POWER CONTROL FOR COLLABORATIVE BEAMFORMING IN WIRELESS SENSOR NETWORKS

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ABSTRACT

Energy-efficient communication in wireless sensor networks (WSNs) is addressed in the physical layer by implementing collaborative beamforming (CB). CB achieves directional gain and at the same time distributes the corresponding energy consumption over the collaborative sensor nodes. However, sensor nodes in practice may have different energy budgets assigned to CB transmission. Thus, equal power CB can deplete energy from sensor nodes with smaller energy budget faster than the rest of sensor nodes. In this paper, CB with power control is developed to prolong the lifetime of a cluster of collaborative sensor nodes by balancing the sensor node lifetimes. A novel strategy is proposed to utilize the residual energy information (REI) available at each sensor node. Power control adjusts the energy consumption rate at each sensor node while achieving the required average signal-to-noise ratio (SNR) at the destination. Simulation results show that CB with power control outperforms equal power CB in terms of prolonging the lifetime of a cluster of collaborative nodes.

1. INTRODUCTION

Generally, sensor nodes in wireless sensor networks (WSNs) use batteries or energy harvesting devices as energy sources. However, batteries have limited capacity and harvesting devices provide very small amount of energy. Consequently, energy conservation at individual sensor nodes is a critical issue to achieve practical WSNs. Another concern in WSNs is the unequal energy consumption rate for individual sensor nodes. Typical WSN has identical sensor nodes with sensing, data processing, and communication capabilities that start with the same energy budget once the WSN deployed. However, the surrounding environment determines the priority and the load of the different tasks assigned for each sensor node. Therefore, sensor nodes may have different residual energies at their batteries with progress of time.

Energy-efficient communication can be addressed in the physical (PHY) layer by implementing collaborative beamforming (CB) [1]-[3]. In this technique, single-hop transmission is established when a cluster of sensor nodes adjust their carrier phases to cancel out the phase difference due to propagation delay and, thus, signals add coherently at the base station/access point (BS/AP). CB inherently spreads the energy cost over a group of collaborative sensor nodes and achieves directional gain at the destination [4].

Implementing equal power CB can lead to the situation when sensor nodes with smaller energy budgets drain out of energy faster than the others. Therefore, energy consumption is considered in some CB schemes. In [5], sensor node scheduling is proposed for CB where the participating sensor nodes are selected in each round of transmission to balance the remaining energies at all sensor nodes. A game-theoretic model is used in [6] for power control among different WSN clusters utilizing CB for transmission. The power-saving effect of CB is studied in [4] with the assumption of free-space channels between the sensor nodes and the targeted BS/AP.

In this paper, CB with power control is developed to prolong the lifetime of a cluster of collaborative nodes. A novel strategy is proposed to achieve this goal by balancing the lifetime of individual sensor nodes instead of balancing their energy consumption. Residual energy information (REI) available at each sensor node is utilized to adjust the transmission power of each sensor node while achieving the required average signal-to-noise ratio (SNR) at the targeted BS/AP. The proposed algorithm requires significantly low overhead and computational complexity as compared to the centralized algorithms. Note that in WSNs, distributed algorithms are generally preferred over centralized protocols even when they of-

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fer only sub-optimal solutions [7]. Simulation results show that CB with power control outperforms equal power CB in terms of prolonging the lifetime of a cluster of sensor nodes and improving the SNR at the BS/AP.

2. SIGNAL AND CHANNEL MODELS

Consider a cluster of N sensor nodes randomly placed over a plane and one BS/AP, denoted as $\mathcal{D}$, which is located at the point (ϱ_D, φ_D) in the same plane as shown in Fig. 1. Let the rth node located at (ρ_r, ϕ_r). The distances between sensor nodes are typically much smaller than the distance between the cluster center and the BS/AP. Thus, the path losses from sensor nodes to the BS/AP due to the distance are approximately the same and their effect on the channel model can be neglected. The wireless channel attenuation/fluctuation for rth collaborative node is modeled as a_r which is a lognormal distributed random variable, i.e., $a_r \sim \exp\{\mathcal{N}(0, \sigma^2)\}$. We also assume that sensor nodes are frequency and phase synchronized [8].

