On Multi hop Performance of Nearest Neighbor Based Forwarding in CDMA Wireless Sensor Networks

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ABSTRACT—*Energy conservation is one of the most important issues in wireless ad hoc and sensor networks, where nodes are likely to rely on limited battery power. In the present paper we evaluate the performance of a static CDMA wireless sensor network (WSN), where the positions of nodes are more likely to be random maintaining a particular minimum distance between any two nodes. Data generated from the source nodes are received by a sink via multi hop. A routing scheme called nearest neighbor based forwarding where an intermediate node in the route selects the nearest node within a search angle (θ) towards the direction of the destination as the next hop. Energy consumption considering start up energy at each node and delay in successful delivery of data packet from source to sink using end-to-end ARQ under such routing scheme is estimated. Network lifetime, which is an important performance indicator for energy constrained wireless sensor networks, is also evaluated. Further, energy consumption is estimated by incorporating different error control schemes as applicable to WSN and compared with uncoded scheme. A scheme for packet size optimization is introduced which captures the effects of multi hop routing by varying search angle, the broadcast nature of information transmission as in CDMA network. Optimization solution is formalized by using different objective functions, i.e., packet throughput, and resource utilization, which has importance in case of delay sensitive WSN.*

Keywords— Wireless sensor network (WSN), Forwarding protocol , Search angle, Optimization of packet length, Node lifetime, Error control scheme

1. INTRODUCTION

Wireless sensor networks, are expected to be utilized in a wide range of military and civilian applications [1] to monitor and interact with physical world. Relayed transmission is a promising technique that helps in attaining broader coverage without using large transmitter power. Given that the sensors have limited energy, buffer space, and other resources, different MAC protocols are being developed by several researchers [2], [3]. To handle a large number of nodes, where a number of nodes simultaneously and asynchronously access a channel, CDMA is a good choice as a MAC protocol [4], [5], [6]. As WSN are operated without any central infrastructure and all nodes are battery operated with simple transceivers, it is difficult to achieve perfect power control in WSN scenario as in cellular network. CDMA has been advocated for WSN in [4], [5], where distribution of interference power in randomly distributed nodes is discussed. Interference shadowed by same obstacles near a receiver tends to be correlated [7] and such correlation has significant impact on multiple access interferences (MAI) and node interferences (NI) [8]. BER and energy consumption in CDMA WSN multi-hop communication with fixed hop lengths is studied in [9] using infinite automatic repeat request (ARQ) with CRC, where hop by hop ARQ scheme shows significant improvement as compared to an end to end ARQ scheme. Above analysis of multi hop communication do not include any routing scheme for the selection of neighboring nodes until it reaches the destination. A framework is proposed in [10] to model more realistic sensor network scenarios, where the positions of the nodes are random. The intermediate nodes are chosen as the nearest neighboring nodes within a search angle (θ) and in the direction of destination. Lifetime of the network is estimated using an optimal common transmit power at each node [10]. Such analysis can be extended in context of CDMA based sensor networks.

ARQ and forward error correction (FEC) are the key error control strategies in wireless sensor networks [11]. Proper combination of ARQ and FEC using different retransmission strategies needs investigation for minimization of energy in multi hop communication. For example, hop by hop error detection and correction scheme using error control code results in higher energy consumption at every node, especially due to significant energy consumption for decoding which reduces network life time in turn. However, if decoding is considered only at the sink which is not energy constrained, power consumptions at intermediate nodes may be reduced significantly. This technique may be investigated in designing an efficient CDMA wireless sensor network using the network model of [10].

Further, the determination of optimal packet size is an important parameter for energy constrained WSN. A cross layer solution for packet size optimization is presented in [12], where cross layer effects of multi hop routing, the broadcast nature of wireless channel using carrier sense mechanism, and the effects of error control techniques are captured. It will be interesting to extend such analysis in context of CDMA based multi hop WSN using the network model of [10].

Network lifetime is an important performance indicator for wireless sensor networks. The time to the first node failure is defined as the network lifetime [10].

In this paper, we investigate the energy level performance of a multi hop packet transmission from a fixed source node to a sink in a CDMA based static wireless sensor network using end-to-end infinite ARQ between source and sink. It is compared with a scheme using HARQ-I with BCH and RS coding. Information bits are encoded at the source and decoded at the sink. Multi hop communication between a fixed source and sink is realized through regenerative relays, where fresh bits are regenerated from a received signal and transmitted to the next receiving node. Selections of intermediate nodes/ relays are based on a simple routing strategy, where a node within search angle (θ) in the direction of destination is chosen as a neighbor which is nearest to the transmitting node. If the error correction fails at sink, retransmission of the whole packet is requested from the sink to source. Following [12] a solution for packet size optimization in CDMA wireless sensor network is presented in terms of packet throughput, and resource utilization, where cross layer effects of multi hop routing followed by [10], broadcast nature of wireless channel using CDMA, and error control technique with infinite ARQ between source and sink are captured.

The remainder of the paper is organized as follows: Section 2 describes system model. Section 3 presents our analytical approach to evaluate the end-to-end BER, energy consumption, delay, and node/ network life time using different information delivery mechanisms, i.e. end-to-end ARQ, HARQ-I with BCH and RS coding. Cross layer solution for packet optimization is discussed in section 4. Results based on our developed frame work are presented in Section 5. Finally we conclude in Section 6.

2. NETWORK MODEL AND PROBLEM DESCRIPTION

In this section, we describe the wireless sensor network model under present investigation and the basic assumptions considered in the paper.

