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Performance of Smart Antennas With Receive Diversity in Wireless Sensor Networks

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Abstract— In this paper we propose a Geometrically
Based Single Bounce Elliptical Model (GBSBEM) for
multipath components involving randomly placed
scatterers in the scattering region with sensors deployed
on a field. The system model assumes a cluster based
wireless sensor network (WSN) which collects
information from the sensors, filters and modulates the
data and transmit it through a wireless channel to be
collected at the receiver. We first develop a GBSBEM
model and based on this model we develop our channel
model. Use of Smart antenna system at the receiver end,
which exploits various receive diversity combining
techniques like Maximal Ratio Combining (MRC), Equal
Gain Combining (EGC), and Selection Combining (SC),
adds novelty to this system. The performance of these
techniques have been proved through matlab simulations
and further ahead based on different number of antenna
elements present at the receiver array, we calculate the
performance of our system in terms of bit-error-rate
(BER). Based on the transmission power we quantify for
the energy efficiency of our communication model.

I. INTRODUCTION

A wireless sensor networks (WSN) is a network of
wirelessly interconnected devices, called sensor nodes,
which are able to ubiquitously collect/retrieve data to
be sent to a far receiver. Hundreds of nodes are
scattered randomly throughout over a wide area, which
assemble together, establish a routing topology, and
transmit data back to a common collection point [1].
The main features of such networks are high density of
nodes, low-mobility, severe power constraints, and
high correlation of data among the nodes and also that
the nodes can act both as a sensor and as a router
towards a centralized node through multi-hop
 technique. With the development of new wireless
technologies and a growing demand for miniaturized,
low-powered, low-cost yet simpler and reasonably
efficient wireless communication devices, there has
been a growing interest in WSN for a wide variety of
applications ranging from seismic studies and life
sciences, security-sensitive applications, social,
military, and environmental problems.

Wireless communication involves entire
environmental related effects to the propagated signals
between the transmitter and the receiver. Our scenario
assumes that the communication system suffers from
multipath, Doppler spread and high propagation delays.
Due to irregular distribution of scatterers present in the
environment, multipath signals arrive at the receiver
from different directions at different times. All of
these multipaths taken by the wireless signal possess
different properties, and hence, each multipath signal
has its own distinctive carrier phase shift, amplitude,
angle of arrival, and time delay. A possible approach
to address these issues is through the geometrical
definition of the scattering region to calculate the
above parameters. The geometry of the multipath
propagation plays a vital role for communication
systems to suppress multipath [2]. A GBSBEM for
single bounce multipath components involving
randomly placed scatterer is presented here.

In [3], a cooperative diversity scheme that
increases the network lifetime and the communication
reliability has been proposed where the identical
sensors are randomly scattered over a wide area.
These nodes collect a common message and transmit it
towards a fusion center placed in an unarmed air
vehicle (UAV). Practically these scenarios face the
reachback problem where the nodes are designed with
low power transmitters and are often not capable
equipped to directly transmit data to the far receiver [4].
A distributed algorithm capable of computing linear
signal expansions for a sensor broadcast protocol is
presented in [5] where each sensor collects the
correlated samples, broadcasts a rate constrained
encoding of its samples to every other sensor and
forms an estimate of the entire field. To decorrelate,
the sensors need access to samples from a few nearby
sensors only. Typical applications include collection
of data from a remote area. A distributed diversity
approach capable of exploiting spatial distribution of
sensor nodes has been proposed and analysed in [6].
However, idealistic assumptions like synchronization
and cooperation are introduced to ensure improvement
in the network performance. Other than correct
reception of data at the far end receiver and hence
performance improvement, exploiting diversity
techniques at the receiver can help in saving the energy
substantially and leading to reduced battery
consumption and subsequently increasing network
lifetime.

