IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received December 28, 2018, accepted January 25, 2019, date of publication February 18, 2019, date of current version March 12, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2898565

Energy Efficiency in Multipath Rayleigh Faded Wireless Sensor Networks Using Collaborative Communication

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This work of A. Ghani was supported in part by the Higher Education Commission (HEC) of Pakistan under the Indigenous 5000 Ph.D. fellowship program Phase-IV.

ABSTRACT Deployed in harsh or hostile environments, it is usually impossible to replace/recharge the power source of a sensor node in a wireless sensor network. Therefore, the only solution is an energy efficient communication system. This paper presents an energy efficient system based on multipath collaborative communication having noise and fading. The collaborative communication exploits spatial diversity to achieve high gain in received power, low bit error rate *(BER)*, and high energy savings even if the received signals are out-of-phase. The experimental results confirm that the benefits are further enhanced by the use of the multipath environment in combination with collaborative communication. For the trade-off analysis between energy consumption and transmission distances, the multipath collaborative communication is compared with the single-input-single-output (*SISO*) system. Collaborative communication performs better over the long distance; however, the *SISO* is suitable for short distances. The proposed collaborative communication system can achieve 99% energy savings in comparison to the *SISO* system.

INDEX TERMS Wireless sensor networks, collaborative communication, energy efficiency, multipath communication, energy consumption.

I. INTRODUCTION

Wireless Sensor Network (WSN) usually consists of hundreds or even thousands of miniature devices (referred to in this paper as sensor node, sensor, node, or collaborative node) designed to interact with the environment. WSN has numerous applications in healthcare [1]–[3], education, industry, security, military, wildlife monitoring and many others [4], [5]. The emergence of recent technology, such as Internet-of-things (IoT) and Fog Networks, opened new venues for applications of WSN [6]–[10]. However, WSN itself suffers from various issues like resource scarcity, especially limited power source [11]. In random deployments for monitoring harsh environments like battlefield or volcanic area, it is often impossible to recharge or replace the power/energy source of a sensor node. Therefore, developing a communication system for such devices is more challenging than ever.

Over the years many techniques have been proposed to optimized the energy consumption of WSN to save its power source and prolong the overall network lifetime [2], [11]–[15]. One viable solution is multihop communication where the signal received by a sensor node is forwarded to the next sensor node closer to the base station [16]. It is an excellent approach to reduce power consumption of the sensor by preventing it from transmitting over long distances. Each node has to transfer the received signal to its next nearest neighbor at a short distance. However, failure of a single node in the multihop path breaks the whole communication where retransmission may be required.

The associate editor coordinating the review of this manuscript and approving it for publication was Gongbo Zhou.

The retransmission not only affects the sender node but every other node on the multihop path in terms of power consumption. Furthermore, it incurs extra overhead in routing over long distances [17]. Such shortcomings are addressed by the emergence of cooperative communication which uses the concept of spatial diversity to resist against channel fading and interference through wireless broadcast advantage (WBA). Various approaches, for example, Detect & Forward, Amplify & Forward, Compress & Forward, etc have been proposed to achieve cooperation among sensors [18], [19]. These approaches perform well when the convergence communication is synchronized, however, fail in case of imperfect synchronization. it also suffers from other challenges like complex scheduling, increased overhead, increased interference, extra traffic, etc.

Recently, collaborative communication has been introduced as an energy efficiency techniques in WSN. It combines the transmission power of multiple transmitter nodes (spatial diversity) to send information over long distances [20]. In this type of communication, a set of transmitter nodes send the same information toward a common receiver and behave like multiple transmitter antennas mounted on a single node. Collaborative communication has been observed to successfully achieve good performance in terms of received power, energy efficiency, system's capacity, and bit error rate (BER) [21]. Interestingly, collaborative communication can create constructive interference even if the received signals are imperfectly synchronized through a synchronization process [22]. Collaborative communication is reported to have N^2 gain received power for N number of transmitter nodes.

In this article collaborative Communication has been used to investigate energy efficiency in WSN where the channel has the effect of multipath scattering in contrast to previous proposals where the channel is mainly considered as a single path. In multipath collaborative communication, the transmitted signal from a node is scattered into several components due to deflection from objects in the transmission path [5], [23], [24]. Furthermore, the channel is also considered to have the effect of noise and fading.

Main contributions of the article include 1) the development of a mathematical expression for collaborative communication in the multipath channel including the effect of noise, fading, and imperfect synchronization. 2) The derivation of mathematical expression of received power gain as well as BER. The power gain is directly related to the number of collaborative nodes whereas BER is a function of the signal-to-noise ratio. 3) The development of energy consumption model. This model is used to calculate the overall energy consumption of the proposed system. This calculation includes the energy consumption for local communication among collaborative nodes as well as the energy consumed by the collaborative nodes while transmitting to the base station. 4) To use parameters of off-the-shelf devices and develop an energy efficiency model which calculates energy efficiency based on the number of participating nodes, transmission distance, and phase error. Break-even-distances (*SISO* = *Collaborative Communication*) are calculated for trade-off analysis between transmission power and circuit power. 5) Development of a technique to counter the fading effect in order to have increased in the power gain and reduce the per-node transmission power. This is contributed to both by collaborative communication in combination with multipath environment.

II. SYSTEM MODEL

The following assumptions are considered while developing multipath Rayleigh faded energy efficient collaborative communication system for WSN.

A. ASSUMPTIONS

- Randomly distributed nodes from a sensor field transmit the same information toward a common receiver concurrently.
- The noise used in this model is Additive White Gaussian Noise (AWGN).

B. DESCRIPTION

Having a central network controller, in fixed antenna array systems, synchronizing received signals is easy as the central controller knows the exact location as well as the distance of each transmitter node from another. In such systems there are no chances of phase error in synchronizing the receiving signal, therefore, can achieve high gain in received power, energy savings and improved *BER* [25], [26].

However, determining the exact location of a sensor in a random distribution is next to impossible since there is no central network controller. Therefore, position estimation of a node may always have a chance of error known as the displacement error causing the unsynchronized reception of signals at the receiver.

A fully synchronized system in such situation is very difficult to achieve, therefore, in this article, a collaboration-based system is proposed which even in the presence of synchronization error can achieve significant improvements in received power, *BER*, and energy consumption as shown in Figure 1. The figure clearly shows the variation in distance

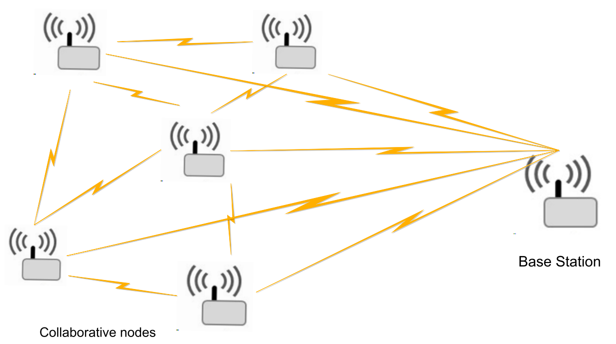

FIGURE 1. The geometry of sensor nodes for multipath collaborative communication.