Collaborative sensor nodes are assumed to have access to the measurements to be transmitted to the BS/AP. During the CB step, collaborative sensor nodes use the same codebook with zero mean, unit power, and independent symbols, denoted as z, i.e., $E\{z_n\} = 0$, $|z_n|^2 = 1$, and $E\{z_n z_m\} = 0$ for $n \neq m$. Each collaborative node $c_r, r = 1, 2, \ldots, N$, transmits the signal

$$t_r = z\, w_r\, e^{j\psi_r}, \quad r = 1, 2, \ldots, N, \tag{1}$$

where w_r is the CB real valued weight for senor node c_r that controls the transmission power, $P_r = w_r^2$, and ψ_r is the initial phase of the carrier. Although, we refer to w_r as the CB weight for simplicity, the actual CB weight is $w_r e^{j\psi_r}$. Under the assumption of far-field region, i.e., $\varrho_D \gg \rho_r$, the Euclidean distance between the collaborative node c_r and a point (ϱ_D, ϕ) in the same plane is given as $\delta_r(\phi) \approx \varrho_D - \rho_r \cos(\phi - \phi_r)$. Thus, the initial phase of each sensor node carrier is set as $\psi_r = (2\pi/\lambda)\delta_r(\varphi_{\mathcal{D}})$ to achieve coherent combining at the destination $\mathcal{D}$, where λ is the wavelength. Then, the received signal at angle ϕ from all collaborative nodes can be written as

$$g(\phi) = z \sum_{r=1}^{N} w_r e^{j\psi_r}\, a_r\;\, e^{\frac{2\pi}{\lambda}\delta_r(\phi)} + w \tag{2}$$

where $w \sim \mathcal{CN}(0, \sigma_w^2)$ is the AWGN at the direction ϕ. The received signal at the BS/AP can be written as

$$y \triangleq z \sum_{r=1}^{N} w_r a_r + w \tag{3}$$

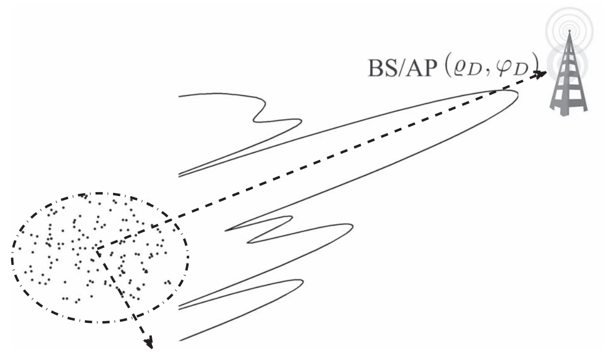

Fig. 1. Cluster of collaborative sensor nodes transmitting to a BS/AP using CB.

3. POWER CONTROL STRATEGY FOR CB

In this section, we present an energy model for WSNs with focus on the energy dissipation corresponding to CB transmission. We introduce new definition for the lifetime of a cluster of collaborative sensor nodes implementing CB transmission. Finally, we propose a low-complexity power control strategy that aims at extending the cluster lifetime by balancing lifetimes of individual sensor nodes.

3.1. Energy Consumption Model

A popular energy consumption model has been introduced in the literature for transmission in WSNs [5], [9], [10]. This model is commonly used for the analysis of the MAC and network layer protocols designed in order to maximize the network lifetime. Other tasks such as sensing and processing are assumed to have smaller energy consumption as compared to the energy consumed for communication [11]. This model considers the energy consumed by the RF transceiver hardware in both transmission and reception. The consumed energy in the transmitter is dissipated on the circuit electronics and the power amplifier, where most of the consumed energy goes to the power amplifier. On the other hand, the receiver does not have a power amplifier and the energy is dissipated on the the circuit electronics only. Therefore, less energy is consumed during reception than during transmission.

The minimum energy consumed by the transmitter to achieve certain desired SNR, γ, at the destination can be expressed as

$$E_{\mathrm{t}x} = E_{\mathrm{t}x}^{\mathrm{e}} + E^{\mathrm{a}} \tag{4}$$

where $E_{\mathrm{t}x}^{\mathrm{e}}$ represents the energy consumption of the transmitter electronics and E^{a} is the energy consumed by the transmit power amplifier. The energy $E_{\mathrm{t}x}^{\mathrm{e}}$ is consumed in the transmitter hardware, including the oscillator, frequency synthesizer, mixers, filters, baseband processor, etc. This energy is considered constant for specific hardware. The energy E^{a} is the transmitted energy and it has to compensate the attenuation due to propagation distance. If free-space propagation is considered, E^{a} can be modeled as

$$E^{\mathrm{a}} = e\, d^{\alpha} \tag{5}$$

where e is the received energy at the destination corresponding to γ, d is the distance over which data is being communicated, and α is the path loss exponent. The energy consumed at the receiver can be expressed as

$$E_{\mathrm{r}x} = E^{\mathrm{e}}_{\mathrm{r}x} \tag{6}$$

where $E^{\mathrm{e}}_{\mathrm{r}x}$ represents the energy consumption of the receiver electronics. Similar to $E^{\mathrm{e}}_{\mathrm{t}x}$, $E^{\mathrm{e}}_{\mathrm{r}x}$ is considered constant for specific hardware.

