NODE SELECTION FOR SIDELOBE CONTROL IN COLLABORATIVE BEAMFORMING FOR WIRELESS SENSOR NETWORKS

Mohammed F. A. Ahmed and Sergiy A. Vorobyov

Department of Electrical and Computer Engineering, University of Alberta
Edmonton, AB, Canada.
Emails: {mfahmed, vorobyov}@ece.ualberta.ca

ABSTRACT
Collaborative beamforming (CB) is a new technique for energy-efficient long-distance communications in wireless sensor networks (WSNs). It is based on the fact that the distributed nodes of a WSN can synchronize their carrier phases to form a beampattern with a stable mainlobe (independent on the node locations). However, sidelobes of such beampattern are found to be severely dependent on the particular node locations. High level sidelobes can cause unacceptable interference to unintended base stations and access points (BSs/APs). Therefore, controlling the sidelobes of CB has the potential to increase the network capacity and wireless channel availability. In this paper, we propose node selection for CB sidelobe control. A selection algorithm with low implementation complexity is developed to search over different node combinations. It aims at minimizing the interference at unintended BSs/APs. The performance of the proposed algorithm is analyzed in terms of the average number of trials and the achieved interference suppression. Simulation results match the analytical approximations and show the effectiveness of node selection for limiting the interference.

1. INTRODUCTION

Limited power and computational capabilities of individual nodes in wireless sensor networks (WSNs) cause new challenges for data communication which are not found in the traditional communication systems [1]. Many WSN applications require deployment of nodes over wide area and communication with far base stations or access points (BSs/APs). Direct transmission is not suitable in these applications because the transmission range of individual nodes is short. However, high density deployment of nodes can be used to introduce communication schemes that target WSNs and overcome the aforementioned limitations. Particularly, collaborative beamforming (CB) has been introduced in WSNs for the uplink communication with a BS/AP [2]-[6]. CB extends the transmission range and avoids the dependence of communication quality on individual nodes [2]-[5]. It also distributes power consumption over large number of nodes and balance their lifetime [6]. Moreover, CB creates a direct link to the BS/AP and allows single-hop transmission. Therefore, it reduces the communication delay and data overhead. Transmission medium can be utilized more efficiently if different sets of collaborative nodes are allowed to transmit data simultaneously to different BSs/APs. In this case, however, the interference caused by the collaborative sets to unintended BSs/APs has to be minimized.

In CB, nodes adjust their carrier phases to cancel out the phase difference due to propagation delay and, thus, signals add coherently at the destination. Assuming perfect synchronization, CB guarantees a deterministic mainlobe at the intended direction for any network realization. However, the sidelobes are shown to be random and depend on node locations [2]-[4]. Reducing interference caused by high level sidelobes at the directions of unintended BSs/APs has the potential to increase the network capacity [7]. Unfortunately, existing sidelobe control techniques are not attractive in the context of WSNs because of the high complexity and data exchange overhead between the nodes.

In this paper, node selection is introduced for CB in WSNs in order to achieve a beampattern with low level sidelobes at the directions of unintended BSs/APs. A low-complexity algorithm is proposed to overcome node limitations and avoid complex central weight design and communication. Node selection is carried out when the network is deployed for the first time and can be repeated when the network configuration changes. The performance of the proposed algorithm is analyzed in terms of the average number of trials and the achieved interference suppression. Simulation results demonstrate the effectiveness of the node selection for improving the CB beampattern. Finally, we would like to note that the importance of relay nodes selection for improving the network capacity has been recently recognized in the context of cooperative relay based communications [8]-[11].

The rest of the paper is organized as follows. In the next section, we present the system model and summarize the as-
2. SYSTEM MODEL

We consider a WSN with randomly located nodes in a field as shown in Fig. 1. Each node has single antenna and operates in a half duplex mode. We assume that the power consumed for communication among nodes can be neglected. For data transmission, a set of collaborative nodes uses CB to transmit data to one of multiple BSs/APs located far away from the coverage area of each individual node. For simplicity, we assume that the nodes and the BSs/APs are located in a plane. Furthermore, the wireless channel is assumed to be ideal and the fading effects are neglected.

Let the \( k \)th node has a polar coordinates \((r_k, \psi_k)\) and the BSs/APs, denoted as \( D_i, i = \{0, \ldots, K\} \), are located at directions \( \phi_0, \phi_1, \ldots, \phi_K \), respectively. Without loss of generality, we assume that the intended destination BS/AP is \( D_0 \). For source node \( S \), let \( \mathcal{M} \) be the set of nodes in its coverage area and \( \mathcal{C} \) be a set of collaborative nodes to be selected from \( \mathcal{M} \), i.e., \( \mathcal{C} \subseteq \mathcal{M} \), where the cardinalities of \( \mathcal{M} \) and \( \mathcal{C} \) are \( |\mathcal{M}| = M \) and \( |\mathcal{C}| = N \), correspondingly, and \( N < M \).

