Energy Savings from Implementing Collaborative Beamforming for a Remote Low Power Wireless Sensor Network

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Abstract

This paper outlines the implementation of collaborative beamforming to a remote low power wireless sensor network and presents its energy saving potential. The directivity procured from the beamforming allows power to be saved, which is distributed over the network. This allows each sensor within the network to have the same prolonged lifetime, and thus create a long lasting reliable network. The associated overhead with collaborative beamforming is in conjunction examined, where Single Frequency Networks (SFN) are taken as reference for synchronisation procedures. Finally, the influences of various network operating parameters on the energy benefit that can be obtained from collaborative beamforming in respect to network sizes are presented.

1. Introduction

Wireless sensor networks have become feasible in recent years due to the affordability of small and powerful silicon chips, as well as due to improved low-power techniques for wireless circuits. There is, however, one factor that tends to remain a constant source of power consumption, regardless of the power reductions achieved within the circuits – the transmission power.

This issue has initially been addressed by the research community with three promising comparable techniques developed for lowering the power required for transmitting data. These techniques are: Smart Antennas, Single Frequency Networks (SFN) and Collaborative Beamforming. Smart antennas operate by using an antenna array to specifically align the radiation and/or reception pattern automatically to a specific direction for optimal transmission or reception of data [1]. The transmission power is lowered through the increased directivity, which focuses the radiated transmission power in the desired direction, minimising the propagation loss. The problem with utilising smart antennas for a remote low power wireless sensor network is its restriction to high frequencies that allow for small antennas. This prohibits the use of lower carrier frequencies commonly employed by low power wireless sensor networks.

An SFN operates by having several completely separate transmitters all transmitting the same data on exactly the same carrier frequency to increase transmission coverage and/or to possibly decrease transmission power [2-3]. By having several transmitters all operating on the same carrier frequency at the same time, the received signal incorporates all of the transmitted signals from the network. Transmission power is then able to be scaled back to provide a power saving. Typical SFN applications either neglect the potential of beamforming or aren't able to implement it due to their operation, such as in Digital Audio Broadcast (DAB) and Digital Video Broadcast (DVB) systems which have multiple receivers. However the synchronisation procedures of a SFN are applicable to wireless networks using collaborative beamforming.

Collaborative beamforming applies beamforming commonly found in smart antennas to arrays of multiple transceivers [4]. A sensor network implementing collaborative beamforming is able to have multiple sensors collaboratively transmit data back to a base station, or another wireless sensor network, allowing each sensor to share in generating the required transmission power, while providing a directivity gain. Initial research into collaborative beamforming, [4], has presented the ideal and non ideal expected directivity from a randomly distributed network and have indicated its potential.

Implementing collaborative beamforming in a wireless sensor network over a single unaided transmitting sensor requires additional power and time overhead. The overhead not only arises from data distribution over the network but also from the synchronisation between nodes, due to local oscillator frequency drifts and random start up phases. Nevertheless energy savings are possible given a proficient directivity and modest overhead energy use.

This paper analyses the energy saving potential of utilising collaborative beamforming on a remote low power wireless sensor network. The techniques and issues for typical SFN synchronisation are outlined and accounted for in providing an accurate representation of the additional overhead. Section 2 of this paper presents the network structure and operation of a wireless sensor network implementing collaborative beamforming. Based on this, section 3 provides the expected energy savings when compared to a single transmitting sensor structure. The energy saving potential is then highlighted for a sample sensor network in section 4, with the influence of circuit and system design examined. The potential of this technique is finally concluded in section 5.

2. Wireless Sensor Network Structure and Operation

A wireless sensor network using collaborative beamforming has a structure shown in Figure 1. It consists of a remote wireless sensor network situated a great distance away from a base station.

