Energy Efficiency of Collaborative Communication with imperfect Frequency Synchronization in Wireless Sensor Networks

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Abstract. Collaborative communication produces significant (N^2 where N is number of nodes used for collaboration) power gain and overcomes the effect of fading. With imperfect frequency synchronization significant but slightly less than N^2 power can be achieved. As the N increases more power gain can be achieved at the expense of more circuit power. In this paper an energy consumption model for collaborative communication system with imperfect frequency synchronization is proposed. The model to calculate the energy consumed by the sensor network for local communication and communication with base station is presented. Energy efficiency model for collaborative communication for the off-the shell products (CC2420 and AT86RF212) are presented. It is also shown that significant energy can be saved using collaborative communication as compared to traditional SISO (Single input single output) for products. The break-even distance where the energy consumed by SISO and collaborative communication is also calculated. From results it is revealed that collaborative communication using 5 nodes produces efficient energy saving.

Keywords: Sensor Network; Collaborative Communication; Bit Error Rate; Rayleigh Fading; Energy Consumption; Frequency Synchronization; energy Efficiency;

1 Introduction

A sensor network is composed of a large number of low cost, small size sensor nodes. Due to limited power of sensor nodes, an energy efficient transmission is the key requirement in sensor networks [1], [2]. Recent literature reports that a large power gain can be achieved at the base station using Cooperative communication, Multi- Hop Routing, and Beamforming [3]-[5].In Collaborative communication a set of sensor nodes transmit the same data at same time towards the base station [3]. If time synchronization, frequency synchronization and phase synchronization are achieved, collaborative communication produces a large power gain [3]-[7]. Without phase and frequency errors, the collaborative communication of N nodes will produce N^2 gain in the received power [5]. Another factor that significantly degrades the data transmission and results more power required is the channel fading. In recent work related to collaborative communication [3] and [5]-[7], it is shown that substantial power can be achieved with imperfect frequency synchronization.

In our recent work [7], a collaborative communication model is presented and it is shown that significant power gain and robustness to fading can be achieved with imperfect frequency synchronization. In [7] a theoretical model and performance analysis for collaborative communication in sensor networks in presence of AWGN, Rayleigh fading and frequency offsets are presented. The theoretical results are confirmed by simulation and it is analyzed that substantial power gain and reduction in BER can be achieved with imperfect frequency synchronization. It is analyzed that power gain and BER depends upon the number of sensor nodes used in collaborative communication. But as the number of nodes increases the more operational power of the network (Circuit power) is required. So the total energy saving depends upon the energy gain and circuit energy used by the network. In this paper we have presented a model to investigate the energy efficiency using collaborative communication with imperfect frequency synchronization in Wireless sensor network. The trade-off analysis between the required circuit power and achieved power gain using collaborative communication is analyzed.

In [8]-[10] different energy efficient models for the SISO systems are proposed to investigate the optimized system parameters. It is observed that high power gain can be achieved using multi input and multi output (MIMO) systems but due to complex circuit in MIMO more operational (circuit) power is required. An energy consumption model for MIMO system is proposed, analyzed and compared with SISO in [11]. It is shown in [11] that for short range the SISO systems are more efficient than the MIMO systems. But for large transmission distances, the MIMO systems are more energy efficient than SISO. Energy efficiency of major cooperative diversity techniques such as decode-and-forward and Virtual multi input single output (MISO) are presented and analyzed in [12]. The results shows that decode-and-forward technique is more energy efficient than the virtual MISO [12].

In this paper an energy consumption model is proposed modeled and analyzed for collaborative communication with imperfect frequency synchronization by considering the system parameters of the off-the-shelf products CC2420 [15] and AT86RF212 [16]. The total energy required by collaborative communication is the sum of circuit energy and transmission energy for local communication (within the sensor network) and energy consumed by the sensor network and the base station. The energy consumption model for local communication and with the base station is presented. This model is compared with the SISO system without frequency offsets. The energy efficiency is calculated over different transmission distance for different frequency offsets, number of nodes used for collaborative communication (*N*) and CC2420 and AT86RF212. The break-even distance where the energy of SISO and collaborative communication is equal is also calculated.

