Capacity Gain in Spread Spectrum Based Collaborative Communication in Wireless Sensor Networks

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Abstract

Even with imperfect phase and frequency synchronization, collaborative communication can mitigate the effect of fading and produce a significant gain in received power. This article investigates the benefits of spread spectrum based collaborative communication in the presence of noise and fading. A mathematical expression for calculating capacity gain is derived showing that the use of spread spectrum significantly suppresses the effect of noise and fading. The proposed model is analyzed as well as compared with the simulated results to gauge its performance. The results show that channel capacity behaves as a function of the number of collaborative nodes and channel parameters. It can be concluded that the use of collaborative communication in combination with spread spectrum reduces energy consumption leading to improvement in network capacity.

Keywords: Wireless sensor networks, Collaborative communication, Capacity gain, Wideband channel

1 Introduction

The scarce nature of energy source in wireless sensor networks *(WSN)* makes energy efficient communication a crucial requirement. It has been seen that high gain in received power is possible through collaboration in Wireless networks [1-9], if frequency and phase synchronization is achieved. But a fundamental problem with such kind of networks is a measurement of their capacity.

Collaborative communication can produce gain in received power and improve error rate even in the presence of imperfect phase synchronization [2]. This article combines the inherent benefits of spread spectrum with collaboration to improve received power and network capacity gain in the presence of fading and noise. Spread spectrum is famous for its success against inter-symbol interference (ISI) and mitigation of noise effect [10-12]. It also offers other benefits, like immunity against crosstalk interference, multipath fading, jamming and provide inherent security, greater coverage capability. Spread spectrum uses a much wider band than conventional narrowband systems (order of 20 to 254 times) [12]. The wastage of bandwidth due to spreading is recovered from, by allowing multiple users to use the same frequency, presented in Figure 1.

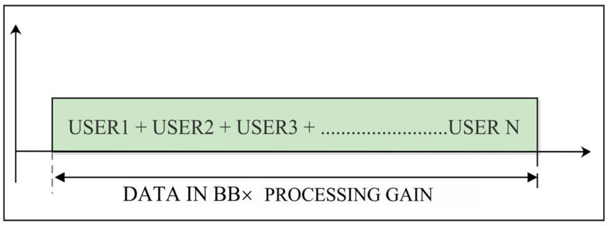

Figure 1. Universal frequency reused by spread spectrum

The traditional method of measuring capacity of a system in cellular network can be applied to sensor networks within star configuration, where a sensor node communicates directly with a base station (BS) [13]. Using collaboration in sensor networks, aims at achieving spatial diversity, to gain benefits like improvement in the received power and ultimately high gain in capacity. However, calculating network capacity of such system is a challenging task [14-16].

The major contributions of this article are; (1) a mathematical model for computing capacity gain of spread spectrum based collaborative communication where the received signals are considered to be noisy (AWGN) and out-of-phase. (2) A theoretical expression proving that an increase in the number of collaborative nodes significantly improves power and capacity gain. (3) A technique to reduce the transmit power of each collaborative node thereby saving its energy. The benefits are further enhanced by the use of spread spectrum due to its inherent features.

It is evident from the results that simulated and theoretical results are almost matching. The use of

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wideband channels in combination with collaborative communication successfully mitigated the noise and fading effects leading to significant gain in capacity.

2 Related Work

Recently a considerable amount of efforts and time has been invested in investigating diversity gains in cooperative communication [17] and beamforming [3, 18]. Multi-way channels are extensively investigated in [14] covering channels introduced till 1976. An extensive analysis of the relay channels is part of the study. In [15], theorems for calculating capacity of different channels like feedback relay, reversely and Gaussian degraded channels are presented.

The authors in [19] argued that maximum diversity gains in amplify-&-forward and "decode-&-forward" relays is directly related to the number of degree of freedom in the channel. This scheme has been extended in [20], to develop space-time code based system and prove that diversity gain can be achieved. In [21], a tradeoff between diversity and multiplexing for traditional MIMO with centralized array antenna is presented.

Using Nakagami [22] and independent non-identical Rayleigh channels [23], a closed form expression for forward relay [16, 24] and cooperative diversity [25] has been derived. To provide a solution for the upper and lower capacity bounds in the case of BER and capacity of the channel. Authors in [22] and [26] presented and analyzed channel capacity for cooperative and noise channels.

