Analysis of Energy Consumption on Data Sharing in Beamforming for Wireless Sensor Networks

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***Abstract*—Collaborative beamforming is a transmission technique by using multiple transmitters to form antenna arrays and creating highly directional beams to a distant receiver. Collaborative beamforming can enhance energy efficiency in wireless sensor networks. However, the same information needs to be shared among the transmitters in advance. As a result, communication among the transmitters is required; this consumes energy and shortens the lifetime of the sensor network. In this paper, we propose a procedure for data sharing when multiple sensing nodes and multiple transmitters are used and examine the energy consumption for beamforming. We show that beamforming is energy-efficient when the sensor nodes are deployed far away from the base station and the energy consumed for data sharing has negligible effects on the network's lifetime.**

I. INTRODUCTION

Wireless sensor networks (WSNs) can be used in many applications, such as habitat monitoring, environment observation, and health condition tracking. Sensor nodes collect and transmit data to a base station, where the data are stored and analyzed. In most applications, sensor nodes need to be small with limited energy. The base station is often far from the sensor nodes. For example, on the Great Duck Island, sensor nodes are deployed to monitor the seabird nesting environment and behavior [1]. In the Hawaii Volcanoes National Park, sensor nodes are deployed to study the environment of the rare and endangered species [2]. In both applications, the base stations are located several kilometers away from the sensing area. Sensor nodes are usually powered by batteries and replacing or charging the batteries is difficult. Hence, energy-efficient sensing and transmission are the key factors to prolong the lifetime of the sensing network.

Collaborative beamforming [3] in WSNs uses multiple transmitters to form antenna arrays and create highly directional signals for transmission or reception, as shown in Figure 1. Beamforming enhances the transmission range, and saves energy for long distance transmissions [4], [5], [6]. However, one important issue has not been addressed in the literature: the transmitted data have to be the same to create constructive interference of the electromagnetic waves at the receiver. Hence, sensed data need to be shared among all transmitters before creating directional beams. Data sharing requires communication among the transmitters and consumes energy. The energy for data sharing abates the energy saved by beamforming. In order to prolong network lifetime, we have to examine and reduce the energy consumed for data sharing.

In most applications, in order to accurately model the sensed phenomena, sensor nodes are densely deployed and multiple sensing nodes are used for each measurement. For example, 100 biomedical sensors are used on one artificial retina [7]. In [8], 200 sensor nodes are deployed to measure the rainfall level for flood detection. In the Great Duck Island project [1], 100 nodes are required in one interested area for sensing the temperature and occupancy of the birds. In these applications, multiple measurements are taken at each round to develop predictive models. Using all available sensing nodes can provide the maximum number of measurements, but the energy consumption is high. Therefore, only some sensing nodes are used in each round to conserve energy [9]. The number of sensing nodes can be determined based on the accuracy required by the application.

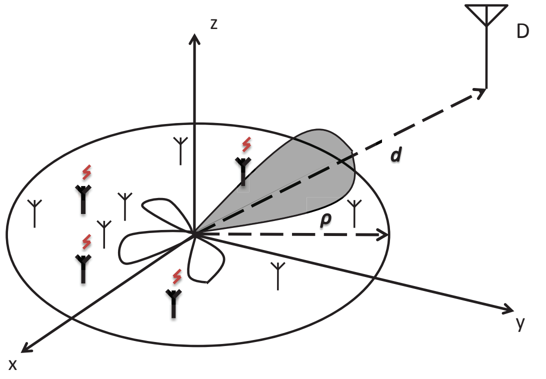

Fig. 1. Distributed beamforming. Ten nodes are randomly deployed in a circle. The shaded area shows the radiated wave pattern with the selected four transmitters (four antennae in bold). D is the receiver, i.e. the base station.