The paper is organized as follows. Section 2 describes the collaborative communication model, Section 3 presents the energy consumption model for SISO and collaborative communication, Section 4 presents the analysis and results and section 5 gives the conclusions.

2 Collaborative Communication Systems

Let *N* be number of nodes in the network. The data needs to be transmitted to the base station is exchanged among the nodes. So, all the nodes transmit the same data to base station. Each node has the independent oscillator, there could be frequency offset in the carrier signal of each transmitted signal. The physical model is shown in Fig. 1.

In our recent work [7] a collaborative communication model with imperfect frequency synchronization is proposed in which one node in the network exchange the data with a set of nodes in the network denoted as collaborative nodes. All collaborative nodes transmit the data towards base station as shown in Figure 1.

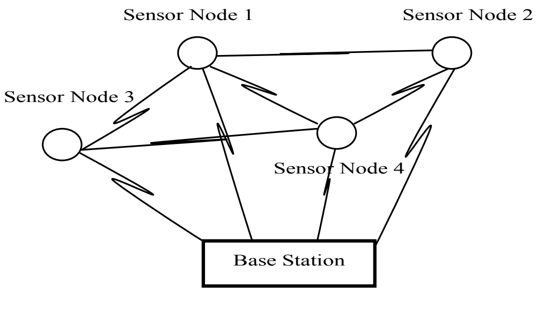

Figure. 1 Geometry of sensor Nodes [7]

As the sensor nodes have their own oscillators that may cause frequency mismatch among the transmitted signal. The proposed collaborative communication model can achieve high signal to noise ratio gain and reduction in BER with imperfect phase synchronization.

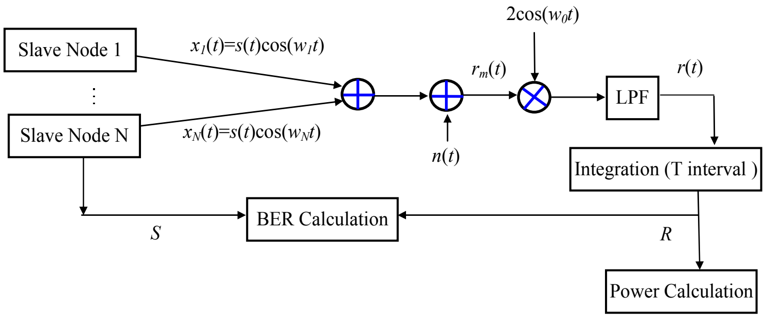

Figure. 2 Theoretical Model of the System [7]

2.1 Theoretical Model

Theoretical model of the system is shown in Figure 2. Let N collaborative nodes make a network to transfer the information from master node to the base station. Let $s(t)$ be the information data to be transmitted to base station.
The received signal at the base station is given by [7]

$$r_m(t)=\sum_{i=1}^{N}h_i s(t)\cos(w_i t)+n(t)\,, \tag{1}$$

where $n(t)$ is AWGN and h_i is the Raleigh fading.
After the modulation the signal at the decision circuit is given by [7]

$$R=\sum_{i=1}^{N}h_i S\frac{\sin(\Delta w_i T)}{\Delta w_i T}+n\,, \tag{2}$$

where Δw_i is the frequency error, $S = \pm\sqrt{E_b}$ is the signal amplitude and n is the noise amplitude at sampling time T.
The expressions of average received power and BER in the presence of frequency errors, AWGN and Rayleigh fading are derived and simulated in [7] and is given by

$$E[P_R]=NS^2\left[1+\frac{(w_eT)^4}{180}-\frac{(w_eT)^2}{9}\right]+\frac{N(N-1)b^2S^2}{2}\left[1-\frac{(w_eT)^2}{18}\right]^2+\frac{N_0}{2}\cdot \tag{3}$$

where w_e is distribution limit of frequency error and b is the mode of Rayleigh random variable h.
The probability of error of the received signal is given by

$$P_e=0.5\,erfc\left(\frac{\sqrt{\pi}\,b\left[1-\frac{(w_eT)^2}{18}\right]}{\sqrt{2}}\sqrt{\frac{N^2(E_b/N_0)}{\left(2Nb^2u(E_b/N_0)+1\right)}}\right). \tag{4}$$

where $u=0.429-0.048(w_eT)^2+0.0063(w_eT)^4$.

