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Procedia Computer Science 10 (2012) 933 – 938

Procedia Computer Science

The 2nd International Workshop on Emerging Topics on Sensor Networks

Multi-hop Interference-Aware Routing Protocol for Wireless Sensor Networks

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Abstract

Wireless Sensor Networks (WSN) have gained much attention in recent years, however, these networks suffer from limited energy supply and noisy wireless links. Thus, efficient energy management and noise handling are key requirements in designing WSNs. This paper proposes an interference-aware and energy-aware routing algorithm such that power dissipation is uniform among all sensors. The proposed algorithm utilizes time synchronization and traffic scheduling to avoid interference. This work mathematically models the problem as node clustering optimization. Simulation results show the optimized proportions of packets sent by nodes to ensure uniform energy dissipation, as well as, reduced interference within clusters.

Keywords: Wireless sensor network, Multi-hop routing, Time synchronization, Interference-awareness, Scheduling

1. Introduction

Recent advances in wireless communications and electronics have enabled the development of low-cost multifunctional sensors that exploit a physical phenomenon to provide data about the state of the environment. These tiny sensors have instigated the concept of Wireless Sensor Networks (WSNs). Such networks suffer from limited resources, e.g., energy supply and computing power. When a sensor node's energy is depleted or falls below a certain threshold, the sensor will fail to monitor and communicate any abnormal phenomenon in its sensing range. Thus, efficient energy management is a key requirement for the design of WSNs. Moreover, sensor nodes communicate over error-prone wireless broadcast links, such that sensor nodes can transmit and receive simultaneously on multiple channels [1].

Interference happens when two radio signals are transmitted on the same frequency at the same time. Interference over multiple simultaneous transmissions reduces the performance of WSNs [2]. The interference cannot be totally eliminated due to the limited number of available channels. Researchers have employed channel assignments to decrease the effect of interference; however, this results in far from optimal performance as it can be seen in [3]. Since, channel assignments have an impact on link bandwidth; channel assignment and routing are associated. This work proposes an interference-aware energy-aware multi-hop routing protocol that offers improvement by considering time synchronization and priority of transmission. Furthermore, in this work, the problem of uniform energy dissipation for a system with number of nodes greater than 5 is investigated. Simulation results show the optimized proportions of the packets sent over WSN with the number of nodes in a cluster. This paper is organized as follows:

doi:10.1016/j.procs.2012.06.126

Related works are briefly introduced in Section II. Section III presents the system model adopted in this paper. Section IV models the uniform energy dissipation problem as an optimization one and shows the simulation results for the adopted scenario. We develop an algorithm based on slotted time synchronization and transmission priority in Section V. Finally, Section VI provides concluding remarks.

2. Related Work

This section studies related literature in three fold; energy-aware routing, interference models, and time synchronization. Much research work has been directed to develop energy-aware routing protocols. Prominent work include Low Energy Adaptive Clustering Hierarchy (LEACH) in which most nodes transmit to cluster heads, and the cluster heads aggregate and compress the data and forward it to the base station. Each node uses a stochastic algorithm at each round to determine whether it will become a cluster head in this round. In direct transmission protocol, nodes use high energy to transmit if they are not close to cluster heads. This depletes energy, thus, nodes further from the cluster head will die earlier than others. Moreover, nodes closer to cluster head relay large amounts of information compared to the nodes that are far from the cluster head. Hence, in comparison some regions in cluster are overloaded more than other. The work in [4] describes a multi-path energy-aware WSN routing protocol that optimizes proportions of packet transmission to better guarantee uniform energy dissipation for small sized clusters ($\leq$ 4 nodes).