2.1. Network Architecture

Following [10], we consider a random topology of network, where N numbers of nodes are distributed uniformly over an arbitrary square region of area A with $2Y$ as length of each side. We also consider a minimum distance of r_0 between two nodes, which is sufficiently small as compared to the distance between source and final destination, i.e. sink. Hence, in this case, the node spatial density ρ_S may be approximately defined as $\rho_S = N / A$. Since the positions of nodes in the network are independent and uniformly distributed, it can be shown that the number of nodes in an area has a two-dimensional Poisson distribution [13].

Now we describe the routing scheme considered in the paper.

2.2 Routing Protocol

We consider a routing scheme following [10], where each intermediate node in a multi-hop route selects the nearest node within a sector of angle $'\theta'$ towards the direction of the destination as the next hop as shown in Fig. 1. Let ‘ w ’ be a random variable denoting the distance to the nearest neighbor in a two dimensional Poisson node distribution. For a fixed node spatial density with large $'N'$, the CDF of the distance to the nearest neighbor within a sector angle of $'\theta'$ in a torus, as expressed in [10], [13] is appropriately modified in context of our scenario where we incorporate a minimum distance (r_0) parameter as:

$$F_W^{(\theta)}(w) = 1 \qquad w > Y$$

$$= 1 - e^{\rho_s \theta (w - r_0)^2 / 2} \qquad r_0 \le w \le Y \qquad (1)$$

$$= 0 \qquad \text{otherwise}$$

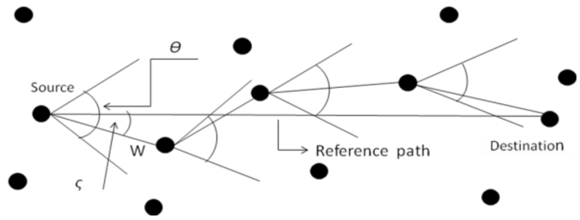

Figure 1: Possible multi-hop route based on search angle between source and destination in a random topology.

The number of hops depends on the node density of the network, search angle 'θ' and distance between the source and destination. In our analysis we consider an average number of hops to evaluate the performance of WSN. Following [10], [13], and with appropriate modification for incorporating a minimum distance (r_0) parameter, the average number of hops on a route is estimated as :

$$\bar{n}_{rand} = \frac{\frac{Y}{3}[\sqrt{2} + \ln(1+\sqrt{2})]}{(\sqrt{\pi/(2\rho_S \theta)} + r_0)\cdot(2/\theta)\cdot\sin(\theta/2)} \qquad (2)$$

2.3 MAC Protocol and Transmission Scheme

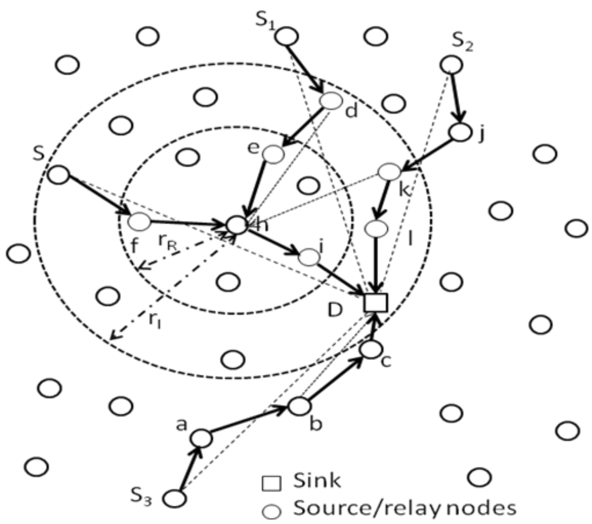

Figure 2 : Signal flow at a particular instant in multi-hop communication for a particular search angle

Here we consider a CDMA-based MAC protocol. We assume a node can identify its intended neighbour, governed by the routing protocol as described above, ensures the data flow from source to sink in multihop. For example in Fig.2, destination node, i.e. sink, D is receiving information from the source nodes S, S1, S2, S3 etc., via multi-hop communication using digital relays. As we are considering a CDMA sensor network, any node can transmit to its nearest next neighbour node at any time, so that source information finally reaches at the destination D. At a particular instant, considering a particular search angle (θ), nodes (f,h,i), (d,e,h,i), (j,k,l), (a,b,c) are used as intermediate nodes to route the information from source nodes S, S1, S2 ,S3 respectively to the sink D. Here we consider that each transmitter adjusts its transmission power so as to achieve a given level of received power (P_r) at its intended receiver. Accordingly the transmit power at each hop , e.g. at 'n'-th hop, depends upon the distance between the transmitter and the receiver pair ($r_{Rn} = w$) and the statistics of shadowing and power control error. Several concurrent nodes those are sending their information to any intermediate relay node on the path, e.g. 'h' within the area $\pi r_{Rn}{}^2$ would cause MAI at 'h'. The concurrent transmitted signal power generated by the source/relay nodes situated within the interference range r_{In} $(r_{In} = 2r_{Rn})$ of 'h', which are sending information to their respective destination node, might be sensed by 'h'. This would cause NI to 'h'. During propagation of signal from source to sink via different nodes, the desired signal at each receiver node is accompanied with MAI and NI. To obtain the interference power distribution at each receiver node, we use the assumptions and definitions as in [5], [9].

3. ANALYSIS OF ROUTE BER , ENERGY CONSUMPTION, DELAY, AND LIFETIME

We assume that H is the average number of hops between source S and destination D for a particular node density (ρ_S) and search angle (θ). Channel conditions are assumed to be remaining same from source to sink.