In this paper, we combine the GBSBEM with
other aspects of fading channel and establish a vector
channel model fulfilling the simulation requirements of
smart antennas employed at the mobile receiver. Since
we are using a cluster based model, the sensor nodes
do not face the reachback problem as they have to
transmit the information at a shorter distance to the
cluster head, hence can be designed to work at
comparatively lower powers. The rest of the paper is
organized as follows. In section II, we develop the system and the channel models for the GBSBEM. Then we develop the receiver structure exploiting receive diversity followed by various diversity combining techniques for receiving the signal. Some numerical results are presented in section III based on the transmitting power and the number of antenna elements used in the antenna array. Finally we present our conclusions in section IV.

II. MODEL DEVELOPMENT

A. System Model

We consider a cluster based WSN architecture with $N$ number of identical sensors deployed over a wide area. The goal is to collect the observations gathered by all the sensors to the cluster head to be transmitted to the receiver. We assume that all the sensors collect the same data and are capable of developing an ad-hoc network to disseminate the information among them via efficient flooding. The sensors pass on the information to the cluster head, where this information is filtered and modulated using BPSK and sent to the receiver. Another assumption is that the whole architecture is synchronous and the communication channel between the cluster head and the receiver is subjected to fading, multipath, and noise.

The system model block diagram for a cluster based WSN architecture is shown in Fig. 1. When the signal is transmitted, reflections from large objects, diffraction of the waves around objects, and signal scattering dominate the received signal resulting in the presence of multipath components, or multipath signals, at the receiver. Figure 2 depicts a general example of this multipath environment. Each signal component propagates through a different path, determining the amplitude $a_n$, time delay $\tau_n$, angle of arrival $\theta_n$, the power for the multipath components, and Doppler shift $f_d$ of the $n$th multipath signal component. Accordingly, each of these signal parameters will be time-varying [7].

In the GBSBEM, scatterers are uniformly distributed within an ellipse as shown in figure 2. An essential attribute of this model is the physical interpretation that the multipath signals which arrive with an absolute delay $\tau_{\text{max}}$ are only accounted. The sensors are such located that they are surrounded by scatterers and each signal transmitted by each sensor experiences a different multipath environment that determines the amplitude, the time delay, Direction-of-Arrival (DOA), and the power for each multipath component for each sensor.

Considering the distance between the sensor nodes and the receiver to be $D$, all the scatterers giving rise to single bounce components arriving between time $t$ and $t+\Delta t$ lie in the region bounded by the ellipse with semi-major axis $a_n$ and its semi-minor axis $b_n$ and are related to the maximum specified delay $\tau_{\text{max}}$.

\begin{equation}
\begin{aligned}
a_n &= \frac{c \tau_{\text{max}}}{2}, \\
b_n &= \frac{1}{2} \sqrt{\tau_{\text{max}}^2 - D^2}
\end{aligned}
\end{equation}

where $c$ is the speed of propagation. The choice of these parameters is determined by the maximum delay, $\tau_{\text{max}}$ of the multipath. Larger values of $\tau_{\text{max}}$ imply greater path loss for the multipath and, consequently, lower relative power compared to those with shorter delays.

B. Channel Model

The complex envelope model for the multipath channel impulse response is given by

\begin{equation}
\begin{aligned}
h(t) &= \sum_{i=1}^{L} a_i \delta(t-\tau_i) \\
\end{aligned}
\end{equation}

where $a_i$ is the complex amplitude of the $i$-th multipath component and $\tau_i$ is the path delay for that component. The parameter $L$ is the number of the multipath components and is assumed to be the same for all the sensors.

Our goal is to determine the values of the amplitude $a_i$, path delay $\tau_i$, DOA $\theta_i$, the power for the multipath components. We start with determining the distribution of the DOA for a particular multipath component as a function of time-of-arrival. To simplify the notation, it is convenient to introduce the normalized multipath delay $r_i = c \tau_i / d_n = \tau_i / \tau_{\text{max}}$. The distribution of $r_i$ is given by

\begin{equation}
\begin{aligned}
f_r(r) &= \frac{2r^{1-1}}{\beta N r^{1-1}} \quad 1 \leq r \leq r_{\text{max}}
\end{aligned}
\end{equation}
where \( \beta = r_m \sqrt{\frac{2}{\pi}} - 1 \) and \( r_m = \frac{r_u}{r_0} \) is the maximum value of the normalized path delay. Several techniques for selecting \( r_m \) are outlined in \[2\]. A detailed analysis on the pdf of multipath delays, AOA and power spectrum of the elliptical channel model can be found in \[8\].