In this paper, we present the procedures for data sharing when multiple sensing nodes and transmitters are used in each round of sensing and transmission. We define one round of sensing and transmission as the time from the sensing nodes collecting data to the time the data have been received by the base station. The network lifetime is the maximum number of successful beamforming transmissions achieved before there are insufficient transmitters or sensing nodes. We analyze the energy consumed on data sharing for different numbers of sensing nodes and transmitters, and the impact on beamforming transmissions. We believe this is the first paper showing how energy consumed on data sharing affects the network lifetime in beamforming. This paper has the following contributions: (i) We show how data can be shared among the transmitters when there are multiple sensing nodes and transmitters in each round. (ii) In each round, nodes are categorized into four types of roles as described in Section

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III-C. We examine the energy consumed on each type of nodes in data sharing. (iii) We compare the energy consumed by direct transmission and beamforming to achieve the same number of transmissions.

II. RELATED WORK

A. Beamforming

Using collaborative beamforming to enhance energy efficiency for wireless sensor networks has been studied by many researchers [10], [6], [11]. In [6], Ochiai et al. analyze the characteristics of collaborative beamforming's patterns when the nodes are deployed with a uniform distribution. Ahmed et al. [10] show the beamforming performances can be improved when nodes are deployed in Gaussian distributions. All these studies show that signal strengths or transmission ranges can be increased using beamforming. Due to various reasons, such as different distances and initial phase offsets, signals from collaborating transmitters may have different phases at the receiver. Beamforming performance depends on these phase differences [12]. Chang et al. [13] propose *phase partition*: it divides transmitters into several groups based on their phases. Each round of beamforming uses only one group. In this paper, we assume that transmitters for each round of beamforming are scheduled using phase partition.

B. Data Sharing in Pre-Beamforming

Sensor nodes participating in the current beamforming transmission are called transmitters. Data sharing is necessary because each node is detecting its local information and the information detected by two nodes at different locations may be different. Therefore, data need to be shared before performing beamforming transmissions. Siam et al. [14] propose an energy-efficient clustering and routing scheme. In their approach, nodes are deployed along the path from the sensing area to the base station and divided into clusters. Transmissions are performed using hop-by-hop routings between clusters. The amount of communication is relatively small due to the small size of the cluster. In this paper, we assume that sensor nodes are deployed far away from the base station and collaborative beamforming is used. In each beamforming transmission, more transmitters are used to increase the transmission distance. The amount of communication among the sensor nodes increases when more transmitters are used. We propose a generalized data sharing procedure for a given deployment and we examine the energy consumed on data sharing and its impact on network lifetime.

C. Energy Model

We use the energy model presented in [15]. Here $e_{tx}(b, d)$ is the total energy consumed by one node for transmitting b bits of data across distance d; $e_{rx}(b)$ is the energy consumed by one node for receiving b bits of data. Table I defines the symbols and lists the values used in this paper.

$$e_{tx}(b, d) = \epsilon_e \times b + \epsilon_a \times b \times d^{\alpha} \tag{1}$$

$$e_{rx}(b) = \epsilon_e \times b \tag{2}$$

TABLE I
SIMULATION PARAMETERS

Parameter	Symbol	Value
Packet Size	b	bits
Free Space path-loss exponent	α	2
Energy consumed on radio circuitry	ϵ_e	50nJ/bit
Energy consumed on radio amplifier	ϵ_a	100pJ/bit
Transmission distance	d	meter

III. ENERGY-EFFICIENT DATA SHARING

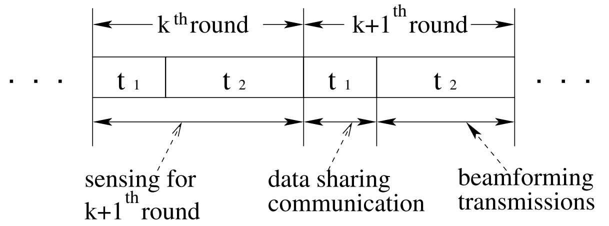
A. Problem Description

In a sensing area of radius ρ meters, Q sensor nodes are randomly deployed. Nodes can communicate with each other in one hop. The signal from each node has a phase difference ϕ_i at the base station, due to its phase offset and distance to the base station. We assume the phase differences are uniformly distributed in $[-\pi, \pi]$ and Q nodes are divided into H groups based on their phase differences. The number of transmitters N in each group may be different, but on average $N = Q/H$. Each beamforming transmission is assigned to one group of nodes. The groups transmit to the base station in turns.

