RESIDUAL ENERGY-AWARE COLLABORATIVE TRANSMISSION BEAMFORMING IN WIRELESS SENSOR NETWORKS

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ABSTRACT

Energy-Efficient transmission techniques are very important for extending the lifetime of a wireless sensor network (WSN) given that recharging batteries of a large number of WSN nodes is a very difficult and expensive operation. Collaborative transmission beamforming (CTB) saves energy consumed by each node by distributing between different WSN nodes the required total power transmission to get a desired bit error rate (BER) at the receiver. Moreover, by coherently combining the different signals transmitted by the WSN nodes, CTB increases the signal strength in the direction of the receiver, therefore decreases the total power transmission of the WSN.

In this paper, we propose a new CTB technique that minimizes the total power transmission of the WSN while balancing the residual energy in different nodes. By solving this multi-objective optimization problem, we show that the WSN lifetime can be improved up to 30 % compared to the basic CTB algorithm, which aims at minimizing the total power transmission without taking into account the residual energy.

1. INTRODUCTION

Wireless sensor networks (WSNs) offer a great potential for data collection applications such as military surveillance, environmental monitoring and so on [1]. Most of time, the nodes are deployed close to each other but far away from the base station (BS), where the collected data are to be analyzed [2]. In a military application for instance, sensor nodes can be deployed in enemy territories and the BS placed a in friendly military base that is located some miles away. In this kind of scenario, high transmission directivity is desirable to reduce the power transmission of each individual node and also increase security. However, since recharging a large number of nodes in such scenario is a very difficult operation and even dangerous, energy conservation in WSN is crucial in extending the lifetime of energy-constrained WSN [1, 2, 3].

Collaborative transmission beamforming (CTB) [2, 4], also known in the literature as distributed transmit beamforming (DTB) [5, 1], is an energy-efficient technique that adjusts the phases and amplitudes of electromagnetic (EM) waves transmitted by different WSN nodes so that they create constructive interferences at the receiver. This increases the signal strength in the targeted direction, which reduces the total power transmission required to get a given bit error rate (BER). The basic CTB scheme consists of minimizing the total power transmission in the WSN without taking into account the residual energy in each node [3]. However, the lifetime of a WSN using this scheme would be very short since nodes with very good channel conditions would tend to contribute more than other nodes with poor channel conditions. This is because the good nodes are expected to use less transmission power than the poor nodes [3]. As a consequence, nodes with good channel conditions will run out of their battery power more quickly. As a result the number of cooperative nodes will decrease and cause an increase of the aggregate transmission power, which again cause the remaining good nodes to run out of battery power quickly and so on ... [3]. Recently, [2] has proposed an algorithm to schedule the participating nodes in each round of transmission based on the residual energy in each node. Even though the proposed scheme allows to extend the lifetime of a WSN, selecting the subset of nodes implies an exhaustive search in all possible subsets before each transmission period. This operation becomes very complex as the number of nodes increases.

In this paper, we present an alternative CTB scheme that also takes into account the residual energy in each node. Firstly, we demonstrate that minimizing the total power transmission of a WSN (by maximizing the CTB gain) while balancing the residual energy over different WSN nodes yields a conflicting multi-objective optimization problem. Secondly, we propose a single objective function that is a good compromise between the two conflicting objectives. The performance of the proposed residual energy aware CTB is evaluated by computing the WSN lifetime in terms of the number of packets transmitted from the WSN to the BS before the former runs out of energy.

The reminder of this paper is organized as follows. In Section 2, we first present our system moded and then derive power and energy consumption models at node level taking into account the CTB. In Section 3, we analyze and propose a solution to the multi-objective optimization problem associated with the residual energy-aware. Then, in Section 4 we evaluate the performances of the proposed technique relative to the basic CTB scheme described above. Finally, we present our conclusions in Section 5.

In the sequel, we use roman letters to represent scalars (x), single underlined letters to denote column vectors ($\underline{x}$) and double underlined letters to represent matrices ($\underline{\underline{X}}$).