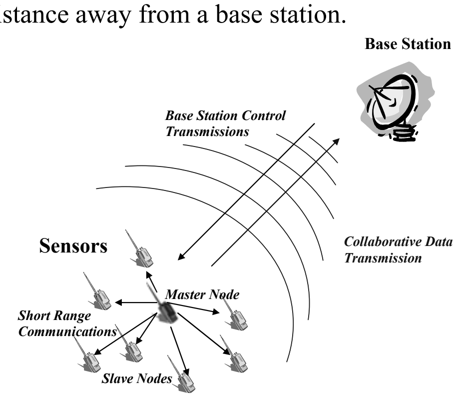

Figure 1. Network structure

The network has both short range communication between nodes and long range communication to the base station. Short range transmissions are required for the synchronisation and data distribution within the network which is covered in sections 2.1 and 2.2 respectively. Long range transmissions are used for relaying sensor data back to a base station, or to another sensor network. Collaborative beamforming over multiple transmitters provides an energy saving to the sensor network when compared to a single sensor transmitting, hence is implemented for the long range transmission.

2.1. Synchronisation

For the synchronisation and regulation of the network a synchronisation source is required. This can be performed in two different forms: from the base station, or from one of the sensors – a master node. This is referred to as closed loop for base station control and open loop for master node control in [4]. In both control methods the remaining sensors are slave nodes and implement the beamforming and synchronisation based on the data they receive from the synchronisation source.

The synchronisations required within both cases include the alignment of both the carrier frequency and local oscillator phase at each slave node. The alignment of the carrier frequency is performed by the detection of the frequency difference of the local oscillator in respect to the received synchronisation transmission at each slave node.

The alignment of the local oscillator phase is typically performed utilising a reference clock, such as the Global Positioning System (GPS) clock. Alternatively the phase of the local oscillator can be aligned to the synchronisation source through a synchronisation transmission, which either has embedded a time stamp or position of the synchronisation source.

2.2. Data Distribution

Before sensor networks can collaboratively beamform, the sensor data needs to be distributed over the network. The sensor with the originating data message is identified by a base station broadcast or is defined to be the master node in the master node control method. In other words, any sensor can become the master node and initiate a collaborative beamforming transmission of its data.

As the sensors are located close to one another compared to the distance back to the base station, the local transmission power is comparably smaller, allowing for busy communications between the nodes. However as will be seen in sections 3 and 4 both the local receiver and transmitter energies must be taken into account due to their contribution to the network energy growing accordingly with the size of the network.

2.3. Beamforming

The beamforming process is performed by specifically delaying and phase rotating the transmissions of the slave nodes so that all transmissions simultaneously arrive at the base station. Implementation of the beamforming makes use of additional overhead in calculating the exact transmission phase and delay at each slave node.

Base station control implements beamforming by having each slave node measure the phase and using inverse of this phase for its own transmission. Master node control implements beamforming by manipulating the phase of the slave node's transmission to achieve reception at the base station that is concurrent with the master node's transmission. Equation 1 gives the dependence of the phase rotation, $\Delta\varphi_n$, on the distance from the base station to the slave node, d_{slave}, and the distance from the base station to the master node, d_{master}, where λ is wavelength of the carrier frequency.

$$\Delta\varphi_n = \frac{2\pi}{\lambda}\left(d_{master} - d_{slave}\right) \tag{1}$$

A complicating issue with typical beamforming is the effect of Inter Symbol Interference (ISI) in digital transmissions, which occurs for beamforming phase rotations greater than 2π. The ISI is corrected by rescheduling each of the slave node transmissions before or after a fixed common delay specified by the synchronisation source. For the master node control method, this variation in delay is calculated as shown in Equation 2 where T is the period of the carrier frequency. For the base station control method the delay would have to be derived from bit transitions in the synchronisation transmissions.

$$\Delta delay_{slave} = T \cdot round\left(\frac{\left(d_{master} - d_{slave}\right)}{\lambda}\right) \tag{2}$$

A trade-off is seen between the calculation precision required for the delay and ISI in the reception. The trade off occurs for lower bit rates, where ISI has a diminished affect on the received data, allowing the processing load for calculating the delay to be reduced.

