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Optimizing Physical Layer Energy Consumption for Reliable Communication in Multi-hop Wireless Sensor Networks

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Abstract

Developing energy efficiency protocols to optimize the energy consumption is most important for lifetime of Wireless Sensor Networks. We consider multi hop WSNs whose lifetime is critically dependent upon the rate of energy consumption of the battery of various constituent sensor nodes**. Objectives**: Our objective is to develop a cross layer energy efficient protocol which optimizes energy consumption of the sensor nodes at the Network, MAC and Physical layers of the protocol stack as most of energy consuming factors exist in these three layers. But, in this paper we focus only on optimizing physical layer in terms of energy consumption for WSNs. **Methods/Analysis**: We define and implement a mathematical model for the physical layer of Wireless Sensor networks in MATLAB. Our objective is to study the transmission energy only, so we do not consider other factors such as buffer overflows, link congestions etc. We assume that each link in the network has infinite large transmit buffer. We also assume that all nodes receive signals of same strength; hence the bit error rate is same for all links. To study these tradeoffs, we implement total transmission energy per packet against varying number of nodes (for different values of link errors). **Findings:** The results show that for lower values of the link error rates, the large number of short range hop nodes leads to a significant reduction in the total energy consumption. However, when this number of nodes tends to surpass the optimal value, error rates becomes higher and potential power savings due to the introduction of large number of intermediate node are negated by a sharp increase in effective bit error rate. **Novelty of the Study:** Traditionally, the problem of energy consumption optimization is considered separately at different layers of the protocol stack. We propose a cross layer energy efficient protocol which optimizes energy consumption of the sensor nodes at the Network, MAC and Physical layers of the protocol stack simultaneously. **Conclusion:** Choosing a communication path having large number of short hop nodes over a path having less number of long hop nodes leads to a significant reduction in the total energy consumption and a comprehensive, cross layered scheme of energy optimization is better approach to cope with the problem of energy consumption.

Keywords: Energy Consumption, Multi Hop, Physical Layer, Wireless Sensor Network

1. Introduction

Wireless Sensor Networks (WSNs) are required to be operating for months to years but constituent sensor nodes have limited battery power. Therefore, survivability is one of the critical issues and the most important research factor in the field of Wireless Sensor Networks (WSNs)[1,2]. Hence, energy efficiency is most important criteria for survivability and lifetime of WSNs. Therefore, developing approach to optimize the energy consumption has been a major consideration in WSNs. The major sources of energy waste[3,4] in WSNs are the following:

- **Collisions**: When two nodes simultaneously try to transmit data, the transmitted packets gets corrupted, they has to be discarded, and the follow-on retransmissions increase energy consumption.

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- **Control Packet Overhead**: Sending and receiving control packets consumes energy too, and less useful data packets can be transmitted.
- **Idle Listening**: Listening to receive possible traffic that is not sent.
- **Overhearing**: meaning that a node picks up packets that are destined to other nodes.
- **High Transmission Power**: Unnecessarily high transmission power leads to energy wastage.

Traditionally, the problem of energy consumption optimization is considered separately at different layers of the protocol stack. At Network Layer, inefficient routing of packets can lead to waste of energy. A protocol that needs many routing advertisements will make use of sensors energy to send them, reducing the network lifetime[5]. Thus energy efficient routing protocols can help to reduce energy consumption by avoiding retransmissions and less control packets. At Data Link Layer, error control techniques are necessary as wireless links are not reliable. In order to avoid collisions, WSNs should use contention less medium access and coordinated sleep schedules[6]. But all these solutions are energy consuming, since the techniques to solve them require resources from one or more nodes. Thus, every proposed solution needs to be energy efficient. At Physical layer, transmission power is to be optimized in order to have energy efficient routing protocol since most of the energy efficient routing protocols assign link cost as some function of transmission power which further depends upon several metrics like path loss, Signal to Interference plus Noise Ratio (SINR), Bit Error Rate (BER) etc. Even though a vast variety of single layer energy efficient solutions exist for different layers of protocol stack, but none of the single layer solution can optimize energy consumption well, as energy consuming factors are distributed across the layers of the protocol stack. A comprehensive, cross layered scheme of energy efficiency solutions seems to be the best approach to cope with the problem of energy efficiency as depicted in Figure 1[7]. Cross-layer design states that parameters of two or more layers can be retrieved and/or changed in order to achieve an optimization objective[8]. Cross-layering is still in its early development in this type of networks since it has not been deployed on many networks yet. However, different solutions which have already been proposed, and at least in simulations, they have proven to achieve better performance gains than their single layered counterparts[9]. Since most of the energy consuming factors exist in the first three layers of the protocol stack, therefore we limit our research to the Network, MAC and Physical layer aspects.

