low complexity technique for combating ISI. The proposed hybrid smart antenna system involves the features of directional elements arranged to cover the entire spatial region. Based on the multipath structure and the array geometry, the smart antenna array can be split into two subarrays. One subarray contains the elements with no ISI, which can be processed with a simple maximum ratio combiner (MRC). The second subarray includes the elements with the ISI interference, which require the use of a reduced-size optimum beamformer for interference suppression. Finally, the output signals of the two subarrays can be combined to detect the transmitted signals. The major difference of this paper from [4]-[6] is the formation of the subarrays according to ISI instead of the signal strength. Simulation results confirm that, when directional antennas with medium beamwidth are used, the proposed low complexity system can provide robust performance under frequency-selective channel, and outperform the conventional smart antenna system with omni-directional elements due to the use of directional antennas and utilization of multipath diversity gain.

II. HYBRID SMART ANTENNA SYSTEM MODEL

Unlike a conventional smart antenna system which utilizes omni-directional elements, a hybrid smart antenna system combines the advantages of the analog switched-beam and adaptive digital beamforming systems through the use of directive elements. Such a directive beam pattern for an array element is shown in Figure 1 [4]. The pattern has a main beam with a ϕ -degree beamwidth and the gain of the antenna is approximately estimated by $360/\phi$. Moreover, the pattern has a

sidelobe that is 20dB lower than the main beam. As a result of this antenna gain pattern, a 20dB interference suppression will take place when the desired signal falls into the main beam region and the interference falls into the sidelobe region resulting in an increased performance level. Due to digital beamforming capabilities, additional performance gain will be achieved through interference nulling using a smaller number of received signals than the conventional adaptive systems.

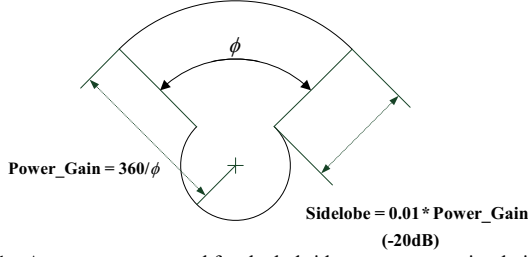


Figure 1. Antenna pattern used for the hybrid smart antenna simulations

In this paper, wideband communication systems in which the transmitted symbol period is much smaller than the delay spread of the channel are considered. As a result, the propagation channel becomes frequency selective with different AOA and TOA for multipath. For example, in the case of an eight-element array with ϕ equals to 90° , the main beams of all elements will be partially overlapping to provide the 360° coverage as shown in Figure 2. The hybrid smart antenna system with this array configuration is employed in a propagation environment with two major paths having 30° direction of arrival (DOA) spread and different TOA as shown in Figure 2. With this configuration, antenna 1 and 4 will receive ISI free signals whereas antennas 2 and 3 will experience ISI since they receive both multipath signals. In such a scenario, the hybrid smart antenna system that is expected to exploit the frequency-selective diversity gain and suppress the ISI is shown in Figure 3. It consists of multiple directional antennas, RF/IF downconverters, analog-to-digital converters (ADC), and two receiver branches. The first branch is the subarray system with non ISI interference. The other branch is the subarray system with ISI interference. The receiver operation will be described in the following section.

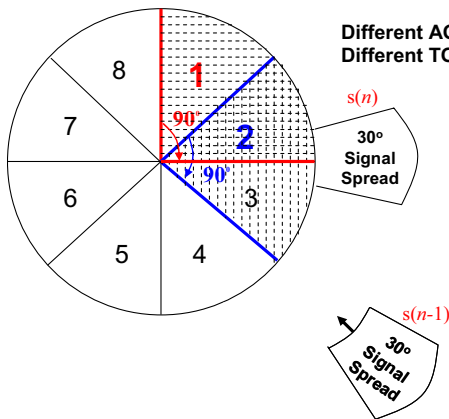


Figure 2. Example of a 90° beamwidth system used in a propagation environment with two paths and 30° DOA spread.

