Resource utilization of multi-hop CDMA wireless sensor networks with efficient forwarding protocols

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Abstract

In this paper, we propose a new forwarding scheme for a multi-hop CDMA wireless sensor network (WSN). Selection of intermediate nodes considers detection probability along with maximum forwarding distance by taking into account the wireless channel condition, like path loss, and shadowing. Energy and latency performance using infinite ARQ between source and final destination of proposed scheme is studied. Performance of this scheme is compared with nearest neighbor based routing scheme, where an intermediate node in the route selects the nearest node within a sector angle, considered as search angle, towards the direction of the destination as the next hop. Further a framework for packet size optimization based on resource utilization, capturing both energy consumption and delay, is presented.

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1. Introduction

Energy conservation is one of the key technical challenges in wireless sensor networks. It is necessary to devise networking schemes which make judicious use of limited energy resources without compromising the network connectivity and the ability to deliver data reliably to the intended destination. Many new algorithms have been proposed for the problem of routing data in sensor networks. These routing mechanisms have considered the characteristics of sensor nodes along with the application and architecture requirements. Almost all of the routing protocols can be classified as data-centric, hierarchical or location-based although there are few distinct ones based...
on network flow or QoS awareness [1]. Data-centric protocols are query-based and depend on the naming of desired data, which helps in eliminating many redundant transmissions. Hierarchical protocols aim at clustering the nodes so that cluster heads can do some aggregation and reduction of data in order to save energy. Location-based protocols utilize the position information to relay the data to the desired regions rather than the whole network. The last category includes routing approaches that are based on general network-flow modelling and protocols that strive for meeting some QoS requirements along with the routing function. Several routing protocols are described in the literature, based on location information of sensor / relay nodes [2, 3, 4, 5, 6, 7].

A routing scheme where each intermediate node in a multi-hop route selects the nearest node within a sector of angle (θ) toward the direction of the destination as the next hop, is considered in [2]. However, node isolation may occur in case of low search angle in such scheme. Geographic-information-based forwarding (GIF) [3] is an efficient scheme for finding the appropriate relay node for next hop utilizing the location information while avoiding a large number of control packets during route discovery. Relay nodes are selected based on a single criterion, i.e., the maximum advanced distance, to minimize the number of hops from the source to the destination node. Performance may degrade substantially over a bad channel with increase in energy consumption for successful transmission of a packet due to increase in number of retransmissions. An effective approach for the reduction of unnecessary retransmissions due to propagation impairment is to choose the next hop relay node that is in good channel condition. This will offer efficient packet transmission and increase energy efficiency. In designing efficient packet-forwarding strategy in WSNs, an efficient advancement metric (EAM), considering the forwarding distance and the probability of successful packet transmission in a wireless channel within a specified region is proposed in [4]. However, in a wireless channel with a fixed path loss factor and shadowing, selection of intermediate nodes in a multi hop transmission, jointly based on probability of detection following [12] and maximum advanced distance, may be another promising approach to reduce retransmissions due to propagation impairment. 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 [8, 9, 10]. CDMA has been advocated for WSN in [9, 10], where distribution of interference power in randomly distributed nodes is discussed. Bit Error Rate (BER) and energy consumption in CDMA WSN multi-hop communication with fixed hop length is studied in [11] using infinite Automatic Repeat reQuest (ARQ) with CRC. Above analyses of multi hop communication do not include any routing topology for the selection of neighbouring nodes.

In this paper, we propose a new routing protocol based on preselected probability of detection of neighbours considering a sensing range in shadowed environment [12] and combined with maximum advanced distance with respect to the final destination for the selection of intermediate nodes. The selection parameter is based jointly on probability of detection and maximum advanced distance. Detection probability includes parameter of shadow faded channel implicitly with an objective of reducing energy consumption (i.e. energy spent in communication). Maximum distance means that the chosen node is nearest to sink, with an objective of reducing number of hops in the multi hop transmission. We analyze the performances of CDMA based multi-hop WSNs using the proposed routing protocol and compare with the routing protocol as proposed in [2] under the same wireless channel environment.