There are two widely used models to characterize interference relationship in WSNs, namely, the physical model and the protocol model [5]. The physical model, known as the Signal to Interference plus Noise Ratio (SINR) model, is based on practical transceiver designs that treat interference as noise. Under the physical model, a transmission is successful if and only if SINR at the intended receiver exceeds a threshold so that the transmitted signal can be decoded with an acceptable bit error probability. To circumvent the complexity issue associated with physical model, the protocol model [5], also known as unified disk graph model, has been widely used by researchers in WSN community as a way to simplify the mathematical characterization of physical layer. Under the protocol model, a successful transmission occurs when a node falls inside the transmission range of its intended transmitter and falls outside the interference ranges of other non-intended transmitters. The setting of transmission range is based on the SINR threshold.

Time synchronization is a critical piece of infrastructure for any distributed system [6]. WSNs make extensive use of synchronized time; *e.g.,* to integrate data, to localize objects, to distribute control commands, or to suppress redundant messages and information. The broad nature of WSN applications leads to timing requirements whose scope, lifetime, and precision differ from traditional systems [6]. In addition, many nodes in the emerging sensor systems will be untethered and have small energy reserves. All communication, even passive listening, will have a significant effect on those reserves. Time synchronization methods for WSNs must be mindful of the time and energy they consume.

3. System Model

In this section, the system model adopted in this paper is introduced, as well as, the assumptions on which the model is built. The spatially distributed nature of WSN applications results in the use of wireless technologies. Sensor nodes can control their transmission power to send data with different frequencies and to different distances. Thus, nodes have variable transmission and interference ranges/regions. Moreover, it is assumed that the environment is a 2D plane with n sensor nodes. Sensors are distributed within the plane such that the distance between two adjacent nodes is given by d. Thus, node density is inversely proportional to distance d. We also assume that the energy required to transmit message a over distance d is directly proportional to d^v, where v is a constant [4].

This work employs the energy-aware routing protocol from [4]. In this protocol, the sensor nodes neither transmit all their packets to their nearest nodes nor directly transmit to the cluster head. Instead, nodes forward different portions of their packets to nodes at different distances. Every node generates m packets, which it needs to send to the cluster head via different intermediate nodes, unlike previous works, where a node sends packet to cluster head directly or in one hop. Hence, each node transmits its own packets, as well as, packets received from nodes further away from the cluster head. In the scenario shown in Figure 1, the cluster head, labeled as node 1, is responsible to receive and fuse all measurements from the nodes in the cluster, while, the other 9 nodes send *m* packets to the cluster head. The transmissions can be divided in two types: Short Transmission where the distance between the nodes is less than or equal to d, and Long Transmission where the distance between the nodes is greater than d.

Variable	*Value*
E_{elec}	50nJ/bit
E_{agg}	5nJ/bit
ε_{amp}	100pJ/bit/m2
E_i	0.5J
Ed	0.05J
M	1 packet/round
Pks	2000 bits
D	15m to 35m
V	2

Table 1: Simulation values

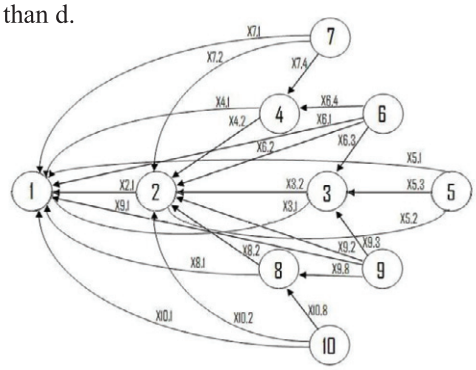

Figure 1: Adopted Scenario with n=10 nodes

4. Uniform Energy Dissipation Approach

This work proposes a modification to optimize energy dissipation over the optimal multi-path energy-aware routing protocol and investigates clusters with number of nodes greater than 5. Communication protocols for WSNs have to not only maximize the average life-time of sensor nodes, but also, minimize the variance of sensor remaining energy. This can be viewed as a multi-objective function which can be modeled as an optimization problem. All existing works in energy-aware protocol emphasize on maximizing the average network lifetime without considering the variance in sensor node energy [4].