2.2 Analysis and Results of Collaborative Communication Systems

We have performed Monte Carlo simulation for the above system in MATLAB. BER in the presence of AWGN and Raleigh fading at the base station is shown in Figures 3, 4, 5 and 6.

It is analyzed that simulation results match nicely with theoretical findings, which confirm validity of our theory and simulation. To calculate the BER we set the energy per bit of each collaborative node to be E_b/N^2 i.e., total transmission energy is E_b/N. It is analyzed that BER decreases as the number of transmitter increases. It is the confirmation of the fact that collaborative communication overcomes the fading effect. These results is used in section 4 to calculate the energy saving.

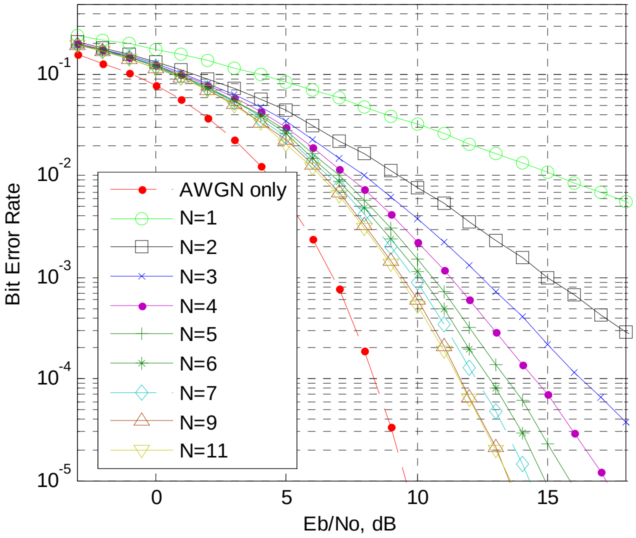

Figure 3: BER for CC2420 with total transmitted power E_b/N, frequency error 200 KHz and data rate 250 Kbps

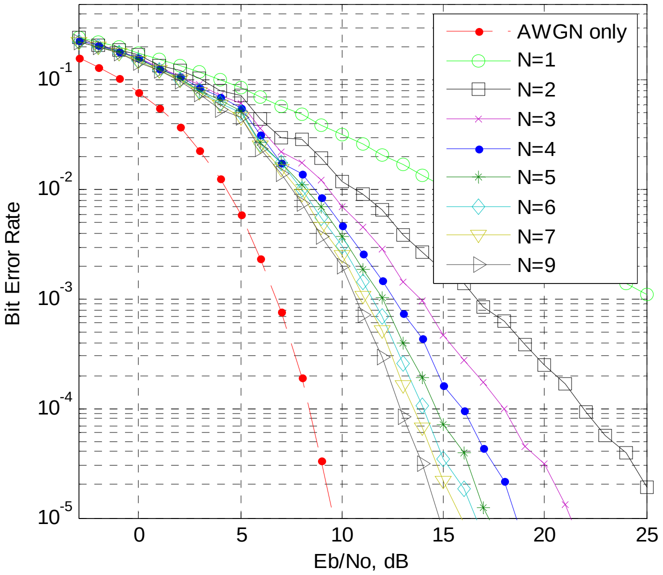

Figure 4: BER for CC2420 with total transmitted power E_b/N, frequency error 350 KHz and data rate 250 Kbps