In the following analysis, we only consider the energy consumption corresponding to the CB transmission in WSNs and, thus, we neglect $E^{\mathrm{e}}_{\mathrm{t}x}$ and $E^{\mathrm{e}}_{\mathrm{r}x}$. The energy consumed in the power amplifier depends on the CB weights $w_r, r = 1, 2, \ldots, N$ assigned for sensor nodes $c_r, r = 1, 2, \ldots, N$. The transmitted power from each individual sensor node is $P^{\mathrm{a}}_r = w_r^2$. A time-slotted transmission is considered and sensor nodes transmit data to the BS/AP over time slot t of length T seconds. The energy consumed at the power amplifier, E^{a}, of a sensor node c_r during the tth time-slot for CB transmission is given by

$$E^{\mathrm{a}} = e^t_r = w_r^2 T = P^{\mathrm{a}}_r T, \quad r = 1, 2, \ldots, N. \tag{7}$$

3.2. Lifetime of a Cluster of Sensor Nodes

The network lifetime has many definitions in the literature. However, the common understanding of the network lifetime is the time period until the WSN stops performing its assigned tasks [12]. Particular definitions depend on the criteria according to which the network is recognized as not functional.

In the context of WSNs, where a cluster of collaborative nodes utilizes CB for transmission, two main tasks should be performed in order for the network to be functional. First, sensor nodes are required to collect information from the surrounding environment. Second, sensor nodes are required to communicate the collected information to the BS/AP using CB. Thus, we define the lifetime of a cluster of collaborative sensor nodes, denoted hereafter as T_0, as the time period during which the number of sensor nodes alive is larger than a certain value and the collaborative sensor nodes are able to achieve acceptable SNR at the targeted BS/AP.

3.3. Power Control Strategy

In this subsection, we propose a simple power control scheme for CB aiming at balancing the lifetimes of individual sensor nodes to maximize the lifetime of a cluster of collaborative nodes. Power control for CB should achieve the following purposes:

- CB weights should balance the lifetime of individual sensor nodes instead of equalizing the energy consumed for individual CB transmissions.
- It should be guaranteed that the received SNR, γ, at the BS/AP achieves a predetermined average value $\bar{\gamma} \triangleq E\{\gamma\}$ over the lifetime.

To achieve the aforementioned requirements, power control can be performed in two steps. Namely, the first step is to calculate a normalized CB weights based on the REI at each sensor node to balance the lifetime of individual sensor nodes. The second step is to find a scaling factor, i.e., maximum CB weight, to achieve the required average SNR, $\bar{\gamma}$, at the targeted BS/AP.

Let the vector $\boldsymbol{u} = [u_1, u_2, \ldots, u_N]^T \in [0, 1]^N$ stands for the normalized CB weight vector and $w_{\max}$ is the maximum CB weight. Then, the CB weight vector is $\boldsymbol{w} = [w_1, w_2, \ldots, w_N]^T \in [0, w_{\max}]^N$, where $w_r = w_{\max} u_r$, $r = 1, 2, \ldots, N$. Also, let us introduce the vector $\boldsymbol{e} = [e_1, e_2, \ldots, e_N]^T \in [0, E_{\max}]^N$ as the REI vector, where $E_{\max}$ is the battery capacity.

