On the Feasibility of Receive Collaboration in Wireless Sensor Networks

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Abstract—**In this paper, a new type of collaboration in wireless sensor networks (WSN) is suggested that exploits array processing algorithms for better reception of a signal. For receive collaboration, the transmission power during intra-cluster transmissions decreases at the expense of increasing the inter-cluster communications. It is shown that, as a result of using receive collaboration, the destination node's power consumption and the network interference level decrease which considerably improve the data transmission performance and network life time. This method is applicable both for cluster based and non-cluster based WSNs.**

In order to show the feasibility of receive collaboration and also to evaluate its performance, an LS-CMA based channel equalization scheme is also simulated which is performed during cooperation between cluster nodes. The comparison of the output BER between random distributed and uniform linear distributed cases shows a good performance of receive collaboration.

Keywords-receive collaboration; wireless sensor network; channel equalization

I. INTRODUCTION

Limited lifetime of WSNs due to relatively small and non-renewable batteries of their nodes makes power consumption a primary objective of network design [1]. With transmit collaboration it is possible to reduce the power required for transmission by a single node by, for instance, superimposing transmit signals from various nodes. As a result of using transmit collaboration [2, 3], a group of nodes cooperate together to transmit a signal with lower power. The overall transmission power required is divided among distinct nodes by this approach. Although the superimposition of cooperating nodes increase the computational load, this approach is suited to positively affect the WSNs lifetime, since communications of the nodes are generally more energy consuming than their computations [1].

There are various methods to benefit from transmit collaboration. In [1] and [3], transmit collaboration is suggested as distributed or collaborative beamforming. There, after introducing the advantages of using beamforming in WSN, challenges regarding the implementation of this scheme are considered. According to this technique, neighboring nodes form a virtual array and cooperate to sense and transmit environmental parameters of interest. It is shown that, in the case of using distributed beamforming, the power consumption per node decreases considerably. Of course, differences between virtual arrays in WSNs and array sensors cause some challenges, especially during synchronization, which are discussed in [4].

Despite transmit collaboration, some tasks such as the reception of impinging signals are performed inefficiently in this scheme. Also, the approach to distributed transmit beamforming detailed in [1] and [4] suffers from a comparably long and therefore energy consuming iterative synchronization process in which nodes are constantly transmitting to a remote receiver.

In this paper, another version of collaboration is introduced. We consider receive collaboration in which cluster nodes cooperate as a virtual array for better reception of impinging signals. In particular, Information about a signal received by distributed nodes over distinct channels is aggregated and combined for the reception. Receive collaboration can be used in different forms such as channel equalization [5] or blind beamforming [6]. The key parameter to determine which of these schemes can be implemented as receive collaboration depends on the type of received signals as well as accessible information about the destination and the virtual array. In this paper we show the feasibility of receive collaboration in WSNs. The problem of receive collaboration is analyzed for a straightforward channel equalization problem.

The discussion is organized as follows. In the next section transmit collaboration is reviewed briefly. After that, the idea of receive collaboration in WSNs is introduced in section III. A mathematical analysis of the receive collaboration problem as well as simulation results are presented in sections IV and V, respectively. Finally, section VI concludes this paper.

II. TRANSMIT COLLABORATION

Transmit collaboration in WSNs usually involves techniques in which some sensors cooperate to send their common data. According to this general definition, transmit collaboration includes different schemes such as distributed beamforming [1] and [3] and virtual multi-input multi-output (MIMO) systems [7]. In virtual MIMO schemes the transmit data is encoded with a certain space-time code (which is selected according to the node and transmission channel characteristics) and transmitted via cooperating nodes to a destination.

In distributed beamforming, several nodes cooperate to steer a directive beam to a certain destination. The key point of different beamforming schemes is having synchronous nodes and applying proper phase shifts according to the direction of the destination. Transmit signals are combined constructively at the destination. However, in WSNs, the use of individual local oscillators causes deviations in the phase synchronization process. Moreover, random distribution of nodes and unknown direction of the destination node make it impossible for cluster nodes to estimate proper phase offsets on their own.

