Energy Efficient Collaborative Beamforming in Wireless Sensor Networks

Jing Feng, Yung-Hsiang Lu, Byunghoo Jung, and Dimitrios Peroulis
School of Electrical and Computer Engineering, Purdue University, West Lafayette, Indiana 47906, USA

***Abstract*— Reducing energy consumption is critical for wireless sensor networks. The dominant factor is the energy for data transmission. Collaborative beamforming can save transmission energy by improving the directivity of electromagnetic waves so that the signal at the receiver is stronger. Compared with a single transmitter, collaborative beamforming spreads the long distance transmission energy over multiple transmitters. This balances the battery lifetime on individual nodes because each transmitter can use lower power. However, beamforming depends on proper coordination of phases among the participating sensor nodes. This requires communication among the sensor nodes and consumes energy. This paper investigates whether the transmission energy can be saved by using beamforming based on the number of nodes and the total size of data needed to transmit. We determine the minimum size of data to balance the communication overhead when given the total number of nodes.**

I. Introduction

Wireless sensor networks [4], [6], [9] provide great potential for studying environment and military surveillance. One critical issue is to conserve energy. A major energy consumer is the wireless network interface. Many studies have been devoted to reducing energy consumed for wireless communication, for example, using energy-efficient routing algorithms [8], [11]. In some applications, the sensors are deployed close to each other but far away from the receiver (base station), where the data are collected and analyzed. For example, sensors deployed in a forest may have to transmit data to a weather station miles away. For military applications, the sensor nodes may be deployed in enemy territories and the receiver is in a friendly military base or a satellite. For these applications, it is desirable to have high directivity in transmission for better energy efficiency and security. Previous studies [1], [2], [7], [10] show that collaborative beamforming can be used in sensor networks to improve the directivity of electromagnetic waves; signals are stronger at the receiver and weaker in other directions. Energy consumed for long distance transmission is spread over multiple transmitters. Thus, collaborative beamforming can save energy on individual transmitters because each transmitter can send the signals at lower power.

Collaborative beamforming is achieved by adjusting the phases of electromagnetic waves so that they create constructive interferences at the receiver. Several approaches have been proposed to control the phases of the transmitters. One approach requires accurate knowledge of the transmitters' locations relative to the receiver; it is also necessary to synchronize the transmitters' clocks. This approach does not need feedback from the receiver. Another method requires the receiver's feedback. The transmitters randomly adjust their phases and the receiver informs the transmitters of the signal strength. Bucklew et al. [2] show convergence after several thousand iterations for ten transmitters. Even though beamforming has the potential benefits of saving energy, no existing study has been devoted to the analysis of the energy overhead *before* beamforming.

Collaborative beamforming can be adopted for three reasons: (1) To minimize sensor black-out spots. Transmission energy on individual transmitters is balanced and saved over multiple transmitters. Each transmitter can use a lower power level and the directive electromagnetic waves can reach the receiver at the desired signal strength. This prevents some of the nodes from running out of energy much faster than the others. (2) To reach a receiver too far for an individual transmitter. If the receiver is beyond the range of a single transmitter, beamforming allows signals to travel farther. (3) To improve data security. Beamforming reduces or completely eliminates signals at undesired directions. This paper uses *sensor nodes* and *transmitters* interchangeably.

There is a crucial question in beamforming: *"If there are s sensor nodes, does beamforming save energy for transmitting d bytes to the receiver?"* This paper analyzes the energy consumption for creating collaborative beamforming using a random walk algorithm and the conditions when beamforming can save energy. We propose to relax the convergence requirement so that transmitters can determine their phases an order-of-magnitude faster and save energy in pre-beamforming preparation. We compute the energy overhead in this preparation period and compare it with the energy savings from beamforming. Our analysis shows that the number of nodes and the amount of data are two critical factors for determining whether beamforming can save energy.