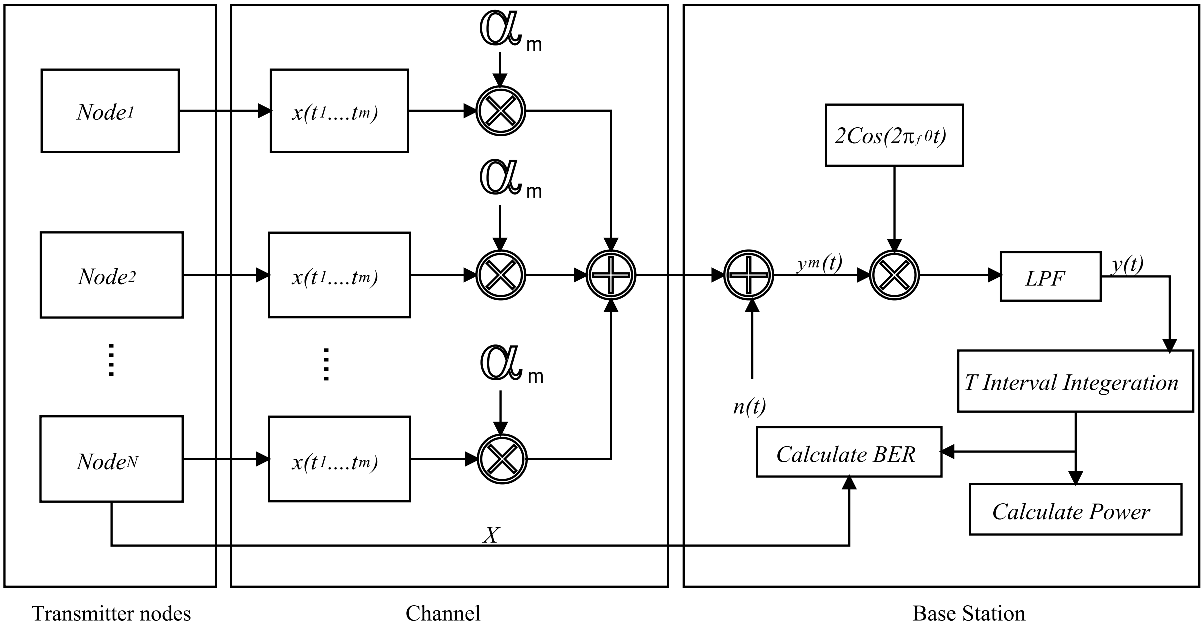

FIGURE 2. **Theoretical model for multipath collaborative communication.**

of each node from the BS. It means the signal from the farthest collaborative node arrives late as compared to the nearest collaborative node. This delay leads to imperfect phase synchronization. A detailed theoretical model for a case of N collaborative nodes is shown in Figure 2.

C. THEORETICAL MODEL

In collaborative communication based system of N nodes, each at a different distance from the base station, the signal can get deflected from different objects dividing it into multiple scatter signals following different paths to reach the base station creating a multipath effect, as shown in Figure 2.

In a randomly distributed deployment if every node transmits a data signal $x(t)$ using $\cos(2\pi f_0 t)$ as a carrier signal achieving synchronization among signals from multiple nodes or their scatter components may be difficult since exact position of the node cannot be estimated correctly. This result in an error termed as “displacement error” [27]. For an initial distance d_o the phase is $\theta_0 = 2\pi f_0 d_0/c$, c is the “speed of light” and due to displacement error $d_r(i)$ the corresponding phase is $\theta_r(i) = 2\pi f_0\, d_r(i)/c$. The sum of all signals received at the receiver (base station) is as follows

$$y_m(t) = \Re\left(\sum_{i=1}^{N}\sum_{j=1}^{M}\alpha_{ij}x(t)e^{j(2\pi f_0 t+\theta_0+\theta_r(i))}\right) + n(t) \quad (1)$$

here α_i is the attenuation factor, M represents scatter components and $n(t)$ is AWGN.

Here, it is assumed that the bit length of time “T” is comparatively very large than the delay spread of the arriving signals providing enough guard band to avoid inter-symbol interference *(ISI)*. Also, there is no “line-of-sight” communication, therefore, “Rayleigh fading” model is used.

Signal in Equation (1) is demodulated, integrated at the base station and then passed through LPF, yields the following result

$$Y = \sum_{i=1}^{N}\sum_{j=1}^{M}\alpha_{ij}X_{ij}\cos(\theta_r(ij)) + n \quad (2)$$

here $X = \pm\sqrt{E}$ and n represent signal and noise amplitudes respectively.

Strength of the signal received at the base station is as follows

$$P_Y = \left[\sum_{i=1}^{N}\sum_{j=1}^{M}\alpha_{ij}X_{ij}\cos(\theta_r(ij)) + n\right]^2 \quad (3)$$

Equation (3), consists of multiple identical independent random variables, like $\theta_r(ii)$, α_{ij} and zero mean noise n. Therefore the above equation can be expanded as follow

$$\begin{aligned} E[P_Y] &= E\left[\sum_{i=1}^{N}\sum_{j=1}^{M}\alpha_{ij}X_{ij}\cos(\theta_r(ij))\right]^2 \\ &\quad + E\Bigg[\left(\sum_{i=1}^{N}\sum_{j=1}^{M}\alpha_{ij}X_{ij}\cos(\theta_r(ij))\right) \\ &\quad \left(\sum_{i=1}^{N}\sum_{\substack{l=1\\ l\neq i}}^{M}\alpha_{kl}X_{kl}\cos(\theta_r(kl))\right)\Bigg] + \sigma_n^2 \end{aligned} \quad (4)$$