The work previously done on the cooperative transmission is unable to solve the issues of synchronization. To address these issues, the idea of collaborative communication and beamforming [1-3, 5, 7, 9, 18, 27] were introduced. One such effort to calculate the capacity gain in a randomly distributed sensor network using collaborative communication for noisy channel with fading has been present presented in [1, 2]. In channels with Rayleigh fading and noise, strategies like compress-&-forward or decode-&-forward may be applied [6]. The capacity gain for a randomly distributed wireless network with n nodes has been presented in [13] where the distribution of node is considered to be over an area of $1m^2$.

The focus here is on improving power efficiency in *WSN* using distributed space-time coding with single hop communication between the collaborative nodes and the *BS* to achieve diversity gain, not multiplexing gain. Therefore, the *BS* is considered to be a single antenna receiver. A scheme similar to the proposed scheme has been presented in [28], using non-negative repeater relay and network nodes. It is a type of virtual *SISO* channel in the context of routing in wireless ad-hoc networks.

This article considers synchronization as a degenerating factor as well as an averaging effect. In the first case, it affects performance because of inter-symbol interference and co-channel interference and in the latter case it improves predictability and reliability of the channel. However, the requirement is more relaxed beamforming [3], where timing and phase synchronization of the collaborative nodes, is a strict requirement.

3 System Model

3.1 Assumptions

The following assumption are taken into consideration while developing the proposed model.

a. Randomly distributed (m-collaborative nodes) transmit same data at the same time to a common receiver (*BS*) using same modulation.

b. The noise is zero-mean *AWGN*.

3.2 Description

In random distribution of nodes in sensor network, the exact location of a sensor is difficult to determine. Secondly, in the absence of central controller [7-8], it is almost impossible to achieve phase, frequency and time synchronization. It may lead to errors in estimating the position of sensor nodes - displacement error. As a consequence reception at the *BS* is out-of-phase. To achieve high power gain, collaborative communication must synchronize the received signals in time, phase, and frequency. In addition to synchronization, collaboration should exploit features of spread spectrum to achieve space/antenna diversity to improve the signal-to-power ratio and reduce bit-error-rate (BER) [29]. Only one signal component is considered to be received by the receiver per node, i.e. multipath scenario is not considered.

However, fully synchronizing the system is almost impossible, since position estimation gives the probable position of the transmitter. Therefore, a spread spectrum based collaborative architecture has been proposed where each node uses the same carrier to transmit the same information at the same time as shown in Figure 2.

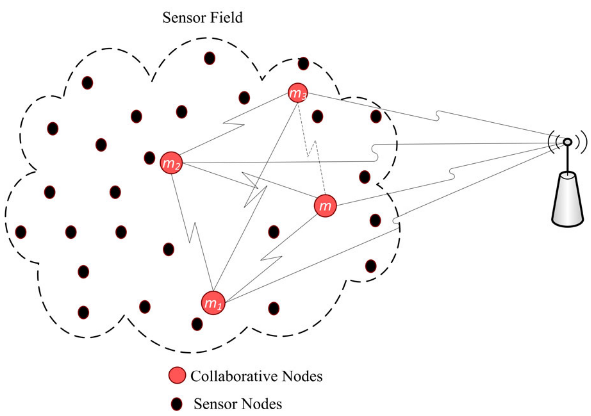


Figure 2. Geometry of sensor nodes

3.3 Mathematical Model

The proposed system with m nodes, each transmitting signal $x(t)$ towards the *BS*. The signal of each node is correlated with a unique pseudo-random chip code c_i of length l. The channel has Rayleigh fading and AWGN as shown in the Figure 3.