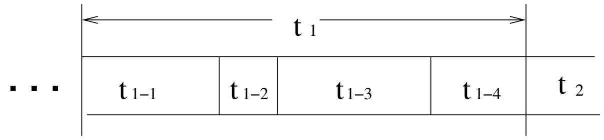
As shown in Figure 2(a), sensing and transmissions are divided into rounds. Each round of sensing takes time t. Each round of communication and transmission takes time t as well, $t = t_1 + t_2$. Here t_1 is the time for data sharing among all transmitters and t_2 is the time for one beamforming transmission. Sensing is performed simultaneously with communication and transmission. The data collected by the sensing nodes in the current round will be shared and transmitted to the base station in the next round. One example is shown in Figure 2(a). At the beginning of the $k + 1^{th}$ round, data collected in the k^{th} round by the sensing nodes are shared among the transmitters during time t_1. At t_2, the data are sent to the base station using beamforming. In this paper, we assume all transmissions are properly scheduled using TDMA and the channel is reliable, i.e. all transmissions can reach their intended destinations.

In each round, among Q nodes, there are N transmitters and S sensing nodes. Transmitters are the nodes that belong to the selected transmission group and sensing nodes are the nodes that detect the events. The number of transmitters, N, affects the beamforming transmission distance. Collaborative beamforming with N transmitters with no phase difference can extend the transmission distance by N times [16]. For a farther base station, N needs to be larger. Hence, either more nodes are deployed or nodes are divided into fewer groups. The size of S depends on the accuracy that is required by the application. Sensing nodes and transmitters may be different in each round, i.e. $S \neq N$. We assume the numbers of sensing nodes are the same for all rounds.

Among all transmitters, the one with the highest remaining energy in the currently selected group is a master node. The master node gathers the data from all sensing nodes. All sensing nodes in each round are sensing the same event. In order to reduce energy consumed on long distance transmissions, the master node aggregates and compresses the data from all sensing nodes and forms a final data packet for beamforming transmission. The master node multicasts the final data to the other transmitters. The final data are created based on the data



(a) Sensing is performed simultaneously with communication and transmission. Data collected in k^{th} round is shared and transmitted in the $k+1^{th}$ round.



(b) Four steps for data sharing in t_1.

Fig. 2. Example of timing diagram: t_1 is the time for sharing data among all the transmitters and t_2 is the time for beamforming transmission.

sent by all sensing nodes and have the same size as a data packet from one sensing node. The receiver (i.e. base station) is d meters away from the center of the deployment, $d \gg \rho$. No sensor nodes are deployed between the sensing area and the base station; thus, multi-hop transmission is beyond the scope of this paper. We assume the propagation loss is the same for all transmitters. N nodes extend the transmission distance by $N \times e$ times, where $e = E[\sum_{i=1}^{N} \cos \phi_i]$ is the beamforming efficiency [12]. $E[\cdot]$ is the expectation operator and $\phi_i, i = 1...N$ are the phase differences of the nodes in one group. In this paper, we define the network lifetime to be the number of successful beamforming transmissions before there are insufficient sensing nodes or transmitters because some nodes have depleted their energy.

We assume all nodes are synchronized and can perform simple computation, such as averaging, counting, and multiplication. Beamforming scheduling is performed offline and the transmission schedule is shared with all nodes. Each node has an initial energy e_i and it is randomly distributed in range $(0, e_{max}]$, for reasons such as different times of deployments. During the data sharing period t_1, control packets b_1 are used for information exchanges, such as electing the master node and exchanging the remaining energy level of nodes. A control packet contains the node's ID, remaining energy, and an ACK. The data packets containing monitored events are called b_2 and the control packets for communication among the nodes are called b_1. The size of b_2 is larger than the size of b_1.

B. Data Sharing Procedures

Data sharing in beamforming is necessary because the data sent by all transmitters need to be the same to create constructive interference of the electromagnetic waves at the receiver. Data sharing is necessary even when the sensing nodes are the same as transmitters, since sensing nodes provide localized measurements and two sensing nodes from two different locations may have different measurements.