Inaccuracy in the position estimates of the sensors will lead to errors in beamforming and synchronisation, misaligning their transmissions. Position-estimation inaccuracies for a sensor network has previously been discussed in [4] for collaborative beamforming in respect to the directivity of randomly distributed sensor networks. Errors of up to 40% of a wavelength are shown in [4] to produce degradation in the directivity at less than 3dB. Position-estimation accuracy is therefore related to carrier frequency with lower carrier frequencies allowing less accurate techniques, such as using Global Positioning System (GPS).

In summary, obtaining an energy saving from collaborative beamforming requires that energy benefit from beamforming to be greater than the energy overhead associated with it. The relationship between transmission energy saving and energy overhead is presented in the next section. In this section, we make use of the beamforming theory of randomly spaced arrays presented in [5], which has recently been extended to incorporate randomly distributed wireless sensor networks in [4].

3. Energy Savings and Energy Overhead

3.1. Transmission Energy Savings

The transmission energy savings obtained from collaborative beamforming over the single sensor transmission is shown in Equation 3, where T_{data}, is the sensor data transmission time, $EIRP_{max}$ the maximum Effective Isotropic Radiated Power, G_{single} and $G_{network}$ the antenna gains for a single sensor and sensor network, respectively. The $EIRP_{max}$ is the maximum radiated power in any direction for a given frequency band and is related to G_{Tx} the gain of the transmitter and P_{Tx} the transmission power, as shown in Equation 4. Alternatively, $EIRP_{max}$ can be expressed in terms of $P_{R,BS}$, the received power strength at the base station, d_{BS} the distance between sensor and base station, $G_{Rx,BS}$, the base station receiver antenna gain, λ the wavelength of the carrier frequency and k the exponential loss component. The desired received power strength is commonly defined as some threshold value above the receiver's sensitivity.

$$E_{saving} = T_{data} EIRP_{\max}\left(\frac{1}{G_{single}} - \frac{1}{G_{network}}\right) \tag{3}$$

$$EIRP_{\max} = G_{Tx} P_{Tx} = \frac{P_{R,BS}\left(\frac{4\pi}{\lambda}\right)^2 \left(d_{BS}\right)^k}{G_{Rx}} \tag{4}$$

The network gain, $G_{network}$, is dependent on the directivity of the antenna and its efficiency. From [4] the lower bound average directivity of a randomly distributed wireless sensor network is shown to be dependent on N, the number of elements within the network and $\widetilde{R}$, the radius of the disk that encompasses the network relative to the wavelength. The network gain, $G_{network}$, can be calculated as shown in Equation 5, where $\widetilde{D}_{av}$ is the average directivity taken from [4], η_r, is the transmitting antenna's efficiency, $|\Gamma|^2$ is the power reflection coefficient for the transmitting antenna, and c_0~1.1727 a positive constant independent of N and $\widetilde{R}$.

$$G_{network} = \eta_r\left(1 - |\Gamma|^2\right)\widetilde{D}_{av} = \frac{\eta_r\left(1 - |\Gamma|^2\right)N}{1 + \left(1 - \frac{1}{N}\right)\frac{c_0}{4\pi}\frac{N}{\widetilde{R}}} \tag{5}$$

3.2. Energy Overhead

The energy overhead required for implementing collaborative beamforming for a network compared to a single sensor is given in Equations 6 and 7 for the base station control method and the master node control method, respectively. These equations are expressed in terms of power-time products for the overhead operations associated with collaborative beamforming. The various power-time products are described below. N represents the number of sensor within the network.