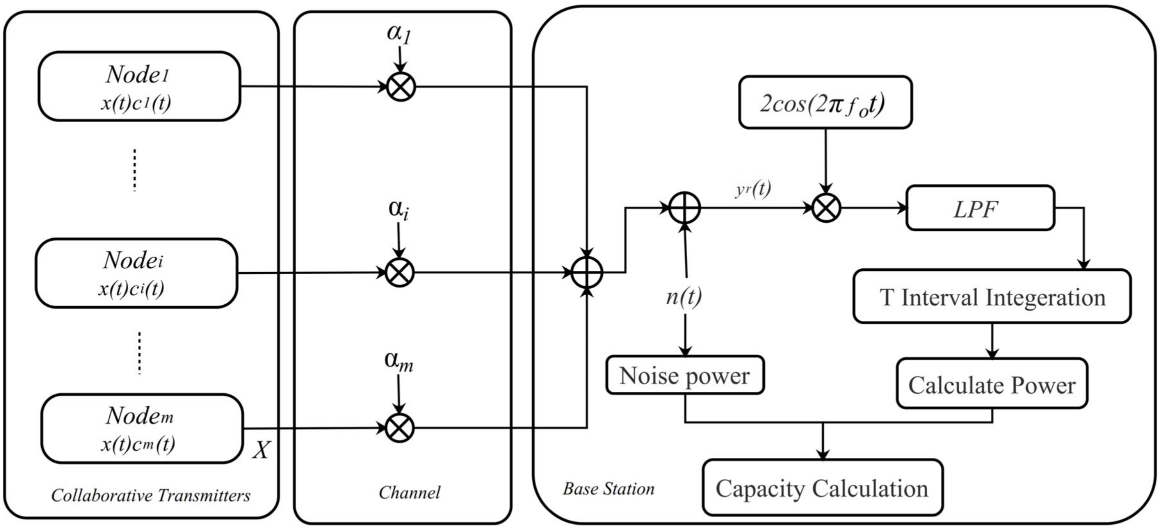


Figure 3. System model

If d_0 and f_0 are nominal distance and carrier frequency respectively with line-of-sight propagation, then the phase produced by d_0 is $\Theta_0 = 2\pi f_0 d_0 / c$, where c is the speed of light. Due to estimation error, let the d_i, is the distance which if translated into phase error produces $\Theta_i = 2\pi f_0 d_i / c$. If $\cos(2\pi f_0 t)$, is the carrier signal and the delay spread is almost negligible as compared to bit length discouraging any chances of inter-symbol interference which are even further diminished by the use of spread spectrum chip code.

Data $x(t)$ at the sender is first correlated with the chip sequence and modulated using $\cos(2\pi f_c t)$, resulting in the following signal,

$$s(t) = \frac{1}{\ell} x(t) c(t) \cos(2\pi f_c t) \tag{1}$$

where ℓ is the length of *PN* sequence and f_c is modulation frequency. The received signal form all m nodes, at *BS* with phase error Θ_i is as follow

$$y(t) = \frac{1}{\ell} \sum_{i=1}^{m} \sum_{j=1}^{\ell} \alpha_i x(t) c_j(t) \cos(2\pi f_c t + \Theta_i) + n(t) \tag{2}$$

where α_i is fading co-efficient of $i^t h$ signal and $n(t)$ is additive white Gaussian noise *AWGN*. The signal received in equation (2) is demodulated, and De-correlated against the *PN* sequence c_j. We also know from the properties of spread spectrum self correlation of chip code always gives 1 i.e, $\frac{1}{\ell}\sum_{j=1}^{\ell} c_j \times c_j = 1$, quation 2 can be rewritten as

$$Y = [\sum_{i=1}^{m} \alpha_i X \cos(\Theta_i) + \frac{1}{\ell}\sum_{j=1}^{\ell} n \times c_j] \tag{3}$$

where amplitude of signal and noise are $X = \pm\sqrt{E}$ and and n respectively.

To calculate the power of the received signal P_Y, it is clear that α_i, Θ_i, n and c_j are independent random processes, distributed identically, so the expected value of power is calculated at the receiver. It is also known that the correlation between noise and chip sequence results in variance of noise divided by the length of the chip sequence. Therefore, the expected value of the received power can be expressed as

$$E[P_Y] = E[\sum_{i=1}^{m} \alpha_i X \cos(\Theta_i)]^2 + \frac{\sigma_n^2}{\ell} \tag{4}$$

summation can be taken inside, since its a linear operator, let $n = \sigma_n^2$, represent noise power, then the above can take the following from

$$E[P_Y] = \sum_{i=1}^{m} X^2 [\cos^2(\theta_i)] E[\alpha_i^2] + \sum_{i=1}^{m}\sum_{\substack{j=1 \\ j\neq 1}}^{m} X^2 [\cos(\theta_i)\cos(\theta_j)] E[\alpha_i \alpha_j] + \frac{N}{\ell} \tag{5}$$

as Θ_i, Θ_j, h_i and h_j are i.i.d random, therefore, $E[\Theta_i] \approx E[\Theta_j] \approx E[\Theta]$, $E[\alpha_i] \approx E[\alpha_j] \approx E[\alpha]$ and $E[\alpha_i^2] \approx E[\alpha^2] = 1$. From [30] its evident that