2. SYSTEM MODEL

Figure 1 shows a simplified model representing a wireless communication between an outdoor WSN and a distant BS. On the one hand, the WSN is composed by n_T solar powered nodes, each having a single omni-directional antenna. On the other hand, the BS has a directional radiation pat-

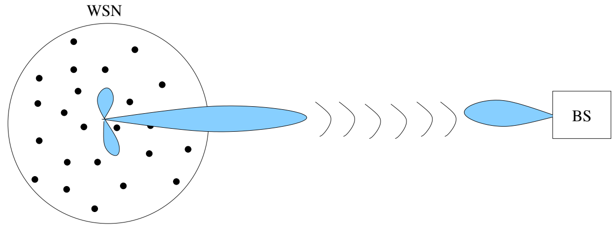

Figure 1: System model of a long haul communication from an energy-constrained WSN to a base station (BS).

tern, obtained either with a single directional antenna or a multi-antenna array. The BS is assumed to be continuously connected to a power source. Moreover, we assume that the distance from the monitored area to the BS is very large such that the signal transmitted by an individual node cannot reach the BS. This motivates the use of CTB in the WSN in order to get a higher signal strength in the direction of the BS. In this study, we assume that all WSN nodes have the same information before sending it to the BS. This may be achieved by using existing protocols such as [6].

In the following, we use the following denotations:

- $h_i[k]$ represents the flat fading channel between the i^{th} node and the BS during the k^{th} transmission period. The resulting multiple input single output (MISO) fading channel between the WSN and the BS is denoted by $\underline{h}[k] := \left[h_1[k], h_2[k], \ldots, h_{n_T}[k]\right]^T$.
- $v^i[k]$ is the CTB weight applied by the i^th sensor during the k^{th} transmission period. The resulting CTB weight vector at the network level is denoted by $\underline{v}[k] := \left[v^1[k], v^2[k], \ldots, v^{n_T}[k]\right]^T$. The latter is normalized to unity ($\left|\underline{v}[k]\right|^2 = 1$) in order to keep the total power consumption unchanged when the CTB is applied.

In this context, the resulting CTB gain is equal to

$$\beta\left(\underline{v}[k]\right) = \left|\underline{v}^H[k]\underline{h}[k]\right|^2. \tag{1}$$

According to [7], the power consumption of a WSN can be divided into two main components: the power consumption of all node's power amplifiers (PA) P_{PA} and the power consumption of all other circuit blocks P_c such as the Digital-to-Analog Converter (DAC), mixer, active filters, etc ...

The first term P_{PA} depends on the CTB gain during a given transmission period. This dependency is explained as follows. Firstly, the P_{PA} is a function of the total transmit (TX) power $P_{out,WSN}$ which, according to [7], is given by

$$P_{out,WSN}[k] = \overline{E}_b R_b \times \frac{(4\pi d)^2}{G_{WSN}[k] G_{BS} \lambda^2} M_l N_f, \tag{2}$$

where $\overline{E}_b$ is the required energy per bit at the BS for a given bit error rate (BER) requirement, R_b is the bit rate, d is the transmission distance, $G_{WSN}[k]$ is the WSN array gain and is equal to $\beta\left(\underline{v}[k]\right)$, G_{BS} is the BS antenna gain, λ is the carrier wavelength, M_l is the link margin compensating the hardware process variations and other additive background noise or interference and N_f is the BS noise figure defined as $N_f = N_r/N_0$ with N_0 = -171 dBm/Hz the single-sided thermal noise power spectral density (PSD) at room temperature and N_r is the PSD of the total effective noise at the BS input. Secondly, thanks to CTB the total transmit power is spread over different TX nodes. Therefore, the TX power of the i^{th} node P_i is given by

$$P_{out,i}[k] = \left|v^i[k]\right|^2 P_{out,WSN}[k], \tag{3}$$

with $\left|v^i[k]\right|^2 << 1\ \forall i$ for large size WSN. The resulting PA power consumption $P_{PA,i}$ can be approximated as [8]

$$P_{PA,i}[k] = P_{out,i}[k]/\eta, \tag{4}$$

with η denoting the drain efficiency of the PA.