The idea is first to define an ellipse corresponding to the maximum multipath delay, \( \tau_m \) and uniformly placed scatterers inside the ellipse. The relevant signal parameters can then be calculated from the coordinates of the scatterers. It is assumed that the number of multipaths, \( L \) and the separation distance between the cluster head and the receiver, \( D \) is known. A value of the maximum multipath propagation delay, \( \tau_m \) is chosen and samples of two uniformly distributed random variables, \( x_i \) and \( y_i \), \( i = 1, \ldots, L \) are generated over the interval \([-1, 1]\). These \( L \) samples of a random variable are described by the polar coordinates \( (r_i, \phi_i) \) according to the following relationships

\[
\gamma = \sqrt{x_i^2 + y_i^2}, \quad \phi = \tan^{-1} \left( \frac{y_i}{x_i} \right).
\]

These samples are translated so that they are uniformly distributed in an ellipse; the following two transformations are performed

\[
x_i = a_e \cos(\phi) + \frac{D}{2}, \quad y_i = b_e \sin(\phi)
\]

Thus, the multipath propagation distance, \( d_i \), and the propagation delays can be calculated as

\[
d_i = \sqrt{x_i^2 + y_i^2 + (D - x_i)^2 + y_i^2}, \quad \tau_i = \frac{d_i}{c},
\]

respectively. Following that the receiver system is located at the origin of the coordinate system, the angle of arrivals (AOA) of the multipaths at the receiver are given by

\[
\theta_i = \tan^{-1} \left( \frac{x_i}{y_i} \right).
\]

The power of the direct path component (LOS) can be calculated as below

\[
P_d(dBm) = P_{\text{ref}}(dBm) - 10 \log \left( \frac{f}{f_{\text{ref}}} \right) + G_t(\theta_i) + G_r(\gamma_i)
\]

(4)

where \( P_{\text{ref}} \) is the reference power measured at a distance \( d_{\text{ref}} \) from the transmitter using omni-directional antennas at the transmitter and the receiver. \( P_{\text{ref}} \) can be calculated using Friis’ free space propagation model given by

\[
P_{\text{ref}}(dBm) = P_t(dBm) - 20 \log \left( \frac{4 \pi d_{\text{ref}}}{\lambda} \right)
\]

(5)

where \( P_t \) is the transmitted power and \( \lambda = \frac{c}{f} \) is the wavelength for a particular carrier frequency, \( f \). The path loss exponent, \( \alpha \) typically ranges from 3 to 4 in a microcell environment. \( G_t(\theta_i) \) and \( G_r(\gamma_i) \) are the gains of the transmit and the receive antennas as functions of the angle of departure, \( \theta_i \) and the angle of arrival, \( \gamma_i \), respectively. For the LOS component, \( \theta_i \) and \( \gamma_i \) are both zero. The power of each of the multipath component can be calculated as

\[
P_i(dBm) = P_{\text{ref}}(dBm) - 10 \log \left( \frac{f}{f_{\text{ref}}} \right) - \alpha \gamma_i - c_1(\theta_i) - c_2(\gamma_i) - c_3(\theta_i) - c_4(\gamma_i)
\]

(6)

where \( L_i \) is the path loss in dB. Assuming the phase of the multipath components, \( \gamma_i \) are uniformly distributed over the interval \([0, 2\pi]\), the complex amplitudes of the multipath components are calculated as below

\[
\alpha_i = 10^{(\gamma_i - \beta)/20}
\]

C. Receive Diversity

It can be generally supposed that the signal transmitted by the cluster head travels through several resolvable discrete multipaths and arrives at the receiver arrays, each multipath having its own independent DOA, time delay, and amplitude. As a result the received signal \( s(t) \) can be represented as

\[
y(t) = \sum_{i=1}^{L} a_i(t) y_i(t) \delta(t - \tau_i) + n(t)
\]

(7)

where \( s(t) \) is the input signal, \( n(t) \) is the additive white Gaussian noise, \( a_i(t) \) the attenuation factor for the signal received on the \( i \)-th path. As per antenna array theory, each multipath signal brings multiple signals at the receiving array. The effect of every individual multipath signal on every element of the antenna array can be equalized to multiply by \( a_i(\theta_i) \), known as the steering vector of antenna array where \( \theta_i \) represents the index of antenna array.