In order to dissipate energy uniformly among the nodes, communication load has to be uniformly distributed too. The proposed approach divides each packet into smaller portion x_{ij} dependent of the node position relative to the cluster head, then, relay it to a node in that cluster that will guarantee uniform energy dissipation in the whole cluster, where x_{ij} is the portion of the packet that node *i* transmits to node *j*. Matrix X represents the ratio of packets transmitted from source i to destination j, such that the columns of the matrix X represent the nodes which are receiving packets, while the rows are nodes which are transmitting packets. Moreover, the presence of “0”s indicates that transmission from source to destination is not taking place. The distance between adjacent nodes is given by d where d_{ij} is the distance from node-i to node-j. The corresponding distance matrix D is shown below where “0” indicates that the distance is not necessary to consider since no transmission takes place between the nodes. Distances between nodes represented in Matrix D are used to calculate the communication power dissipation of each node.

The main objective of this section is to optimize the total cost of receiving and forwarding packets from node-j towards the sink. The communication cost function is denoted as C_j and is given by:

$$c_j = E_{elec} \times (m + R_j) \times pks + E_{agg} \times R_j \times pks + \mathcal{E}_{amp} \times pks \times \sum_{i=j-1}^{1} x_{ji} \{d\}^V \tag{1}$$

Where E_{elec} is the energy dissipated to run both transmitting and receiving circuitry, E_{agg} is the energy dissipated for data aggregation, ε_{amp} is transmissions amplify energy, and E_i is the initial energy for each node. Moreover, m is the numbers of generated packet at each node; R_j is the number of packets received by node j, pks is the size of generated packet, d is the distance between two adjacent nodes, and v is a constant. To minimize the variance between the energy of the nodes, we optimize to equate C_j for all nodes to find optimal proportions x_{ji} such that $C_2 = C_3 = \cdots = C_i = \cdots = C_N$. Since the proposed approach divides the packets into portions to send to the cluster head via different intermediate nodes, each packet portion should be equal or less than the original packet size $0 \le X_{ij} \le 1 \ \forall\, i < j,\ i \ge 1,\ j > 1$. Moreover, the system should be modelled to guarantee that all the portions of the packets are transmitted this can be written as $\sum_{i=j-1}^{1} x_{ij} = 1$. Thus, by

$$X=\begin{pmatrix} x_{2,1} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ x_{3,1} & x_{3,2} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ x_{4,1} & x_{4,2} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ x_{5,1} & x_{5,2} & x_{5,3} & x_{6,4} & 0 & 0 & 0 & 0 & 0 \\ x_{6,1} & x_{6,2} & x_{6,3} & x_{7,4} & 0 & 0 & 0 & 0 & 0 \\ x_{7,1} & x_{7,2} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ x_{8,1} & x_{8,2} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ x_{9,1} & x_{9,2} & 0 & 0 & 0 & 0 & 0 & x_{9,8} & 0 \\ x_{10,1} & x_{10,2} & 0 & 0 & 0 & 0 & 0 & x_{10,8} & 0 \end{pmatrix} \qquad D=\begin{pmatrix} D & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 2d & d & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ \sqrt{3}d & D & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 3d & 2d & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ \sqrt{7}d & \sqrt{3}d & D & d & 0 & 0 & 0 & 0 & 0 \\ \sqrt{7}d & 2d & 0 & d & 0 & 0 & 0 & 0 & 0 \\ \sqrt{3}d & d & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ \sqrt{7}d & \sqrt{3}d & D & 0 & 0 & 0 & 0 & D & 0 \\ \sqrt{7}d & 2d & 0 & 0 & 0 & 0 & 0 & D & 0 \end{pmatrix}$$

equating the power dissipation of all nodes, we get sufficient number of linear equations to solve this optimization problem. Since $E_{elec} \cong e\times\varepsilon_{amp}$ and $E_{agg} \cong f\times\varepsilon_{amp}$, we substitute to simplify equations further.