To find the normalized CB weights, $\boldsymbol{u}$, assume that each sensor node can measure its own REI e_r. The normalized CB weight vector is designed to balance the lifetime of different sensor nodes so that larger CB weights are assigned to sensor nodes with larger REIs. A simple choice to the normalized CB weights can be expressed as

$$u_r = \frac{e_r}{E_{\max}}, \quad r = 1, 2, \ldots, N. \tag{8}$$

The scaling factor $w_{\max}$ corresponding to $\boldsymbol{u}$ is used to adjust the average received SNR at the BS/AP. The average SNR, $\bar{\gamma}$, at the targeted BS/AP, $\mathcal{D}$, can be then found as

$$\begin{aligned}\bar{\gamma} &= E\{\gamma\} = \frac{E\left\{\left|z \sum_{r=1}^{N} w_r a_r\right|^2\right\}}{\sigma_w^2} \\ &= \frac{w_{\max}^2 N \sigma_u^2 \sigma_a^2 + N(N-1) w_{\max}^2 m_u^2 m_a^2}{\sigma_w^2}\end{aligned} \tag{9}$$

where m_u, σ_u^2, m_a, and σ_a^2 are the mean and variance of the normalized CB weights and the mean and variance of the corresponding channel gains, respectively. Then, the maximum transmission CB weight corresponding to the average SNR (9) at the targeted BS/AP, $\mathcal{D}$, can be expressed as

$$w_{\max} = \sqrt{\frac{\bar{\gamma}\sigma_w^2}{N\sigma_u^2\sigma_a^2 + N(N-1)m_u^2 m_a^2}}. \tag{10}$$

The mean and variance of the normalized CB weights can be found from the mean m_e and variance σ_e^2 of the REI as

$$m_u = \frac{m_e}{E_{\max}}, \quad \sigma_u^2 = \frac{\sigma_e^2}{E_{\max}^2} \tag{11}$$

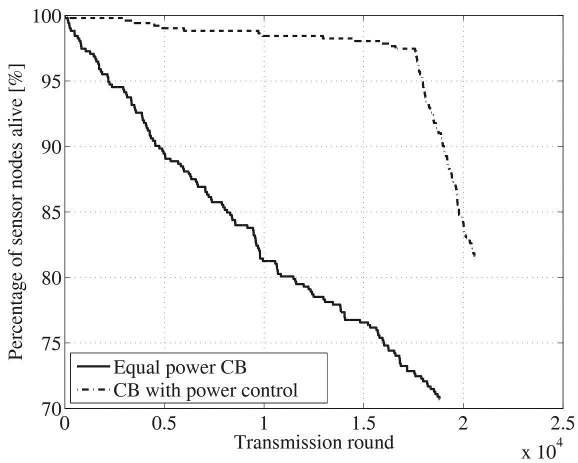

Fig. 2. Percentage of sensor nodes alive versus time.

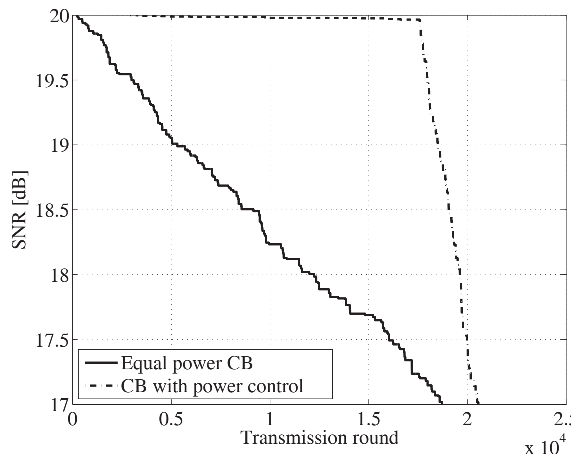

Fig. 3. Received SNR, γ, at the targeted BS/AP versus time.

where m_e and σ_e^2 can be obtained through consensus or distributed estimation algorithms. Note that the number of sensor nodes N in the cluster should be large enough to achieve the required SNR with $w_{\max} \leq W_{\max}$, where W_{max}^2 corresponds to the maximum transmitted power given by the specifications of the sensor node transmitter.

Let e_r^0 be the initial energy budget dedicated to CB at each sensor node $c_r, r = 1, 2, \ldots, N$. Then the residual energy at the sensor node c_r at the end of the t_0th transmission round is

$$e_r^{t_0} = e_r^0 - \sum_{t=1}^{t_0} e_r^t. \quad (12)$$

The residual energy at the sensor node c_r when the cluster of sensor nodes dies, denoted as e_r^w, is given by

$$e_r^w = e_r^{T_0} = e_r^0 - \sum_{t=1}^{T_0} e_r^t. \quad (13)$$

Finally, the wasted energy is defined as the total unused energy in the cluster of sensor nodes when it dies and it is given by