σ_n^2 in Equation (4), represents variance of noise. The sum of the power of all M scatter components must not be greater than the original signal i.e, $X_{ij} and X_{kl} \approx X$, which is the maximum value i.e. X. It is also known that $\theta_r(i)$, $\theta_r(j)$, $\theta_r(k)$, $\theta_r(l)$, α_i, α_j, α_k and α_l, are independent random variables, therefore "$E[\theta_r(i)] \approx E[\theta_r]$, $E[\theta_r(j)] \approx E[\theta_r]$, $E[\theta_r(k)] \approx E[\theta_r]$, $E[\theta_r(l)] \approx E[\theta_r]$ and $E[\alpha_i] \approx E[\alpha]$, $E[\alpha_j] \approx E[\alpha]$, $E[\alpha_k] \approx E[\alpha]$, $E[\alpha_l] \approx E[\alpha]$". Also $\theta_r(i)$, $\theta_r(j)$, $\theta_r(k)$ and $\theta_r(k)$ are independent random variable with "uniform distribution" over the interval "$-\phi \rightarrow \phi$" for all i, j, k and l, then $\theta_r(i) \approx \theta_r$, $\theta_r(j) \approx \theta_r$, $\theta_r(j) \approx \theta_r$ and $\theta_r(j) \approx \theta_r$. Now expanding Equation (4), give the following result

$$\begin{aligned} E[P_Y] &\\ = N \times MX^2 &\Big[E\left[\alpha^2\right] E\left[\cos^2(\theta_r)\right] \\ &+ (E\left[\alpha\right] E\left[\cos(\theta_r)\right]) MN(MN-1) E\left[\alpha\right] E\left[\cos(\theta_r)\right] \Big] + \sigma_n^2 \end{aligned} \tag{5}$$

We know that variance $Var(\alpha) = \sigma_\alpha^2 = \left(2 - \frac{\pi}{2}\right)$ and mean $E[\alpha] = \mu_\alpha = \sqrt{\frac{\pi}{2}}$. Using values from Equation (32) and Equation (33); Equation (5) can be simplified as follow, considering mean value of α^2 i.e, $E[\alpha^2] = 1$.

$$\begin{aligned} E[P_Y] = N \times MX^2 &\Bigg[\left(\frac{1}{2} + \frac{\sin(2\phi)}{4\phi}\right) \\ &+ \frac{\pi MN(MN-1)b^2}{2} \left(\frac{\sin(\phi)}{\phi}\right)^2 \Bigg] + \frac{N_0}{2} \end{aligned} \tag{6}$$

In Equation (6), ϕ represents distribution bound of the phase error and a Rayleigh random b known as the mod of α. It is clear from Equation (6) that the contribution to the received power gain is not only due to the number of collaborative nodes "N", but the scatter components "M", also contributes to it. The scatter components produce a virtual spatial diversity. Section IV discusses the implementation results obtained using Equation (6).

D. AVERAGE PROBABILITY OF ERROR

If a signal in a Rayleigh faded channel is modulated using BPSK, then the received signal Y, is a combination of two identically independent random variables α and θ_r. The number of bits arrived in error are given by the Equation (2). According to central limit theorem "for a sufficiently large value of N, the sum of two identical independent random variables turn to Gaussian". So by this theorem $Y = s + n$, tends to Gaussian as it is the sum of two i.i.d random variable i.e. $Y = \sum_{i=1}^{N} \sum_{j=1}^{M} X \cos(\theta_r(ij))$ (in internal summation $j \neq i$). Therefore, the error rate is given by

$$P_e = 0.5 erfc\left(\frac{\mu_Y}{\sqrt{2\sigma_Y^2}}\right) \tag{7}$$

Since θ_r and α are two different i.i.d random variables, therefore

$$\mu_Y = \mu_s + \mu_n \tag{8}$$

Putting values of μ_s and μ_n in Equation (8), we get

$$\begin{aligned} \mu_Y &= E\left[\sum_{i=1}^{N}\sum_{j=1}^{M} \alpha_{ij} X_{ij} \cos(\theta_r(ij))\right] + E[n] \\ &= X \sum_{i=1}^{N} E\left[\alpha_{ii}\right] E\left[\cos(\theta_r(ii))\right] \\ &\quad + X \sum_{i=1}^{N} \sum_{\substack{j=1 \\ j\neq i}}^{M} E\left[\alpha_{ij}\right] E\left[\cos(\theta_r(ij))\right] \end{aligned} \tag{9}$$

The above equation produces different values depending upon the value of N and M. In the case of $N = M$, the proposed system behaves like a single path system.

Taking values from Equation (32) as well as putting $E\left[\alpha\right]$, the expression in Equation (9), can be written as

$$\mu_Y = \frac{\sqrt{\pi} bNMX \sin(\phi)}{\sqrt{2}\phi} \tag{10}$$

Here ϕ represents the bound on phase error distribution and its mode is represented by b, having the property of zero mean Gaussian distributed random variable. Since Y is also i.i.d random so its variance can be calculated as follow

$$\sigma_Y^2 = \sigma_s^2 + \sigma_n^2 \tag{11}$$

$$\begin{aligned} \sigma_Y^2 &= Var\left[\sum_{i=1}^{N}\sum_{\substack{j=1 \\ j\neq i}}^{M} \alpha_{ij} X \cos(\theta_r(ij))\right] + Var\left[n\right] \\ &= \sum_{i=1}^{N} Var\left[\alpha_{ii} X \cos(\theta_r(ii))\right] \\ &\quad + \sum_{i=1}^{N}\sum_{\substack{j=1 \\ j\neq i}}^{M} Var\left[\alpha_{ij} X \cos(\theta_r(ij))\right] + \frac{N_0}{2} \end{aligned} \tag{12}$$

putting values from Equation (36), Equation (12) will become

$$\sigma_Y^2 = NMb^2X^2\left[1 - \frac{\pi}{2}\left(\frac{\sin(\phi)}{\phi}\right) + \frac{\sin(2\phi)}{2\phi}\right] + \frac{N_0}{2} \tag{13}$$

Now taking values from Equation (10) and Equation (13), in Equation (7) we get the relation represented in Equation (14).

Now putting $X^2 = E_b$, the error rate expression in Equation (14), as shown at the top of the next page, can be simplified into the form as shown in Equation (15), as shown at the top of the next page.

Special Case:

If amplitude of signal from each transmitter node is "$X = \pm\sqrt{E_b}/N$", then relation in Equation 15, can be turned into a more simplified as shown in Equation (16), as shown at the top of the next page.