For the scenario adopted, MATLAB was used in solving this optimization problem. By using matrices D and X, we substituted in the above equations to find optimal portions x_{ij} for different distances of d. For a simple energy model, we assume e = 500 and f = 50, the simulation values are given in Table 1. Table 2 shows the optimized values of packet proportions for different values of d. Figure 2 plots the average packet proportion versus the distance between nodes. It can be seen that packet proportion decrease as the distance increase. This is attributed to the increased power needed to transmit to longer distances. Figure 3 shows the graphical representation of the optimized communication between sources and destinations.

d	$X_{7,2}$	$X_{7,1}$	$X_{10,2}$	$X_{10,1}$	$X_{9,2}$	$X_{9,1}$	$X_{8,2}$	$X_{8,1}$	$X_{6,2}$	$X_{6,1}$	$X_{5,2}$	$X_{5,1}$	$X_{4,2}$	$X_{4,1}$	$X_{3,2}$	$X_{3,1}$
15	0.0035	0.5267	0.0035	0.5265	0.0176	0.5224	0.2708	0.7292	0.0176	0.5224	0.2141	0.3159	0.2708	0.7292	0.7012	0.2988
20	0.0097	0.3803	0.0097	0.3803	0.0223	0.3777	0.4701	0.5299	0.0223	0.3777	0.1618	0.2282	0.4701	0.5299	0.7843	0.2157
25	0.0105	0.2795	0.0105	0.2795	0.0229	0.2771	0.6122	0.3878	0.0229	0.2771	0.1223	0.1677	0.6122	0.3878	0.8441	0.1559
30	0.0113	0.2087	0.0113	0.2087	0.0087	0.2115	0.7145	0.2855	0.0087	0.2115	0.0948	0.1252	0.7145	0.2855	0.8891	0.1109
35	0.0066	0.1634	0.0066	0.1634	0.0200	0.1600	0.7783	0.2554	0.0097	0.2015	0.0 720	0.0980	0.7783	0.2217	0.9136	0.0864

Table 2: Optimized packets proportions to guarantee uniform energy dissipation over the cluster

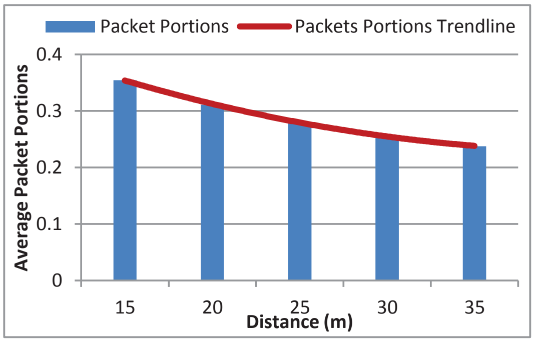

Figure 2: Average optimized packet proportion vs. distance.

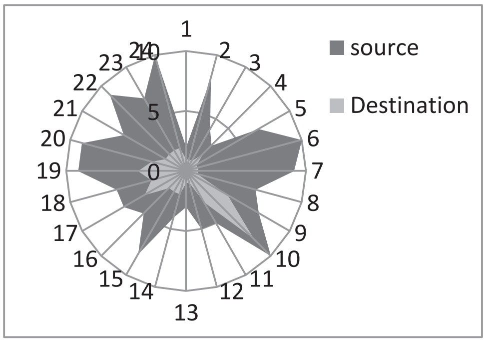

Figure 3: graphical representation of the optimized communication between sources and destinations

5. Proposed Interference-Aware Algorithm

Interference degrades the system efficiency and consumes power in the form of data correction or retransmission. This work proposes an algorithm that avoids interference while conserving energy. The interference-aware algorithm runs on top of energy-aware routing protocol and schedules data transmissions according to the distance between two nodes and the proportions of packets to be sent. Sensor nodes are assumed to be static. Moreover, in-cluster time synchronization between nodes is assumed to be deployed and accurate. We also assumed a single shared channel for all the nodes to communicate. For two nodes to communicate directly, they need to be within the transmission range of each other. In the scenario adopted shown in Figure 1, it is assumed that each node can reach all other nodes within the cluster, which also means that each node has information about rest of the nodes in the cluster. The transmission range of a node is denoted by R_t. The distance between the nodes u and v is given by r(u, v). An edge e(u,v) Є E exist if and only if $r_t(u, v) \leq R_t$. This means that an edge between two nodes only exists if the distance between the two nodes is less than or equal to the transmission range. An edge in this case is representing packet transmission between the nodes u and v. A pair of nodes that use the same channel and are within each other's transmission range may interfere in each other's communication even if they are not communicating. We denote interference range by R_i , where R_i is given by q x R_t such that q is a constant equal to 1.