The paper is organized as follows: The system model along with the proposed protocol is presented in section 2. Section 3 presents our analytical approach to evaluate the end-to-end BER, energy consumption, and delay. Cross layer solution for packet optimization is discussed in section 4. Results based on our developed framework 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 using two forwarding protocols and the basic assumptions considered in the paper.

2.1. Routing protocol based on search angle

We first consider the network architecture for the nearest neighbour based forwarding protocol [2], where \( N \) numbers of nodes are distributed over a region of area ‘A’, obeying random topology. To avoid edge effect of a finite area, as explained in [2, 15], we assume the network surface to be the surface of a torus with \( 2Y \) as length of
each side, i.e. \( A = (2Y)^2 \). A minimum distance of \( r_0 \) between any two nodes is considered, which is sufficiently small as compared to the distance between source and final destination, i.e. sink. The node spatial density \( p_s \) may be approximately defined as \( p_s = N/A \). Following [2], the average number of hops on a route for a search angle \( (\theta) \) under the constraint of \( r_0 \) is estimated as [13]:

\[
\bar{n}_{rand} = \frac{Y}{3} \left[ \sqrt{2} + \ln(1 + \sqrt{2}) \right] \left( \frac{1}{\pi(2p_s\theta + r_0) \cdot (2/\theta) \cdot \sin(\theta/2)} \right) \left( \frac{Z}{Z} \right) \left( \frac{2}{\sin(\theta/2)} \right)
\]

where \( Z \) represents average length of the reference path between a source and destination node. Let ‘ \( w \) ’ be a random variable denoting the distance to the nearest neighbour in a two dimensional Poisson node distribution. Following [2], the CDF of the distance to the nearest neighbour within a sector angle of \( \Theta \) in a torus, for fixed node spatial density with large \( N \) under the constraint of \( r_0 \) is estimated as [13]:

\[
P_{w_{\theta}}(w) = \begin{cases} 
1, & w > Y \\
1 - e^{-\rho(N)w^2}, & r_0 \leq w \leq Y \\
0, & \text{otherwise}
\end{cases}
\]

2.2. Forwarding protocol based on probability of detection combined with maximum forwarding distance

The proposed forwarding protocol based on detection probability is developed on a simulated test bed. In the next sections, as we compare the performance of the proposed protocol with the protocol based on search angle, source to sink distance is considered to be the same \( (\bar{Z}) \) in both cases. Though our model is circular, we have maintained same distance from source to sink as considered in [2] where the network model is square. We consider the network architecture where nodes are uniformly distributed over a circular region of radius \( Z \), as stated in (1). Minimum distance between two nodes is equal to \( r_0 \). Sink is considered to be at the centre and sources are at the periphery of the circular region, i.e. at farthest distances, to keep the reference distance between the source and sink same in both protocols. Other nodes are considered only as intermediate relay nodes. Channel conditions, i.e. path loss and shadowing are assumed to be fixed at a particular level throughout the network.

Selection of intermediate relay nodes to send the packet from source to the destination i.e. the sink is governed by the following algorithm, simulated on MATLAB:

- Considering a maximum forwarding / sensing distance and standard deviation of shadowing, average sensing distance \( \bar{R} \) is determined following [12]. Next probability of detection of all other nodes from the designated source node is estimated using (13) of [12] as:

\[
P_{\text{det}}(r_{Sh}) = \left( \frac{10\log_{10}(r_{Sh})}{\sigma} \right), \text{ where } r_{Sh} \text{ is the distance between the designated source node and the 'n-th' node in the area under investigation.}
\]

- The next relaying node is selected as the one with probability of detection greater than or equal to a preselected value at that channel condition and closest to the destination, i.e. the sink, and towards the sink.