III. DEVELOPMENT OF PROPOSED HYBRID SMART ANTENNA RECEIVER

A hybrid smart antenna receiver is developed whose overall schematic diagram is depicted in Figure 3. First, after the transmitted signal is passed through the multipath channel, which is modelled with L resolved Rayleigh fading paths, the received baseband signal of the n th antenna can be written as

$$x^{(n)}(t) = \sum_{l=1}^L \alpha_l^{(n)} f_n(\theta_l^{(n)}) s(t - \tau_l) + n(t) \quad (1)$$

where $\alpha_l^{(n)}$, τ_l , and $\theta_l^{(n)}$ are the complex Gaussian random variables, TOA, and AOA from the l th fading path respectively, and the $n(t)$ is the AWGN noise with power σ_n^2 . The function $f_n(\cdot)$ denotes the antenna amplitude pattern of the n th antenna element. For the omni-directional antenna this value is unity and for the directional antenna with 90° beamwidth $f_n(\cdot)$ will be set to 2 when the arrival angle $\theta_l^{(n)}$ falls within the main lobe. $s(t)$ is the desired signal with a symbol period T_s . Here we assume the channel taps can be resolved with T_s -spacing, which implies $\tau_l = lT_s$.

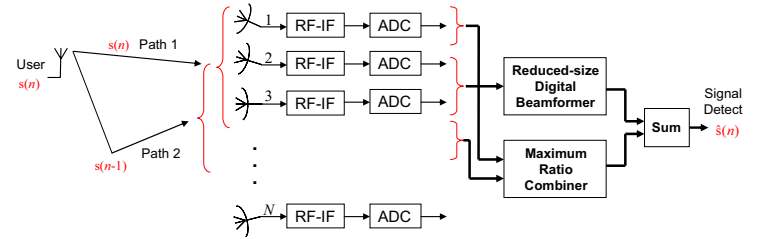


Figure 3. Low complexity hybrid smart antenna system over frequency-selective fading channel

Under the assumption of perfect synchronization at the receiver, the received signal at the n th antenna sampled at the i th discrete-time interval is given by $x^{(n)}(i) = x^{(n)}(t_i)$ with $t_i = iT_s$, i.e.,

$$x^{(n)}(i) = \sum_{l=1}^L \alpha_l^{(n)} f_n(\theta_l^{(n)}) s(i - l + 1) + n(i) \quad (2)$$

For the i th sampling instant, the received signal at the antenna array can be written in vector form as follows:

$$\begin{aligned} \mathbf{x}(i) &= \sum_{l=1}^L \{ \mathbf{a}_l \odot \mathbf{f}(\theta_l) \} s(i - l + 1) + \mathbf{n}(i) \\ &= \sum_{l=1}^L \boldsymbol{\beta}_l s(i - l + 1) + \mathbf{n}(i) \end{aligned} \quad (3)$$

where $\mathbf{x}(i) = [x^{(1)}(i) \cdots x^{(N)}(i)]^T$, $\mathbf{a}_l = [\alpha_l^{(1)} \cdots \alpha_l^{(N)}]^T$, and $\mathbf{f}(\theta_l) = [f_1(\theta_l^{(1)}) \cdots f_N(\theta_l^{(N)})]^T$. $\boldsymbol{\beta}_l = \mathbf{a}_l \odot \mathbf{f}(\theta_l)$ is the composite channel vector, which $\odot$ denotes the element-wise multiplication. Next, due to the switched-beam nulling effect of directional antennas, the composite channel can be split into two components, i.e.,

$$\mathbf{\beta}_l = \mathbf{\beta}_l^{(no)} + \mathbf{\beta}_l^{(o)} \quad (4)$$

where $\mathbf{\beta}_l^{(no)}$ and $\mathbf{\beta}_l^{(o)}$ are the non-overlapping and overlapping composite channels, respectively. For example, in Figure 2 scenario, the DOA spread of the 1st path is occupied in the mainbeam region of the directional antenna 1, 2, and 3, i.e., $\mathbf{f}(\theta_1) = [f_1(\theta_1^{(1)}) f_2(\theta_1^{(2)}) f_3(\theta_1^{(3)}) 0 0 0 0 0]^T$. Similarly, for the signal arriving through the 2nd path $\mathbf{f}(\theta_2) = [0 f_2(\theta_2^{(2)}) f_3(\theta_2^{(3)}) f_4(\theta_2^{(4)}) 0 0 0 0]^T$. Based on $\mathbf{f}(\theta_1)$ and $\mathbf{f}(\theta_2)$ scenarios with antenna 2 and 3 overlapping, the composite channels can be rewritten by $\mathbf{\beta}_l = \mathbf{\beta}_l^{(no)} + \mathbf{\beta}_l^{(o)}$, $l=1$ and 2 with