$$\begin{aligned} E_{overhead,BS} &= N\left(P_{sync,Rx}T_{sync} + P_{pos}T_{pos}\right) \\ &+ P_{dist,Tx}T_{data} + \left(N-1\right)P_{dist,Rx}T_{data} \\ &+ \left(N-1\right)P_{prep}T_{prep} + NP_{digital}T_{digital} \end{aligned} \qquad (6)$$

$$\begin{aligned} E_{overhead,MN} &= P_{sync,Tx}T_{sync} + \left(N-1\right)P_{sync,Rx}T_{sync} \\ &+ NP_{pos}T_{pos} \\ &+ P_{dist,Tx}T_{data} + \left(N-1\right)P_{dist,Rx}T_{data} \\ &+ \left(N-1\right)P_{prep}T_{prep} + \left(N-1\right)P_{digital}T_{digital} \end{aligned} \qquad (7)$$

The synchronisation power-time product, $P_{sync,Rx}T_{sync}$, $P_{sync,Tx}T_{sync}$ accounts for the energy expended in synchronising the sensor network. This synchronisation takes the form of a single synchronisation broadcast per message from either the base station or master node. The synchronisation transmission aligns both the carrier frequency and local oscillator phase to the synchronisation source. This power-time product does not take into account any additional digital computations.

The position estimation power-time product, $P_{pos}T_{pos}$, accounts for the energy expended in calculating the precise positions for each sensor. The sensors require exact position data to align the phase of the local oscillator and to adequately determine the phase rotation and delay required for beamforming. Because this power-time product includes all energies associated with obtaining position data, e.g., a low power GPS receiver, we have separated this calculation from the other digital calculations. Note that if the sensor positions do not change prior to transmission this power-time product can be neglected on subsequent transmissions.

The data distribution power-time product, $P_{dist,Tx}T_{data}$, $P_{dist,Rx}T_{data}$, accounts for the energy expended in distributing (transmitting and receiving) the data message to all sensors within the network. Note the receiver power is taken into account within the data distribution power-time product due to its scaling with network size.

The transmission preparation power-time product, $P_{prep}T_{prep}$, accounts for the energy expended in communication operations prior to collaborative transmission such as modulation, mixing, filtering. This power-time product includes the energy required in operating a frequency synthesizer for transmission. Note this power-time product term accounts for the additional *N-1* sensors during collaborative transmission.

The digital computations power-time product, $P_{digital}T_{digital}$, accounts for the energy expended in performing all calculations associated with synchronisation and beamforming, except the position estimation calculations. We assume these calculations are to be performed by a low power microprocessor. Also, the processing times will likely vary between the two different control methods due to different beamforming procedures.

Note that any P_{Tx}, transmission power in Equation 6 and 7 is for short range transmissions and can be calculated as in Equation 8. In this equation the transmission distance is at most $2R$, where R is the radius of the disk that encompasses the network. Also $P_{R,node}$, is the received power for all of the slave nodes, $G_{Rx,node}$ is the receiver antenna gain for all of the slave nodes, G_{single} is the single transmitter gain for all of the sensors, λ is the wavelength for the transmission and P_{prep} is the power expended for communication operations prior to transmission.

$$P_{Tx} = \frac{P_{R,node}\left(\dfrac{4\pi}{\lambda}\right)^2 \left(2R\right)^k}{G_{Rx,node}G_{\mathrm{single}}} + P_{prep} \qquad (8)$$

3.3. Energy Saving Conclusions

The overall energy balance, E_{total}, is the difference between the energy savings and the energy overhead, ($E_{total} = E_{saving} - E_{overhead}$); it clearly depends on how these two quantities scale with network size. As the number of sensors, N, increases, the average directivity saturates driving the energy savings to also saturate, while the energy overhead increases linearly. Thus, the total energy, E_{total}, peaks at an optimal network size. Furthermore, there is a critical network size, after which E_{total} is always negative and no longer provides an overall energy saving.

Low power operation is a general aim of wireless sensor networks which coincides with the energy benefits of collaborative beamforming. It is also interesting to note that greater energy savings are possible for larger radiated transmission powers. Legal limitations are placed on the $EIRP_{max}$ of frequency bands, which therefore make frequency bands with larger $EIRP_{max}$ desirable. Larger $EIRP_{max}$ combined with the use of low frequencies provide greater transmission distances and larger sensor coverage areas, making remote monitoring applications the ideal candidate for collaborative beamforming. The next section provides a specific case study of collaborative beamforming with a remote low power wireless sensor network.