For an \( N \)-element linear antenna array the channel impulse response of the \( i \)-th user can be expressed as

\[
b_i(t) = \sum_{j=1}^{N} a_{ij}(\theta_i) y_j(t) \delta(t - \tau_{ij})
\]

(8)

The \( N \times 1 \) array response vector or the steering vector \( a(\theta_i) \) is defined as

\[
a(\theta_i) = \begin{bmatrix} e^{-j2\pi \alpha_d \sin(\theta_i) \Delta} \\ \vdots \\ e^{-j2\pi \alpha_d (N-1) \sin(\theta_i) \Delta} \end{bmatrix}
\]

(9)

where \( d \) is the element spacing and \( \Delta \) is the angle spread of the \( i \)-th user.

The collection of independently fading signal branches can be combined in a variety of ways to improve the received SNR. Since the chance of having two deep fades from two uncorrelated signals at any instant is rare, combining them can reduce the effect of the fades.

Diversity is a powerful communication receiver technique that provides wireless link improvement at relatively low cost. Diversity exploits the random nature of radio propagation by finding independent signal paths for communication. In virtually all applications, diversity decisions are made by the receiver, and are unknown to the transmitter. The diversity concept can be explained simply. If one radio path undergoes a deep fade, another independent path may have a strong signal. By having more than one path to select from, both the instantaneous and average

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SNRs at the receiver may be improved. There are a variety of ways in which the independently fading signal branches can be combined; hence, the three most prevalent space diversity-combining techniques used are the Maximal Ratio Combining (MRC), Equal Gain Combining (EGC), and Selection Combining (SC). These combining techniques are discussed and analysed in this section.

1) **Selection diversity:** Selection diversity is the simplest of all the diversity schemes. It is based on the probability that the received signals are greater than a threshold. An ideal selection combiner chooses the signal with the highest instantaneous SNR of all the branches, so the output SNR is equal to that of the best incoming signal and makes it available to the receiver at all times. Multiple branches will improve the probability of having a larger SNR at the receiver [9]. A block diagram of SC is given in figure 3.

2) **Maximal ratio combining:** MRC presents the receiver with a signal-to-noise ratio that is the direct sum of all individual SNRs in the branches. The main drawback of using MRC is that the signal level and noise power at each branch needs to be correctly estimated for all instances in time. The M signals are weighted proportional to their signal voltage-to-noise power ratios and then summed. The block diagram of MRC is shown in figure 4.

3) **Equal Gain Combining:** EGC diversity receiver is of practical interest because of its reduced complexity relative to optimum maximal ratio combining scheme while achieving near-optimal performance [9]. It is the sum of all the signals received in order to increase the available SNR at the receiver. The gain of all of the branches is set to a particular value that does not change which is in contrast to MRC. The block diagram of EGC is shown in figure 5. EGC is similar to MRC, but there is no attempt to weight the signal before addition.

The performance of SC, MRC, and EGC is compared in figure 6. It can be seen that selection diversity scheme has the poorest performance and maximal ratio the best. The performance of EGC is only marginally inferior to MRC. The implementation complexity for EGC is significantly less than the MRC because of the requirement of correct weighing factors.