3.1 Estimation of Interference Power

To determine the distribution of the transmit power from a node 'd' to a local neighbor'e', $P_{t,de}$ as shown in Fig.2, we note that to achieve a desired received power threshold P_R, the required transmit power $P_{t,de}$ for a distance d_{de} is expressed by the relation:

$$P_{t,de} = P_R d_{de}^{\alpha} e^{-S_{de}} e^{R_{de}} \tag{3}$$

where $m_{S_{de}}$, $m_{R_{de}}$ are the mean and $\sigma_{S_{de}}$, $\sigma_{R_{de}}$ are the standard deviation of shadowing (S_{de}) and pce (R_{de}) respectively for the arbitrary path de and α is the path loss exponent $2 < \alpha < 6$. As seen in Fig.2, the distance of interfering transmitter 'd' from the node of interest 'h', d_{dh} is a r.v. in $(r_0, r_I]$ and the interfering received power at node 'h' due to transmitter d is given by

$$P_I = P_{t,de} d_{dh}^{-\alpha} e^{S_{dh}} = P_R \left(\frac{d_{de}}{d_{dh}}\right)^{\alpha} e^{S_{dh}} e^{-S_{de}} e^{R_{de}} \tag{4}$$

$r_0 < d_{de} \le r_R, r_0 < d_{dh} \le r_I$; $m_{S_{dh}}$, $\sigma_{S_{dh}}$ are the mean and standard deviation of shadowing of the path d_{dh} between the nodes d and h.

The mean value of the collected interference power η' from an interfering node is given by [8]:

$$\eta' = \eta . e^{\left(m_{S_{dh}} + \frac{\sigma_{Sdh}{}^2}{2}\right)} . e^{-\left(m_{S_{de}} + \frac{\sigma_{S_{de}}{}^2}{2}\right)} . e^{\left(m_{R_{de}} + \frac{\sigma_{R_{de}}{}^2}{2}\right)} \tag{5}$$

η is given as [5]:

$$\eta = \frac{4 \mathrm{P_R} \left(r_R^{\alpha+2} - r_0^{\alpha+2}\right)\left(r_I^{\alpha-2} - r_0^{\alpha-2}\right)}{\left(\alpha^2 - 4\right) r_0^{\alpha-2} r_I^{\alpha-2} \left(r_I^2 - r_0^2\right)\left(r_R^2 - r_0^2\right)} = \gamma P_R \tag{6}$$

Under the Poisson approximation, for very large number of nodes (N) and very small area of interference region compared to the total area (A), the expected numbers of nodes within the receiving and interference range of the receiver at 'n'-th hop are [5]:

$$c_{1n} = \rho_S \pi r_{Rn}^2 \tag{7}$$

$$c_{2n} = \rho_S \pi (r_{In}^2 - r_{Rn}^2) \tag{8}$$

where ρ_S is the node density, r_{In} is the interference distance at 'n'-th hop, equal to $2r_{Rn}$. Activity factors determine the number of active nodes at any instant contributing MAI and NI, which are fractions of c_{1n} and c_{2n} as given in (7) and (8).

3.2 Estimation of Average Route BER, Energy Consumption and Latency

In estimating route BER, we first estimate link BERs, where pair wise correlation amongst all NIs, MAIs, and between MAIs and Nis are considered. Using the value of c_{1n} and c_{2n} as derived above, separately for each hop, and assuming a fixed node activity factor, number of interferers causing NI (t_1, a fixed fraction of c_{1n}) and MAI (t_2 a fixed fraction of c_{2n}) at any receiving node, for different $r_{Rn} = w$, are evaluated. As the sum of log-normal is approximated by an equivalent log-normal r.v. (Z), using (3) and (4), total interference power due to t_1 number of correlated NI components and t_2 number of correlated MAI components is expressed as [8]:

$$I = P_R e^{\phi} = \eta \sum_{i=1}^{t_1} e^{Z_i} + P_R \sum_{i=1}^{t_2} e^{R_i} \quad (9)$$

where ϕ is the corresponding Gaussian of equivalent log normal. Applying Wilkinson's approach [7], by estimating first moment (u_1) and second moment (u_2) of I, the mean m_{ϕ}, and the standard deviation σ_{ϕ} of ϕ in (9) are estimated as:

$$m_{\Phi} = 2\ln(u_1/P_R) - \frac{1}{2}\ln\left(u_2/P_R{}^2\right) \quad (10)$$

$$\sigma_{\Phi}^2 = \ln\left(u_2/P_R{}^2\right) - 2\ln(u_1/P_R) \quad (11)$$

For simplicity all interferers are assumed to have identical statistics for all $i \neq j$. We express the received signal $S = P_R e^R$, where R is a Gaussian r.v. with mean m_R and variance σ_R^2. With direct sequence BPSK of spreading bandwidth BW and constant received signal power levels, the probability of error under the Gaussian approximation is:

$$P_e = Q\left(\sqrt{2\frac{E_b}{\chi}}\right) = Q\left(\sqrt{\frac{2P_R e^R/R_b}{I/BW}}\right) = Q\left(\sqrt{\frac{2P_R e^R/R_b}{P_R e^{\phi}/BW}}\right) = Q\left(e^{\psi}\right) \quad (12)$$

The mean and variance of ψ are [14]:

$$m_{\psi} = E(\psi) = \frac{1}{2}\left[\ln(2.pg) - m_{\phi}\right] \quad (13)$$

$$\sigma^2{}_{\psi} = \mathrm{var}(\psi) = \frac{1}{4}\left(\sigma_R{}^2 + \sigma_{\phi}{}^2\right) \quad (14)$$

Following [14], the mean probability of error at any hop can be approximated by

$$\overline{P_e} = \frac{2}{3}Q\left(e^{m_{\psi}}\right) + \frac{1}{6}Q\left(e^{m_{\psi}+\sqrt{3}\sigma_{\psi}}\right) + \frac{1}{6}Q\left(e^{m_{\psi}-\sqrt{3}\sigma_{\psi}}\right) \quad (15)$$

We consider multi-hop paths between sources and the sink with an average number of hops (H), and average distance at each hop r_{Rn}, as expressed by (1). The route BER for H hops, without any error correction mechanism applied at the intermediate relay nodes, is expressed by the relation [13],

$$\overline{(P_e)}_H = 1 - \prod_{n=1}^{H}\left(1 - \overline{P_e}^{(n)}\right) \quad (16)$$

where $\overline{P_e}^{(n)}$ is the mean probability of error at n-th hop.