$Var(\alpha) = \sigma_\alpha^2 = (2 - \frac{\pi}{2})b^2$ and $E(\alpha) = \mu_\alpha = (\sqrt{\frac{\pi}{2}})b.$

Mean values of cosine taken from (11), (12) (see Appendix), and value of expectation of α taken from (14), equation (5) can be written as

$$E[P_Y] = mX^2[\frac{1}{2} + \frac{\sin(2\phi)}{4\phi}] + \frac{\pi m(m-1)b^2X^2}{2}[\frac{\sin(\phi)}{\phi}]^2 + \frac{N}{\ell} \quad \textbf{(6)}$$

φ is bound Rayleigh distribution and *b* is the mode of Rayleigh fading respectively. An observation of equation (6) shows that number of nodes *m* is directly related to the gain in received power. This gain is further improved by the use of spread spectrum where *PN* sequence mitigates the effect of noise. The power of noise is inversely affected by the length of the *PN* sequence. So the long the *PN* sequence, the less the effect of noise.

$$C = \frac{1}{2}\log_2(1 + \frac{S}{N}) \quad \textbf{(7)}$$

Equation (7) is combination of signal and noise components. Therefore, capacity gain of collaborative communication can be calculated as follow

$$C = \frac{1}{2}\log_2(1 + (m[\frac{1}{2} + \frac{\sin(2\phi)}{4\phi}] + \frac{\pi m(m-1)b^2}{2}[\frac{\sin(\phi)}{\phi}]^2)\frac{\ell P}{N}) \quad \textbf{(8)}$$

here $P = X^2$ represents signal power.

In case where signals from all collaborative nodes are perfectly synchronize which means $\theta = 0$, then capacity gain of collaborative communication is given by

$$C = \frac{1}{2}\log_2(1 + [m + \frac{\pi m(m-1)b^2}{2}]\frac{\ell P}{N}) \quad \textbf{(9)}$$

Special Case: When P = m

In case each node transmits a power of $P = m$, then equation (7) can be rewritten as

$$C = \frac{1}{2}\log_2(1 + [(\frac{1}{2} + \frac{\sin(2\phi)}{4\phi}) + \frac{\pi(m-1)b^2}{2}(\frac{\sin(\phi)}{\phi})^2]\frac{\ell P}{N}) \quad \textbf{(10)}$$

Equation (10) shows reduction of transmitted power by a factor of *m*. Means increasing the number of collaborative nodes; transmit power of each node be reduced, leading to longer lifetime of the network. The effect of this reduction can be investigated on the capacity gain in total transmitted power. An analysis of results produced in this section has been presented in section 4.

4 Results and Discussion

Monte Carlo simulation of the proposed system is performed to analyze the capacity gain of *WSNs* using spread spectrum based collaborative communication. Considering the received signals from different nodes are not in perfect synchronization. AWGN and Rayleigh fading blocks of SIMULINK environment of MATLAB are used. The curves obtained during the experiments show that the simulated and analytical results are a perfect match.

The proposed system is tested with no phase error i.e. perfect phase synchronization. In this case the theoretical results become equal to simulated results, proving the correctness of the proposed scheme as shown in Figure 4.

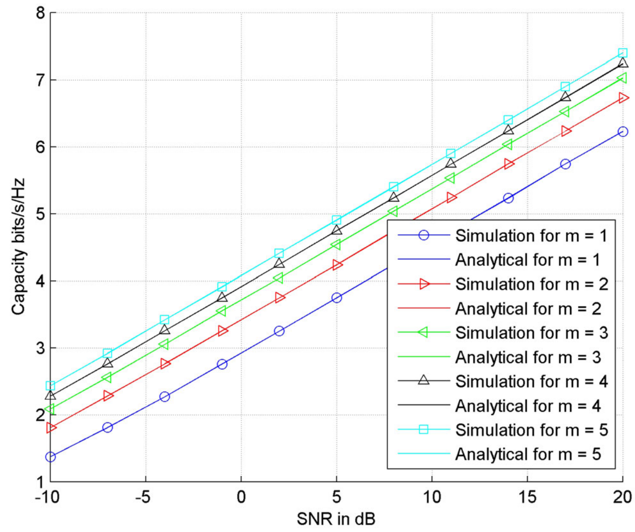


Figure 4. Capacity gain in case of perfect phase synchronization in the received signal $\theta = 0$

In addition to the imperfect synchronization in phase, the proposed approach is also analyzed under the effect of fading and noise. Different error distributions are considered for phase error. The analysis of the proposed approach has been divided into two different cases.