$$\begin{aligned} \mathbf{\beta}_1^{(no)} &= [\alpha_1^{(1)} f_1(\theta_1^{(1)}) \ 0 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0]^T \\ \mathbf{\beta}_1^{(o)} &= [0 \ \alpha_1^{(2)} f_2(\theta_1^{(2)}) \ \alpha_1^{(3)} f_3(\theta_1^{(3)}) \ 0 \ 0 \ 0 \ 0 \ 0]^T \\ \mathbf{\beta}_2^{(no)} &= [0 \ 0 \ 0 \ \alpha_2^{(4)} f_4(\theta_2^{(4)}) \ 0 \ 0 \ 0 \ 0]^T \\ \mathbf{\beta}_2^{(o)} &= [0 \ \alpha_2^{(2)} f_2(\theta_2^{(2)}) \ \alpha_2^{(3)} f_3(\theta_2^{(3)}) \ 0 \ 0 \ 0 \ 0 \ 0]^T. \end{aligned}$$

Therefore, at the receiver, we can utilize two branches to detect the received signal. In the first branch, due to no ISI, we can directly use the MRC technique to combine the non-overlapping received signals, i.e.,

$$z^{(no)}(i) = \sum_{l=1}^L \mathbf{\beta}_l^{(no)H} \mathbf{x}^{(no)}(i+l-1) = \sum_{l=1}^L \mathbf{\beta}_l^{(no)H} \mathbf{\beta}_l^{(no)} s(i) + \tilde{n}(i) \quad (5)$$

where $\tilde{n}(i)$ is the MRC output noise and $\mathbf{x}^{(no)}(i+l-1)$ is the nonoverlapping received signal during the $(i+l-1)$ th symbol period. Thus, the received signal $\mathbf{x}(i)$ in (3) can be written by the summation of the overlapping and non-overlapping received signals $\mathbf{x}^{(o)}(i)$ and $\mathbf{x}^{(no)}(i)$, respectively, i.e., $\mathbf{x}(i) = \mathbf{x}^{(o)}(i) + \mathbf{x}^{(no)}(i)$.

Next, in the second branch with ISI effect, the optimum weight vectors can be used to combine the overlapping received signals, i.e.,

$$z^{(o)}(i) = \mathbf{w}_l^H \mathbf{x}^{(o)}(i+l-1) = \mathbf{w}_l^H \mathbf{\beta}_l^{(o)} s(i) + \bar{n}(i) \quad (6)$$

where $\bar{n}(i)$ is the optimum combining output noise and the optimum weight vector can be derived by Maximum SINR criterion [7], i.e.,

$$\mathbf{w}_l = \mathbf{R}_m^{(o)-1} \mathbf{\beta}_l^{(o)} \quad (7)$$

where $\mathbf{R}_m^{(o)}$ is the interference-plus-noise correlation matrix of the overlapping received signal $\mathbf{x}^{(o)}(i)$, i.e., the correlation matrix of $\mathbf{x}^{(o)}(i)$

$$\mathbf{R}_x^{(o)} = E \left\{ \mathbf{x}^{(o)}(i) \mathbf{x}^{(o)H}(i) \right\} = \mathbf{\beta}_l^{(o)} \mathbf{\beta}_l^{(o)H} + \mathbf{R}_m^{(o)} \quad (8)$$

with $\mathbf{R}_m^{(o)} = E \{ (\mathbf{i}(i) + \mathbf{n}(i))(\mathbf{i}(i) + \mathbf{n}(i))^H \}$ and the interference

$$\text{being } \mathbf{i}(i) = \sum_{\substack{k=1 \\ (k \neq l)}}^L \mathbf{\beta}_k s(i-k+1).$$

Finally, combining the output signals of two branches in (5) and (6), the transmitted signal $s(i)$ can be robustly detected, i.e.,

$$\begin{aligned} \hat{s}(i) &= \mu (z^{(o)}(i) + z^{(no)}(i)) \\ &= \mu \left(\mathbf{w}_l^H \mathbf{\beta}_l^{(o)} + \sum_{l=1}^L \mathbf{\beta}_l^{(no)H} \mathbf{\beta}_l^{(no)} \right) s(i) + \mu \tilde{n}(i) \end{aligned} \quad (9)$$

where $\mu = \left(\mathbf{w}_l^H \mathbf{\beta}_l^{(o)} + \sum_{l=1}^L \mathbf{\beta}_l^{(no)H} \mathbf{\beta}_l^{(no)} \right)^{-1}$ is the normalization

factor. After the hybrid beamforming operation, the 16 QAM transmitted signal $s(i)$ can be detected by demodulator, and the composite noise is $\hat{n}(i) = \tilde{n}(i) + \bar{n}(i)$.