- This node becomes in turn the transmitter for the next hop, and the packet reaches the final destination through multi hop transmission. All link / hop distances \( (r_{Sh}) \) are calculated from the known locations of the selected relay nodes, where ‘i’ denotes the i-th hop of multi hop communication.
2.3. MAC protocol and transmission scheme

Here we consider CDMA-based MAC protocol. For example in Fig.1, 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. Relays regenerate the received signal and then transmit the same with power control to the next hop. In CDMA sensor network, any node can transmit to its nearest next neighbour node at any time. Thus at a particular instant, we assume that nodes (E,b,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. As per proposed scheme, next hop relay nodes are selected according to the algorithm presented in Sec. 2.2, while in case of nearest neighbour based scheme, nodes are selected following the algorithm in Sec. 2.1. Further, 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 depends upon the path loss between the transmitter and the receiver pair ($r_{th}$), and the statistics of shadowing. Several concurrent nodes those are sending their information to any particular intermediate relay node on the path, e.g. 'h' within the area $\pi r_{th}^2$, would cause MAI at 'h'. The concurrent transmitted signal power generated by the source/relay nodes situated within the interference range $r_{th}$ ($r_{th} = 2r_{ao}$) of 'h', which are sending information to their respective destination node, might be sensed by 'h', which 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. We obtain the interference power distribution at each node following [10, 11].

3. Analysis of Route BER, Energy Consumption and Delay

We assume H is the average number of hops between source S and destination D. Channel conditions are assumed to be same from source to sink.

Following [10], the mean value of the collected interference power $\eta'$ from an interfering node (i.e. d is transmitting signal to it’s intended receiver e) to any desired receiver (i.e. h):

$$\eta' = \eta_e e^{-\frac{\eta_{de}}{2}} e^{-\frac{\eta_{de} + \eta_{dh}^2}{2}} e^{-\frac{\eta_{de} + \eta_{dh}^2 + \eta_{de} + \eta_{dh}^2}{2}}$$

(3)

$\eta$ can be found out as in [10] as:
\[
\eta = \frac{4P_k \left( \frac{\sigma_{\text{Sm}}^2}{\alpha^2 - 4} \right) \left( \frac{\sigma_{\text{Sm}}^2}{\sigma_{\text{Sm}}^2} \right)}{\left( \frac{\sigma_{\text{Sm}}^2}{\alpha^2 - 4} \right) \left( \frac{\sigma_{\text{Sm}}^2}{\sigma_{\text{Sm}}^2} \right) - \left( \frac{\sigma_{\text{Sm}}^2}{\sigma_{\text{Sm}}^2} \right)} = yP_k
\]

where \( m_{d_{\text{Sm}}} \), \( m_{d_{\text{Sm}}} \) are the mean and \( \sigma_{d_{\text{Sm}}} \), \( \sigma_{d_{\text{Sm}}} \) are the standard deviation of shadowing \( s_{d_{\text{Sm}}} \) and pce \( s_{d_{\text{Sm}}} \) respectively for an arbitrary path \( d_{\text{Sm}} \). Further \( \alpha \) is the path loss exponent \( 2 < \alpha < 6 \) and \( m_{d_{\text{Sm}}} \), \( m_{d_{\text{Sm}}} \) are the mean and standard deviation of shadowing of the path \( d_{d_{\text{Sm}}} \) between the nodes \( d \) and \( h \). The expected numbers of nodes within the receiving and interference range of the receiver are given by (5) respectively [10]

\[
c_1 = P_r \sigma_{d_{Rm}}^2
\]

\[
c_2 = P_r \sigma_{d_{Rm}}^2
\]

where \( P_r \) is the node density. Activity factors determine the number of active nodes at any instant contributing MAI and NI, which are fractions of \( c_1 \) and \( c_2 \) as given in (5). Following [14], the mean probability of error at any hop can be approximated by

\[
P_e = \frac{2}{3} Q(\sqrt{\gamma_e}) + \frac{1}{6} Q(\sqrt{\gamma_e + \sqrt{\gamma_e}}) + \frac{1}{6} Q(\sqrt{\gamma_e - \sqrt{\gamma_e}})
\]

We consider multi-hop paths between source and the sink with average number of hops \( H = n_{\text{rand}} \), and average distance at each hop \( w = r_h \), as expressed by (1) and (2) respectively. The route BER for H hops, without any error correction mechanism applied at the intermediate relay nodes, is expressed as [15],

\[
(P_e)_H = 1 - \left( 1 - (P_e)_{H_i} \right)^H
\]

where \( (P_e)_{H_i} \) is the mean probability of error at i-th hop.