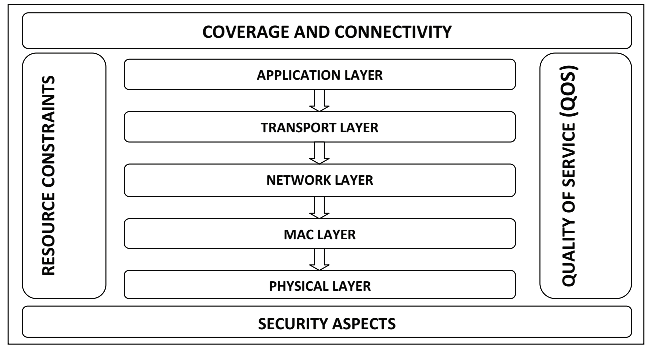

Figure 1. Cross layer issues in WSNs.

A few cross-layer protocols have been proposed for WSNs in literature. These cross-layer protocols jointly optimize the different layers among Physical (PHY), Medium Access Control (MAC), Network (Routing) and Transport layers. In [1], authors proposed an Energy Optimization Approach named as EOA based on Cross-Layer for Wireless Sensor Networks, which considered the joint optimal design of the physical, Medium Access Control (MAC) and routing layer. In the physical layer, EOA controls transmission power dynamically and obtains the proper transmission power level between two nodes. In the meanwhile, each node maintains a neighbor table to record this proper transmission power level. Then each node in the network layer constructs its routing table by utilizing the neighbor table of the physical layer. Finally, EOA uses the cross-layer routing information to determine the duty-cycle of each node, and meanwhile EOA also pays attentions to collision and overhearing problem in the MAC layer. In [6], authors gathered and discussed most of the recent research in the field. Paper has shown that there are different categories of WSNs, and that each of them has their own set of problems to be addressed. Furthermore, well-known problems have been discussed and some available cross-layer solutions have been briefly presented. Then, the layers and used technologies have been discussed, also presenting cross-layer approaches that are examples of the used technologies. Finally, concluded that there is still much to be done in order to achieve a comprehensive cross layer design that addresses the issues at every layer of the stack in an energy-efficient manner. In [10], authors proposed a cross-layer medium access control/routing protocol called RSSI-based Forwarding (RBF), which was based on a Received Signal Strength Indicator (RSSI) as a routing parameter for multi-hop WSN. In this protocol, the next-hop node for data-forwarding task is determined without using prior knowledge of nodes geographical locations and without maintaining neighborhood routing tables. For an arriving beacon signal transmitted by the sink, received power levels are computed for each sensor node in the network and these levels are then used as a decision parameter for the nodes to contend for the forwarding task of the data packets. In [11], authors presented a cross layer design approach with the concept of cooperation among the nodes with best farthest neighbor scheme. In this paper, the information about wireless medium of physical layer and MAC sub layer is passed to the network layer and the information of network is transmitted to lower layers. Information about the physical channel condition is transmitted from physical layer to network layer. Data rate and power information were transmitted from network layer down to the physical interface. In [12], authors proposed a unified cross-layer framework that includes connection admission control together with QoS routing in the network layer and distributed opportunistic proportional fair scheduling in MAC layer. A novel utility function is defined which is exchanged between an efficient distributed opportunistic proportional fair scheduler and a multi-constrained QoS routing algorithm. Furthermore, a novel tightly-coupled design method for joint routing and admission control has been demonstrated, where a unified optimization criterion "QoS performance index" combine multiple QoS constraints to indicate the QoS experience of each proposed route. In [13], authors considered the joint optimal design of the physical, Medium Access Control (MAC), and routing layers to maximize the lifetime of energy-constrained wireless sensor networks. The problem of computing lifetime-optimal routing flow, link schedule, and link transmission powers for all active time slots is formulated as a non-linear optimization problem. The link schedules were restricted to the class of interference-free Time Division Multiple Access (TDMA) schedules. In this special case, the optimization problem was formulated as a mixed integer-convex program, which can be solved using standard techniques. Moreover, when the slots lengths were variable, the optimization problem is convex and can be solved efficiently and exactly using interior point methods. For general non-orthogonal link schedules, an iterative algorithm was proposed that alternates between adaptive link scheduling and computation of optimal link rates and transmission powers for a fixed link schedule. In [14], authors performed the routing decision as a result of successive competitions at the medium access level. The next hop is selected based on a weighted progress factor and the transmit power is increased successively until the most efficient node is found. Moreover, on-off scheduled are used. The performance evaluations of all these propositions present the advantages of cross-layer approach at the routing and MAC layer. These above works provide analytical and simulation results without any communication protocol design and performed cross-layer design within limited scope, which do not consider all of the layers of the protocol stack involving in the communication in WSN, such as routing, medium access and physical layers. Thus, there is a need of comprehensive cross layer energy efficient protocol design. Cross-layer approach mentioned above considers the interaction between corresponding protocol layers, and preserves the traditional layered structure. Each layer is informed about the conditions of other layers, while the mechanisms of each layer still stay intact. Guided by above cross-layer principle, we design our cross-layer energy efficient protocol as in Figure 2. Firstly at physical layer, the protocol calculates the path loss based upon RSSI by means of beacon packet transmission from a sink node. Using path loss, a node decides whether or not to participate in contention to be a relay node. Secondly at network layer, a node with larger RSSI value (or with a shorter path loss as compare to the sender) is selected for the data forwarding task as next-hop node.