The synchronization and modification of the phases of the transmit signals for beamforming is usually performed together. Different closed- and open-loop synchronization schemes are presented in [4].

III. RECEIVE COLLABORATION

Receive collaboration includes techniques in which several nodes cooperate to improve the reception of a signal. According to this definition, receive collaboration contains a wide range of schemes to increase the array gain in a certain direction [8], blind beamforming to improve the reception of signals with certain characteristics (maximum signal to noise ratio [6], constant modulus [5] or cyclo-stationary [8] property), channel equalization to remove or at least decrease undesired transmission channel effects [5] and MIMO data reception [9].

During receive collaboration the impinging signal is received by all cooperating nodes. In order to keep the battery storage balanced among all receivers, one node is selected randomly to process the received data. Dependent on the network structure, different methods may be applied to implement this random process. We propose that after receiving a signal, nodes radiate a special collaboration signal after a random idle time. These contain the node-ID. The first node whose signal is received is selected as the processor node.

In dense networks whose inter-node distances are relatively short, the time delays of inter-cluster transmissions are neglectable, but in some situations the synchronization step is necessary due to network density. To synchronize the cooperating nodes, the processor node broadcasts a message and receives feedbacks from cooperating nodes. The achieved time delays of the local communications from the feedbacks are used to synchronize the aggregated signals by the processor node.

The processor node collects all received data from other nodes and performs the particular receive collaboration scheme. In most array processing schemes, the processing load decreases when it converges to its optimum weighting coefficients. After convergence, it just needs to update its weighting coefficients due to the transmission channel variation. Therefore, receive collaboration has a reasonably low computational load.

More especially, for CDMA based networks, aggregation of the entire received signals by the cooperating nodes increases the memory demand of the processor node. Partially aggregation of the received signals or distributed signal combination, in which signal aggregation is performed in several steps, can decrease the memory need of the processor node.

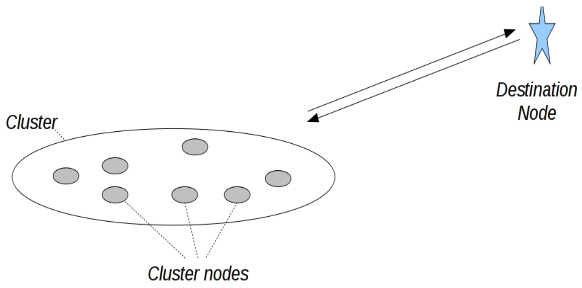


Figure 1. Geometrical distribution of the cluster and destination nodes

Generally, it can be said that receive collaboration is a way to reduce the power per symbol during intra-cluster transactions. Although receive beamforming causes an increase in the inter-cluster communications, it efficiently reduces the power consumption of the remote node and the interference level for other nodes. Decreasing the interference level is also a way to save energy in the network. For a fixed detection threshold, decreasing the interference level has the same result on the received SNR as increasing the signal power. Therefore, it is possible to save further energy by transmission at reduced power.

One limiting parameter in the expansion of WSNs is increased transmission power because of long distances between some clusters and remote node. Receive collaboration may be suggested as a solution due to the ability of array processing schemes to gain a certain performance with lower SNRs,

The question which arises is when receive collaboration should be used. During the synchronization of beamforming schemes [4], there are different transactions between destination and cluster nodes. As an example, in one of the synchronization schemes, referred to as full-feedback closed-loop, the destination broadcasts a signal. Cluster nodes receive it and transmit back to the destination. The destination node finally estimates proper phase shifts and sends it back to each node. In the case of M nodes in a network, consequently, the destination node receives M different signals, modifies and returns them. This leads to a severe computational complexity and power consumption for the destination node.