To analyze the performance of the proposed system under low transmission power, the transmitted power by each collaborative node is lessened by a factor of $N \times M$ in the total

$$P_e = 0.5erfc\left(\frac{\frac{\sqrt{\pi}bNMX\sin(\phi)}{\sqrt{2}\phi}}{\sqrt{2\left(NMb^2X^2\left[1-\frac{\pi}{2}\left(\frac{\sin(\phi)}{\phi}\right)^2+\frac{\sin(2\phi)}{2\phi}\right]+\frac{N_0}{2}\right)}}\right) \tag{14}$$

$$P_e = 0.5erfc\left(\frac{\sqrt{\pi}b\sin(\phi)}{\sqrt{2}\phi}\sqrt{\frac{N^2M^2(E_b/N_0)}{\left(2NMb^2\left[1-\frac{\pi}{2}\left(\frac{\sin(\phi)}{\phi}\right)^2+\frac{\sin(2\phi)}{2\phi}\right]\left(\frac{E_b}{N_0}\right)+1\right)}}\right) \tag{15}$$

$$P_e = 0.5erfc\left(\frac{\sqrt{\pi}\sin(\phi)}{\sqrt{2}\phi}\sqrt{\frac{(E_b/N_0)}{\left(\frac{2b^2}{NM}\left[1-\frac{\pi}{2}\left(\frac{\sin(\phi)}{\phi}\right)^2+\frac{\sin(2\phi)}{2\phi}\right]\left(\frac{E_b}{N_0}\right)+1\right)}}\right) \tag{16}$$

transmitted power by all transmitters. The same approach is used for analyzing Bit Error Rate in the transmitted signal. It is clear from Equation (16) that an increase in the number of collaborative nodes reduce the required power transmitted per node, i.e., "$\sqrt{E_b}/N_o$", thereby prolonging a node's life. Similarly, the number of multipath components has a significant reduction impact on the Bit Error Rate. Reduction in BER means less number of retransmission which means a longer lifetime of a node.

III. ENERGY CONSUMPTION MODEL

For the sake of comparison and to highlight the benefits of using multiple transmitters, energy consumption model for single transmitter systems (SISO) as well as multi-transmitter (collaborative communication) are developed in this section. In the development of these models, different parameters are taken into consideration. For example, the energy consumed during the network circuit operations, the distance between transmitters and the base station and total received power. In addition to these parameters, collaborative communication also considers the out-of-phase reception of signals or their scatters components at the base station. Both the models are analyzed for energy efficiency.

A. SISO: *ENERGY CONSUMPTION MODEL*

The transmission of information in SISO systems is carried out through one transmitter and one receiver. The total energy depletion of *SISO* system is calculated from the energy consumed by a transmitter (P_{tr}) as well as the energy consumed by the receiver (P_{rv}). Therefore, total depletion of energy of these systems is the sum of energy depleted by transmitter and receiver.

$$E_{SISO} = (P_{tr} + P_{rv})/R_s \tag{17}$$

here R_s represents the rate of information transfer.

Sklar [28] argued that the desired power for transmission of information can be estimated through simplified path loss (long distance) model. If "G_r" and "G_t" are the gains of antenna directivity of receiver and transmitter antenna respectively and both "G_r" and "G_t" are equal to 1, then power consumed by the transmitter P_{tr} is given by [29].

$$P_{tr} = P_{cir} + \frac{(4\pi)^2P_rd^\beta}{d_r^{\beta-2}\lambda^2} \tag{18}$$

The required power for circuit operations of the transmitter is represented as P_{cir}, λ and f_0 are the wavelength and frequency of the carrier signals respectively i.e. $\lambda = c/f_0$ where c is the "speed of light". β is the "exponent of path loss", "d" represents the separation between transmit and receive antenna whereas d_r is far-field region reference point in terms of distance.

The minimum required received power P_r, to achieve the anticipated bit error rate computed as follows

$$P_r = P_s + r_{eber} \tag{19}$$

P_s represents receiver's sensitivity (in Watt) and "r_{eber}" is "E_b/N_0 (in Watt)" used to obtain the anticipated *BER* for a Rayleigh faded AWGN system. r_{eber} in [30] and [31], is shown to be calculated as

$$r_{eber} = \frac{\left((1-2P_e)^2/1-(1-2P_e)^2\right)}{\left(erfc^{-1}(2P_e)\right)^2} \tag{20}$$

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

Taking values from Equation 18, Equation (19) and Equation (20), total consumption of energy in *SISO* systems can be obtained using the following expression

$$E_{SISO} = \left(P_{cir} + \frac{(4\pi)^2P_sr_{eber}d^\beta}{dr^{\beta-2}\lambda^2} + P_{rv}\right)\Big/R_s \tag{21}$$

As mentioned in the beginning R_s is the data rate. Therefore, it is clear that higher error rate mean more retransmission which in turn will reduce the lifetime of node hence shortening the overall network's lifetime. Results obtained using Equation (21) are further discussed and analyzed in section IV.

B. ENERGY CONSUMPTION MODEL FOR MULTIPATH COLLABORATIVE COMMUNICATION

The energy consumption model of collaborative communication consists of two parts; one energy consumption during communication among collaborative nodes for synchronization purposes, it is denoted by E_l. The second part is the energy consumed in communication between collaborative nodes and the base station, denoted by E_t. The expression for total energy consumption of collaborative communication is

$$E_{COL} = E_l + E_t \tag{22}$$

Both channels; the one used to synchronize the transmitter nodes and the channel that connects the collaborative node to the base station are "Rayleigh fading" channels. The separation among transmitter nodes is considered to be maximum (local communication) leading to maximum energy consumption, although the distance of collaborative nodes from the base station may vary. For the case of local communication among collaborators, energy consumption is given as follows

$$E_l = (P_{tr\_l} + NP_{rv\_l})/R_s \tag{23}$$

here N is the number of transmitter nodes in collaboration in the sensor network. P_{tr_l} can be derived from Equation (18), can be written in the following form

$$E_l = \left(P_{cir} + \frac{(4\pi)^2 P_s r_{rber\_l} d_l^{\beta}}{d_l^{\beta-2}\lambda^2} + NP_{rv\_l}\right) \Big/ R_s \tag{24}$$

Energy consumed during communication between transmitter nodes and the receiver at the base station is given by

$$E_t = (P_{tr\_t} + P_{rv})/R_s \tag{25}$$

where P_{tr_t} is the total energy depletion of all "N" transmitter nodes and can be expressed in the following form

$$P_{tr\_t} = NP_{cir} + \frac{(4\pi)^2 P_{r\_t} d^{\beta}}{Ndr^{\beta-2}\lambda^2} \tag{26}$$

To obtain the desired "Bit Error Rate (BER)", the minimal received power required "P_{r_t}" and expressed as

$$P_{r\_t} = P_S + r_{col\_ber} \tag{27}$$

where "r_{col_ber}" represents ratio between "E_b/N_0 (for system with phase error)", AWGN and Rayleigh fading, and For systems where only *AWGN* is considered, this ratio is equal to "E_b/N_0 (in Watt)", to obtain the desired *BER*. "r_{col_ber}" can be re-written as

$$r_{col\_ber} = \frac{BER^{-1}(P_e, N)}{(erfc^{-1}(2P_e))^2} \tag{28}$$

here "BER^{-1}" is the converse of Equation (15). Therefor E_t can be written as follows

$$E_t = \left(NP_{cir} + \frac{(4\pi)^2 P_{r\_t} d^{\beta}}{Nd_r^{\beta-2}\lambda^2} + P_{rv}\right) \Big/ R_s \tag{29}$$