Case-I:

In the first case the phase error is considered to be distributed over {−0.1π~0.1π} interval. Here *P* is considered to be the transmit power of each transmitter node. So the transmitted power of *m* transmitters is $m \times P$. Results for the first case are shown in Figure 5 and Figure 6.

Figure 5 and Figure 6, show that an increase in the number of collaborative nodes affect the results in two ways. First, gain in capacity increases and second, the gap between the simulated and analytical results closes. Therefore, increasing the number of collaborative transmitters will improve the results by reducing the required transmission power per node and narrowing the gap between simulated and analytical results.

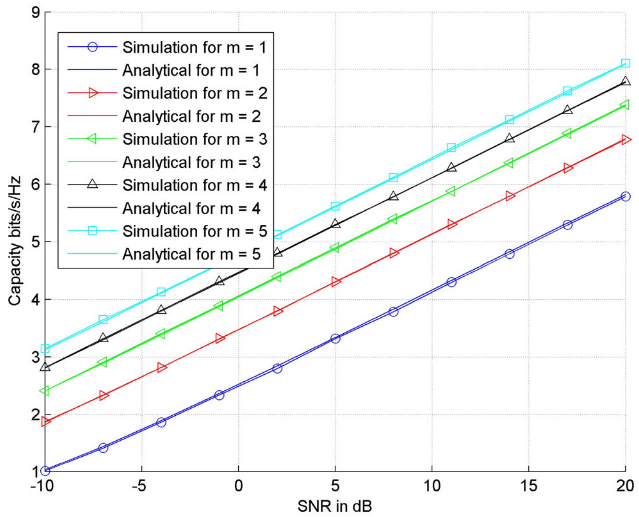


Figure 5. Capacity for phase error distributed over {−0.1π~0.1π} and each node transmits power P, so total transmitted power by the network is *mP*

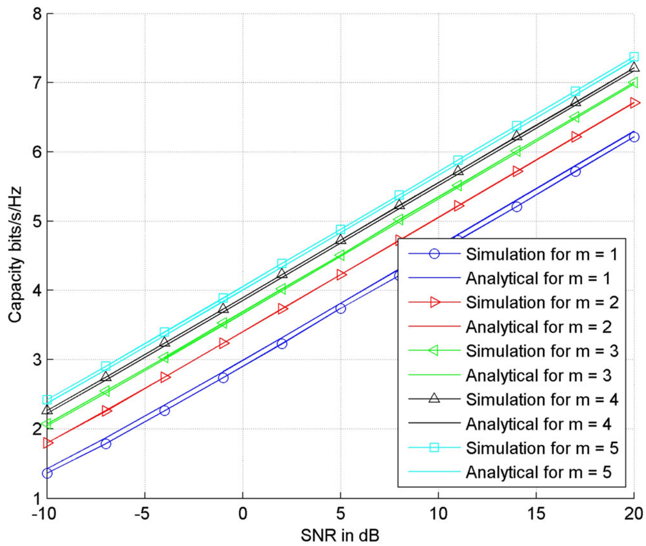


Figure 6. Capacity for phase error distributed over {−0.4π~0.4π} and each node transmits power *P*, so total transmitted power by the network is *mP*

Another reason for the slighter gap between the simulated and analytical results may be the approximation applied during the Mathematical derivation of the proposed approach.

Case-II:

Here the distribution of phase error is considered {−0.4π~0.4π}. The transmit power of each node is considered as *P/m*, leading to a total network transmitted power *P*. Results produced in this case are shown in Figure 7 and Figure 8. It can be seen that the analytical and simulated results are a match.

Figure 7 and Figure 8, reveal that the power transmitted by the network in total is reduced by a factor *m*, where *m* where *m* represents the number of collaborative nodes. It means reducing the transmit power by this factor and still produces significant capacity gain is the success of collaborative