II. Related work

A. Synchronization and Localization

To achieve efficient beamforming, the transmitters have to coordinate their phases with high accuracy. The accuracy is measured by the wireless carrier's frequency and wavelength. To achieve $\pi/6$ accuracy of a 900 MHz carrier, the transmitters' clocks must be synchronized within 0.1 ns and the location error cannot exceed 2.8 cm. The requirement is unreachable by existing software-based synchronization or localization algorithms [7]. Mudumbai et al. [7] propose to use hardware to synchronize the carrier frequency. This requirement can be relaxed by using a lower carrier frequency. For example, if

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the carrier frequency is 28 MHz, the required synchronization accuracy is 3 ns and the localization accuracy is 89 cm. At this frequency, the wavelength is 11 m. An efficient antenna's length has to be comparable to the wavelength so that further reducing the carrier's frequency may be impractical.

B. Receiver Feedback

Beamforming adjusts signals' phases to form constructive interference at the receiver. Feedback control convergence [2] examines the sum of the electromagnetic waves at the receiver without synchronizing or localizing the transmitters. Suppose there are s stationary transmitters and one receiver. Let $\phi_{i,j} \in (-\pi, \pi]$ be the phase of the carrier signal from transmitter i at iteration j, $1 \le i \le s$. At each iteration, each transmitter randomly shifts the phase by a small amount $\mu\gamma_{i,j}$. Here μ is the step size and $\gamma_{i,j}$ is a random variable of normal distribution with zero mean and variance of 2. At each iteration, the i^{th} transmitter sends the same data (i.e. same electromagnetic waveforms) with 2 different carrier phases. In the first iteration, each transmitter sends with phase $\phi_{i,j}$ and followed by phase $\phi_{i,j} + \mu\gamma_{i,j}$. The receiver sends feedback to all transmitters to inform them which signal is stronger. In the next iteration, $\phi_{i,j+1}$ is $\phi_{i,j} - \mu\gamma_{i,j}$ if the first is stronger or $\phi_{i,j} + \mu\gamma_{i,j}$ if the second is stronger [2]. Bucklew's method requires two transmissions and one reception at each sensor node in every iteration. After n iterations, each node has to transmit $2n$ times and receive n feedback. We suggest a simple improvement: the receiver remembers the strength of the stronger signal in every iteration. Starting from the second iteration, the receiver informs the transmitters whether the current signal is stronger than the previous signal. This can reduce the number of transmissions at each sensor node from $2n$ to $n+1$ times. The value of μ is chosen based on the accuracy in required phase differences and the total number of transmitters. Lager μ is chosen for smaller set of transmitters or less accuracy in phase differences; and vice versa.

C. Energy Model

Feeney et al. [3] model the energy for transmission and reception in wireless sensor networks. This paper uses the following two models, point-to-point send E_{tx} and broadcast receive E_{rx}:

$$\begin{aligned} E_{tx} &= 1.9 \cdot b + 420\mu J \\ E_{rx} &= 0.5 \cdot b + 56\mu J, \end{aligned} \tag{1}$$

here, b is the number of bytes in each data packet, including data and overhead. In this model, we do not consider propagation loss. This paper assumes that the transmitters use 25 bytes for pre-beamforming coordination; the feedback from the receiver is 18 bytes. Both include 16-byte preamble. After beamforming is ready, a packet has 36 bytes, a typical packet size for Mica2 [5], but the actual size depends on the applications.

This is the first paper to analyze the energy savings of wireless sensor networks using beamforming. This paper has the following contributions: (1) We demonstrate that beamforming may save energy even though the transmitters have large phase errors. (2) Adding transmitters requires more iterations to converge in pre-beamforming preparation. Meanwhile, each transmitter can use a lower power level. There is a trade-off between beamforming's efficiency and the energy needed to achieve the efficiency. (3) We show that whether beamforming can actually save energy depends on the amount of information to transmit (d) and the number of transmitters (s).

III. Collaborative Beamforming

This section first defines the problem of collaborative beamforming using receiver feedback. Section III-B improves [2] by relaxing the convergence requirements. Section III-C analyzes the energy overhead to prepare for beamforming and savings from beamforming. Section III-D analyzes the scenarios where energy can be saved.