4. Sample Energy Savings

To demonstrate the energy savings from collaborative beamforming, a sample remote low power wireless sensor network based on the master node control method is taken along with some typical low power wireless sensor network assumptions:

1) The Sensor network is located within a disk of radius 20λ
2) A Free space loss environment, i.e. k = 2
3) The Sensors have a $EIRP_{max}$ of 30dBm.
4) A typical low data rate of 4kbps is taken for transmitting a small packet of 300 bits for sensor position and recorded data [6-7]
5) A practical synchronisation header size of 100 bits is assumed, which takes 25ms over 4kbps
6) The Base station and sensor nodes are assumed to have ideal receive antennas ($G_{Rx,BS}$ = 1 & $G_{Rx,node}$ = 1)
7) Each sensor is assumed to have an ideal dipole antenna, to give a transmission gain G_{single}= 1.64, maximum radiation efficiency, η_r = 1, and zero antenna power reflection, $|\Gamma|^2$ =0, for each sensor
8) A conservative power estimate of 1mW is taken for a low power low frequency receiver within the sensors [8-9]
9) A moderate received power threshold of -70dBm is taken for the sensors, 30dBm above typical receiver sensitivities of -100dBm [8-9]
10) A reasonable extra transmitter power of 1mW is assumed for modulation, mixing and filtering the signal before transmission (including the frequency synthesizer) for the sensors [8-9]
11) Digital energy required for overhead is assumed to be 100nJ, based on a maximum of 10,000 instructions from a CoolRISC-DL 816 core presented in [10]
12) Each node is assumed to be static, with positions already known hence no position estimation during transmission setup, i.e. P_{pos} = 0 & T_{pos} = 0

Based on these assumptions, Figures 2 through 4 show the influence of system design on the energy savings and network sizes. The thick dotted lines in all of the figures are the energy consumed by a single sensor transmission and represent the maximum positive overall energy savings.

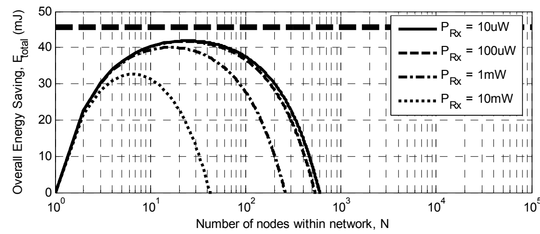

Figure 2. Overall energy savings vs. network size due to receiver circuit design

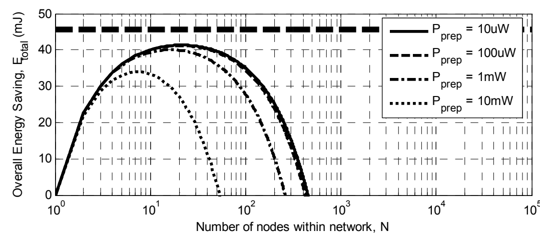

Figure 3. Overall energy savings vs. network size due to transmitter circuit design

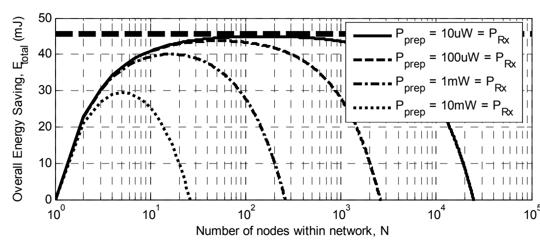

Figure 4. Overall energy savings vs. network size due to transmitter and receiver circuit design

The variation in E_{total} as a function of the number of sensor nodes is shown for: (a) different receiver powers in Figure 2, (b) different transmitter preparation powers in Figure 3, and (c) as the receiver and transmitter powers vary together in Figure 4. These figures show that peak energy savings are evident at increasing network sizes for decreasing receiver and transmitter energies. As a result of the peak energy saving network sizes, smaller subnets for transmission instead of the whole network may also be warranted for optimal energy savings.