The proposed algorithm allows simultaneous packet transmissions if the transmissions do not lie in the interference range of other nodes. Simultaneous link transmission on a common channel, of two distinct edges $e_1 = (u_1, v_1)$ and $e_2 = (u_2, v_2)$, is possible if and only if all four pairs of nodes (u_1, u_2), (v_1, v_2), (u_1, v_2), (u_2, v_1) are at least R_i apart, thus, there will be no interference. To mathematically formulate the problem,

$$Let\ X_{e,T} = 1, \quad e \in E, \quad iif\ e\ is\ active\ in\ time\ slot\ T$$

To avoid interference when simultaneous transmissions take place, the proposed algorithm utilizes scheduling based on synchronized time slots and the distance between nodes. Each sensor nodes is dynamically assigned a time slot to communicate. If the distance between two nodes is more than d, then this transmission is considered 'long' and has higher probability to interfere with other transmission taking place at the same time slot. So, in each time slot, there can be either only one edge e(u, v) if the transmission is 'long' ($R_t > d$), or multiple edges if all transmissions are short ($R_t \leq d$) and not in overlapping interference range. An edge exists only if there is an active communication between the source and the destination.

The proposed algorithm assigns different priorities to different transmissions in the scheduling process. Higher proportion means that a higher percentage of packets have to be transmitted, thus, such transmission consume more energy and have higher probability of interference. Hence, our algorithm assigns higher priorities to higher proportion transmissions. To make sure that all of the data has been transferred, this higher proportion transmission will be given two time slots to guarantee that the shared channel is free before other transmissions start. To maximize the channel utilization, the threshold for which transmission is considered higher proportion has to be set large enough to benefit from the two time slots, but also small enough not to interfere with later transmissions. Accordingly, if any specific proportion p for an edge e is greater than 0.5 then it will be assigned two consecutive time slots, otherwise, only one time slot will be assigned. Consider $e_i (u_i, v_i)$ and $e_j (u_j, v_j)$ have same proportion p and for both of them $r(u, v) \leq d$, then one of them will be given priority over the other randomly.

To illustrate the efficiency of the proposed approach, we further studied the distribution of packet proportions among all the nodes for the distance $d = 15$ from Section 4. We used our scheduling methodology to come up with an interference free scheduling scheme. The values of proportions for $d=15$ are used from the Table 2. Table 3 shows how the algorithm schedules all 24 transmissions for d = 15 and illustrates that transmissions are assigned to the timeslots in descending order of packet proportions. Transmissions that have proportion more than 0.5 are assigned two consecutive time slots. For example T13 and T14 are consecutively assigned for a transmission from node 9. Also we can see that in time slot T17, two transmissions are taking place simultaneously because the satisfied the necessary conditions for avoiding interference. From Figure 4, the proposed algorithm prefers short distance communication over long ones due to the higher energy consumption for long distance communication. However, the algorithm might choose longer distance communication over shorter ones for the purpose of keeping the energy reserves uniform within the clusters. Figure 5 demonstrates the higher communication overhead on the cluster head (node 1), as well as, nodes close to it in proximity. While, Figure 6 displays the decreasing packet proportions as the time increases. This is attributed to proposed scheduling scheme that gives higher priority to higher proportions. Figure 7 shows the relation between the packet proportions, transmission distance, and time. Finally, Algorithm 1 shows the pseudo code for the proposed scheduling scheme.