A. Problem Description

There are s sensor nodes randomly deployed; each is capable of transmitting data at different phases and power levels. At the highest power level, a single transmitter can generate signals reachable at the receiver with the lowest acceptable signal-to-noise ratio. Beamforming is divided into two stages: preparation and operation, as explained in Section II-B. In the operation stage, the data are broadcast to all sensor nodes before being sent to the receiver using collaborative beamforming. We assume that the transmitters are close to each other and the receiver is sufficiently far away from the transmitters. Thus, the wave magnitudes are approximately the same at the receiver and the energy used for inter-transmitter communication is ignored. We assume that the preparation stage is a one-time overhead because the transmitters and the receiver are stationary and clock drifting is ignored. The question is whether beamforming can save energy if there are d bytes of data, including preamble, packet header, and payload.

Example: Suppose there are 5 sensor nodes. After 30 iterations, they achieve 80% *efficiency* of beamforming. In other words, when the 5 nodes send the data together, the signal strength at the receiver is 4 times higher. Thus, each node needs to transmit at only $1/4$th of the power level compared with transmitting using only one transmitter. In each iteration, each node consumes $1.9 \cdot 25 + 420 + 0.5 \cdot 18 + 56 = 532.5\mu J$. The energy overhead in preparation is $30 \cdot 532.5 + 1.9 \cdot 25 + 420 = 16442.5\mu J$.

Without beamforming, each sensor has to consume $1.9 \cdot 36 + 420\mu J$ per packet for $d/36$ packets. With beamforming each sensor consumes $(1.9 \cdot 36 + 420)/4 \cdot (d/36) + 16442.5\mu J$. For beamforming to save energy, the following condition must be true

$$\begin{aligned} &(1.9 \cdot 36 + 420) \cdot \frac{d}{36} > \frac{1.9 \cdot 36 + 420}{4} \cdot \frac{d}{36} + 16442.5 \\ &\Rightarrow \frac{3}{4}(1.9 \cdot 36 + 420) \cdot \frac{d}{36} > 16442.5 \\ &\Rightarrow d > 1616. \end{aligned} \tag{2}$$

If the sensor network transmits more than $\lceil 1616/36 \rceil = 45$ packets, beamforming saves energy.

B. Pre-Beamforming Preparation

In the ideal scenario, the phase difference is zero for waves arriving at the receiver to achieve 100% efficiency. *Efficiency* (e) is defined as the ratio of *achieved* signal strength and the

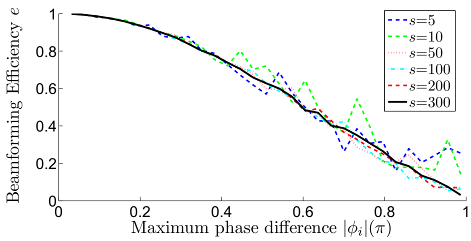

Fig. 1. Beamforming efficiency and the phase differences at the receiver for different numbers of transmitters. For a small s, large phase differences ($> 0.3\pi$) affect the beamforming efficiency significantly and cause instability. A larger s stabilizes beamforming.

highest possible signal strength. If there are 10 transmitters and the signal strength is 7 times higher, the efficiency is 70%. If the transmitters are allowed to have phase differences, the efficiency is lower but convergence is faster. Without loss of generality, we use the first transmitter's phase as the reference, $\phi_1 = 0$. Fig 1 shows the efficiency at different phases. The horizontal axis shows the largest allowed phase difference, namely $\max|\phi_a - \phi_1|$ for transmitter a and the first transmitter, $1 \le a \le s$. At $\pi/6$, all transmitters are allowed to have phase difference between $[-\pi/6, \pi/6]$. Within this interval, the phase difference is randomly distributed. At this phase difference, the efficiency is 95%. Efficiency can be computed using the following formula.

$$e = \frac{1}{s} \cdot \sum_{i=1}^{s} \cos(\omega t + \phi_i). \tag{3}$$

High efficiency provides high directivity in beamforming. This is because the received signals are constructed at the receiver and destructed in the other directions.