S sensing nodes and N transmitters are used in each round. For S sensing nodes to broadcast their own data packet one after another, it requires S transmissions. Since there are N transmitters, each transmitter receives one data packet from one sensing node. Therefore, it requires $S \times N$ receptions of data packets. It is energy-efficient to elect a master node to gather the data from the sensing nodes and then multicast a final data packet to all transmitters. The data from these sensing nodes are aggregated at the master node; the final data packet is of the same size as a single data packet from one sensing node. The $S \times N$ receptions of data packets in the previous approach can now be reduced to $S + N$ receptions and one transmission of data packet, with N control packets. For the master node to gather the data from S sensing nodes, S receptions of data packet are required. N receptions and one transmission are required for the master node to broadcast the final data packet to the transmitters. N control packets are used to elect the master node among the transmitters and this is explained later in this section. Data sharing with multiple sensing nodes and transmitters in this approach can be achieved in four steps, as shown in Figure 2(b).

- t_{1-1} Election for the master node in this group. Multiple sensing nodes are used in each round. For all transmitters to have the same information, we use a master node to gather the data from all sensing nodes and then forward the data to the transmitters. The master node is elected among the transmitters to reduce the amount of communication. Each transmitter multicasts its ID and remaining energy to the other transmitters. Thus, every transmitter knows the remaining energy of the other transmitters in the same group. The transmitters know which node has the highest remaining energy, i.e. the master node. Since transmitters are scheduled in advance, every node knows its own group.
- t_{1-2} Share the master node's ID with sensing nodes and select the sensing nodes for the next round. In time t_{1-1}, the master node is elected among the transmitters by exchanging their own remaining energy. To save energy consumed over the network, nodes other than transmitters do not participate in the communication in t_{1-1}. However, as we mentioned earlier, the sensing nodes may not be the transmitters in the same round. In order to know where to forward their data packets, the sensing nodes also need to know which node is the master node. In t_{1-2}, the master node broadcasts its ID to all other nodes. In the case that sensing nodes are not pre-scheduled, the master node can also assign the sensing nodes for the next round. It is more energy-efficient for the sensing nodes to receive one control packet with the master node ID than to receive several control packets from all transmitters with their remaining energy.
- t_{1-3} Sensing nodes forward their data to the master node.
- t_{1-4} Master node multicasts the final data for beamforming. The final data will be transmitted to the base station.

To reduce the communication in data sharing, this master node election procedure in t_{1-1} does not need to be performed in every round. In t_{1-1}, transmitters exchange their remaining energy using control packets. Based on this information, every transmitter knows the remaining energy of the master node and the other transmitters in the same group. Based on the master node's remaining energy, transmitters can estimate the number of rounds that the master node can perform before it is energy-exhausted. This number is the lower bound for how often we need to elect the master node.

C. *Overhead Analysis*

There are four types of nodes in each round of sensing and transmission: beamforming transmitters, a master node, sensing nodes, and the other nodes in the deployment area that are not transmitters or sensing nodes. A master node is one of the transmitters. A transmitter can also be a sensing node, and vice versa. In this section, we analyze the energy consumed on each type of nodes. We examine the amount of transmissions and receptions performed on each type of nodes in one round. If a sensing node is also a transmitter, the energy consumed on that node is the sum of the energy consumed on a transmitter and a sensing node. The master node is one special node among the transmitters and the energy consumed on a master node is more than a normal transmitter.

- Transmitter: Multicast one control packet containing its remaining energy to the other transmitters and receives N-1 control packets from other transmitters in t_{1-1}. Receive one control packet containing master node's ID in t_{1-2}. Receive final data packet from the master node in t_{1-4}.

$$e_{ct} = e_{tx}(b_1, \rho) + e_{rx}(b_1) \times N + e_{rx}(b_2) \tag{3}$$

- Master node: Multicast one control packet containing its remaining energy to the other transmitters and receive N-1 control packets containing remaining energy from other transmitters in t_{1-1}. Broadcast one control packet to confirm that it is the master node and the selected sensing nodes for the next round in t_{1-2}. Receive S data packets from sensing nodes in t_{1-3}. Multicast the final data to the other transmitters in t_{1-4}.

$$\begin{aligned} e_{cc} \quad = \quad & 2 \times e_{tx}(b_1, \rho) + e_{rx}(b_1) \times (N-1) \\ & + e_{rx}(b_2) \times S + e_{tx}(b_2, \rho) \end{aligned} \tag{4}$$

- Sensing node: Receive one control packet from the master node in t_{1-2} and send a data packet to the master node in t_{1-3}.

$$e_{cs} = e_{rx}(b_1) + e_{tx}(b_2, \rho) \tag{5}$$

- All other nodes (i.e. nodes that are not sensing or transmitting): Receive one control packet from the master node in t_{1-2}.

$$e_{co} = e_{rx}(b_1). \tag{6}$$

According to the derivation, the total energy consumed on data sharing in each round over the network is the summation of the energy consumed on all types of nodes.