Now by putting values from Equation (24) and Equation (29) in Equation (22) to represent the total energy consumption of collaborative communication as follows

$$E_{COL} = \left(\left(P_{cir} + \frac{(4\pi)^2 P_s r_{rber\_l} d_l^{\beta}}{d_l^{\beta-2}\lambda^2} + NP_{rv\_l}\right) + \left(NP_{cir} + \frac{(4\pi)^2 P_{r\_t} d^{\beta}}{Nd_r^{\beta-2}\lambda^2} + P_{rv}\right)\right) \Big/ R_s \tag{30}$$

The total energy saving for the proposed collaborative communication model can be achieved using the following equation.

$$E_{saving}(\%) = \left(\frac{E_{SISO} - E_{COL}}{E_{SISO}} \times 100\right)\%. \tag{31}$$

Using Equation 31, comparative energy savings has been calculated. It is clear from the equation that energy saving for small distances is dominated by energy consumed in circuit operations. Saving is 0% when $E_{SISO} = E_{COL}$, and such distances are termed as "break-even-distance".

IV. RESULTS AND PERFORMANCE ANALYSIS

Analysis of the proposed system is performed using *Monte Carlo* simulation in *MATLAB*® using parameters of "off-the-shelf" products i.e. "AT86RF212" [32] and "CC2420" [33]. Table 1 summarizes the parameters of these devices and their description used in the simulation.

TABLE 1. Product information and description of parameters.

Symbol	Description	AT86RF212	CC2420
-	Modulation	BPSK	BPSK
f_0	Operating frequency	915MHz	2.45GHz
R_s	Transmission data rate (BPSK)	40Kbps	250Kbps
U	Operating voltage (typical)	3V	3V
I_{rx}	Currency for receiving states	9mA	17.4mA
P_{rx}	Receiving power, $P_{rx} = UI_{rx}$	27mW	52.2mW
I_{idle}	Currency for idle states	0.4mA	0.4mA
P_{cir}	Electronic circuitry power, $P_{cir} = UI_{idle}$	1.2mW	1.2mW
Ps	Receiver sensitivity	-110dBm	-95dBm

The basic purpose of collaboration is to achieve a gain in energy consumption and received power, and reduce *BER* even if the synchronization in received signals is imperfect. Four different phase error intervals have been used to test the proposed system and the effect of phase error on system behavior in terms of the figures of merit used. The phase error intervals used here are: "$\{-0.1\pi \sim 0.1\pi\}$, $\{-0.2\pi \sim 0.2\pi\}$, $\{-0.3\pi \sim 0.3\pi\}$ and $\{-0.4\pi \sim 0.4\pi\}$". In addition to the effect of phase error on the performance, it is also of interest to see the effect of multipath scattering on the results.

Results of normalized received power and average received power for the proposed model are shown in Figure 3 and Figure 4. The figure clearly shows a close resemblance between simulated and analytical results. Some of the figures have been omitted due to space limitation.

Figure 3, shows an approximate decrease of 10% in received power when the phase error interlude over "$\{-0.1\pi$ to $0.1\pi\}$". Similarly a decrease of 19% for a phase error

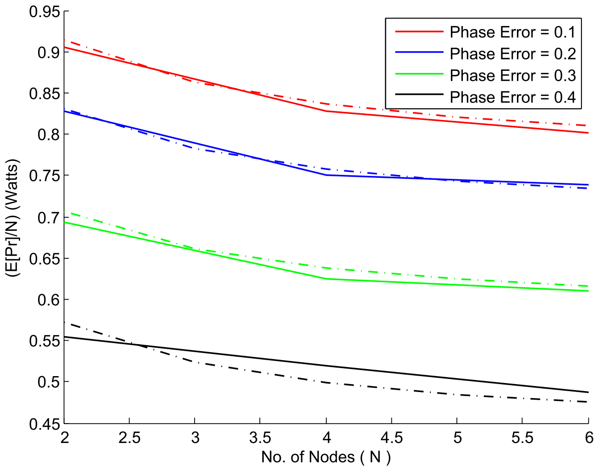

FIGURE 3. Normalized received power against the number of transmitter nodes with in the presence of fading, noise and imperfect phase synchronization.

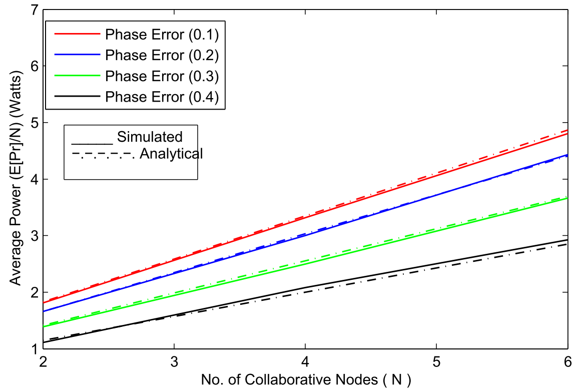

FIGURE 4. Received average power/N against the number of transmitter nodes in the presence of fading, noise and imperfect phase synchronization.

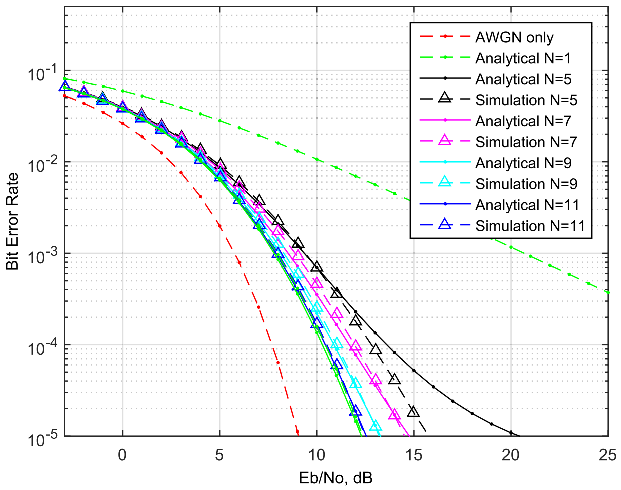

FIGURE 5. ***BER*** **in presence of fading and total transmitted energy “E_b/N_0” against the number of transmitters nodes for phase error interval over $\{-0.1\pi$ to $0.1\pi\}$ for scatter components $m = 3$.**