Further \( n_f \) bits per packet including CRC and overhead (8 bits) 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 retransmission, ARQ mechanism is used for error correction. In the present scheme, the packet is checked only at sink for error control; retransmissions of the packet are requested to source, with a NACK coming back from sink to source through the same multi-hop path till the packet is received correctly.

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

\[
(P_e)_H = 1 - (1 - (P_e)_H)^H
\]

where \( (P_e)_H \) is given in (7). Average number of retransmissions for successful delivery of a packet [11]:

\[
(N)_{\text{ARQ}} = 1/(1 - (P_e)_H)
\]

The energy \( E_b \) required to communicate one bit of information from source to sink through H-hop communication i.e. end-to-end delivery [16]:

\[
E_b = \sum_{i=1}^{H} (P_i + P_e) / R_b
\]

where \( R_b \) is the data rate, \( P_e \) is the mean of transmitted power for i-th hop of length \( r_h \), and is represented by
We have included the energy consumption due to start-up transients of transceivers in estimating total energy consumption. Assuming average start-up energy from sleep mode to either transmit/receive mode is equal to 10 micro Joule [17, 18], 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:

\[ (E_{m})_{s} = E_t \cdot n_f + E_r \cdot n_r + 10 \times 10^{-6} \cdot H \]  

(12)

Nodes are assumed to be wake up from sleep state to active state at the beginning of transmission and remain in that state till successful delivery of packet. Since on the average, each packet requires \( N_{abq} \) number of retransmissions from source to destination for successful delivery, average energy consumed by a packet for successful transmission via H multi-hop is:

\[ E_{av}^{ABQ} = (N_{ABQ})_{av} \cdot (E_t \cdot n_f + E_r \cdot n_r) + 10 \times 10^{-6} \cdot H \]  

(13)

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

\[ D_{av}^{ABQ} = (N_{ABQ})_{av} \cdot n_f / R_b \]  

(14)

4. Packet Size Optimization

Following [20], we estimate optimal packet size which optimizes 'resource utilization' \( (U_{res}) \), a metric that considers both energy consumptions and delay for successful packet transmissions under present routing schemes as:

\[ U_{res} = E_{av}^{ABQ} \cdot D_{av}^{ABQ} / l_d \cdot \left[ 1 - (P_r)_{H} \right] \]  

(15)

where \( l_d = (n_f - \beta) \) is the message length. Minimizing this function by setting \( \frac{d}{dr_d} (U_{res}) = 0 \) results in optimal packet size \( (l_{res}^{opt}) \), that balances the trade-off between energy consumption and latency, especially useful for delay sensitive WSN. After simplification, \( l_{res}^{opt} \) is obtained as:

\[ l_{res}^{opt} = \frac{\beta^2}{2} \left[ \ln \left[ \frac{4\beta}{\ln(1 - (P_r)_{H})} \right] - \beta \right] \]  

(16)

5. Results

Same channel condition and average reference distance between source and sink are considered for both schemes. 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. We assume that 50% of total nodes within receiving distance \( (r_g) \) of sink are active for MAI while 25% of nodes between \( r_g \) and \( r_f \) of sink are active for NI. As we consider uniform distribution of nodes, and \( r_f \approx 2r_g \), 25% of total nodes within \( r_g \) of other intermediate relay nodes are active for MAI while same percentage of nodes between \( r_g \) and \( r_f \) of other intermediate relay nodes are active for NI at any instant. All parameters at each hop are calculated considering distance between two consecutive nodes as \( r_h \) meter, where \( r_h \) are calculated by using (1) and (2) for search
angle based protocol. The procedure adopted for the evaluation of link BER, followed by route BER and average route BER for the estimation of different QoS parameters, using the two forwarding protocols, are described below:

Table 1: Parameters used

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value of $Y$</td>
<td>100 m</td>
</tr>
<tr>
<td>Min. distance between two nodes ($r_0$)</td>
<td>1 m</td>
</tr>
<tr>
<td>Processing Gain ($pg$)</td>
<td>128</td>
</tr>
<tr>
<td>Constant receive power ($P_r$)</td>
<td>$1.0 \times 10^{-7}$ mW</td>
</tr>
<tr>
<td>Path loss parameter ($a$)</td>
<td>3</td>
</tr>
<tr>
<td>Transmission rate ($R_b$)</td>
<td>20.0 kbps</td>
</tr>
<tr>
<td>NACK/ACK ($n_b$)</td>
<td>2 bits</td>
</tr>
<tr>
<td>Standard deviation of pce ($\sigma$)</td>
<td>1 dB</td>
</tr>
<tr>
<td>Standard deviation of Shadowing ($\sigma_s$)</td>
<td>3 dB</td>
</tr>
<tr>
<td>Band width</td>
<td>5 MHz</td>
</tr>
<tr>
<td>Overhead ($\theta$)</td>
<td>8 bits</td>
</tr>
<tr>
<td>Start up energy/node</td>
<td>10 micro Joule</td>
</tr>
<tr>
<td>Maximum forwarding / sensing distance</td>
<td>30 m</td>
</tr>
</tbody>
</table>

(A): Forwarding protocol based on search angle with nearest neighbour:

- Average number of hops between source and destination $n_{rad}$ is calculated by using (1) for a particular search angle ($\theta$), and reference distance as expressed in (1), considering $Y=100m$.
- Average hop distances ($r_0$) are estimated by using (2) by generating $n_{rad}$ number of random variables.
- Link BER at each hop is evaluated using (7), followed by route BER for that $\theta$ using (8). Average route BER, route energy consumption, and average delay for successful transfer of information from source to sink, and resource utilization are evaluated.

(B): Forwarding protocol based on probability of detection with maximum advancement:

Under the proposed protocol, $r_{th}$s are estimated after selection of intermediate relay nodes by the algorithm as described in section 2.2. Next the QoS parameters are evaluated in same way as in scheme A.

Figure 2 compares the variation of average route BER with node densities under two different protocols. Impact of search angles $\theta$ for nearest neighbor based protocol, and various probabilities of detections with sensing distance of 30m for proposed protocol are shown. In case of nearest neighbour based protocol, with increase
in node density or search angle, number of nodes within a particular θ increases, which results in decrease in hop length and increase in average number of hops. In this case, decrease in average hop length is associated with reduction in interference, which improves the link BER. This in turn results improvement in average route BER with node density or θ (curves i and ii). In case of channel aware forwarding protocol, higher probability of detection reduces distance of next hop neighbour, which results in improved link BER followed by lower route BER as seen in curves iii and iv. With increase in node density, keeping probability of detection fixed at a level, number of interferers increases, thus average route BER increases. Thus channel aware forwarding protocol may outperform the other in some cases and choice of search angle plays an important role.

Figure 3 compares the variation of average energy consumed by all participating relay nodes for successful transmission of a packet of length 64 bits with search angle (θ) / probability of detection for different values of node densities. In case of nearest neighbour based forwarding protocol, with increase in node density or search angle link distance decreases with increase in number of hops. Though transmit power at each node decreases, but combination of start up energy of all participating nodes results in increase in average energy consumed for successful transmission of a packet from source to sink (curve i, iv). However, in case of channel aware forwarding protocol, for a fixed shadowing and path loss, variation of link distance is insignificant with increase in node density, thus average energy consumption for successful transmission of packet from source to sink primarily depends upon the number of retransmissions and total start-up-energies of participating relay nodes. High detection probability (i.e. $P_{\text{det}} \geq 0.99$) results in low number of retransmissions, but increases combined start-up-energy significantly. This increases average energy consumption for successful transmission of information at a fixed node density (curve ii). With increase in node density, number of interferers increases followed by increase in number of retransmissions for successful delivery of information and average energy consumptions. For lower value of detection probability ($P_{\text{det}} \geq 0.8$), link distance increases which causes higher transmit energy at each node and increase in number of retransmissions at higher node densities. However, it also results in significant reduction in the total start- up-energies due to lower number of hops. Combination of these two factors lowers the average energy consumption with decrease in probability of detection (curve iii).