IV. SIMULATION AND ANALYSIS

In this section, we analyze the energy saved by using beamforming and how the energy consumed on data sharing affects the maximum number of beamforming transmissions. In this section, we show that (1) using beamforming, the energy consumed on each transmitter is much less than the energy consumed in direct transmission; (2) for the same number of transmissions, whether beamforming saves energy over the network depends on the radius of the deployment and the number of transmitters; (3) the number of successful beamforming transmissions reduces when more sensing nodes are used.

TABLE II

SYMBOLS AND THE VALUES USED IN THE SIMULATIONS.

Parameter	Symbol	Value
Number of Total Deployed Nodes	Q	100
Number of Sensing Nodes	S	10-100
Number of Transmitters in Each Round	N	average 16
Number of Transmission Groups	H	6
Deployment Radius	ρ	100m
Distance to Base Station	d	50000m
Control Packet	b_1	4 bytes
Data Packet	b_2	25 bytes
Beamforming Efficiency	e	
Node Energy (maximum)	e_{max}	1000J
Data Sharing Energy Per Transmitter	e_{ct}	J/Round
Data Sharing Energy Per Sensing Node	e_{cs}	J/Round
Data Sharing Energy Per Master Node	e_{cc}	J/Round
Data Sharing Energy Per Node other than Transmitters or Sensing Nodes	e_{co}	J/Round
One Direct Transmission Energy Per Transmitter	e_d	J/Round
One Beamforming Transmission Energy Per One Transmitter	e_b	J/Round

We use the following parameters in our simulation: Q=100 nodes are deployed in a circle of radius ρ=100 meters, the base station is at d =50000 meters. Sensor nodes are divided into H=6 groups based on their phase differences. The typical data packet for Mica2 is 36 bytes [17]. In this paper, we assume each data packet and control packet contains 2 bytes of header. The data packet b_2 is 25 bytes and the control packet for data sharing communication b_1 is 4 bytes. The actual size of the data packet and control packet depends on the applications. We assume the maximum energy carried by one node e_{max} is 1000 J, as suggested in [15]. The parameters and values used in our simulation are listed in table II.

A. *Energy Saved On Each Transmitter by Using Beamforming*

A data packet b_2 can be transmitted from the sensing area to the distant base station in two different ways. (i) This data packet can be directly transmitted to the base station using one transmitter with high power. The energy consumed on each transmitter is $e_d = e_{tx}(b_2, d)$. (ii) This data packet can also be transmitted using beamforming with N transmitters and each transmitter can use lower transmitting power. Assuming 100 nodes are divided into H groups, there are $N = 100/H$ transmitters in each group and the phase differences of the nodes in the same group are in the range of [0, $2\pi/H$]. In beamforming transmissions, N transmitters with a beamforming efficiency e can extend the transmission range by $N \times e$ times. Hence, the transmission energy consumed on each transmitter in beamforming is $e_b = e_{tx}(b_2, \frac{d}{N \cdot e})$. Beamforming requires communication among the transmitters for data sharing and the distance between every two collaborating nodes affects the total energy overhead for beamforming. In Section III-B, we