Regarding the second term P_c that gathers the energy consumption of other blocks excluding the PA, this term is independent of the CTB gain and thus stays constant for different packet transmission periods. For the sake of readability, we therefore omit this term in the mathematical derivations presented in the sequel.

At this point, considering a fixed bit rate communication, the PA energy consumption at the i^{th} node for transmitting one packet $E_{pt,i}[k]$ can be obtained as

$$E_{pt,i}[k] = N_b P_{PA,i}[k]/R_b. \tag{5}$$

where N_b is the number of bits in one packet.

Replacing successively (4), (3) and (2) in (5), the expression of the PA energy consumption can be formulated as

$$E_{pt,i}[k] = \frac{\left|v^i[k]\right|^2}{\beta\left(\underline{v}[k]\right)} \times E_{SISO}, \tag{6}$$

in which the first product term varies during each transmission period while the second product term, which is actually the average PA energy consumption in the case of a single TX node, is given by

$$E_{SISO} = \frac{N_b \overline{E}_b}{\eta} \frac{(4\pi d)^2}{G_{BS}\lambda^2} M_l N_f \tag{7}$$

and remains constant during different transmission periods.

Finally, the residual energy at the i^{th} node after the transmission of the k^{th} packet, which is denoted by $E_{res,i}[k]$, can be easily calculated by

$$E_{res,i}[k] = E_{res,i}[k-1] - E_{pt,i}[k]. \tag{8}$$

In the following, we introduce the residual energy-aware collaborative transmission beamforming as a multi-objective optimization problem.

3. RESIDUAL ENERGY-AWARE COLLABORATIVE BEAMFORMING: A MULTI-OBJECTIVE OPTIMIZATION PROBLEM

In this section, we first demonstrate that minimizing the total power transmission of a WSN (meaning maximizing the CTB gain) on the one hand and balancing the residual energy over different WSN nodes on the other hand are two conflicting objectives. Next, we propose a single objective function that is a good compromise between the two considered objectives.

3.1 Minimize the total power transmission of a WSN

The total power transmission of a WSN is minimized by maximizing the CTB gain, which means maximizing the signal strength in the direction of the BS. The corresponding objective function is formulated as

$$f_1 = \max_{\underline{v}[k]} \underline{v}^H[k]\underline{\underline{R}}_h[k]\underline{v}[k], \tag{9}$$

where $\underline{\underline{R}}_h[k] = \underline{h}[k]\underline{h}^H[k]$ is the channel correlation matrix during the k^{th} transmission period.

3.2 Balancing the residual energy over different WSN nodes

An optimization problem which objective is to keep a well balanced energy reserve within the WSN can be interpreted as *minimizing the variance of the residual energy in the WSN nodes*.

Using (8), the residual energy variance in the WSN after the k^{th} transmission period $\sigma^2_{E_{res}}[k]$ is given by

$$\sigma^2_{E_{res}}[k] = \frac{1}{n_T}\sum_{i=1}^{n_T}\left(E_{res,i}[k] - \overline{E}_{res}[k]\right)^2, \tag{10}$$

with $\overline{E}_{res}[k]$ denoting the mean of the residual energy in the WSN at that time period and given by

$$\overline{E}_{res}[k] = \frac{1}{n_T}\sum_{i=1}^{n_T} E_{res,i}[k]. \tag{11}$$

Substituting successively (8) and (6) in (10) and after several mathematical rearrangements (cfr the appendix for interested readers), the residual energy variance in the WSN can be approximated by

$$\begin{aligned}\sigma^2_{E_{res}}[k] \approx{} & \sigma^2_{E_{res}}[k-1] \\ & - 2\frac{E_{SISO}}{n_T} \times \frac{\underline{v}^H[k]\underline{\underline{E}}_{res}[k-1]\underline{v}[k]}{\underline{v}^H[k]\underline{\underline{R}}_h[k]\underline{v}[k]} \\ & + 2\frac{E_{SISO}\overline{E}_{res}[k-1]}{n_T} \times \frac{1}{\underline{v}^H[k]\underline{\underline{R}}_h[k]\underline{v}[k]},\end{aligned} \tag{12}$$

where $\underline{\underline{E}}_{res}[k-1]$ is a diagonal matrix of size n_T containing the residual energy of different WSN nodes on its diagonal before the k^{th} transmission period.