The superimposition of transmitted signals constructively combines at the destination, when cluster nodes transmit with phase shifts equal to the difference between the phases of their received signals and that of a reference signal. According to the reciprocity theorem, when the transmission channel does not affect the received signal severely, proper phase shifts are calculated by selecting a cluster node as the reference and comparing the signal of the other nodes with this node's signal. The resulting constant offset in the phase shifts has no effect on the beamforming process. However, when the received signal is distorted such that the above method is impossible, the reference signal may be achieved by the use of channel equalization schemes.

Receive collaboration can also be used to increase the directivity of a virtual array to improve the reception quality of an impinging signal. Based on the reciprocity theorem, it is possible to use the phase shifts which are estimated during transmit beamforming [4] to steer a directive beam to the destination. These are two possible examples of receive collaboration applications but alternative implementations are also possible.

Each WSN whose nodes are able to cooperate together can benefit from receive collaboration. Since the neighboring nodes do not need a manager node, receive collaboration is applicable in both cluster-based and non cluster-based networks. It is scalable and considering this feature for WSNs does not increase the sensor nodes complexity.

IV. COLLABORATIVE CHANNEL EQUALIZATION

In this section the receive collaboration problem is presented as a channel equalization scheme.

A. Signal and Channel Model

The assembly of nodes is schematically illustrated in Fig. 1. In this model, M nodes are distributed uniformly at random on a disk of radius R. Provided that all nodes receive line of sight (LOS) rays of the destination node, there is no limitation regarding the position of the sensor nodes. It is also assumed that nodes do not possess any information about their positions or the destination node's direction.

A multi-path Rayleigh fading channel [10] with additive white Gaussian noise (AWGN) is considered. Although in this model impinging signals are received by the nodes after scattering, reflection or diffraction from the objects of the transmission channel, for ease of presentation some transmission channel effects such as angular spreading or Doppler frequency shift are neglected. These phenomena happen due to the high density of scattering objects in urban environments and the mobility of the transmission channel elements, transmitter or receive, respectively.

To model the transmit signal, we assume a data sequence b_k with rate R_b spreaded by a spreading code c_k (here we use the Walsh-Hadamard code) with length L_c. The spreaded sequence with bit rate $R_c = L_c R_b$ is mapped into a symbol constellation and is up converted in the modulation block. Different modulation schemes can be used in this block.

Although the channel equalization scheme which is used in this paper was originally suggested for constant envelope signals, it can be used also for limited-value variable-envelope modulations such as ASK or higher orders of QAM. The destination node's antenna radiates the transmit signal s_n. Assuming a rather flat environment without considerable scatterers and consequently negligible multi-path effect, received signals by cluster nodes at time k can be written as

$$\mathbf{x}_k = \begin{bmatrix} x_k^1 & x_k^2 & \cdots & x_k^M \end{bmatrix} \tag{1}$$

here, x_k^i, the baseband equivalent of the revived signal of the i-th node at time k, is

$$x_k^i = A_k^i s_k e^{j\varphi_k^i} + n_k^i \tag{2}$$

In this formula, φ_k^i is the phase shift because of the distance between destination node and i-th cluster node, A_k^i is the Rayleigh fading coefficient, and n_k^i is the additive noise for the i-th node.

As mentioned before, after receiving the signal, a node is selected as the processor node that gathers all received signals from the other nodes after synchronization (if is necessary) and then applies the channel equalization scheme. Finally, this node generates a $1 \times M$ weight vector $\mathbf{w}_k$, to form the output as $y_k = \mathbf{w}_k . \mathbf{x}_k^H$ for each time instance k such that the channel effects are partially removed from this signal.

B. Channel Equalization Algorithm

The major goal of channel equalization algorithms is to remove or at least decrease the undesired effects of the transmission channel (fading and noise). Most channel equalization schemes in digital communication benefit from the constant envelope property of digital modulated signals. Least squares Constant Modulus Algorithm (LS-CMA) [5] is one of the algorithms we use to equalize the transmission channel during cooperation between cluster nodes to exhibit the efficiency of receive collaboration.