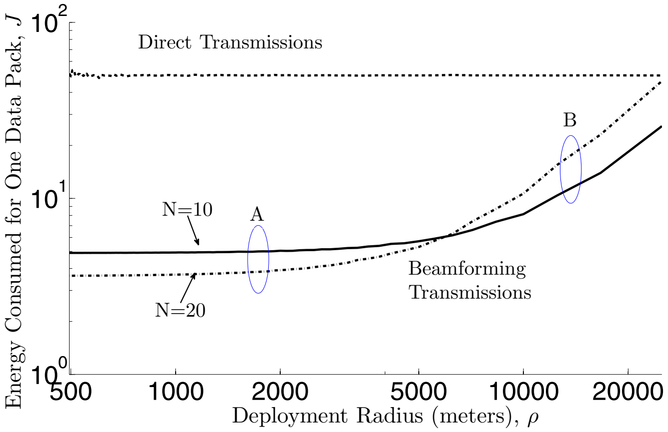


Fig. 3. Compared with direct transmission, beamforming always saves energy on each transmitter. The distance to the base station d is 50000 meters. The energy consumption in this figure is averaged by 20 random deployments.

show that during each round of transmission, each transmitter consumes energy e_{ct} for data sharing. Therefore, the total energy consumed on one transmitter in one round is $e_b + e_{ct}$. As shown in Figure 3, using direct transmission, one transmitter consumes 500J to transmit a b_2 data packet from the origin to the base station. Compared with direct transmissions, beamforming consumes less energy on each transmitter even when the deployment radius is large, e.g. ρ=10000 meters.

The number of the transmitters in each group also affects the amount of communication in data sharing. More transmitters require more communication, but in the transmission to the base station, each transmitter can use lower power. In Figure 3, when ρ increases, the total energy consumption for beamforming increases. Energy consumed on one transmitter in beamforming is the sum of the energy consumed on data sharing e_{ct} and the energy consumed on the transmission to the base station e_b. When N is larger, e_{ct} is larger, since more communication is required for sharing the data. However, when N is larger, e_b is lower, since each transmitter can use lower transmitting power. Point A in Figure 3 shows that using more transmitters, when ρ is smaller, the total energy consumption is lower. This is because the energy consumed on the beamforming transmission dominates. As ρ increases, e_{ct} increases. The total energy consumption is larger when using more transmitters. This is shown as point B in Figure 3.

B. Energy Saved by Beamforming Over The Network

Different from direct transmissions, beamforming requires collaboration between multiple transmitters in each round and communication needs to be performed among multiple nodes to share data in pre-beamforming. Hence, beamforming requires additional energy consumption overhead. In beamforming, nodes other than transmitters also consumes energy for data sharing; in direct transmission, communication among the nodes is not required.

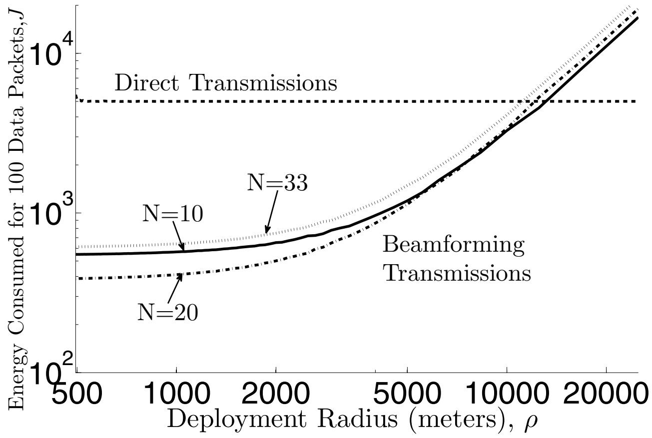


Fig. 4. Energy consumed over the network when using direct transmission and beamforming transmission respectively. The distance to the base station is fixed to be d=50000 meters. The energy consumption in this figure is averaged by 20 random deployments.

In this section, we compare the energy consumption for 100 transmissions using direct transmission and beamforming transmission respectively. Whether beamforming saves energy depends on the deployment radius ρ and the number of transmitters. One node with high transmission power is used in direct transmission. Figure 4 shows the total energy consumed over the network using direct and beamforming transmissions respectively. When the deployment radius is large, $\rho > 10000$ meters, energy consumed on beamforming transmissions is higher than the energy consumed on direct transmissions. As the deployment radius becomes smaller, the energy for data sharing reduces and the energy consumed on the transmissions to the base station dominates. In Figure 4, the energy consumed on direct transmissions is not a constant with the change of deployment radius, but the fluctuation is small. This is because the nodes are randomly deployed in the circle. The distance from each node to the base station may be different, but the average distance is constant.