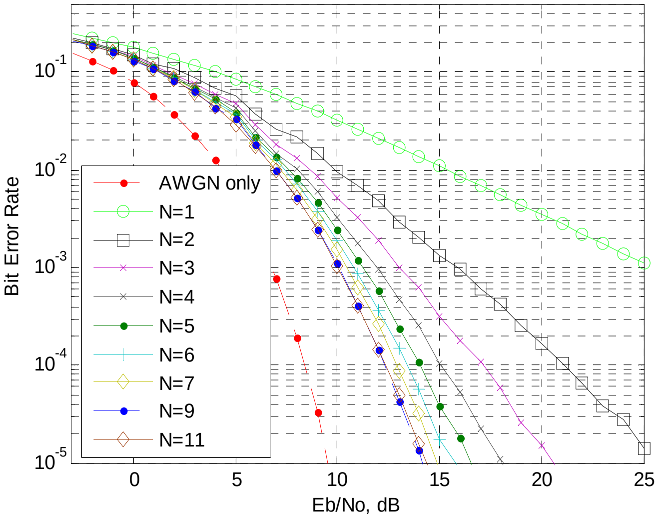

Figure 5: BER for AT86RF212 with total transmitted power E_b/N, frequency error 55 KHz and data rate 40 Kbps

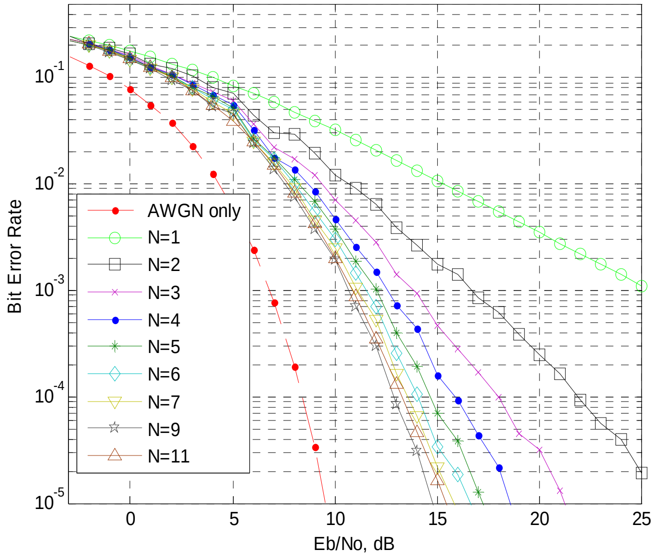

Figure 6: BER for AT86RF212 with total transmitted power E_b/N, frequency error 70 KHz and data rate 40 Kbps

3 Energy Efficiency of Collaborative Communications System

In this section we present an energy consumption model for collaborative communication system with imperfect frequency synchronization and SISO system. The energy consumption model is a function of the total received power, required circuit power and transmission distance. The developed energy consumption model is used to calculate the energy efficiency in wireless sensor network in presence of frequency errors.

3.1 SISO Energy Consumption Model

In SISO, there is single transmitter single receiver, so the total energy consumption is the sum of total power consumed by transmitter P_{tx} and receiver P_{rx}. The energy consumed by unit bit is given by

$$E_{SISO} = \left(P_{tx} + P_{rx}\right) / R_s \,, \tag{5}$$

where R_s is the transmission data rate.

The power required for data transmission in Rayleigh fading channel can be calculated by simplified path loss model (log-Distance path loss) [13]. The log-Distance path loss model has a concise format and captures the essence of signal propagation [14]. By assuming the transmitter antenna gain G_t and receiver antenna gain G_r equal to 1, P_{tx} is given by

$$P_{tx} = P_{cir} + \frac{(4\pi)^2 P_r d^{\alpha}}{d_0^{\alpha-2} \lambda^2} \,. \tag{6}$$

where P_{cir} is the power consumed by transmitter circuitry, P_r is the power of received signal, $\lambda = c/f_c$, c is speed of light, f_c is the carrier frequency, α is the path loss exponent, d is the actual distance between transmitter and receiver, d_0 is the reference distance for far-field region.

To achieve desired BER, minimum received power required P_r is given by

$$P_r = P_s \times r_{eber} \,. \tag{7}$$

where P_s is the receiver sensitivity (in Watt) required to achieve desired BER with AWGN only and r_{eber} is the E_b/N_o (in Watt) to achieve the required BER with Raleigh fading and AWGN.