By analyzing (12), it is clear that the residual energy variance decreases as the second term increases since this term is the only one with a negative sign in (12). From this observation, an objective function that minimizes the residual energy variance in the WSN can be formulated as

$$f_2 = \max_{\underline{v}[k]} \frac{\underline{v}^H[k]\underline{\underline{E}}_{res}\underline{v}[k]}{\underline{v}^H[k]\underline{\underline{R}}_h[k]\underline{v}[k]}. \tag{13}$$

3.3 Formulation of a new objective function

By analyzing the two maximizing objective functions defined in (9) and in (13), one unfortunately notes that maximizing one implies minimizing the other one and vice versa.

In order to make a good compromise between the two conflicting objective functions, we have intuitively created the following single objective function

$$\tilde{f} = \max_{\underline{v}[k]} \underline{v}^H[k]\underline{\underline{\Omega}}[k]\underline{v}[k]. \tag{14}$$

with $\underline{\underline{\Omega}}[k] = \underline{\underline{E}}_{res}[k]\underline{\underline{R}}_h[k]$.

The function (14) is maximized by choosing the CTB weight vector $\underline{v}[k]$ to be the first eigenvector of $\underline{\underline{\Omega}}[k]$.

In the following, we evaluate using MATLAB simulations the performance of the proposed CTB technique relative to the existing CTB algorithm, which simply minimizes the total power transmission of a WSN without taking into account the residual energy in each WSN node.

4. PERFORMANCE ANALYSIS

4.1 Simulation parameters

We consider a WSN with 100 nodes monitoring an area located far away from the BS. During daytime, the WSN nodes are powered by solar ambient energy. In the same time, the energy storage devices of different WSN nodes are recharged in the provision of the nighttime operation.

4.1.1 Technical specifications of the RF module embedded in each wireless node

We assume that each wireless node is equipped with the CC2420 radio frequency (RF) module developed by Texas Instrument [9]. Table 1 summarizes the physical layer (PHY) features of this module used in this study.

Table 1: Considered PHY features of the RF module CC2420 [9]

Data rate	R_b	250 kbps
Bandwidth	W	5 MHz
Carrier frequency	f_c	2.45 GHz
Modulation scheme	-	O-QPSK
Link margin	M_l	40 dB
Receiver noise figure	N_f	10 dB
Packet size	N_b	128 bytes

In order to compute the power consumption of CC2420 for different TX power levels, we have used the relationship between the drain efficiency of CC2420 and its TX power as represented in the Fig.4.2 from [8]. In that paper, it is shown that the drain efficiency η of CC2420 varies from 0.007 to 0.037 as the TX power goes from 0 mW to 1 mW.

4.1.2 Propagation channel between the WSN and the BS

In order to study the long haul communication scenario, we consider a distance of 1 km between the WSN and the BS. According to the datasheet [9], one CC2420 can actually transmit up to a distance of 300 m.

Furthermore, we model the channel fading effect between each WSN node and the BS using the classical frequency flat Rayleigh model. Let us mention that for the considered distance, the pathloss exponent is typically equal to 2.

4.1.3 Input energy figures

In our simulation, we have targeted a BER of 10^3 at the BS. For offset quadrature phase shift keying (O-QPSK) modulation schemes, this corresponds to an energy per bit noise ratio E_b/N_0 of 8 dB.

Assuming a BS with an antenna gain of 15 dB and taking into account the different parameters of CC2420 mentioned above, we have calculated E_{SISO} using (7). We have found that in the considered scenarion E_{SISO} is equal to 0.72 J.

Finally, we have assumed that the initial energy reserve of different WSN nodes at sunset is uniformly distributed between 0 and $E_{max} = 1$ J.