To construct a mainlobe pointing at the intended destination \( D_0 \), the carrier of each node is synchronized with initial phase \( \Psi_k = -\frac{2\pi}{\lambda} d_k(\phi_0) \), where \( \lambda \) is the wavelength and \( d_k(\phi) \approx A - r_k \cos(\phi - \psi_k) \) is the Euclidean distance between the \( k \)th node and a point \((A, \phi)\) at the reference sphere \( r = A \). The array factor corresponding to the nodes in \( \mathcal{C} \) can be written as

\[
F(\phi/\mathcal{C}) = \frac{1}{N} \sum_{k \in \mathcal{C}} e^{j\Psi_k} e^{j\frac{2\pi}{\lambda} d_k(\phi)}
\]

(1)

where \( 1/N \) is the normalization factor. Note that selecting a set of collaborative nodes \( \mathcal{C} \subseteq \mathcal{M} \) will not change the mainlobe because it is independent on the node locations and the number of nodes as far as \( N \) is sufficiently large [4]. However, even with carrier synchronization, sidelobes are random because of the random node locations, i.e., sidelobes corresponding to different sets of collaborative nodes \( \mathcal{C} \) are different. Therefore, the sidelobes can be controlled by using node selection even if each selected node uses a unit weight. Moreover, a beampattern with desired interference levels at arbitrary directions can be formed.

The array factor at angle \( \phi \) in the sidelobe region, i.e., the region away from the mainlobe, can be modeled as an uncorrelated complex Gaussian random variable with real part

\[
X = \sum_{k \in \mathcal{C}} \text{Re}\left\{ e^{j\Psi_k} e^{j\frac{2\pi}{\lambda} d_k(\phi)} \right\}
\]

and imaginary part

\[
Y = \sum_{k \in \mathcal{C}} \text{Im}\left\{ e^{j\Psi_k} e^{j\frac{2\pi}{\lambda} d_k(\phi)} \right\}, \quad \text{i.e.,}
\]

\(1\)Note that far-field region is assumed, i.e., \( A \gg r_k \).

3. SELECTION ALGORITHM

In this section, we outline the communication protocol and provide the details of the node selection algorithm for CB sidelobe control.

3.1. Communication protocol

Consider a two-phase communication protocol where source node \( S \) is willing to communicate data to the destination \( D_0 \) with the help of the collaborative nodes \( \mathcal{C} \). In the first phase, which is a listening phase, the source node \( S \), which has data to transmit, broadcasts its identification number (ID) and the ID of the intended BS/AP \( D_0 \). In this case, other source nodes are not allowed to transmit data to the same BS/AP. Time-division multiple-access (TDMA) scheme is employed in the first phase to avoid collision between different source nodes. Nodes in the coverage area of the source node, i.e., nodes from the set \( \mathcal{M} \), receive these IDs. A predetermined set of collaborative nodes \( \mathcal{C} \) assigned to the \( S-D_0 \) pair continues the listening phase, while other nodes go back to idle mode for the next listening phase. Source node then transmits its data to the collaborative nodes. In the second phase, which is a CB phase, collaborative nodes \( \mathcal{C} \) transmit the data to \( D_0 \) using CB.

3.2. Collaborative nodes selection

The node selection process must be performed at the initial setup of the WSN and can be repeated anytime if the network
configuration changes. Each source node assigns a set of collaborative nodes \( C \) for each destination. The source node \( S \) initiates the node selection process by broadcasting a \textit{select message} to the nodes in the set \( M \). A set \( c_i \) of \( L \) (\( \leq N \)) candidate nodes is randomly assigned from \( M \) and transmits a \textit{test message}, that contains the intended BS/AP ID, using CB to the intended destination. While the intended BS/AP receives a predetermined power, the power levels at the unintended BSs/APs are unexpected because of the random side-lobes. BSs/APs with different ID measure the received power and can be used in future trials. If no message is received from any of the BSs/APs, then the candidate set \( c_i \) is randomly assigned from \( M \). A set \( c \) of the BSs/APs, then the candidate set \( c_i \) is returned to the pool of nodes \( M \) and can be used in future trials. If no message is received from any of the BSs/APs, then the candidate set \( c_i \) sends back an \textit{approval message} to the source node \( S \) and stores the IDs of the source node \( S \) and the intended BS/AP. Collaborative nodes assigned for \( S-D_i \) pair can not participate in future trials and, therefore, there is no overlap between sets of nodes serving different destinations. To obtain \( N \) collaborative nodes, this step is repeated till \( N/L \) candidate sets \( c_i, i = 1, 2, \ldots, N/L \), are approved and then \( C = \bigcup c_i \). At the end of the selection process, the source node \( S \) broadcasts an \textit{end message}. The pseudocode of the node selection algorithm is given in Table 1.