Further n_f bits/packet is considered in forward transmission of information and n_b bits/packet for NACK /ACK with an assumption of instantaneous error free reception of NACK/ACK. Assuming perfect error detection of a CRC code and infinite retransmissions from sink to source, ARQ and HARQ-I mechanisms are used for error correction. The packet is checked only at sink (D) for error control. The sink sends an ACK/NACK to the source via multi-hop. In case of NACK, the source retransmits the packet via same multi-hop route till it is received correctly. Considering the sink is not an energy constrained node, three schemes of error control are investigated:

Scheme I: Error control is based on simple ARQ, i.e. the packet from source consists of n_f bits, including CRC and overhead (β bits), is transmitted and is checked at sink only for correctness. It sends a retransmission request to the source for an entirely new retransmission in case of receipt of erroneous packet.

Scheme II: Error control is based on hybrid ARQ type I (HARQ-I), where the packet from source, consists of n_f bits (including overhead) and encoding bits for different error correction capability using BCH coding, is transmitted. At sink, the packet is decoded. It discards erroneous packets (when errors remain after BCH decoding), sends a retransmission request to the source for an entirely new retransmission. Retransmissions take place at the same code rate until the packet is correctly decoded.

Scheme III: Here, instead of BCH coding as in scheme II, RS coding is used for error control.

We now evaluate energy consumptions and delay associated with each scheme.

3.3.1 Scheme I

Average end-to-end packet error level for H hops is

$$\overline{(P_f)}_H = 1-(1-\overline{(P_e)}_H)^{n_f} \tag{17}$$

where $\overline{(P_e)}_H$ is given in (16). Average number of retransmissions for successful delivery of a packet [15]:

$$\overline{(N)}_I = 1/\left(1-\overline{(P_f)}_H\right) \tag{18}$$

The energy E_{bI} required to communicate one bit of information from source to sink through H-hop communication i.e. end-to-end delivery [16]:

$$E_{bI} = \sum_{n=1}^{H}(P_{tn}+P_r)/R_b \tag{19}$$

where R_b is the data rate, P_{tn} is the mean of transmitted power in (3) of n-th hop of length r_{Rn} , and is represented by

$$P_{tn} = P_R r_{Rn}^{\alpha} e^{-\left(m_{S_{rRn}}+\frac{\sigma_{S_{rRn}}{}^2}{2}\right)} . e^{\left(m_{R_{rRn}}+\frac{\sigma_{R_{rRn}}{}^2}{2}\right)} \tag{20}$$

We have included the energy consumption due to start-up transients of transceivers while evaluating the energy consumption for data communication. It is observed that start-up energy consumed in the transmitter / receiver varies approximately from 10 micro Joule to 45 micro Joule [17], [18]. Assuming a typical value of average start-up energy from sleep mode to either transmit/receive mode as 10 micro Joule, the energy consumed per packet from source to sink, i.e. single loop transmission of information from source to sink via H hops, with ACK/NACK from sink to source via multi-hop is:

$$(E_{pkt})_I = E_{bI}\cdot n_f + E_{bI}\cdot n_b + 10\times 10^{-3}\cdot H \tag{21}$$

Since on the average, each packet requires $\overline{(N)}_I$ number of retransmissions from source to destination for successful delivery, average energy consumed by a packet for successful delivery through multi-hop communication of H hops is :

$$E_{av,I} = \overline{(N)}_I.(E_{bI}\cdot n_f + E_{bI}\cdot n_b) + 10\times 10^{-3}\cdot H \tag{22}$$

Assuming insignificant delay in transmitting ACK/NACK, average packet delay for successful transmission of packet is obtained as [19]:

$$D_{av,I} = \overline{(N)}_I.n_f / R_b \tag{23}$$

3.3.2 Scheme II

The packet error rate (PER) in HARQ-I scheme with BCH code is given as in [11]:

$$(PER_{HARQ-I})_{BCH} = 1-\sum_{i=0}^{t}\binom{\ell_{BCH}}{i}.(\overline{(P_e)}_H)^i.(1-\overline{(P_e)}_H)^{\ell-i} \tag{24}$$

Here t represents number of bits to be corrected, $\ell_{BCH} = (\partial + n_f)$ is the total number of bits to be transmitted and is the sum of length of frame check sequence ∂, and n_f bits as described above. Average number of retransmissions for successful reception of a packet [15]:

$$\overline{(N)}_{II} = 1/(1-(PER_{HARQ-I})_{BCH}) \tag{25}$$

In the present case, we assume negligible energy for BCH encoding at source node, and energy consumed at sink is ignored since the sink is assumed not to be a power constrained node. With these assumptions, the energy consumed per packet by the source and relay nodes in a single loop transmission of information via H hops including start up energy of each node, with ACK/NACK via multi-hop is:

$$(E_{pkt})_{II} = E_{bI}\cdot \ell_{BCH} + E_{bI}\cdot n_b + 10\times 10^{-3}\cdot H \tag{26}$$

where E_{bI} is expressed in (19). Average energy required for successful delivery of packet

$$E_{av,II} = \overline{(N)}_{II}.(E_{bI}\cdot \ell_{BCH} + E_{bI}\cdot n_b) + 10\times 10^{-3}\cdot H \tag{27}$$