In [2], the authors set the step size μ to 0.0005, for $s = 10$ transmitters; after 30,000 iterations, the phase error at the receiver is nearly zero. Their method requires two transmissions and one reception per iteration and consumes $3 \cdot 10^4 \cdot (2 \cdot (1.9 \cdot 25 + 420) + 0.42 \cdot 18 + 56) = 29.96$J.

We relax the phase difference requirement for faster convergence. Beamforming can increase the received signal strength even when the phase differences are greater than zero. When the maximum phase difference is $\pi/3$, beamforming can achieve 70% efficiency, as shown in Fig 1 and the signal strength is $0.7s$ at the receiver. Since the goal is not zero phase difference, we can also enlarge the step size μ without causing instability. Convergence can be much faster with a larger phase difference and a larger step size. Fig 2(a) shows the convergence of the phase differences for 10 transmitters and $\mu =$ 0.05. After 70 iterations, the differences are within $\pi/3$. After 100 iterations, the differences are within $\pi/5$.

When there are more transmitters, beamforming may increase the signal strength. However, more iterations are needed to converge and achieve acceptable efficiency. Fig 2(b) shows the maximum phase differences for different numbers of transmitters (s). When there are more than 100 transmitters, the phase difference remain nearly unchanged after 200 iterations. Fig 2(c) shows the relationship between the efficiency and the number of iterations. As the two figures indicate, the phase differences remain high. Hence we have to decrease the step size even more when the number of sensor nodes (s) is large.

C. Energy Savings by Beamforming

After the preparation stage, the transmitters enter the operation stage and use beamforming to send data. Section III-A assumes that each transmitter has sufficient power to reach the receiver but beamforming allows the transmitters to reduce the power levels. Suppose p_m is the maximum power level for one transmitter. With beamforming, the signal strength increases by $s \cdot e$ times and each transmitter can use a lower power level $P_m/(s \cdot e)$. Let E_m be the energy that single sensor needs to transmit one byte at power P_m. With beamforming each transmitter needs to use only $E_m/(s \cdot e)$ for sending one byte. Suppose d is the number of bytes to send, the energy consumption for each node in the operation stage is

$$\begin{array}{ll} E_m \cdot d & \text{without beamforming} \\ E_m \cdot d \cdot \frac{1}{s \cdot e} & \text{with beamforming.} \end{array} \tag{4}$$

The energy saved by beamforming is

$$E_{\text{saving}} = E_m \cdot d(1 - \frac{1}{s \cdot e}). \tag{5}$$

Let E_p be the energy for pre-beamforming preparation. Beamforming can save energy if

$$E_m \cdot d > E_p + E_m \cdot d \frac{1}{s \cdot e} \tag{6}$$

$$d_{min} = \frac{E_p}{E_m \cdot \frac{1}{(1 - \frac{1}{s \cdot e})}}. \tag{7}$$

Here, d_{min} is the minimum data size required to transmit using beamforming to balance the preparation overhead.

D. Analysis

In this section, we demonstrate the relationship between the minimum size of transmitted data d_{min} and the total number of nodes s. Fig 3 and Fig 4 show the minimum size of data d_{min} needed to transmit for beamforming to save energy when the number of sensor nodes s is given. In Fig 3, the x-axis shows the number of transmitters and the y-axis shows the corresponding d_{min}; each line represents a selected beamforming efficiency. In Fig 4, the x-axis shows beamforming efficiency from 30% to 90% and each line means a different number of s, from 10 to 70. As we mentioned in section III-B, for a larger amount of transmitters we need to choose a smaller step size. Fig 3 and Fig 4 use $\mu = 0.04$ as the step size for converging the phase in pre-beamforming stage. This is because e=90% cannot be achieved by choosing $\mu = 0.05$ when $s > 60$.