### Table 1: Node selection algorithm for CB sidelobe control

<table>
<thead>
<tr>
<th>Step</th>
<th>Description</th>
<th>Conditional Logic</th>
</tr>
</thead>
<tbody>
<tr>
<td>1:</td>
<td>At ( S ): {Counter ( \leftarrow ) 1}.</td>
<td>\</td>
</tr>
<tr>
<td>2:</td>
<td>If {Counter &lt; ( \frac{N}{L} }}.</td>
<td>\</td>
</tr>
<tr>
<td>3:</td>
<td>\textbf{Then} ( S ) broadcasts the \textit{select message}, \textbf{Else} ( c_i ) sends an \textit{approval message} to ( S ).</td>
<td>\</td>
</tr>
<tr>
<td>4:</td>
<td>A candidate set ( c_i ) is assigned.</td>
<td>\</td>
</tr>
<tr>
<td>5:</td>
<td>( c_i ) transmits the \textit{test message} using CB.</td>
<td>\</td>
</tr>
<tr>
<td>6:</td>
<td>\textbf{Otherwise Go to} 12.</td>
<td>\</td>
</tr>
<tr>
<td>7:</td>
<td>At ( D_i ), other than ( D_0 ): If { ( P &gt; P_{\text{thr}} ) }.</td>
<td>\</td>
</tr>
<tr>
<td>8:</td>
<td>\textbf{Then} ( D_i ) sends a \textit{reject message} to ( c_i ).</td>
<td>\</td>
</tr>
<tr>
<td>9:</td>
<td>\textbf{Else} \ No reply.</td>
<td>\</td>
</tr>
<tr>
<td>10:</td>
<td>( c_i ) sends an \textit{approval message} to ( S ).</td>
<td>\</td>
</tr>
<tr>
<td>11:</td>
<td>At ( S ): {Counter ( \leftarrow ) ( \text{Counter} + 1 )}.</td>
<td>\</td>
</tr>
<tr>
<td>12:</td>
<td>\textbf{Go to} 2.</td>
<td>\</td>
</tr>
<tr>
<td>13:</td>
<td>( S ) broadcasts the \textit{end message}.</td>
<td>\</td>
</tr>
</tbody>
</table>

3.3. Node assignment implementation

The assignment of candidate sets \( c_i, i = 1, 2, \ldots, N/L \), can be implemented using one of two mechanisms. In the first mechanism, the source node is responsible for the node assignment. It keeps a record of nodes in the coverage range and broadcast IDs of the assigned nodes. This mechanism is suitable for small scale networks where the source node can keep records of all candidate nodes. In large scale networks, node assignment task is preferred to be achieved in a distributed manner among nodes. When nodes receive the \textit{select message}, each node starts a random delay using an internal timer. After the random delay is finished, the node responds by a collaboration \textit{offer message} which contains its ID. The source node responds by an \textit{approval message} which can be one bit only. If collision occurs between two nodes, the source node responds with a different bit value and the timers in both nodes start over a new random delay.

Fig. 2 shows the beampattern corresponding to CB with node selection in comparison to the average beampattern of nodes in the coverage area is \( M = 512 \), the desired number of collaborative nodes is \( N = 256 \), and \( P_{\text{thr}} = 10 \log_{10}(1/N) \) is the average sidelobe level for the CB beampattern without node selection \[2\], \[3\]. The intended BS/AP is located at \( \varphi_0 = 0^\circ \) and three neighboring BSs/APs at \( \varphi_1 = -125^\circ \), \( \varphi_2 = -50^\circ \), and \( \varphi_3 = 80^\circ \) are also present. It can be seen from the figure that there is an evident improvement achieved by using the node selection algorithm in reducing the sidelobe levels at the directions of neighboring BSs/APs.

### 4. Statistical Analysis of the Node Selection Algorithm for CB

In this section, we find a closed form expression for the average number of trials required for convergence of the node selection process and the corresponding achievable average interference. Besides the average CB performance, we also find the complementary cumulative distribution function (CCDF) of the beampattern level.
4.1. Average number of trials and average interference

For candidate set $c_i$, the array factor at a given angle $\phi$ can be written as

$$F(\phi/c_i) = \frac{1}{L}(X_i - jY_i).$$  \hspace{2cm} (4)