The r_{eber} may be calculated as

$$r_{eber} = \frac{\left((1-2P_e)^2\right) / \left(1-(1-2P_e)^2\right)}{\left(erfc^{-1}(2P_e)\right)^2} \,. \tag{8}$$

where $erfc^{-1}$ is the inverse of the complimentary error function i.e., $erfc(x) = \frac{2}{\sqrt{\pi}} \int_x^{+\infty} e^{-t^2} dt$.

Using equations (5), (6) and (7), total energy consumed by SISO may be written as

$$E_{SISO} = \left(P_{cir} + \frac{(4\pi)^2 P_s r_{eber} d^{\alpha}}{d_0^{\alpha-2} \lambda^2} + P_{rx} \right) / R_s \tag{9}$$

3.2 Collaborative Communication Energy Consumption Model

According to the collaborative model is shown in Figures 1 and 2. The total energy consumption of collaborative communication system is the sum of energy consumed for local communication by sensor nodes within the network i.e., E_{local} and energy consumed for transmission with base station i.e., E_{long}. We have considered Rayleigh Fading channel within sensor network and between the sensor network and base station. The distance between collaborative nodes is different, but we have considered the maximum distance that gives the maximum energy consumed for local communication. The energy consumed by sensor network for local communication may be written as

$$E_{local} = \left(P_{tx\_local} + N P_{rx\_local}\right) / R_s \tag{10}$$

where N is number of collaborative nodes in the sensor network and P_{tx_local} can be calculated like SISO.

The energy consumption for communication between the sensor network and base station may be written as

$$E_{long} = \left(P_{tx\_long} + P_{rx}\right) / R_s \tag{11}$$

where P_{tx_long} is the total energy used by all (N) collaborative nodes.

The P_{tx_long} is given by

$$P_{tx\_long} = NP_{cir} + \frac{(4\pi)^2 P_{r\_long} d^{\alpha}}{N d_0^{\alpha-2} \lambda^2} \tag{12}$$

Minimum received power required to achieve desired BER P_{r_long} may be written as

$$P_{r\_long} = P_s \times r_{col\_ber} \tag{13}$$

where r_{col_ber} is E_b/N_o (in Watt) for the collaborative communication system with frequency error, Raleigh fading and AWGN and E_b/N_o (in Watt) for the system with AWGN only to achieve the required BER.

The r_{col_ber} may be calculated as

$$r_{col\_ber} = \frac{BER^{-1}(P_e, N)}{\left(erfc^{-1}(2P_e)\right)^2} \tag{14}$$

$BER^{-1}(.)$ is the inverse function of equation (4).

Using equations (11), (12), (13) and (14) the total energy consumed by collaborative communication system may be written as

$$Ecolab = \left(\begin{array}{l} P_{cir} + \dfrac{(4\pi)^2 P_s r_{eber\_local} d\_local^{\alpha}}{d\_local_0^{\alpha-2} \lambda^2} + NP_{rx} + \\ NP_{cir} + \dfrac{(4\pi)^2 P_{r\_long} d^{\alpha}}{N d_0^{\alpha-2} \lambda^2} + P_{rx} \end{array} \right) / R_s \tag{15}$$

The energy saving using collaborative communication model may be written as

$$E_{saving}(\%) = 100 \times \frac{E_{SISO} - E_{colab}}{E_{SISO}} \% \tag{16}$$

It is analyzed that for small transmission distance, the circuit energy is dominant over energy saved using collaborative communication. For a transmission range when energy consumed by SISO is equal to energy consumed by collaborative communication, the energy saving is 0% and this distance is called beak-even distance.

4 Analysis and Results of Energy Efficiency Model

For our analysis we have considered off-the-shelf RF product's circuit parameters i.e., CC2420 [15] and AT86RF212 [16]. The break-even distance for different number of collaborative nodes for different frequency errors are calculated. Maximum local distance among collaborative nodes is considered to be 1 meter and the required BER is 10^{-5}.

The reason to select these products is its support BPSK. The considered value of path loss exponent α is between 4.0 and 6.0 [17]. Product data and the parameters used for calculation of energy efficiency are shown in Table 1.