The variation in E_{total} as a function of the number of sensor nodes is shown for different data rates in Figure 5. The solid lines in Figure 5 represent the energy consumed by a single sensor transmission at each data rate and thus are the maximum positive overall energy savings. The greater energy savings from lower data rates, emphasises that collaborative beamforming is better suited for slower data rates commonly found in sensor networks.

The variation in E_{total} as a function of the number of sensor nodes is shown for different position estimation energy in Figure 6. As position estimation energies varied from 0J to 10mJ, the critical network size was seen to decrease, indicating that current GPS position estimation energies (100-600mJ) are to high to achieve a positive energy benefit with collaborative beamforming. One way around this difficulty is to change the traditional GPS processing paradigm such that the sensors only receive the GPS signal long enough for the triangulation component of the GPS processing. The decoded GPS satellite's almanac and ephemeris data must then be recovered by the sensor from the base station.

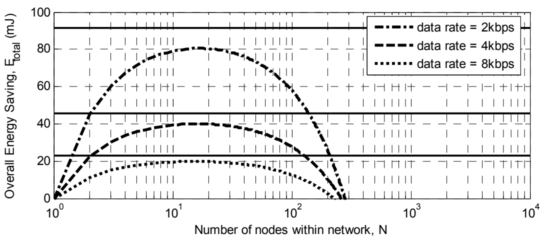

Figure 5. Overall energy savings vs. network size due to data rate

The variation in E_{total} as a function of the number of sensor nodes is shown for different $EIRP_{max}$ (20dBm to 30dBm) in Figure 7. The solid lines in Figure 7 represent the energy consumed by a single sensor transmission and thus are the maximum positive overall energy savings for each $EIRP_{max}$. Larger $EIRP_{max}$ along with lower carrier frequencies are able to accommodate greater remoteness and larger coverage areas.

In summary, these simulations show that collaborative beamforming spreads the transmission load over the network, allowing each sensor's energy consumption to remain close to the network average. This results in a sustainable network that minimises sensor black-out spots produced from individual sensors burning out quicker than the network average. Within the constraints indicated by the figures discussed above, there is the possibility that collaborative beamforming may be able to provide long lasting reliable sensor networks to remote areas such as the Australian outback where maintenance and replenishment would be difficult and expensive.

5. Conclusion

In this paper, we have analysed the energy saving potential of collaborative beamforming for a remote wireless sensor network. It was shown that overall energy savings were dependent on the overhead energy and directivity of the beamforming. From these two quantities, optimal energy savings were presented in a particular case study for specific network sizes as a function of a number of important network operating parameters.

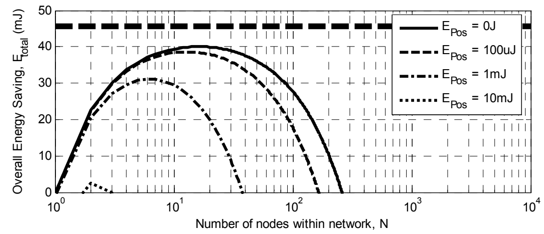

Figure 6. Overall energy savings vs. network size due to positioning energy

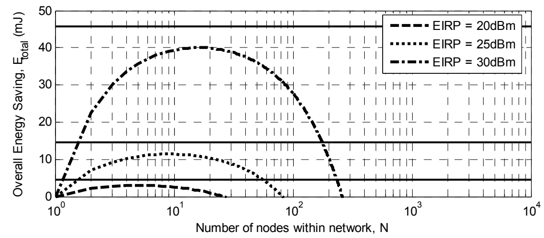

Figure 7. Overall energy savings vs. network size due to $EIRP_{max}$

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