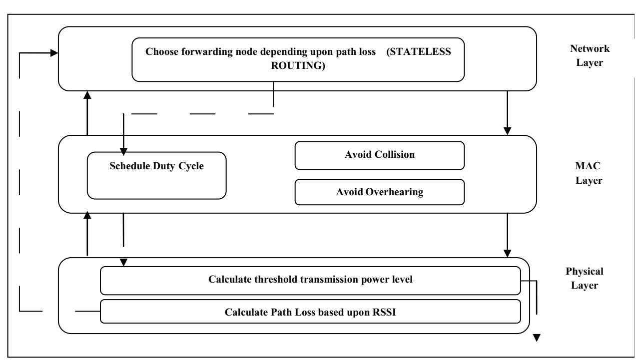

Figure 2. Cross layer design of the proposed protocol.

Thirdly at MAC layer we form the sleep/listen scheduling scheme for each sensor node. By this scheme, a node must be awake if and only if it takes part in the actual transmission activity; otherwise it continues to keep asleep in the rest of time. Finally again at physical layer, this algorithm obtains the threshold transmission power level between the transmitting node and selected next hop node and data transmission takes place with minimum transmission power level just above the threshold transmission power level.

2. Modeling Physical Layer

Multi hop wireless sensor networks have a typical characteristic that communication costs (in terms of transmission energy required) are much higher than computing costs (on individual devices)[15,16]. In scenarios where the transmission power is fixed and each link has the same cost, the minimum hop route is selected. In situations where the transmission power can be varied with the distance of the link, the link cost is higher for longer hops. Therefore, an energy efficient algorithm will select a path with large number of small distance hops rather than a path with small number of large distance hops. However such a formulation based solely on the energy spent in a single transmission can be misleading. The proper metric should include the total energy (including for any retransmissions) spent in reliably delivering the packet to its final destination[17,18]. We first define a link cost that is a function of both the energy required for a single transmission across the link and the link error rate. This cost function will help us to calculate the cumulative energy spend on the reliable data communication. The energy radiated from the antenna of a transmitting node travels over unlimited distances. As it travels in the medium, it scatters and only a smaller fraction of it reaches the receiver antenna. As the signal travels away from the transmitter, the signal strength is attenuated nonlinearly according to the formula.

$$T(r) = K .T (t) D^{-\alpha} \qquad (1)$$

Where T(t) is the amplitude of the transmitted signal, D is the Distance from the transmitter, T(r) is the amplitude of the received signal at Distance D and α is a parameter whose value range from two to four and k is the proportionality constant and consider k = 1 without any loss of generality. In order to achieve successful reception it is first necessary to establish a desired quality of service in terms of the maximum acceptable value of Bit Error Rate (BER).We generally plot the BER (dB) vs. SNR (dB) curves to describe the functionality of wireless communication.