Average packet delay for successful transmission of packet is obtained as [19]:

$$D_{av,II} = \overline{(N)}_{II}.\ell_{BCH} / R_b \tag{28}$$

3.3.3 Scheme III

In this scheme, we consider HARQ-I based transmission with RS coding. Under the assumption of purely random bit errors, and for the same channel condition as in previous schemes, the symbol error rate is given as in [11]:

$$P_{SE} = 1-(1-(\overline{P_e})_H)^m \tag{29}$$

where m is the number of bits per symbol. The packet error rate (PER) for the present scheme with RS code [11]:

$$(PER_{HARQ-I})_{RS} = 1-\sum_{i=0}^{t}\binom{n}{i}.(P_{SE})^i.(1-P_{SE})^{n-i} \tag{30}$$

Here t represents number of symbols to be corrected, and n is the number of symbols per code block, i.e. the block length in symbols.

Average number of retransmissions for successful reception of a packet [15]:

$$(\overline{N})_{III} = 1/(1-(PER_{HARQ-I})_{RS}) \tag{31}$$

As encoding energy using RS coding is quite high as compared to BCH coding, here we include encoding energy for RS coding at source node, and energy consumed at sink is ignored since the sink is not a power constrained node. With these assumptions, the energy consumed per packet by the source and relay nodes in single loop transmission of information via H hops including start up energies of all nodes participating in multi hop path, with ACK/NACK via multi-hop is:

$$(E_{pkt})_{III} = E_{encode} + E_{bI}\cdot\ell_{RS} + E_{bI}\cdot n_b + 10\times10^{-3}\cdot H \tag{32}$$

where E_{bI} is expressed in (19), E_{encode} is the encoding energy at source, and '$\ell_{RS} = n\cdot m$' is the number of bits to be transmitted after encoding. Considering 0.18 μm CMOS, and implementation based on polynomial representation and shift registers as in [20], encoding energy (E_{encode}) is calculated.

Average energy required for successful delivery of packet

$$E_{av,III} = E_{encode} + (\overline{N})_{III}.(E_{bI}\cdot\ell_{RS} + E_{bI}\cdot n_b) + 10\times10^{-3}\cdot H \tag{33}$$

Average packet delay for successful transmission of packet is obtained as [19]:

$$D_{av,III} = (\overline{N})_{III}.\ell_{RS}/R_b \tag{34}$$

3.4 Network Lifetime

Following [10], we consider network lifetime as the time when the first node failure occurs (i.e., a worst-case approach). We assume that every node has an initial finite battery energy denoted by E_{batt} and packets are transmitted with average rate λ_t packets/sec. without queuing. The average energy depleted per second due to transmission and reception is simply $\lambda_t\cdot E_{packet}$, where E_{packet} is the average energy consumed per node while delivering a packet successfully from source to sink, and is determined by dividing the average energy consumed for successful transmission of a fixed length packet (as calculated above in different schemes) with average number of hops at each search angle or node density. Finally, the time it takes to completely exhaust the initial battery energy is

$$\tau = E_{batt}/(\lambda_t\cdot E_{pkt}) \tag{35}$$

This simple analysis does not take into account the energy consumed when a node is processing packets. Thus, the actual lifetime of a node will be shorter than what is predicted by our analysis.

4. PACKET SIZE OPTIMIZATION

Following [12], an optimization framework based on end-to-end performance using infinite ARQ between source and sink, as described in scheme I, may be formulated. Optimization is carried out by using three different objective functions, such as packet throughput, energy consumption per useful bit, and resource utilization. The three objective functions are defined as [12]:

1. Packet throughput: This function considers the end-to-end packet success rate and the average delay for successful reception of a packet of payload $l_d = (n_f - \beta)$ through multi hop communication.

$$U_{pktput} = l_d\cdot\left(1-(\overline{P_f})_H\right)/D_{av,I} \tag{36}$$

Maximizing this function by setting $\frac{d}{dl_d}(U_{pktput}) = 0$ results in optimal packet size L_{opt}^{pktput} that achieves high packet throughput for a particular search angle and node density. After simplification, L_{opt}^{pktput} can be expressed by:

2. $$L_{opt}^{pktput} = \frac{\sqrt{\beta^2 - \frac{4\beta}{\ln\left(1-(\overline{P_e})_H\right)}} - \beta}{2} \quad (37)$$

2. Resource utilization: This function considers both energy consumption and delay for successful reception of a packet, and is expressed by,

$$U_{res} = E_{av,I} \cdot D_{av,I} / l_d \cdot \left(1-(\overline{P_f})_H\right) \quad (38)$$

Minimizing this function by setting $\frac{d}{dl_d}(U_{res}) = 0$ results in optimal packet size L_{opt}^{res}, which balances the trade off between energy consumption and latency, for a particular search angle and node density, especially useful for delay sensitive WSN. After simplification, L_{opt}^{res} can be expressed by:

$$L_{opt}^{res} = \frac{\sqrt{\beta^2 + \frac{4\beta}{\ln\left(1-(\overline{P_e})_H\right)}} - \beta}{2} \quad (39)$$