Hence, the basic idea of diversity reception is that, if two or more independent samples of a signal are taken, then these samples will fade in an uncorrelated manner. This means that the probability of all the samples being simultaneously below a given level is much less than the probability of any individual sample being below that level. The probability of M samples all being simultaneously below a certain level is \( p^M \), where \( p \) is the probability that a single sample is below the level. Thus, it can be seen that a signal composed of a suitable combination of various samples will have much less severe fading properties than any individual sample alone.
III. NUMERICAL ANALYSIS AND SIMULATION RESULTS

In this section we present some basic simulation results to evaluate the performance of our system. We discuss the reliability and robustness of cluster based WSN by using smart antennas at the receiver. The proposed model has been simulated for a microcell environment. The focus of the model is to consider the scenario of local scattering giving rise to multipaths. This multipaths and the resulting fading are modeled as stochastic processes and channel characteristics like time-variation, amplitude, and angular spread are modeled using GBSBEM. We consider a cluster-based model with N sensor nodes randomly scattered over a large area. These nodes collect a common message and transmit it towards the cluster head. The information received at the cluster head is filtered and modulated and transmitted to the receiving station. The cluster head is located within a range of 1-2 km from this receiving station. In this case both the cluster head and the receiver are surrounded by scatterers and the receiving antenna array is not well above the surrounding objects. The model parameters were chosen to fit the scenario. Assuming a microcell environment, Table 1 refers to the set of parameters used for simulations to develop the channel and the system model. The transmitted symbol is a BPSK modulated signal with a symbol rate of 10000 symbols per second. The channel considered here is a time-varying channel; therefore channels are generated for each transmitted symbol using the proposed model. The performance improvement of the system employing smart antennas has been proved through matlab simulations and has been demonstrated in figures 7 - 11.

Table 1 demonstrates the BER at different signal-to-noise ratios (SNR) for different transmission power. Figure 8 shows the BER performance of the model as a function of SNR under different values of transmission power based on numerical simulation.

Table 2 shows the performance of the system with receive diversity techniques employed at the receiver with 2 antenna elements. The transmission power is 10W and all other parameters kept same as in table 1. MRC shows the best performance amongst the three types of techniques used.

EGC, SC, and the MRC with different number of antenna elements at the receiver, respectively. The three graphs shows that the performance of the system increase as the number of antenna elements increases.

![Graph 7](image7.png)

![Graph 8](image8.png)
Table 3 compares the performance of the three receive diversity techniques. The table demonstrates that the BER of the system increases by increasing the antenna elements and decreases with the increase in SNR. At higher SNR, the BER goes to zero. As seen from the table, MRC gives the best performance.

Table 3: BER at Different SNRs Based on Different Numbers of Receive Antenna Elements

<table>
<thead>
<tr>
<th>No. of Antenna Elements</th>
<th>SNR (dB)</th>
<th>Bit Error Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>EGC</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>0.0018</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>0.0002</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>0.0000</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>1.0e-03 *</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>0.5900</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>0.0200</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>1.0e-03 *</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>0.2300</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>0.0100</td>
</tr>
</tbody>
</table>

Figure 9, 10, and 11 shows the performance of

Figure 11 Performance Comparison of the MRC with 2, 3, 4 antenna elements

IV. CONCLUSION

We analyse the problem from the overall performance of the system. The model represented in this paper has been developed for a microcell environment which has a time-varying channel. A cluster based WSN architecture has been assumed at the transmission side. The cluster head is assumed to be surrounded by local scatterers giving rise to multipath, fading giving rise to time-varying channel. At the receiver, receiving arrays are used to collect all the multipath components of the signal effectively. The advantage of using smart antennas in a cluster based WSN model has been demonstrated using time-varying channels where performance improvements can be realized in terms of received SNR. The numerical simulations reveal that the performance of the system increases if the transmission power increases. Since the cluster head is located very near to the sensor nodes, the sensor nodes do not require high transmission powers so they do not face the reachback problem. The paper justifies the use of receive diversity at the receiver for reliable communication between the cluster head and the receiving arrays and proves that MRC provides the best performance when applying receive diversity. We also quantify the fact that with the increase in the number of antenna elements, we are able to increase the reliability and robustness of the system. The number of antenna elements has been kept low while solving our problem. However, they can be extended to N numbers for a large receiving array.

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