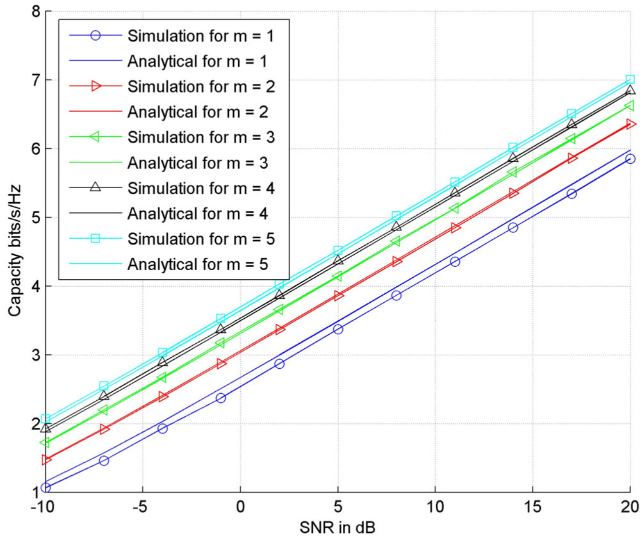


Figure 7. Capacity for phase error distributed over {−0.1π~0.1π} and each node transmits power *P/m*, so total transmitted power by the network is *P*

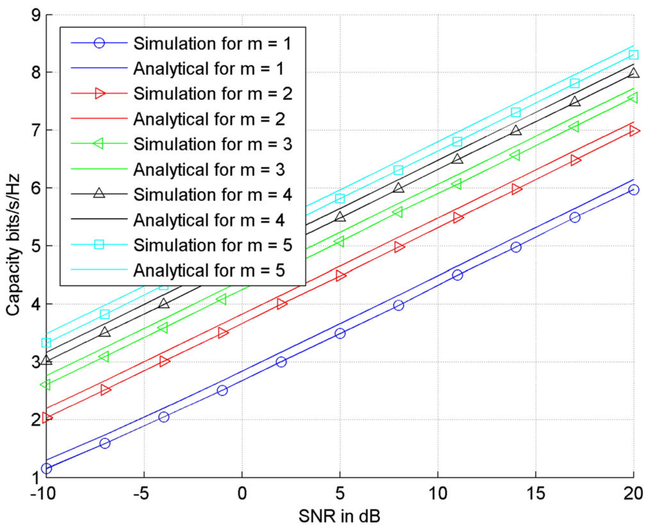


Figure 8. Capacity for phase error distributed over {−0.4π~0.4π} and each node transmits power *P/m*, so total transmitted power by the network is *P*

communication. Analysis, of the analytical results from equation 7, equation 10, and simulated results is performed. It shows that if the transmit power is reduced by a factor m, it affects the capacity gain only by a factor of $0.5\ log_2(m)$, even if there is noise and fading in the channel and the received signals are unsynchronized in phase.

Overall analysis from Figure 5, Figure 6, Figure 7 and Figure 8 confirms that capacity gain has a direct relation with the number of collaborative nodes. It is also evident that phase error has inverse effect on the capacity gain. A decrease of 0.3 bits/sec/Hz is recorded in capacity gain over the phase error distribution from {−0.1π~0.1π} to {−0.4π~0.4π}.

The proposed approach is further validated by the results of comparative analysis with Cui et al. [32], Marcelo et al. [33], Jayaweera et al. [34] and Dohlar et al. [35]. The comparison is based on the power, energy and BER gains achieved by these approaches as shown in Table 1.

Table 1. Comparison with other state-of-the-art approaches

Cui et al. [31]	$\frac{1}{2}\log_2(N-2)$
Marcelo et al. [32]	$\frac{1}{2}\log_2(N-2)$
Jayaweera et al. [33]	$\frac{1}{2}\log_2(N-2)$
Dohlar et al. [34]	$\frac{1}{2}\log_2(N)$
Proposed Approach	$\log_2(N)$

The proposed system computes the system capacity from SNR values shown in equation 8 where the signal power is calculated using equation 6 (Shannon's capacity theorem). The same model has been used in our previous work for calculating power gain and energy savings in Ghani et al. [35]. It is proved that using collaborative communication can achieve a gain in received power equal to the square of the number of collaborative nodes as shown in Figure 4 [35]. Similarly, achieving a BER of 10^{-4} requires an SNR of 7.5dB as shown in Ghani et al. [35] Figure 5, whereas Dohlar et al. [34] requires 13.5dB to achieve the same BER value. It is clear from Table 1 that the proposed approach produces 50% better performance in comparison to the other approaches.

Capacity calculation in the proposed model of collaboration is helpful as desired capacity is maintained even with reduced power transmitted by the network which prolongs network life. If the network configuration is complex, the proposed method can be used to reduce overall power consumed by the network.