According to this algorithm, the weight vector $\mathbf{w}_k$ is generated during minimization of the LS-CMA cost function $J(\mathbf{w}_k)$ with respect to $\mathbf{w}_k$. The cost function is of the form

$$J(\mathbf{w}_k) = E\left[\left(|y_k|^2 - 1\right)^2\right] \tag{3}$$

here, $E[.]$ denotes the expected value.

According to the stochastic gradient method, the weight vector in each time instant is updated based on its previous value and the gradient of the cost function. In practice, the weight vector is updated by the following recursive relation

$$\mathbf{w}_{k+1} = \mathbf{w}_k - \mu \mathbf{x}_k \left(|y_k|^2 - 1\right) y_k \tag{4}$$

where μ is the step size that controls the convergence rate of the algorithm.

It can be seen in (3), (4) that LS-CMA does not need the relative of the nodes. Due to its simplicity, this algorithm is well suited for wireless sensor networks.

V. SIMULATION RESULTS

In this section, the feasibility of receive collaboration is investigated in simulations by using the LS-CMA based channel equalization scheme to improve the quality of a received signal.

A data sequence of 250 bits is spreaded with a Walsh-Hadamard code with length 64. Although spreading the transmit sequence is not necessary, it is helpful in our

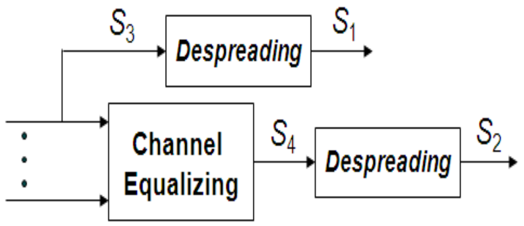


Figure 2. Points of interest to calculate BER in the receiver structure

simulations. We use BPSK unless another modulation scheme is mentioned.

In most of the simulations, it is assumed that $M = 25$ nodes cooperate for channel equalization (unless another value is mentioned). In order to simulate received signals, assuming independent transmission channels between destination and cluster nodes, M vectors containing L (length of the signal after spreading and modulation) Rayleigh random variables are generated as the channel coefficients. These vectors are multiplied by the modulated signal. The additive noise which is also a set of M vectors with length L containing zero mean Gaussian random variables with variance equal to 1, add to the received signal. Finally, dependent on the distance between destination and each individual cluster node, proper phase shifts are calculated and applied.

The block diagram in Fig. 2 illustrates the signal processing flow. The four signals of interest are:

S_1: Before channel equalization and after despreading,

S_2: After channel equalization and despreading,

S_3: Before channel equalization and despreading,

S_4: After channel equalization and before despreading.

In digital communication, BER is a parameter well suited for demonstration and comparison. We utilized it as the major parameter to evaluate our simulations. Simulation results represent median values achieved in 500 simulations.

First, the ability of LS-CMA to extract different symbols and concentrate them around their original positions is investigated. Fig’s 3 and 4 represent S_3 and S_4, respectively. In order to develop a better understanding of the performance of a LS-CMA based equalizer, these signals are illustrated before detection.

As observed in these two figures, LS-CMA can efficiently mitigate the channel effects by concentrating the symbols around their original positions (+1 , -1 in BPSK). For this scenario, the corresponding BER to Fig's 3 and 4 are 0.3176 and 0.0133, respectively.

To obtain a more comprehensive view of the channel equalization performance, the BER of the signals S_1 to S_4 are calculated for different SNR values in Fig 5. Corresponding bit error rates of the signals before and after despreading are plotted separately in Fig's 5-*a* and 5-*b*, respectively. Moreover, the BER curves for before and after channel equalization are marked with circles and dots, respectively.