5. RESULTS

Parameters used in present analysis, based on semi-analytic method, are given in table 1. Mean of all shadowing and pce components are considered to be zero. Pair wise correlation coefficients between different interferers are assumed to be equal to r. We assume that 50% of total nodes within receiving distance (r_R) of sink are active for MAI while 25% of nodes between r_R and r_I of sink are active for NI. As we consider uniform distribution of nodes, and $r_I \approx 2r_R$, 25% of total nodes within r_R of other intermediate relay nodes are active for MAI while same percentage of nodes between r_R and r_I of other intermediate relay nodes are active for NI at any instant. Thus we assume that MAI in the last hop involving sink is more while NI is same across all hops. All parameters at each hop are calculated considering distance between two consecutive nodes as r_R meter, where r_R is calculated by using (1) and (2). The procedure adopted for the evaluation of link BER, followed by route BER and average route BER for the estimation of different QoS parameters is described below:

1. Average number of hops between source and destination $\bar{n}_{rand}$ is calculated by using (2) for a particular search angle θ, and considering Y=100m.
2. Average hop distance for $\bar{n}_{rand}$ hops (r_{Rn}) are estimated by using (1) and by generating $\bar{n}_{rand}$ number of random variables.
3. Link BER for each hop is evaluated using (15), followed by route BER for that θ using (16) for a single realization of from source to destination path. Average route BER is then obtained by using Monte Carlo Simulation.
4. Average route PER for a fixed packet length (n_f), energy consumption, latency, network lifetime, and different objective functions are evaluated by using the value of average route BER.

Table 1: Parameters used in the analysis

Parameter	Value
Y as shown in Fig.1	100 m
Min. distance between two nodes (r_0)	1 m
Processing Gain (pg)	128
Constant receive power (P_R)	1.0x 10^{-07}mW
Path loss parameter (α)	3
Transmission rate (R_b) without ARC	20.0kbps
NACK/ACK (n_b)	2 bits
Correlation coefficient (r)	0.0, 0.6
Standard deviation of pce (σ_R)	1dB
Standard deviation of Shadowing (σ_s)	3 dB
Band width	5 MHz
Overhead (β)	8 bits
Start up energy/node	10micro Joule

Fig. 3 shows the variation of average number of hops with node densities for different values of θ. With increase in node density, number of nodes within a particular angle increases, which results in decrease in hop length and increase in average number of hops. Similarly, for a fixed node density, with increase in search angle (θ), number of nodes within that angle seems to increase. As we are considering only nearest neighbor within that angle as next node, this may lead to increase number of hops with increasing angle.

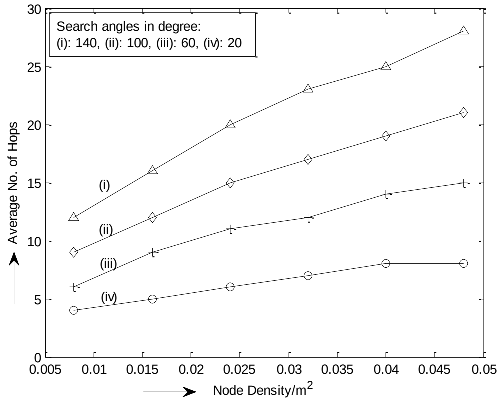

Figure 3: Variation of number of hops with node densities for different search angles, average distance of reference path remains same in all cases.

Fig.4 shows the variation of average route BER with node densities for different values of search angle θ and correlation amongst interferers. With increase in node density, number of nodes within a particular search angle (θ) increases, which results in decrease in hop length and increase in average number of hops. For a fixed link distance, increase in number of hops degrades average route BER as depicted by (16). In our case, the decrease in average hop length reduces link BER due to reduction in interference. Resultant effect of increase in average number of hops and improved link BER results improvement in average route BER with node density. For a particular node density, with increase in search angle, average number of hops increases with the decrease in average hop length which results improved link BER. Thus average route BER improves with increase in search angle. It is seen that average route BER increases with increasing correlation amongst interferers. It is due to degradation of SIR with increase in correlation. BER increases by 49% as correlation increases from 0.0 to 0.6, keeping node density and search angle fixed at 0.024/m^2, 60 degree respectively.

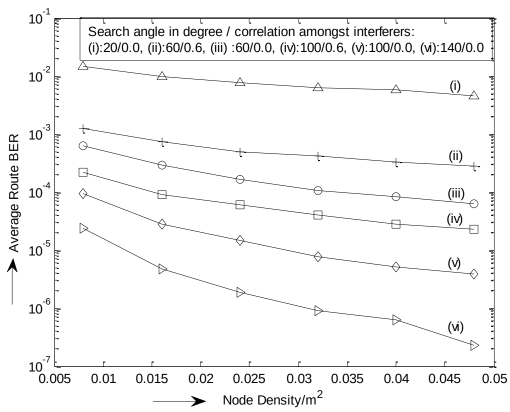

Figure 4: Variation of average route BER with node densities for different search angles, and correlation amongst interferers; average distance of reference path remains same in all cases.

Following the definition of network lifetime as defined earlier, average energy consumed by each node for successful transmission of a packet directly governs the network lifetime. Fig.5 shows the variation of average energy consumed by each node for successful transmission of a packet of length 64 bits including CRC using infinite ARQ between source and sink with node densities for different values of search angle (θ). Average energy consumed by each node decreases with increase in search angle as shown in Fig.5. With increase in search angle, transmit power at each node decreases with a constant start up energy which leads to the decrease in average energy consumed by each node for successful transmission of a packet from source to sink. This results in increase in node lifetime with increase in search angle or node density as shown in Fig.6. It is seen that by increasing search angle from 20 degree to 60 degree average energy consumption/node, network lifetime increases by 0.1% using ARQ between source and sink; keeping node density, packet length, correlation amongst interferers fixed at 0.016/m^2, 64 bits, and 0.0 respectively.