The amounts of data sharing communication also depend on the number of transmitters. Figure 4 shows the comparison of the energy consumed using beamforming when the 100 nodes are divided into 10, 5, and 3 groups. When the total number of nodes is fixed, fewer groups indicate that each group has more nodes and the phase differences of the nodes in the same group has a wider range. For example, when H=3, the phase differences are in range of [0, $2\pi/3$]; when H=10, the phase differences are in range of [0, $\pi/5$]. The transmission distance enhanced by beamforming is proportional to $N \times e$, where $e = E[\sum_{i=1}^{N} \cos\phi_i]$. For a smaller H, the increase in N and the decrease in e are not linearly related. Figure 4 shows that larger N requires more communication in data sharing and it has a earlier energy turn-over point. An energy turn-over point is the point when the energy consumed on beamforming is less than the energy consumed on direct transmissions.

C. Network Lifetime

For a deployment with the values listed in Table II, Figure 5 shows the number of successful beamforming transmissions in three cases: (i) when energy consumed on data sharing is not considered, (ii) when 10 sensing nodes are used in

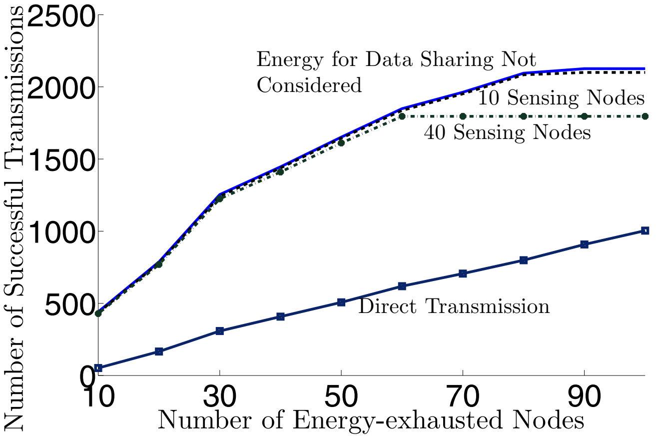


Fig. 5. Energy consumed on data sharing has little affect on the number of successful beamforming transmissions. Distance to the base station d= 50000 meters and the deployment radius is ρ=100 meters.

each round, and (iii) when 40 sensing nodes are used in each round. Energy consumed on data sharing exists in all beamforming transmission scenarios. The beamforming case (i) in this figure is used as a reference to show the number of successful beamforming transmissions without considering the energy consumed on data sharing for beamforming. In the three cases using beamforming for transmissions, the same transmitters are selected. Using beamforming with a required number of sensing nodes in each round, e.g. 10 or 40, a transmission fails when there are insufficient transmitters or sensing nodes, i.e. too many nodes are energy-exhausted. Without considering the energy consumed on data sharing, the number of successful beamforming transmissions increases as more nodes are energy-exhausted. Transmission fails when there are (i) no enough transmitters, (ii) the phase differences of the transmitters are too large to create strong enough signal to reach the base station. With 10 sensing nodes in each round, a transmission also fails when there are fewer than 10 nodes possessing non-zero remaining energy. The number of successful transmissions show almost no reduction for the case when 10 sensing nodes are used in each round. When we increase the number of sensing nodes to 40, the number of successful transmissions saturates when more than 60 nodes are energy-exhausted. The number of successful transmissions drops about 2-3 % compared with the case where 60 nodes are energy-exhausted and no data sharing is considered. From this figure, we can see that since the deployment radius is much smaller compared with the distance to the base station, i.e. 100m:50000m, the energy consumed on long distance transmissions dominates and the energy consumed on data sharing has negligible effect on the network lifetime. In this figure, we also compare the number of successful transmissions at the receiver using direct transmission, i.e. a single node directly transmitting the data to the base station with an increased transmitting power. Direct transmission can transmit much less data than beamforming.

V. CONCLUSION

In this paper, we present the procedures for data sharing when multiple sensing nodes and transmitters are used in each round of beamforming. We show that compared with direct transmissions, beamforming saves energy over the network when the base station is far away. Energy consumed on data sharing has negligible effect on the network lifetime of beamforming.

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