IV. SIMULATION RESULTS

Computer simulations are used to demonstrate the performance of the proposed hybrid smart antenna system over the frequency selective fading channel and compared with the conventional smart antennas employing 8 array elements. For the conventional smart antenna system, omnidirectional element patterns are assumed. The beam pattern of the directional elements for the proposed hybrid smart antenna is shown in Figure 1. For all simulations, $L=2$ independent Rayleigh fading paths are generated with the delays τ_l chosen from $\{0, T_s\}$. The path gains α_l are assumed to be i.i.d. complex random variables with unit variance. All transmitted signals are generated with 16 QAM data modulation. As a performance index, the output BER corresponding to each SNR is obtained by the simulation of a total of 50000 Monte-Carlo trials, in which SNR is defined as the ratio of the signal power to noise power. For performance comparison, the simulations are run for different AOA and TOA signals for different main beamwidth conditions for the hybrid smart antenna system and compared to those of conventional smart antenna systems.

In the first set of simulations, the output BER performance is evaluated as a function of SNR for different AOA and different TOA scenarios with different element beamwidths. As shown in Figure 2, the hybrid smart antenna system with the 45°, 90°, 135°, and 180° beamwidths is assumed to be used in the two 30° DOA spread channels with different TOA and AOA. Moreover, for different beamwidth conditions, the list of received signals of different antennas can be summarized as Table 1-4. Besides the above scenarios, for the conventional smart antenna case with omnidirectional elements, the list of received signals is described in Table 5. The simulation results shown in Figure 4 indicate that the performance of the proposed hybrid smart antenna system approaches the conventional smart antenna system performance when the beamwidth is 180°. Moreover, when the antenna beamwidth is 135°, the proposed hybrid smart antenna system can

outperform the conventional smart antenna system due to the higher antenna gain and the multipath diversity gain. It is confirmed that the proposed system with low complexity can provide robust performance under frequency selective fading channel conditions.

Table 1. For 45° beamwidth

Ant 1	Nothing
Ant 2	S(n)
Ant 3	S(n) & S(n-1)
Ant 4	S(n-1)
Ant 5	Nothing
Ant 6	Nothing
Ant 7	Nothing
Ant 8	Nothing

Table 2. For 90° beamwidth

Ant 1	S(n)
Ant 2	S(n) & S(n-1)
Ant 3	S(n) & S(n-1)
Ant 4	S(n-1)
Ant 5	Nothing
Ant 6	Nothing
Ant 7	Nothing
Ant 8	Nothing

Table 3. For 135° beamwidth

Ant 1	S(n) & S(n-1)
Ant 2	S(n) & S(n-1)
Ant 3	S(n) & S(n-1)
Ant 4	S(n-1)
Ant 5	Nothing
Ant 6	Nothing
Ant 7	Nothing
Ant 8	S(n)

Table 4. For 180° beamwidth

Ant 1	S(n) & S(n-1)
Ant 2	S(n) & S(n-1)
Ant 3	S(n) & S(n-1)
Ant 4	S(n-1)
Ant 5	Nothing
Ant 6	Nothing
Ant 7	S(n)
Ant 8	S(n) & S(n-1)

Table 5. For conventional smart antenna

Ant 1	S(n) & S(n-1)
Ant 2	S(n) & S(n-1)
Ant 3	S(n) & S(n-1)
Ant 4	S(n) & S(n-1)
Ant 5	S(n) & S(n-1)
Ant 6	S(n) & S(n-1)
Ant 7	S(n) & S(n-1)
Ant 8	S(n) & S(n-1)