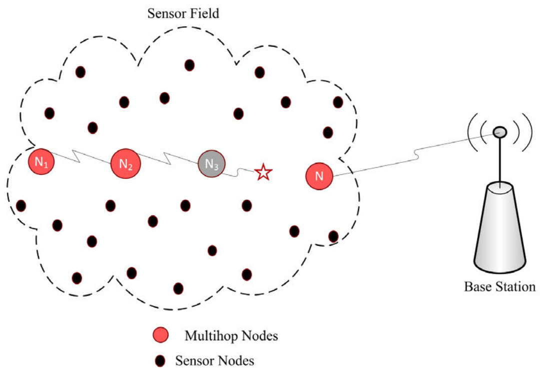
4.1 Comparison with Other Approaches

The capacity gain is related to power gain in wireless communication. A brief theoretical comparison to analyze capacity gain of spread spectrum based collaborative communication with Multihop and Cooperative communication [27, 36-37] is presented.

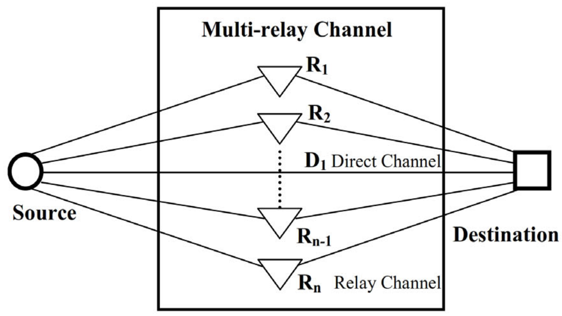
4.1.1 Collaborative vs. Multihop Communication

In multihop communication a sender sends information to a BS passed by other intermediate nodes [24, 38]. It is designed to improve energy consumption and ultimately prolong network's lifetime in *WSN*. However, this approach faces problems when the routing (many approach strive for energy efficient routing [39]) becomes complex and lost data packet is to be retransmitted. Power gain, in this case, is the sum of the power gain of each node. For example, in a four nodes setup ($N = 4$) where each *1m* range, a maximum of, up to *16m* transmission range can be achieved. If range extension is required or a node dies (disconnect ongoing communication) new node must be added. In this scenario, collaborative communication achieves a range of *64m*, by producing a square of the power of each node. Furthermore, it improves the range by reducing transmission power per node and mitigating the effect of noise.

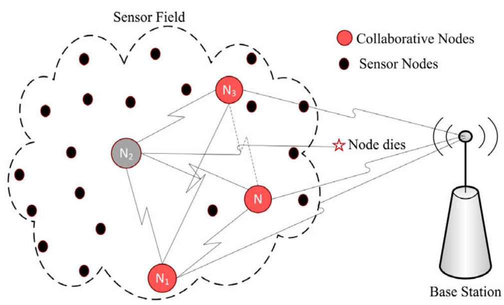
Collaborative communication is usually not affected by a node's death shown in Figure 9c, thus avoid any disruption in ongoing communication. However, in the case of multihop communication, the death of node may cause zero capacity gain and highest BER until new node is searched for and incorporated into the multihop path as shown in Figure 9a.



(a) Multihop system in case of node death



(b) Multihop cooperative communication



(c) collaborative communication in case of node death

Figure 9. Comparison of collaborative and multihop communication in case node death

4.1.2 Collaborative vs. Cooperative Communication

Cooperation communication uses intermediate relay nodes to deliver data to BS [25, 40-41]. Collaborative communication considers all nodes at one hop from the BS. For a N number of cooperative nodes cooperative communication can achieve N times gain in the received power leading N times gain in capacity as capacity is directly calculated from the power of the received signal. Similarly, it can reduce transmission power l times per node where l is the number of relay level. So instead of sending information over long distances, in cooperative communication a node just forwards its data to a nearby relay node to preserve power source which results in prolonged network life, as shown in Table 2.

Table 2. Comparison of capacity gain in terms of power

S/No.	Scheme / Approach	Power Gain	Transmission Power
1	Proposed	$l \times N^2$	$(1/N\times l)\ T_{xp}$
2	Multi hop	N	$N \times T_{xp}$
3	Cooperative	N	$1/l \times T_{xp}$
4	Beamforming	N^2	$1/N\times T_{xp}$

Cooperative communication resolved the problem of communication breakage in multihop communication by introducing multiple intermediate relay nodes. However, it increase the routing complexity. Furthermore, some relay nodes have to forward the received data from a neighbour just for the sack of cooperation. It role may not have an effect on the overall communication. In contrast to cooperative communication, collaborative communication exploit the benefits of spatial diversity to produces N^2 gain in received power. Furthermore, it combines the power of all collaborative nodes in a way to that reduces the transmitted power T_{xp} of each node by a factor of $N \times l$. The advantage here is twofold in the form of significant improvement in energy consumption and gain in the capacity of the system.