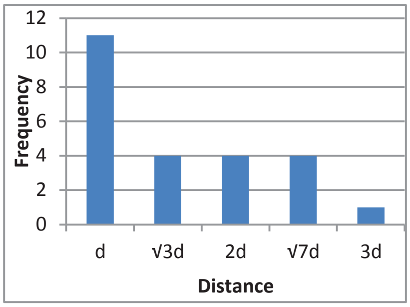

Figure 4: Histogram of distances.

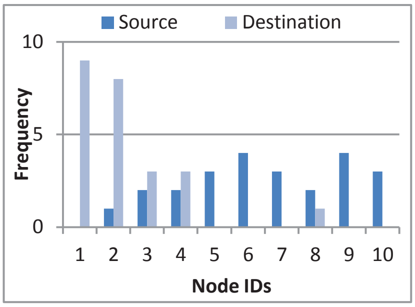

Figure 5: Histogram of nodes transmitting & receiving messages

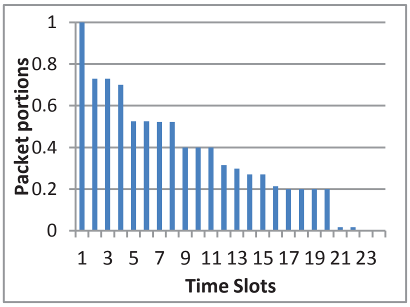

Figure 6: Packet portions verses time slots.

Slot	Node	Slot	Node	Slot	Node	Slot	Node
1	2	9	7	17	7,10	25	6
2		10		18	5	26	9
3	8	11	10	19	5	27	9
4		12		20	3	28	6
5	4	13	9	21	4	29	9
6		14		22	8	30	7
7	3	15	6	23	5	31	10
8		16		24	6		

Table 3: The scheduled time slots for source nodes.

Algorithm 1

```
N = number of transmissions with proportion p Є P
if distance($u_i$, $v_i$) $\le$ d and distance($u_j$, $v_j$) $\le$ d Then
    if distance($v_i$, $v_j$) > d , distance ($u_i$, $u_j$) > d,
        distance ($u_i$, $v_j$) > d, distance ($u_j$, $u_i$) > d,
    where j $\neq$ i, Then
                X ($u_i$, $v_i$), $t_i$, p = 1
                X ($u_j$, $v_j$), $t_i$, p = 1
    else        X ($u_i$, $v_i$), $t_i$, p = 1
                X ($u_j$, $v_j$), $t_i$, p = 0
else    X ($u_i$, $v_i$), $t_i$, p = 1
```

6. Conclusion and Future Work

Much research has been focusing on Wireless Sensor Networks in recent years. However, power limitations, as well as, wireless link characteristics have always been a bottleneck for such networks. This work proposed a modification to the multi-path energy-aware routing protocol via modeling clusters with 5 or more nodes. We also took into account the interference constraint and proposed an algorithm that can avoid inference for both one hop and multi-hop transmission. To increase efficiency, we have also allocated more time slots to the communication with more packets to transmit. Transmission with higher proportions is given higher priority and is transmitted first. The algorithm avoids interference and is an improvement to the previous work on the energy-aware protocol. In future work, we intend to modify the algorithm for mobile WSN and implement it for multichannel communication.

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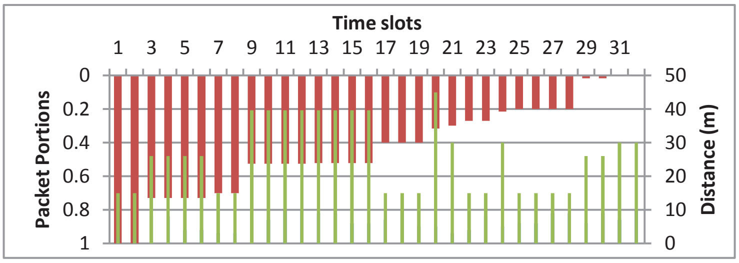

Figure 7: The scheduled time slots for the packet portions vs the distance