We examine two scenarios: (1) With a required minimum beamforming efficiency, Fig 3 tells how many nodes are needed for transmitting d bytes of data. For efficiency lower than e=60%, d_{min} is approximately 4000 bytes. For the applications that require high beamforming efficiency (e=90%), the minimum data size increases to 13000 bytes for a group of 70 sensor nodes. This scenario may apply in military applications, for example, when the sensing area is close to the enemy territories, the security of the transmission is important, and

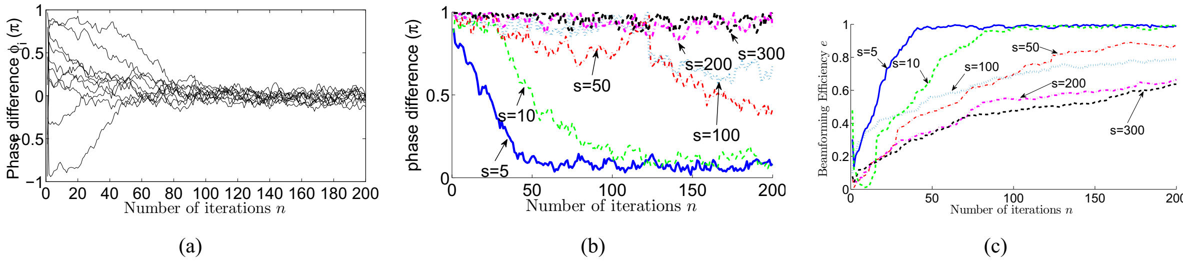

Fig. 2. (a) Phase differences (unit: π) converge faster by choosing a larger step size. Each line shows the phase difference between one transmitter and the first transmitter. (b) Maximum phase difference ($\max|\phi_a - \phi_1|$, $1 \leq a \leq s$) for different numbers of transmitters s. The unit for the vertical axis is π. (c) Beamforming efficiency after n iterations for different s.

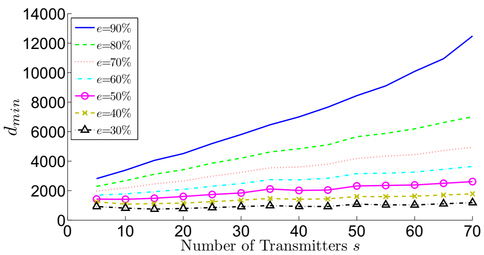

Fig. 3. Relationship between number of sensors s and minimum data size d_{min}. Each line represents different beamforming performance e. The data shown in this figure is the average of 10 convergence tests.

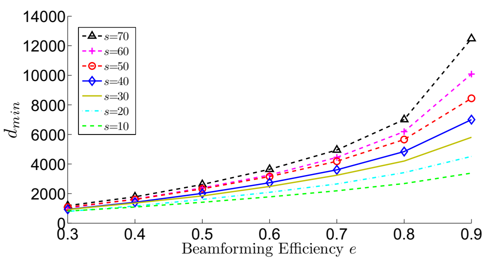

Fig. 4. Relationship between beamforming performance e and minimum data size d_{min}. Each line represents different number of sensors s. The data shown in this figure is the average of 10 convergence tests.

the transmission needs high directivity at the desired direction. This requires a high beamforming efficiency. The number of sensors can be decided by the size of the transmitted data. (2) Given the total number of nodes, Fig 4 indicates how the beamforming efficiency e affects the minimum data size d_{min}. For a fixed number of transmitters s, higher efficiency e requires more iterations in pre-beamforming preparation and a larger d_{min} to compensate this overhead. For a large number of s, the minimum amount of data required increases as e increases. For some applications, the efficiency is not required to be high, there is a trade off between e and d_{min}.

IV. Conclusion

Beamforming improves the directivity of electromagnetic waves, security, and balances the energy consumption over the network. We analyze the energy consumption in pre-beamforming preparation when using the random walk algorithm for converging the phase differences at the receiver and the energy savings from beamforming operation. Our study shows that the number of transmitters and the amount of data are important factors determining whether beamforming is worthwhile. The minimum transmitted data size can be decided based on the total number of nodes and the selected beamforming efficiency.

This paper does not consider propagation loss in the energy model and we used the energy model of a specific wireless card to calculate the overhead. In the future work, the energy model can be generalized by adding the propagation loss and considering different types of wireless cards.

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