4.1.2 Collaborative Communication Vs Beamforming

Collaboration and beamforming are closely related with minor differences [38]. To mitigate the effect of interference and channel fading beamforming uses antenna adjustment approach to stair the combined power of antennas in a specific direction. It leads to high quality of service and increases the coverage range. so the gain in received power and gain in capacity both are almost the same in case both use the same channel. As the proposed scheme is based on wideband channels, therefore, there is an improvement in the power reduction per sensor node as well as gain in the capacity of the system, as shown in Table 2.

5 Conclusion

A spread spectrum based collaborative communication system to investigate capacity gain in *WSN* is presented. Received signals at the *BS* are considered out-of-phase while the channel has the effect noise and fading. It has been observed that the gain in capacity behaves as a function of *SNR* directly related to the number of collaborative nodes. It is also noted that an increase in the phase error degrades capacity gain. However, the use of spread spectrum technique mitigates the effect of noise, which in turn improves the gain in capacity. Collaborative communication also exploits the feature of spatial diversity of transmitter nodes to reduce the transmission power per node by a factor of m (m being the number of total transmitters) resulting in m^2 gain in received power. The higher the strength of received signal, the greater is the SNR ultimately leading to a high gain in capacity.

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Appendix

A.1 Mean value of $\cos(\theta_f)$

$$
\begin{aligned}
E[\cos(\theta_f)] &= \int_{-\infty}^{\infty} \cos(\theta_f) P(\theta_f) d(\theta_f) \\
&= \int_{-\phi}^{\phi} \cos(\theta_f) \frac{1}{2\phi} d(\theta_f) \\
&= \frac{1}{2\phi} \int_{-\phi}^{\phi} \cos(\theta_f) d(\theta_f) \\
&= \frac{\sin(\phi)}{\phi}
\end{aligned} \tag{11}
$$

A.2 Mean value of $\cos^2(\theta_f)$

$$
\begin{aligned}
E[\cos^2(\theta_f)] &= \int_{-\infty}^{\infty} \cos^2(\theta_f) P(\theta_f) d(\theta_f) \\
&= \int_{-\phi}^{\phi} \cos^2(\theta_f) \frac{1}{2\phi} d(\theta_f) \\
&= \frac{1}{2\phi} \int_{-\phi}^{\phi} \cos^2(\theta_f) d(\theta_f) \\
&= \frac{1}{2\phi} (\phi + \frac{\sin(2\phi)}{2}) \\
&= \frac{1}{2} + \frac{\sin(2\phi)}{4\phi}
\end{aligned} \tag{12}
$$

A.3 Variance of cos(θ_f)

$$Var(\cos(\theta_f)) = E[\cos^2(\theta_f)] - (E[\cos(\theta_f)])^2$$

Using equation 11 and 12 in the above equation we get

$$Var(\cos(\theta_f)) = (\frac{1}{2} + \frac{\sin(2\phi)}{4\phi}) - (\frac{\sin(\phi)}{\phi})^2 \quad \textbf{(13)}$$

A.4 Variance of αXcos(θ_f)

Since all of these are independent random variables, therefore, the multiplication can be calculated as

$$\begin{aligned} Var[\alpha X\cos(\theta_f)]) = X^2[Var[\alpha](E[\cos(\theta_f)])^2 + \\ (E[\alpha]^2 Var[\cos(\theta_f)] + Var[\alpha]Var[\cos(\theta_f)]] \end{aligned} \quad \textbf{(14)}$$

Since we know from Equations 11 and 13 that $Var(\alpha) = \alpha_\alpha^2 = (2 - \frac{\pi}{2})b^2$ and $E[\alpha] = \mu_h = (\sqrt{\frac{\pi}{2}})b$ by putting these values in Equation 14, we get

$$Var[\alpha X\cos(\theta_f)]) = b^2 X^2 [1 - \frac{\pi}{2}(\frac{\sin(\phi)}{\phi} + \frac{\sin(\phi)}{2\phi})] \quad \textbf{(15)}$$