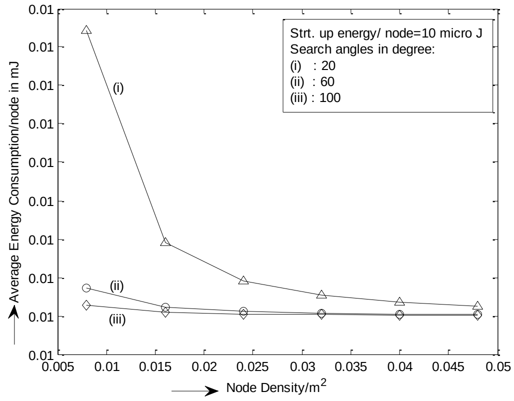

Figure 5: Variation of average energy consumption per node for successful reception of a packet with node densities for different search angles.

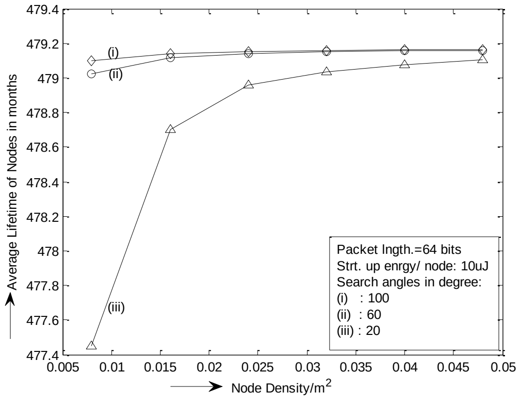

Figure 6: Variation of average node lifetime in months with node densities for different search angles.

Fig.7 shows the variation of latency with node densities for successful transmission of a packet of length 64 bits using infinite ARQ between source and sink under several values of search angles. With increase in node density or search angle, average route BER improves as seen in Fig.4. This results in the improvement of average route PER followed by the decrease in average number of retransmissions for successful delivery of a packet from source to sink. This results in decrease in average delay or latency of the network with increase in search angle (θ) or node density. It is also seen that beyond a certain node density or search angle, the difference in delay is insignificant. It is due to insignificant difference in number of interferers with decrease in hop length, associated with increase in average number of hops beyond a certain node density. Thus number of retransmission does not change significantly beyond a certain node density or search angle which keeps delay nearly fixed at a particular level.

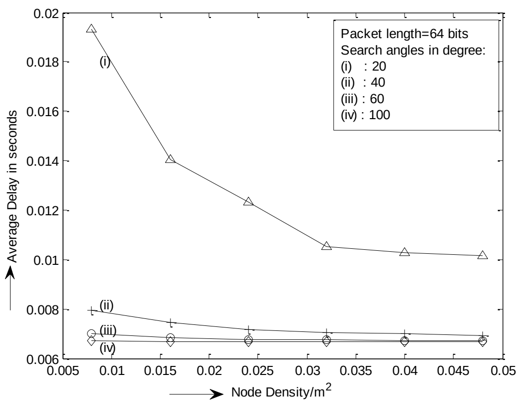

Figure 7: Variation of average delay for successful reception of a packet with node densities for different search angles.

Fig.8 compares the variation of node lifetime with search angles (θ) with error correction schemes using BCH and RS coding at source and sink, and without incorporating error control. For the comparison to be fair, we use BCH code (63, 57, 1) which is suitable to be compared with RS (15, 13). With infinite ARQ, the message length is 57 bits. It is seen that lifetime of each source/ relay nodes of the sensor network system having error correction capability at sink is higher as compared with infinite ARQ from sink to source, in spite of transmission of extra bits due to encoding. This is mainly due to reduction in PER, which subsequently results in significantly less number of retransmissions as compared without error correcting capability at sink. With increase in node densities or with increase in (θ), average hop distance decreases. In this case incorporation of error correction capability is not significant as compared with only ARQ. Thus with increase in (θ), node lifetime remains almost same in all cases. Moreover, schemes using BCH and RS coding show similar performance as seen from the curves (i) , (ii), and (iv), (v). This is due to the fact that the number of extra bits after encoding is almost same in two cases for our chosen parameters. However, RS coding out performs BCH in case of burst error condition, i.e. in case of very high interference condition.

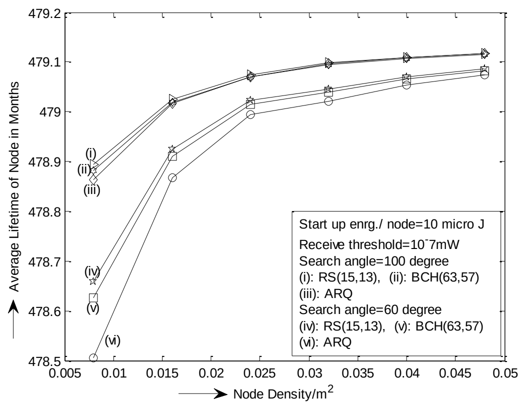

Figure 8: Variation of average node life time with node densities for different search angles and with different error control schemes.

Fig.9 compares the variation of average route delay with search angle **(**θ**)** and node densities with error control using BCH(63,57,1) and RS(15,13) coding at sink and ARQ with 57 bits in case of transmission without error control coding. It is seen that at low search angle or low node density region, where average hop distance is high, average route delay for successful transmission of message from source to sink is significantly high using ARQ as compared to BCH or RS coding. With increase in (θ), or node density, average hop distance decreases which results in significant decrease in average number of retransmissions using ARQ. Thus average route delay decreases with increase in (θ). At high value of (θ), very low average hop distance improves average route BER significantly. In this condition, incorporation of HARQ-I with BCH or RS at sink may lead to increase in delay due to transmission of extra overhead.