Note that $X_i, Y_i \sim N(0, \sigma^2 = L/2)$ in this case. The probability that the candidate set $c_i$ joins the collaborative set $C$ is equivalent to the probability that the beampattern at a given angle $\phi$ is lower than the threshold $P_{thr}$, i.e.,

$$\Pr(P(\phi/c_i) < P_{thr}) = \Pr\left(\frac{X_i^2 + Y_i^2}{L^2} < P_{thr}\right) = \Pr(W < L^2 P_{thr}) = 1 - e^{-\frac{\sigma^2 P_{thr}}{2\sigma^2}} = p$$  \hspace{2cm} (5)

where the random variable $W = X_i^2 + Y_i^2$ has an exponential distribution. As expected, $p$ decreases if the threshold $P_{thr}$ decreases. It can be shown that the number of trials $t$ required to obtain $N/L$ approved candidate sets $c_i$, $i = 1, 2, \ldots, N/L$, follows the negative binomial distribution, $\Pr(t = T) = \binom{T-1}{N-1}p^T (1-p)^{T-N}$, and then the average number of trials is

$$E\{t\} = \frac{N}{Lp}$$  \hspace{2cm} (6)

4.2. CCDF of the beampattern

The array factor corresponding to the collaborative set of selected nodes $C$ is the sum of array factors resulting from the approved candidate sets $c_i$, i.e.,

$$\tilde{F}(\phi/C) = \frac{1}{N} \sum_{i=1}^{N} (\tilde{X}_i - j\tilde{Y}_i)$$  \hspace{2cm} (7)

where $\tilde{X}_i$ and $\tilde{Y}_i$ are truncated Gaussian random variables corresponding to the approved candidate sets $c_i$. The corresponding beampattern can be expressed as

$$\tilde{P}(\phi/C) = \frac{1}{N^2} \left(\sum_{i=1}^{N} \tilde{X}_i^2 + \sum_{i=1}^{N} \tilde{Y}_i^2\right)$$  \hspace{2cm} (8)

and the CCDF of the interference level is given by

$$\Pr(\tilde{P}(\phi/C) \geq P) = \Pr\left(\sum_{i=1}^{N} \tilde{X}_i^2 + \sum_{i=1}^{N} \tilde{Y}_i^2 \geq N^2 P\right).$$  \hspace{2cm} (9)

A closed form expression for the probability in (9) is hard to find in general. Moreover, the approximations which can be derived for this probability are too lose when $\frac{N}{L}$ is small, that is usually the case in our problem. Therefore, simulations are used to verify the algorithm performance.

5. SIMULATION RESULTS

Simulation results are provided in this section to demonstrate improvement in beampattern due to node selection. Monte Carlo simulations are carried out using 1000 runs to obtain each curve. We assume that the total number of nodes in the network is $M = 512$ and the desired number of collaborative nodes is $N = 256$. The intended BS/AP is located at $\phi_0 = 5^\circ$ and, in addition, there is a neighboring BS/AP at $\phi_1 = 65^\circ$.

![Fig. 3. Average number of trials $E\{t\}$ versus threshold $P_{thr}$. $M = 512$, $N = 256$, $\phi_0 = 5^\circ$, and $\phi_1 = 65^\circ$.](image)

![Fig. 4. Average interference versus threshold $P_{thr}$. $M = 512$, $N = 256$, $\phi_0 = 5^\circ$, and $\phi_1 = 65^\circ$.](image)
als can be controlled using $L$. As $L$ increases, the number of trials decreases. It is important to note that because of the normalization factor in (4), the consumed power at each trial is the same for different values of $L$ and the total consumed power in the selection process is proportional to the number of trials.

Fig. 4 shows the average achieved interference corresponding to each threshold value $P_{th}$ for different values of $L$. The sidelobe level is linearly proportional to the threshold $P_{th}$ value. However, for high values of the threshold $P_{th}$, the average sidelobe level is upper bounded with the average level when node selection is not used, that is $10 \log_{10}(1/N)$. Figs. 3 and 4 show the fundamental tradeoff between the number of trials and the achieved average sidelobe level. In general, lower sidelobe level can be achieved by using small values of $L$ at the expense of larger number of trials.

Fig. 5 illustrates the probability that the interference exceeds certain level for different values of the threshold $P_{th}$, i.e., the CCDF of interference. Low probable sidelobes is achieved by reducing the threshold $P_{th}$. The results confirm that node selection in CB limits the interference at directions of interest.

6. CONCLUSION

Node selection is introduced for CB sidelobe control in the context WSNs and an efficient algorithm is developed. The expression for the average number of trials for the proposed node selection algorithm is derived, and the effect of the number of nodes selected at one trial to the CB performance is investigated. Increasing the number of nodes selected at one trial reduces the number of trials at the expense of higher sidelobe levels. It is also shown that the CCDF of the beampattern level depends on the interference threshold value. From both the analytical and simulation results, we have seen that CB provides significant interference reduction when simple node selection is applied.

7. REFERENCES