$$e_w = \sum_{r=1}^{N} e_r^w. \quad (14)$$

4. SIMULATION RESULTS

In this section, numerical simulations are used to illustrate the effect of CB with power control on the lifetime of a cluster of sensor nodes. We consider a cluster of uniformly distributed sensor nodes over a disk with radius $R = 2\lambda$. The BS/AP is located at the direction $\varphi_D = 0^o$. The total number of collaborative nodes in the cluster is $N = 256$ and the required average SNR, $\bar{\gamma}$, at the BS/AP is set to 20 dB. The energies assigned to CB at different sensor nodes are assumed to be uniformly distributed between 0 and $E_{\max}$, however, other distributions can also be used. The maximum energy available at each sensor nodes, $E_{\max}$, is set to 2 J and thus $m_e = 1$ J.

Equal power CB weights are used as the benchmark for comparison. In this case, the CB weights can be found as

$$w_r = \sqrt{\frac{\bar{\gamma}\sigma_w^2}{N\sigma_a^2 + N(N-1)m_a^2}}, \quad r = 1, 2, \ldots, N. \quad (15)$$

Practically, sensor nodes transmit with discrete transmit power levels, thus, the CB weights are quantized into 8 levels in the simulations. The cluster of sensor nodes is considered dead when more than 90% of the sensor nodes deplete energy or the achieved SNR at the targeted BS/AP with CB reduces by 3 dB below the nominal average value.

Fig. 2 shows the percentage of sensor nodes alive versus time for both cases of equal power CB and CB with power control. As expected, the percentage of sensor nodes alive decay linearly with time in the case of equal power CB because the initial energies at sensor nodes are not equal. In the case of CB with power control, the percentage of sensor nodes alive is almost constant at the beginning and then drops abruptly.

Fig. 3 shows the received SNR at the BS/AP versus time. The SNR demonstrates similar behavior as the percentage of sensor nodes alive. For equal power CB, SNR decays linearly because the sensor nodes deplete energy linearly with time as well, while, for CB with power control, SNR is stable over the network lifetime and then drops sharply because of the the drop in the percentage of sensor nodes alive.

Fig. 4 shows the total available energy at all sensor nodes versus time. The cluster starts with total initial energy of 256 J. Then the energy decreases linearly for both cases of equal power CB and CB with power control. However, the decay rate is higher for the case of CB with power control and

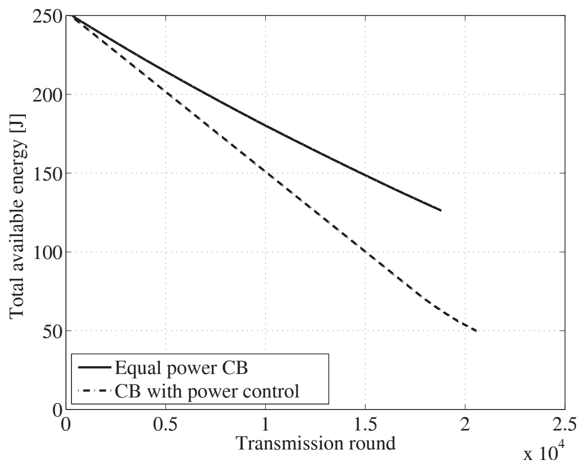

Fig. 4. Total available energy at all sensor nodes versus time.

this results in less wasted energy e_w when the cluster dies. It clearly demonstrates the advantages of using CB power control strategy based on which sensor nodes manage to use most of the cluster energy. In the case of equal power CB, most of the sensor nodes die or unable to achieve acceptable SNR when still about 50% of cluster initial energy is not used, while only 20% of initial cluster energy is not used when the cluster dies if the proposed CB power control is employed.

5. CONCLUSIONS

Energy consumption in a cluster of sensor nodes due to CB transmission has been addressed. In particular, we have presented an energy model with focus on energy dissipated at the power amplifier due to CB transmission. Power control for CB is introduced as a PHY layer solution to maximize the lifetime of a cluster of sensor nodes. A proposed strategy for power control requires only the REI and the statistics of both the channel gains and the energy available at the cluster. Although the proposed strategy is simple, simulation results illustrate very significant improvements of the cluster lifetime due to the CB power control. The proposed algorithm does not guarantee globally optimum CB power control, however, it achieves excellent results with low implementation complexity which is suitable for WSNs. More sophisticated power control strategies are expected to be able to improve the lifetime even further at the expense of the implementation complexity.

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