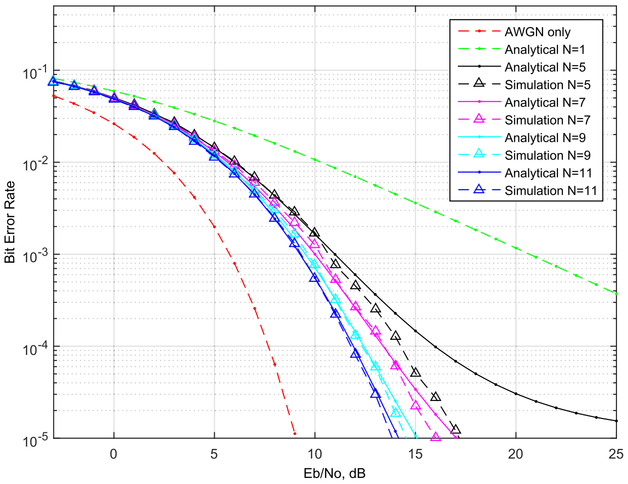

FIGURE 6. ***BER*** **in presence of fading and total transmitted energy “E_b/N_0” against the number of transmitters nodes for phase error interval over $\{-0.3\pi$ to $0.3\pi\}$ for scatter components $m = 3$.**

interlude over “$\{-0.2\pi$ to $0.2\pi\}$”, 33% in case of phase error over “$\{-0.3\pi$ to $0.3\pi\}$” and 49% when the phase mismatch spans over “$\{-0.4\pi$ to $0.4\pi\}$”. It is compared with the power received when there is perfect synchronization among the received signal at the base station, i.e., N^2. Figure 4 depicts that the average received power gain “*power/N*” grows when there is an increase in the number of transmitter nodes as well as multipath components.

A significant improvement in *BER* has been observed in comparison to our previous work [34]. This improvement is due to the use of multipath communication as shown in Figure 5 and Figure 6. It must be noticed that reduced *BER* means less number of retransmissions, thereby reducing the energy consumed per bit. It prolongs a node's lifetime which ultimately leads to longer network lifetime.

In addition to the number of transmitter nodes, the improvement in *BER* is also contributed to by the number of multipath components of the signals from the source nodes. It produces an effect similar to spatial diversity leading to a significant gain in bit error rate. It is clear that the received power gain grows directly with the number of transmitters and scatter components of the signal. However, *BER* has an inverse relation with *SNR*. The results show that in the presence of fading and noise a power gain of “$0.64N^2$” is recorded when the interval of phase error is “$\{-0.3\pi \sim 0.3\pi\}$”. A power gain of “$0.49N^2$” is recorded when the phase error interval is “$\{-0.4\pi \sim 0.4\pi\}$”. It is also analyzed that an increase in phase error inversely affects the gain in received power.

Energy consumption per bit “$E_b = N^2$” is used to analyzed the bit error rate *BER* resulting in “$E_b = N$” energy depleted by N transmitter nodes. Results obtained from Equation 15 are equated and compared with the simulated results in case of phase error mismatch interlude over “$\{-0.1\pi \sim 0.1\pi\}$” and “$\{-0.3\pi \sim 0.3\pi\}$” and shown in Figure 5 and Figure 6. The results are calculated with the effect of fading and noise.

Simulation and analytical curves shown in Figures 5 and Figure 6 are a close match. The slight variation in simulated and analytical results may be the caused of approximation in deriving the mathematical expression of *BER*. It is evident from both simulated and analytical results that in the case of a single node “$N = 1$”, a power of “$6dB$” is required for achieving *BER* of “10^{-3}” in the absence of fading while *AWGN* is considered. A raise in the power requirement has been observed up to “$20.7dB$” when fading is considered. In collaborative communication, with a rise in the number of transmitters up to five nodes “$N = 5$”, over the phase mismatch interval “$\{-0.1\pi$ to $0.1\pi\}$” the required power is $9dB$. However for phase error interval “$\{-0.3\pi$ to $0.3\pi\}$” the required power increases to “$11dB$”. In the case of $N = 7$, and phase error from “$\{-0.1\pi$ to $0.1\pi\}$” the required power is $9dB$ whereas in case of phase error from “$\{-0.3\pi$ to $0.3\pi\}$” the required power raises to $10dB$. Similar effect can be seen for $N = 9$ and $N = 11$. It must be noted that an increase in the phase error cause exponential growth in the required power to achieve the desired *BER*.

As per observation from Figure 3 and Figure 4 increasing, the number of transmitters improves power gain, but at the same time, it incurs more power consumption due to circuit operations. For energy efficiency analysis of the proposed system, “break-even distances” are calculated for varying number of transmitters and different phase error intervals. For computing circuit energy consumption, values from Table 1 are used. The distance between transmitter nodes is $1m$, the acceptable *BER* value is “10^{-5}” and the exponent of path loss “β” is from “4.0–6.0” [35].

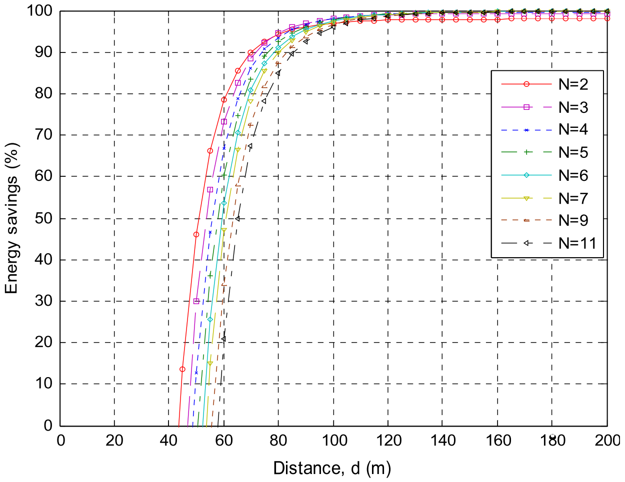

FIGURE 7. Energy efficiency and “break-even distance” for varying number of transmitter nodes using parameters of “*AT86RF212*” over phase error interval $\{-0.3\pi \sim 0.3\pi\}$.

The next series of figures from Figure 7–10, show percentage saving in energy for different values of “N” of transmitter nodes and “break-even distances”.