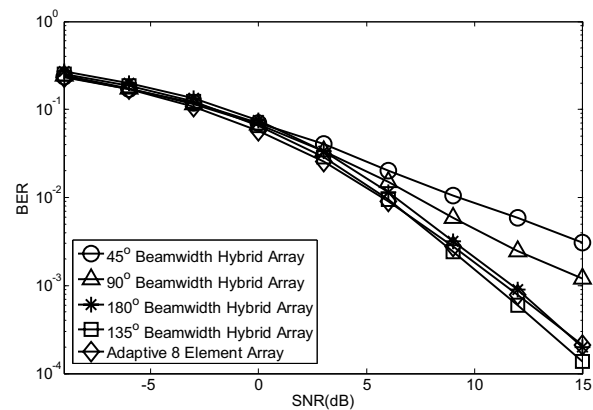


Figure 4. BER performance of a hybrid smart antenna system with 16 QAM modulation as a function of SNR with the different beamwidths of the directional elements over frequency-selective fading channel

In the second set of simulations, the robustness of the proposed hybrid smart antenna system under different AOA and TOA scenarios is demonstrated. The element beamwidth is assumed to be 135°. Figure 2 is the different AOA and TOA case. Figure 5 is the same AOA and different TOA scenario. Next, Figure 6 is the different AOA and same TOA scenario. The scenario with the same AOA and same TOA has been studied by [4], which reduces to the flat fading channel. Based on the four scenarios, the resulting output BER shown in Figure 7 indicates that the proposed hybrid smart antenna with same AOA and same TOA scenario provides the best performance due to no ISI interference. Moreover, the simulation results confirm that the proposed two branch receiver can overcome the different AOA and DOA scenarios and provide the robust performance.

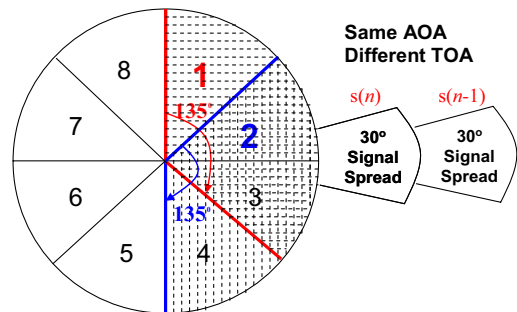


Figure 5. Example of a 135° beamwidth system used in two paths with 30° DOA spreads, same AOA, and different TOA environment

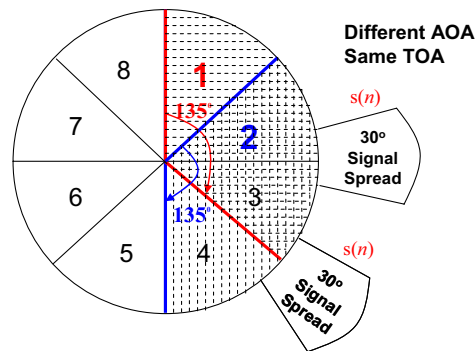


Figure 6. Example of a 135° beamwidth system used in two paths with 30° DOA spreads, different AOA, and same TOA environment

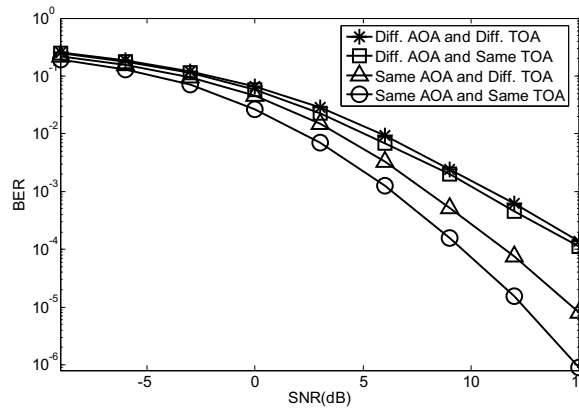


Figure 7. BER performance of a hybrid smart antenna system with 16 QAM modulation as a function of SNR with the different AOA and TOA scenarios

V. CONCLUSIONS

We have proposed a new hybrid smart antenna receiver system which is suitable for frequency selective fading channel environments. Due to the ability of suppressing interference with directional elements, the proposed digital beamforming approach can achieve lower complexity compared to the conventional smart antenna systems. Moreover, the MRC technique can be used to combine the output signal of the branch without ISI. The approach of separately processing the two branches provides the robust performance to combat different AOA and TOA channel effects. Simulation results have confirmed that the proposed smart antenna system can approach the performance of the conventional smart antenna system and provide the robust performance under multipath fading channel environment.

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