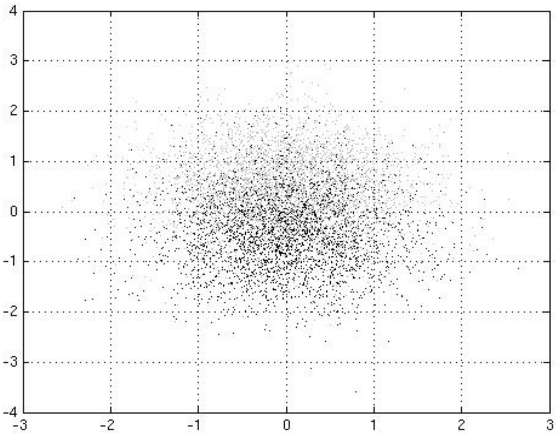


Figure 3. Position of the symbols in the complex plan before channel equalization and despreading; to better illustration of the results, BER's are calculated before dispreading.

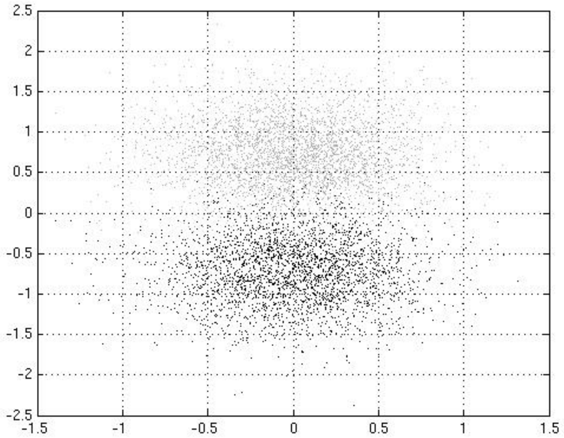
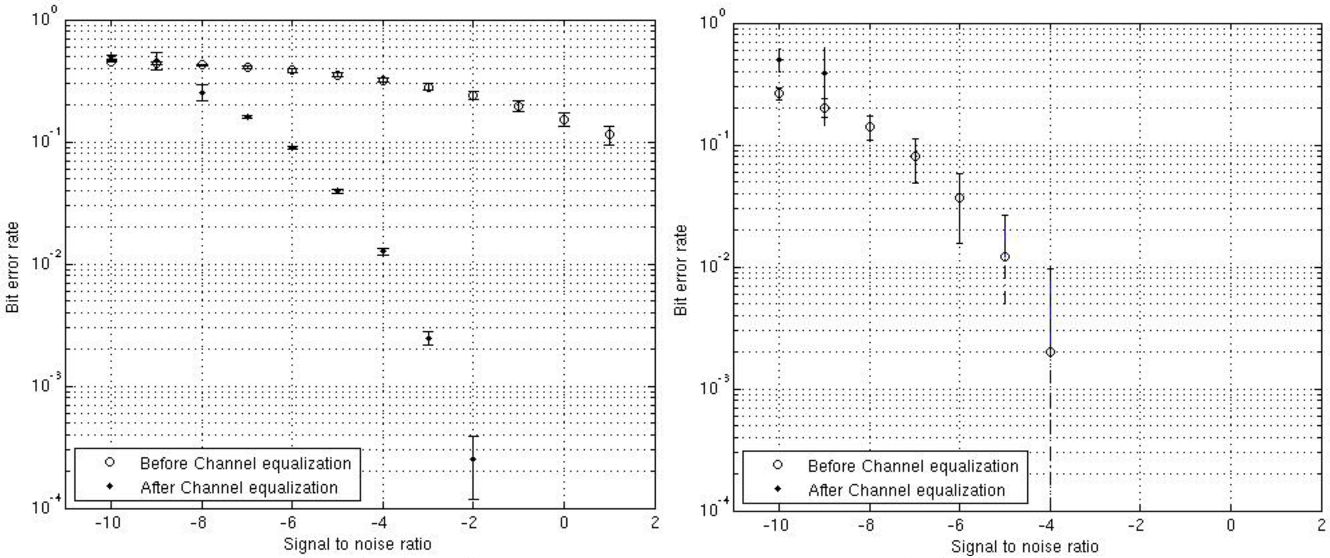


Figure 4. Position of the symbols in the complex plan after channel equalization and despreading; to better illustration of the results, BER's are calculated before dispreading.