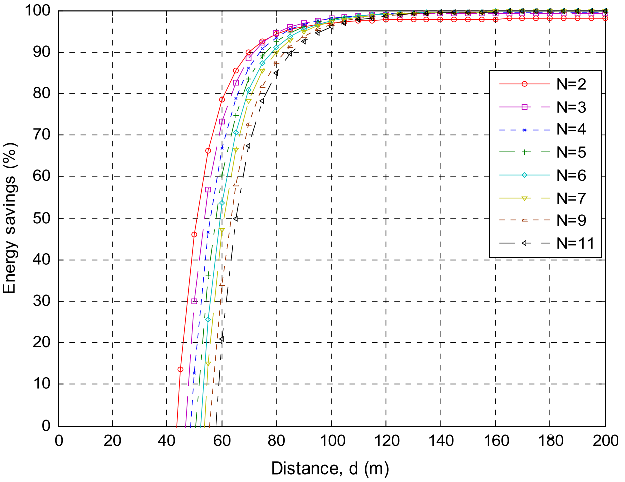

FIGURE 8. Energy efficiency and “break-even distance” for varying number of transmitter nodes using parameters of “*AT86RF212*” over phase error interval $\{-0.4\pi \sim 0.4\pi\}$.

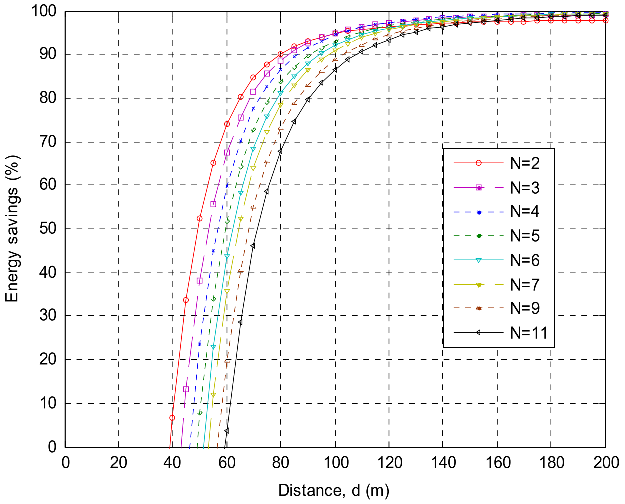

FIGURE 9. Energy efficiency and “break-even distance” for varying number of Transmitter nodes using parameters of “*CC2420*” over the phase error interval $\{-0.3\pi \sim 0.3\pi\}$.

TABLE 2. “Break-even” distances based on the parameters for “CC2420” and “AT86RF212”.

N	CC2420(m)	AT86RF212(m)
2	39	43
3	42.2	45.2
4	46.1	49
5	48.7	50.7
6	51	52.5
7	53.2	53.2
9	56.7	55.7
10	59.8	58.1

It is also revealed from the analysis that an increase in break-even distances is caused by the raise in the number of transmitter nodes. The “break-even distances” for “*AT86RF212*” are greater than the break-even distance for “*CC2420*”, however, “*AT86RF212*” shows more energy

TABLE 3. Percentage Energy Savings for "CC2420".

N	phase error 0.1π		phase error 0.2π		phase error 0.3π		phase error 0.4π	
	200m	100m	200m	100m	200m	100m	200m	100m
2	97.5	95	97.4	94.4	96.5	93.8	94.5	91.5
3	98.9	95.2	99	95	98.8	95	98.5	94.1
4	99.3	94.3	99.2	93.9	99	93.8	98.9	94
5	99.4	93	99.3	92.8	99.1	92.8	99	93
6	99.1	91.9	99.1	92	99.1	91.8	99	91.9
7	99.1	91	99	90.9	99	90.8	99	91
9	99	88.9	99	88.9	99	90	99	88.9
11	98.7	86.3	98.5	86	98.1	89	98	86.5

TABLE 4. Percentage Energy Savings for "AT86RF212".

N	phase error 0.1π		phase error 0.2π		phase error 0.3π		phase error 0.4π	
	200m	100m	200m	100m	200m	100m	200m	100m
2	97.9	96.9	97.5	94.5	96.5	95.4	95	94
3	99.3	97.9	99	94.8	98	97.8	98.6	97.3
4	99.3	97.6	99.4	93.8	98.1	97.9	99.1	97.4
5	99.5	97.3	99.5	92.8	97.4	97.5	99.4	97.3
6	99.5	97.1	99.6	91.8	97.3	97.4	99.47	97
7	99.6	97	99.6	90.8	97.1	97.1	99.7	93.9
9	99.5	96.2	99.6	88.7	96.2	96.2	99.5	95.7
11	99.7	95.8	98.8	85.9	95.8	95.8	98.6	96.3

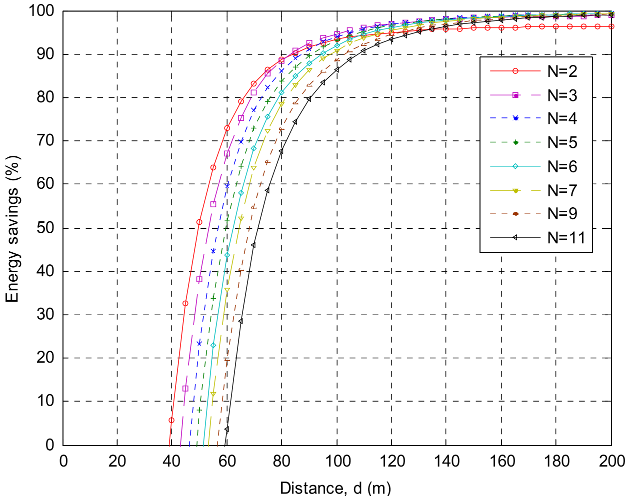

FIGURE 10. Energy efficiency and "break-even distance" for varying number of Transmitter nodes using parameters of "*CC2420*" over the phase error interval $\{-0.4\pi \sim 0.4\pi\}$.

efficient behavior than "*CC2420*" at *100m* and *200m* distances. A significant growth in energy saving in case of "*AT86RF212*" is observed in comparison to "*CC2420*", as growth in distances surpasses the "break-even distances", shown in Figures 7–10. It has been seen that the stability of "*AT86RF212*" is higher than "*CC2420*". "*AT86RF212*" gets stability faster at a distance of *118m* whereas "*CC2420*" gets stable slowly at approximately *148m*.

"Break-even distances" computed using different phase error intervals for "*CC2420*" and "*AT86RF212*" are presented in Table 2.

It has been observed that before getting stable constantly at a certain distance, there is an increase in energy saving with an increase in distances. Percentage energy saving of both products with different interval of phase errors in case of "*100m*" and "*200m*" distances are presented in Tables 3 and Table 4.

A. COMPARATIVE ANALYSIS

It can be seen from the previous results that the proposed system performs well. In this subsection, a comparative analysis of the proposed system with Naqvi *et al.* [31] has been performed to further validate the results. The comparison is based on two parameters: received power gain and BER. The analysis is performed using the same phase error intervals as for the analysis in the previous subsection. Comparative results based on the received power gain are shown in Table 5.