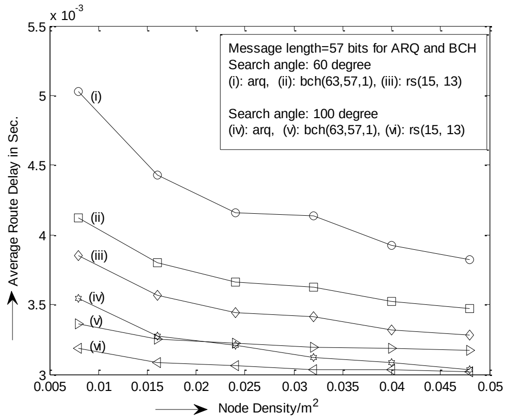

Figure 9: Variation of average delay for successful reception of a packet with node densities for different search angles and error control schemes.

Fig. 10 depicts the variation of packet throughput with packet length, and search angle under ARQ. At low packet length region, low packet throughput is due to overhead, which is comparable with the packet length. At high packet length region, packet throughput decreases due to degradation in PER. This decrease is significant in case of low search angle (curve iv). It is due to higher number of interferers, associated with higher hop length. With increase in search angle, route PER for a fixed packet length improves due to improved route BER. Subsequently, delay for successful delivery of packet decreases (Fig. 7), which causes increase in packet throughput with increase in search angle. The optimized packet lengths (L_{opt}^{pktput}), as obtained from the curves of Fig.10 match with those obtained numerically by using (37), as shown in table 2.

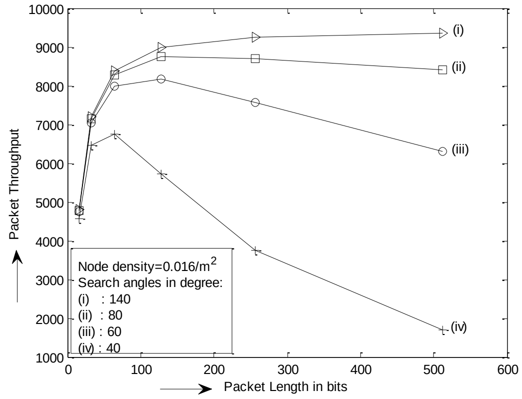

Figure 10: Variation of packet throughput with packet lengths for different search angles.

Table 2 : Optimized packet length using (37) for different search angles; node density 0.016/m^2 in each case.

Search angle in degree	40	60	80	140
Optimized packet length (bits/packet)	65.8	137.8	260.3	882.1

Fig.11 shows the variation of resource utilization with packet length for a fixed node density 0.016/m^2 using infinite ARQ, under several values of search angle. We observe that, increase in search angle is associated with increase in average energy consumption due start up energy of higher number of nodes, as shown in Fig.5. At low search angles, i.e. 40 degree, 60 degree, average hop length is high. Thus, a packet length at lower region yields best resource utilization considering both energy consumption and delay for successful delivery of a packet (curve i, iii). With increase in search angle, average number of hops increases followed by increase in total start up energy and energy consumption for successful transfer of information from source to sink, which causes increase in the level of resource utilization. However, with increase in search angle, average hop length decreases, thus packet length may be increased without sacrificing resource utilization for such search angle, as start up energy overshadows the combined energy consumption due to retransmissions in ARQ. The optimized packet lengths (L_{opt}^{res}), as obtained from the curves of Fig.11 match with those obtained numerically by using (39), as shown in table 3.

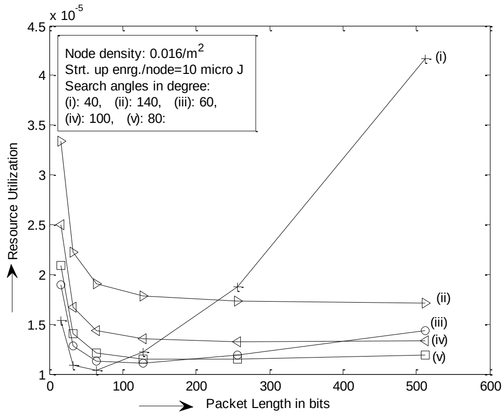

Figure 11: Variation of resource utilization with packet lengths considering start up energy of nodes under different search angles.

Table 3: Optimized packet length using (39) for different search angles; node density 0.016/m2 in each case.

Search angle in degree	40	60	80	140
Optimized packet length (bits/packet)	69.59	141.69	264.22	886.09

6. CONCLUSION

In this paper, using a semi-analytical model, the end-to-end performance of a multi-hop CDMA based random wireless sensor network is evaluated in terms of different metrics like average route BER, latency, energy consumption per node for successful transfer of a fixed length packet, lifetime of a sensor node. Start up energy at each node is considered as in practical cases. Several schemes of transmissions such as infinite ARQ between source and sink, HARQ-I using BCH and RS codes are considered. Selection of intermediate relay nodes for multi hop operation is based on the nearest node within a sector of angle (θ) towards the direction of destination. Average route BER is found to improve with increase in search angle θ, for a fixed node density. Average lifetime of a sensor node increases with increase in search angle or node density. Packet throughput increases with increase in search angle. Optimal packet length corresponding to high throughput also increases with increase in search angle. Resource utilization may be minimized at low search angle with low packet length. As nodes of wireless sensor network are energy constrained, minimization of resource utilization is an important step in designing an energy efficient CDMA WSN with delay sensitive application environment. Inclusion of HARQ-I at sink using BCH or RS coding, where encoding and decoding are done at source and sink respectively, outperform infinite ARQ between source and sink in terms lifetime, delay over a wide range of node densities. Thus above study is useful in designing an energy efficient routing based multi hop CDMA WSN for delay constrained applications.

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