Figures 7, 8, 9 and 10 show the energy saving for different number of collaborative nodes and break-even distance. From results it is analyzed that the break-even distance increases as the number of collaborative nodes increases. AT86RF212 has more break-even distance and less energy savings than CC2420.

Table 1: Product data and parameters [15-16]

Symbol	**Description**	AT86RF212[15]	CC2420 [16]
-	modulation	BPSK	BPSK
w_0	operating frequency	915 MHz	2.45 GHz
Δw	Maximum Frequency error	55 KHz	200 KHz
R_s	transmission data rate (BPSK)	40Kbps	250Kbps
U	operating voltage (typical)	3 v	3 v
I_{rx}	currency for receiving states	9 mA	17.4 mA
P_{rx}	Receiving power, $P_{rx}= UI_{rx}$	27 mW	52.2 mW
I_{idle}	currency for idle states	0.4 mA	0.4 mA
P_{cir}	electronic circuitry power, $P_{cir} =UI_{idle}$	1.2 mW	1.2 mW
Psen	receiver sensitivity	- 110 dBm	- 95 dBm

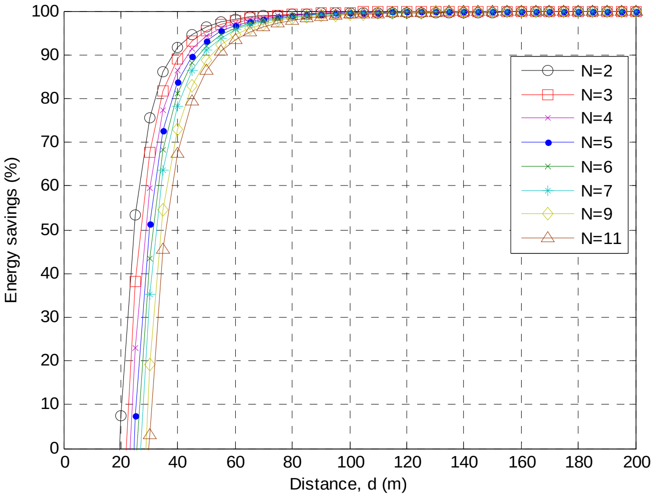

Figure 7: Energy saving and break-even distance with frequency error 200 KHz and data rate 250 Kbps for different *N* for product CC2420

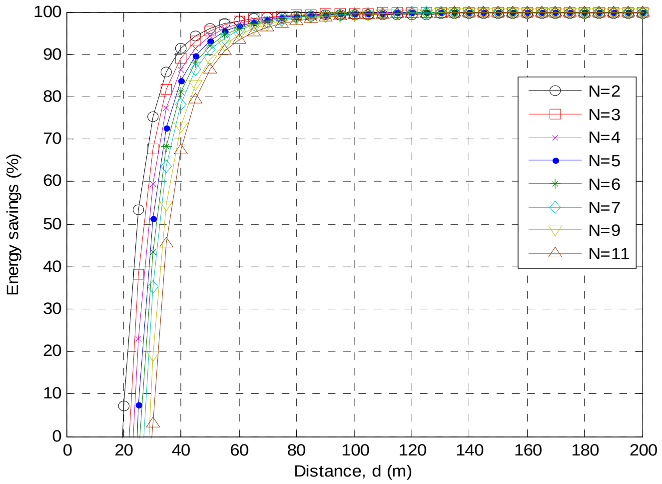

Figure 8: Energy saving and break-even distance with frequency error 200 KHz and data rate 350 Kbps for different *N* for product CC2420