4.2 Performance results

The performance of the proposed residual energy aware CTB has been evaluated by computing the WSN lifetime in terms of the number of packets transmitted to the BS before the WSN runs out of energy. The results of our simulations are analyzed by considering the evolution over time of four WSN's parameters namely the number of active nodes participating in the CTB (Figure 2), the CTB gain (Figure 3), the total energy consumption (Figure 4) and the residual energy variance (Figure 5). Solid and dashed lines represent the results for the proposed residual energy aware CTB and the basic CTB schemes respectively.

We have found that the proposed CTB scheme can transmit up to 760 packets while the basic CTB scheme was only able to send 570 packets. The problem of the existing scheme is that nodes with very good channel conditions tend to contribute more than other nodes with poor channel conditions, since the good nodes are expected to use less transmission power than the poor nodes. Thus, nodes with good channel conditions will run out of their battery power more quickly. As a consequence, the number of nodes that participate in the CTB will decrease (Figure 2), which causes a diminuation of the CTB gain (Figure 3) therefore an increase of the aggregate transmission power (Figure 4). The proposed scheme however tends to balance the residual energy in different WSN nodes (Figure 5), therefore allowing all WSN nodes to participate in the transmission of all packets (Figure 2). This keeps the aggregate transmission power almost constant during the complete WSN lifetime (Figure 4). Let us mention that compared to the existing CTB scheme, the proposed scheme requires the knowledge of the residual energy in each node before each transmission. In [10], a low complexity mechanism for collecting periodically the residual energy information in different WSN nodes has been proposed.

5. CONCLUSION

In this paper, we have analyzed the problem of extending the lifetime of a WSN by using collaborative transmission beamforming (CTB) techniques. We have proposed a CTB scheme that takes into account the residual energy in different WSN nodes. We have shown that this problem involves a multi-objective optimization. We have proposed a single objective function that makes a good compromise between on the one hand minimizing the total PA power consumption in a WSN by maximizing the CTB gain and on the other hand balancing the residual energy over different WSN nodes. Simulation results show that by using the proposed scheme the number of packets transmitted from a WSN to

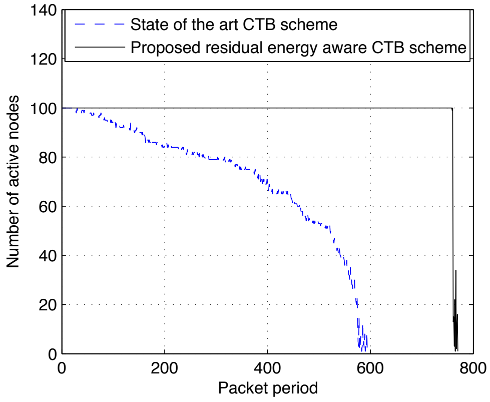

Figure 2: Evolution over time of the number of active nodes until the WSN is completely energy exhausted.

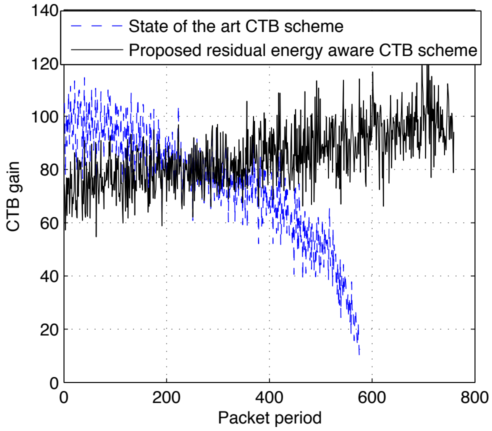

Figure 3: Evolution over time of the CTB gain until the WSN is completely energy exhausted.