![Fig. 3: Variation of average energy consumptions with node density for two different forwarding protocols, considering successful transmission of packet from source to sink.](image)

Figure 4 compares the variation of delay/latency with the two forwarding protocols for successful transmission of a packet of length 64 bits for various node densities. Using nearest neighbour based forwarding protocol, average route BER improves with increase in node density or search angle. Thus average delay of the network decreases with increase in θ or node density due to reduction in number of retransmissions (curves iii, iv). In case of channel aware protocol, with increase in node density/decrease in probability of detection, number of interferers increases, which increases delay (curves i, ii) due to increase in number of retransmissions.
Fig. 4: Variation of average route delay with node density for two different forwarding protocols, considering successful transmission of packet from source to sink.

Figure 5 shows the variation of resource utilization ($U_{res}$) (as in eqn. 15) with packet length under two different forwarding protocols for a fixed node density $0.016/m^2$. At low packet length region, $U_{res}$ is significantly high due to reasonable size of overhead, which is comparable with the message length. At high packet length region, $U_{res}$ increases slowly. It is due to increase in number of retransmissions because of degradation in PER. In case of low search angle, the rate of increase is appreciably high (curve i) due to high link distance. It is observed that there exists an optimum packet length, depending on the network condition, which yields minimum resource utilization beyond which resource utilization increases due to significant increase in route PER. The optimized packet lengths as observed from the curves, for different search angles and detection probabilities, match with those obtained by using (16), as shown in table 2.

Fig. 5: Variation of resource utilization with packet lengths for two different forwarding protocols, considering successful transmission of packet from source to sink.

Table 2: Optimized packet length using (16) for different search angles, probabilities of detection; node density $0.016/m^2$ in each case.

<table>
<thead>
<tr>
<th>Routing protocol based on search angle</th>
<th>Routing protocol based on probability of detection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Search angle</td>
<td>Probability of detection</td>
</tr>
<tr>
<td>40°</td>
<td>=&gt;0.99</td>
</tr>
<tr>
<td>60°</td>
<td>=&gt;0.8</td>
</tr>
<tr>
<td>Optimized packet length (bits/packet)</td>
<td></td>
</tr>
<tr>
<td>69.59</td>
<td>141.69</td>
</tr>
<tr>
<td>164.09</td>
<td>127.8</td>
</tr>
</tbody>
</table>

6. Conclusions

In this paper, using a semi-analytical model, the end-to-end performance of a CDMA based random wireless
sensor network in terms of average route BER, average energy consumption per node, and delay in successful transmission of packetized data from source to a sink via multi hop is estimated using a new channel aware forwarding protocol, where selection of intermediate relay nodes for multi hop operation is based on the probability of detection combined with maximum advanced distance with respect to the destination. The performance is compared with the nearest neighbour based forwarding protocol, where intermediate relay nodes is selected as the nearest node within a sector of angle (θ) towards the direction of destination. Variation of energy consumption with node density is lower in case of channel aware protocol than nearest neighbour based protocol. Resource utilization metric which combines energy consumption and delay is also compared for the two protocols. Optimum packet length which yields best resource utilization is indicated under two protocols. Best resource utilization within a range of packet length is observed with channel aware protocol with high probability of detection. This study is useful for designing energy efficient and delay critical CDMA WSN with efficient resource utilization.

References


[18] “ATMEL Transceiver Designer’s Guide” ATM8RF1212 Transceiver