It is clear from the table that the proposed approach performs better in terms of received power gain. This improvement in the results is due to the multipath components of a scattered signal which contribute to the gain in received power. In contrast to a single path communication, an object in the transmission path may completely block the signal

TABLE 5. Performance comparison of the proposed system with Naqvi *et al.* [31] proposal in terms of received power gain.

Phase Interval	Naqvi et al. [31]	Proposed approach
$-0.1\pi \sim 0.1\pi$	$92N^2$	$97N^2$
$-0.2\pi \sim 0.2\pi$	$80N^2$	$84N^2$
$-0.3\pi \sim 0.3\pi$	$62N^2$	$66N^2$
$-0.4\pi \sim 0.4\pi$	$48N^2$	$50N^2$

TABLE 6. Performance comparison of the proposed approach with Naqvi *et al.* [31] in terms of BER (10^{-3}) for different number of transmitter nodes.

Nodes	$-0.1\pi \sim 0.1\pi$		$-0.3\pi \sim 0.3\pi$	
	[31].	Proposed	[31]	Proposed
AWGN only	7dB	6dB	7dB	6dB
1	24dB	20dB	25dB	21dB
5	11dB	9dB	13dB	11dB
7	10dB	8dB	11.5dB	10.5dB
9	9dB	7.7dB	11dB	10dB
11	9dB	7.5dB	10.5dB	9dB

from reaching to the receiver. In multipath communication, however, one component of a scattered signal is blocked by an object in the transmission path, some components may still reach the receiver. It can contribute positively to the gain in the received power.

Further analysis of the results in Table 5 shows that the gain in received power reduces with increase in the phase error interval from top to bottom. This is logical as we previously analyzed that the increase in the phase error adversely affect the gain in received power. However, it can be observed that it affects the baseline and proposed approach in the same way. The difference at between the baseline and proposed approaches is almost constant for different phase error intervals.

Similarly, the analysis in terms of *BER* between the baseline and proposed system is performed. Here the acceptable value of *BER* is considered to be 10^{-3}. Due to space limitation the analysis is performed for two phase error intervals $\{-0.1\pi \sim 0.1\pi\}$ and $\{-0.3\pi \sim 0.3\pi\}$. The results of this comparison are shown in Table 6. It is clear from the table in case of both phase error intervals that the proposed system requires less transmission power to achieve the required *BER* level.

For the case of AWGN only where no fading is considered, the proposed technique performs slight better than baseline Naqvi *et al.* [31] approach. However, for the rest of the cases, the proposed technique performs significantly better than baseline system. This improvement in the proposed technique is due to the multipath scattering. Each scatter component at the receiver is considered as an independent signal and added to the rest of the signals to achieve spatial diversity. Exploiting spatial diversity is an advantage of collaborative communication which converts a scatter signal into positive gain at the receiver.

It should also be noticed that both techniques are equally affected by the increase in the phase error interval. The change can be observed as we go from top to bottom both in case of baseline and the proposed system in Table 6. The improvement shows that the proposed communication system requires less transmission power to achieve the required *SNR* value and acceptable *BER*. This means that the battery of each sensor will deplete slower in comparison to the baseline system. It means that using the proposed system, a network can survive for a longer time as compared to the baseline approach.

V. CONCLUSION

A collaborative communication model using a multipath channel with fading and noise is presented in this article where the scatter multipath components at the receiver are considered out-of-phase. It has been observed that not only the number of transmitter nodes but an increase in the number of scattered components of a signal, positively affect the received power gain and energy consumption in *WSN*. A comparative analysis of multipath based collaborative communication and *SISO* system reveals that collaborative communication achieved 99% saving in energy over long distances as compared to *SISO* systems. Furthermore, multipath scatter components help collaborative communication to mitigate the fading effects of the channel effectively. The proposed approach shows performance improvements in terms of received power gain and *BER* with the single path communication system.

In the future, multipath based collaborative communication may be investigated with imperfect frequency synchronization as well imperfect frequency and phase.

APPENDIX
TRIGONOMETRIC FUNCTIONS & THEIR EXPECTATION
A. EXPECTATION OF COSINE FUNCTION

$$
\begin{aligned}
E\left[\cos(\theta_f)\right] &= \int_{-\infty}^{\infty} \cos(\theta_f)P(\theta_f)d(\theta_f) \\
&= \int_{-\phi}^{\phi} \cos(\theta_f)\frac{1}{2\phi}d(\theta_f) \\
&= \frac{1}{2\phi}\int_{-\phi}^{\phi} \cos(\theta_f)d(\theta_f) \\
&= \frac{\sin(\phi)}{\phi} \qquad (32)
\end{aligned}
$$

B. EXPECTATION OF SQUARE OF COSINE FUNCTION

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

$$
\begin{aligned}
&= \frac{1}{2\phi}\int_{-\phi}^{\phi}\cos^2(\theta_f)d(\theta_f) \\
&= \frac{1}{2\phi}\left(\phi+\frac{\sin(2\phi)}{2}\right) \\
&= \frac{1}{2}+\frac{\sin(2\phi)}{4\phi}
\end{aligned} \tag{33}
$$

C. VARIANCE OF COSINE FUNCTION

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

Using equations 32 and 33 in the above equation we get

$$Var\left(\cos(\theta_f)\right)=\left(\frac{1}{2}+\frac{\sin(2\phi)}{4\phi}\right)-\left(\frac{\sin(\phi)}{\phi}\right)^2 \tag{34}$$

D. CALCULATING VARIANCE OF COSINE WITH RANDOM VARIABLES

since h and θ_f are i.i.d random, hence calculation of their multiplication may be carried out as follows

$$
\begin{aligned}
Var\left[\alpha X\cos(\theta_f)\right]=X^2\Big[&Var[\alpha]\left(E\left[\cos(\theta_f)\right]\right)^2 \\
&+\left(E\left[\alpha\right]\right)^2 Var\left[\cos(\theta_f)\right] \\
&+Var\left[\alpha\right]Var\left[\cos(\theta_f)\right]\Big]
\end{aligned} \tag{35}
$$

As it is known from Equations (32) and (34) that, $Var(\alpha)=\sigma_\alpha^2=(2-\frac{\pi}{2})b^2$ and $E\left[\alpha\right]=\mu_\alpha=\left(\sqrt{\frac{\pi}{2}}\right)b$.

Now putting values in Equation35, we get

$$Var\left[\alpha X\cos(\theta_f)\right]=b^2X^2\left[1-\frac{\pi}{2}\left(\frac{\sin(\phi_f)}{\phi}\right)^2+\frac{\sin(\phi_f)}{2\phi}\right] \tag{36}$$

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