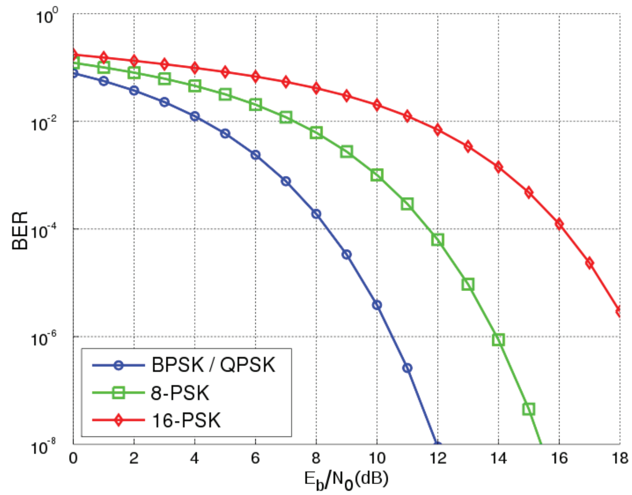

Figure 3. BER (dB) vs SNR (dB).

For any particular link (i,j) between a transmitting node i and a receiving node j, Let $T_{i,j}$ denote the transmission power and $p_{i,j}$ represent the packet error probability. Assuming that all packets are of a constant size, the energy involved in a packet transmission, $E_{i,j}$, is simply a fixed multiple of $T_{i,j.}$ Due to the characteristics of the wireless medium, the transmitted signal suffers an attenuation proportional to D^{α}, where d is the distance between the transmitter and the receiver. If the transmission power is static or constant, $T_{i,j}$ is independent of the characteristics of the link (i,j). In this case, a receiver located farther away from the transmitter will suffer greater signal attenuation (proportional to D^{α}) and will accordingly, subject to larger bit error rate. If the transmission power is dynamic or variable, the transmitting node dynamically adjusts the transmission power $T_{i,j}$ according to the characteristics of the wireless channel, to ensure that the strength of the attenuated signal received by the receiver is above a certain threshold level T_h to negate the effect of bit error rate. Accordingly, the optimal transmission power associated with a link distance d in the variable transmission power scenario is given by:

$$T_{opt} = T_h * \gamma * D^k \qquad (2)$$

where γ is a proportionality constant and k is the coefficient of attenuation. Since T_h is Technology Specific constant, we can see that the optimal transmission energy over such a link varies as

$$E_{opt}(d) \propto D^k \quad (3)$$

It implies that, for a static transmission power model, path with more number of hops may prove better in terms of energy efficiency than the path with minimum number of hops. But in case of dynamic transmission power model, a path with a greater number of hops may not be better always due to the increase in link errors and retransmissions thereafter.

To understand the energy consumption involved in choosing a path with multiple short hops over a single long hop, consider communication between a Sender S and a Receiver R located at a Distance D. The topology uses N hops (indexed as i: i={1,2,……N}) to transmit data from S to R, where node 1 refers to Sender S and Node N+1 refers to Receiver R. In this case, the total optimal energy spent in transmitting a packet once (without considering whether or not the packet was reliably delivered) from sender to receiver over n forwarding nodes is

$$E_{total} = \sum_{i=1}^{N} E_{opt}^{i,i+1} \quad (4)$$

On using equation (3), we get

$$E_{total} = \sum_{i=1}^{N} \alpha D_{i,i+1}^{k} \quad (5)$$

Where $D_{i,j}$ refers to the distance between node i and j and α is proportionality constant. To understand the transmission energy characteristics associated with the choice of n−1 intermediate nodes, we compute the lowest possible value of E_{total} for any given layout of n−1. The minimum transmission energy case occurs when each hop is of equal length $\frac{D}{N}$. In that case, E_{total} is given by

$$E_{total} = \sum_{i=1}^{N} \alpha \frac{(D_1 + D_2 + \dots\dots\dots\dots\dots + D_N)^k}{N^k}$$