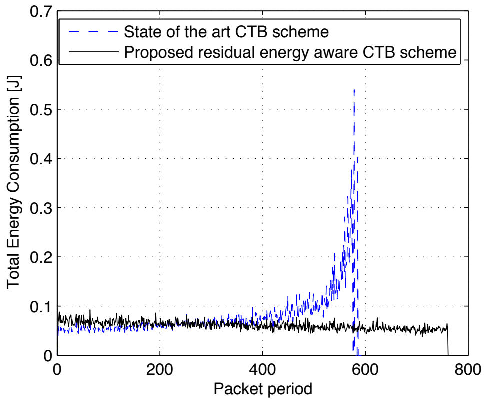

Figure 4: Evolution over time of the total energy consumption until the WSN is completely energy exhausted.

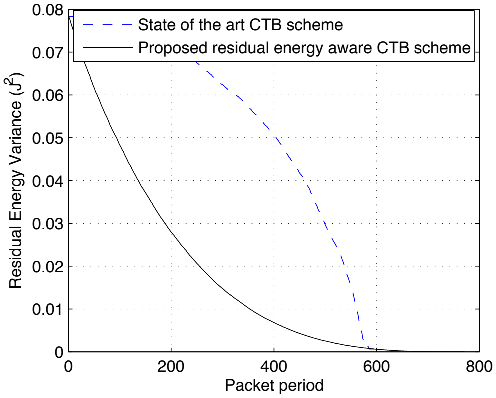

Figure 5: Evolution over time of the residual energy variance until the WSN is completely energy exhausted.

a distant BS can be increased by 30 % relative to existing schemes.

appendix

In this appendix, we derive a quadratic expression of the residual energy variance in the WSN as a function of the CTB vector $\underline{v}[k]$.

Let us start by substituting (8) and (6) in (11). Therefore, the mean of residual energies in the WSN can be rewritten as

$$\begin{aligned}\overline{E}_{res}[k] &= \frac{1}{n_T}\sum_{i=1}^{n_T}\left(E_{res,i}[k-1]-E_{pt,i}[k]\right)\\ &= \overline{E}_{res}[k-1]-\frac{E_{SISO}}{n_T\beta\left(\underline{v}[k]\right)}.\end{aligned} \tag{15}$$

Next, substituting (15) and (8) in (10) and after some simple mathematical manipulations, we get

$$\begin{aligned}\sigma^2_{E_{res}}[k] &= \sigma^2_{E_{res}}[k-1]\\ &\quad -\frac{2E_{SISO}}{n_T}\sum_{i=1}^{n_T}E_{res,i}[k-1]\frac{\left|v_i[k]\right|^2-1/n_T}{\beta\left(\underline{v}[k]\right)}\\ &\quad +\frac{2E_{SISO}\overline{E}_{res}[k-1]}{n_T}\sum_{i=1}^{n_T}\frac{\left|v_i[k]\right|^2-1/n_T}{\beta\left(\underline{v}[k]\right)}\\ &\quad +\frac{\left(E_{SISO}\right)^2}{n_T}\sum_{i=1}^{n_T}\left(\frac{\left|v_i[k]\right|^2-1/n_T}{\beta\left(\underline{v}[k]\right)}\right)^2\end{aligned} \tag{16}$$

Considering WSN with a very large number of nodes $n_T >> 1$, we have observed via simulation that the fourth term in (16) is negligible relative to the other terms. Adopting a vector notation, the residual energy variance in the WSN can be approximated by

$$\begin{aligned}\sigma^2_{E_{res}}[k] \approx& \sigma^2_{E_{res}}[k-1]\\ &-2\frac{E_{SISO}}{n_T}\times\frac{\underline{v}^H[k]\underline{\underline{E}}_{res}[k-1]\underline{v}[k]}{\underline{v}^H[k]\underline{\underline{R}}_h[k]\underline{v}[k]}\\ &+2\frac{E_{SISO}\overline{E}_{res}[k-1]}{n_T}\times\frac{1}{\underline{v}^H[k]\underline{\underline{R}}_h[k]\underline{v}[k]},\end{aligned} \tag{17}$$

where $\underline{\underline{E}}_{res}[k-1]$ is a diagonal matrix of size n_T containing the residual energy of different WSN nodes on its diagonal before the k^{th} transmission period.

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