Fig 5 shows that when the SNR is equal or less than -9 dB, channel equalization fails and BER is equal to its maximum value. For higher SNRs, the channel equalizer works properly and the BER of the equalizer output (S_4) gets less than 0.2 while the final BER (S_1) descends to zero. Comparing the BER curves before and after equalization (before despreading) shows that the equalizer performance increases with increasing SNR.

In Fig 6 the effect of node density on the output BER is illustrated. In this figure, the BER of the equalizer output (S_4) for different SNR values versus the number of nodes per cluster (which is considered as a disk with radius 50*m*) is depicted.

According to this figure, to gain lower values of the BER, the node density should be increased. Moreover, as the SNR gets higher, the slope of the curves increases and the BER decreases with higher rate. This means that increasing the node density for higher NR is more efficient.



(*a*) Before despreading

(*b*) After despreading

Figure 5. BER of the received data before and after channel equalization and before despreading; WSN scenario

In order to evaluate the efficiency loss due to the random distribution of nodes, the same scenario as for Fig 5 is considered based on uniform linear arrays. By comparing both cases we observed that approximately the same results are obtained. This means that a random distribution of nodes in a WSN does not have negative effect on the LS-CMA based equalizer performance. This was also mentioned by Chen and *et al.* in [11].

VI. CONCLUSION

We presented an approach of applying receive channel equalization in wireless sensor networks. The general problem structure was defined analytically. For this scenario, we discussed simulation results obtained in a Matlab-based simulation environment.

Using collaboration by receive nodes affects transmission and energy efficiency positively when compared to conventional wireless sensor networks. The following effects have been derived:

- Increase of the destination node's lifetime due to decreasing transmission power during intra-cluster transactions,
- Decrease of the interference level in the network due to decreasing intra-cluster transactions,
- Power efficiency due to implementation of array processing schemes in the clusters,
- Ability to expand the network dimensions due to increasing sensitivity of nodes.

The aforementioned advantages are achieved at the expense of

- Increasing the inter-cluster communications,
- Increasing the computational complexity for nodes.

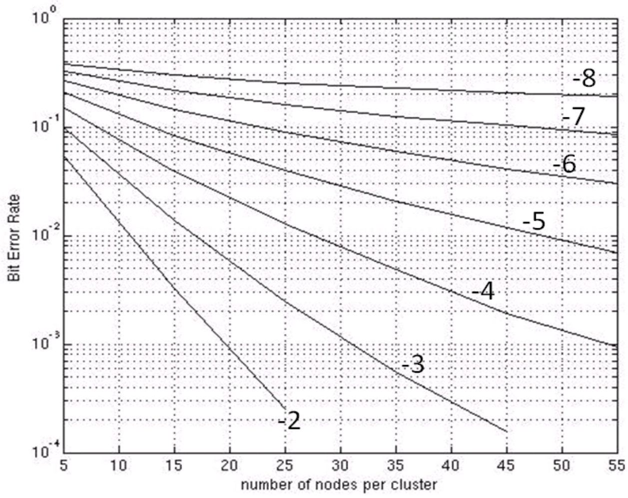


Figure 6. Effect of node density on output BER; to better illustration of the results, BER's are calculated before despreading

Finally, it can be concluded that, with respect to the type of accessible information about the cluster nodes, destination and transmit signal, there are various methods to exploit receive collaboration. Simulation results regarding collaboration of the cluster nodes for channel equalization, approve the efficiency of this approach.

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