Therefore,

$$E_{total} = \frac{\alpha N D^K}{N^K} = \frac{\alpha D^K}{N^{k-1}} \quad (6)$$

To compute the energy consumption in case of reliable transmission, we consider how the choice of N affects the probability of transmission errors and the consequent need for retransmissions. Clearly, increasing the number of intermediate nodes increases the likelihood of transmission errors over the entire path. Assuming that each of the N links has an independent packet error rate of $p_{link,}$ the probability of transmission error over the entire path, denoted by p, is given by

$$p = 1 - (1 - p_{link})^N \quad (7)$$

The number of transmissions (including retransmissions) necessary to ensure the successful transfer a packet between S and D is then a geometrically distributed random variable X, such that the probability P is given by

$$P\{X = k\} = p^{k-1} \times (1 - p), \forall K$$

The mean number of individual packet transmissions for the successful transfer of single packet is thus 1/(1−p). Since each such transmission uses total energy E_{total} given by Equation (6), the total expected energy required in the reliable transmission of a single packet is given by:

$$E_{total}^{EER} = \alpha \frac{D^k}{N^{k-1}} * \frac{1}{1-p}$$

Therefore,

$$E_{total}^{EER} = \frac{\alpha D^K}{N^{K-1} * (1 - p_{link})^N} \quad (8)$$

The equation clearly demonstrates the effect of increasing N on the total energy necessary, while the term N^{K-1} in the denominator increases with N, the error-related term $(1-p_{link})^N$ decreases with N. By treating N as a continuous variable and taking derivative, it is easy to see that the optimal value of the number of hops, N_{opt} is given by:

$$N_{opt} = \frac{(k-1)}{-\log(1 - p_{link})}$$

Thus a larger value of p corresponds to a smaller value for the optimal number of intermediate forwarding nodes. Also, the optimal value of N increases linearly with the attenuation coefficient K. There is thus clearly an optimal value of N, while lower values of N do not exploit the potential reduction in the transmission energy; higher values of N cause the overhead of retransmissions to dominate the total energy.

3. Results

We implement the above defined mathematical model in MATLAB[17]. Our objective is to study the transmission energy only, so we do not consider other factors such as buffer overflows, link congestions etc. We assume that each link in the network has infinite large transmit buffer. We also assume that all nodes receive signals of same strength; hence the bit error rate is same for all links. To study these tradeoffs graphically, we plot E_{total}^{EER} against varying N (for different values of p_{link}).

We take α and D at two and fifteen respectively and K = 4. The graph above shows that for lower values of the link error rates, the large number of short range hop nodes leads to a significant reduction in the total energy consumption. However, when this number of nodes tends to surpass the optimal value, error rates becomes higher and potential power savings due to the introduction of large number of intermediate node are negated by a sharp increase in effective bit error rate.

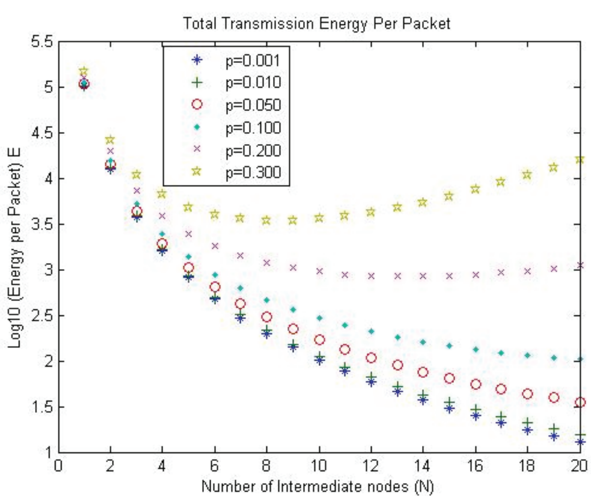

Figure 4. Transmission energy per packet vs. number of nodes.

4. Conclusion and Future Work

In this paper, we have optimized the energy consumption at physical layer of our cross layer energy efficient protocol for Wireless Sensor Networks, which tends to optimizes energy consumption at the lower three layers of the protocol stack by choosing the path with more number of hops over the path with less number of hops. As we have only considered reliable communication, the error rates tend to increase with the increasing number of hops, which led to more energy consumption. Hence we have to limit the number of hops to a certain optimal level, in order to achieve the benefit. In future, we will implement this protocol for the other upper layers of the protocol to verify and then validate the results by comparing them with the results of the existing protocols. With these results validations, we will be able to conclude that the optimization of energy consumption using cross layer approach is better than the single layer approach.

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