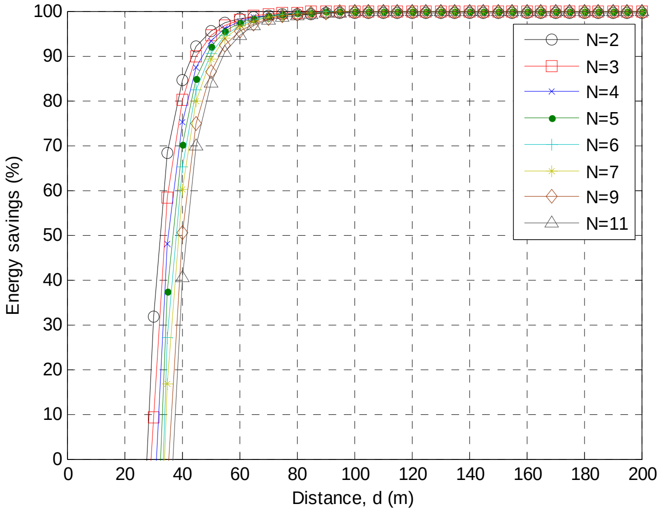

Figure 9: Energy saving and break-even distance with frequency error 55 KHz and data rate 40 Kbps for different *N* for product AT86RF212

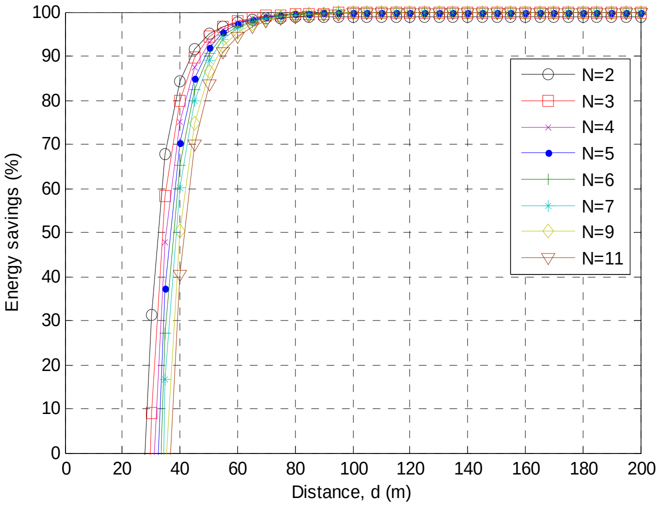

Figure 10: Energy saving and break-even distance with frequency error 70 KHz and data rate 40 Kbps for different *N* for product AT86RF212

The break-even distance for products CC2420 and AT86RF212 is summarized in Table 2 for different number of collaborative nodes. It is also analyzed that as the distance increases the energy saving using collaborative communication also increases. But after a certain distance it achieves its steady state. The energy saving for different frequency errors at distance 60m and 100m for products CC2420 and AT86RF212 are sumarized in Tables 3. From tables 2 and 3 it is also analyzed that for products CC2420 and AT86RF212 the 5 collaborative nodes produce significant energy saving using collaborative communication.

Table 2: Break-even distance for CC2420 and AT86RF212

N	Break-even Distance CC2420	Break-even Distance AT86RF212
2	19m	27.5m
3	22m	29.5m
4	24m	31m
5	25m	32.5m
6	26m	33.5m
7	27m	34m
9	29m	35.5m
11	30m	37m

Table 3: Energy Saving (%) for CC2420

N	CC2420		AT86RF212	
	100m	60m	100m	60m
2	99.73	99	99.45	98
3	99.9	98.7	99.83	98
4	99.94	98.6	99.86	97.5
5	99.96	98.3	99.85	97
6	99.96	98.1	99.84	99.5
7	99.96	97.5	99.8	96
9	99.5	96.5	99.75	95
11	99.4	96	98.7	94

5 Conclusions

We have presented an energy efficiency model for collaborative communication in sensor networks with imperfect frequency synchronization in the presence of noise and Rayleigh fading. The theoretical model of the system is presented, expression for energy consumption and energy saving is derived. The model is analyzed by consider two off-the-shelf products CC2420 and AT86RF212. It is concluded that using collaborative communication 99% energy can be saved with imperfect frequency synchronization. It is also concluded that collaborative communication is very useful when the distance between transmitters and base station is greater than break-even distance. It is also concluded that break-even distance increases as the number of collaborative nodes increases. It is also concluded that collaborative communication of 5 sensor nodes can save energy efficiently. It is included that energy saving increases as the distance between transmitter and base station increases, but after certain distance it achieves the steady state. It is also concluded that the AT86RF212 achieves steady state rapidly than the CC2420.

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