Load-Balanced Routing Scheme for Energy-Efficient Wireless Sensor Networks

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***Abstract*—Wireless sensor networks (WSNs) require appropriate protocols that make judicious use of the finite energy resources of the sensor nodes. In this paper, we investigate the potential energy conservation achieved by balancing the traffic throughout the WSN. We show that distributing the traffic generated by each sensor node through multiple paths instead of using a single path allows significant energy savings. In order to quantitatively evaluate the benefits of the proposed load balancing technique, a new analytical model for load-balanced systems is elaborated and approved by simulations.**

***Index Terms*— Wireless sensor networks, energy conservation, routing, load balancing, performance analysis.**

I. INTRODUCTION

In order to minimize the energy consumption in WSNs, several energy-efficient MAC protocols [1] – [3] and energy-efficient routing protocols [4] [5] have been proposed in the literature. These schemes aim to decrease the energy consumption by using sleep schedules [6]. The key idea behind this concept is to turn off completely some parts of the sensor circuitry (e.g., microprocessor, memory, radio) when it does not receive or transmit data, instead of keeping the sensor node in the idle mode.

Although there is significant energy saving achieved by such schemes based on sleep schedules, the energy efficiency of these protocols could be considerably affected if the traffic is far from being uniformly distributed in the network. Typically, these protocols aim at minimizing the energy consumed by each sensor node subject to a given traffic load to handle. However, there has been little focus on how traffic is balanced throughout the multihop WSN and how it impacts the network lifetime.

In this paper, the utilization of multiple paths between each sensor node and the sink node is considered. It is shown that the network lifetime can be improved by routing efficiently (i.e., balancing) the traffic inside the WSN.

Assuming the network lifetime as the time for the first node in the WSN to fail, a perfect routing protocol would drain energy slowly and uniformly among nodes, leading to the death of all nodes nearly at the same time. Typically, an ideal routing protocol would avoid the fast drain of sensor nodes with high energy consumption. To achieve this, we propose balancing the energy consumption throughout the network by sending the traffic generated by each sensor node through multiple paths instead of forwarding always through the same path. The problem consists then in determining the set of routes to be used by each sensor node and the associated weights (i.e., the routing configuration) that maximize the network lifetime.

Our work is motivated by the results presented in [7], where the authors investigated the problem of the lifetime maximization in WSNs under the constraint of end-to-end transmission success probability. To do so, the authors adopted a cross-layer strategy that considers physical layer (i.e., power control), MAC layer (i.e., transmission control) and network layer (i.e., routing control). Specifically, regarding the network layer, the authors introduced the concept of routing packets such as energy consumption is balanced among multiple paths. However, in doing so, the authors considered a simplistic scenario such as the medium is slotted, for each transmission all the network nodes are supposed to be in sleep state except for the sender and receiver nodes, and thus collision-free transmission is ensured. As such, typical energy wasted by the sensor nodes due to retransmissions, overhearing and idle listening were not considered.

In this paper, a general scenario with conventional contention-based access method to the wireless channel is considered. We develop a new analytical model to calculate the energy consumption at each sensor node per unit of time given a specific routing configuration. The energy consumed by a sensor node corresponds to that used to transmit its own generated messages as well as to relay the pass-through traffic of other sensor nodes. Building on these results, we derive the optimal routing configuration that maximizes the network lifetime. For the numerical results, a variety of network topologies are considered, including regular and arbitrary meshed topologies. As a main contribution of our paper, we show that by efficiently balancing the traffic inside the network, significant energy savings up to 15% can be achieved compared to the basic routing protocols.

The next section formulates the general problem statement and presents the system model to be studied. This model is then formally studied in section III. Specifically, we derive the energy consumed by each sensor node per unit of time given a specific routing configuration. Results are provided in section IV, where we evaluate the performance of our proposal, using two well known routing protocols as baseline examples. The article concludes with a summary of our conclusions and contributions.

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II. Model And Problem Description

A. Network Model

We represent a WSN by a directed graph $G(V, E)$, called a connectivity graph. Each sensor node $v \in V$ is characterized by a circular transmission range $R_t(v)$ and a carrier sensing range $R_h(v)$ (called also hearing range). In our study, we suppose that all the sensor nodes have the same transmission and carrier sensing ranges denoted by R_t and R_h, respectively. During the transmission of a node v, all the nodes inside its carrier sensing range, denoted by $H(v)$, sense the channel to be busy and can not access the medium. Hereafter, we denote by $H^+(v) = H(v) \cup \{v\}$ and by $H^-(v)$ the set of nodes that node v can not hear, i.e., $H^-(v) = V \backslash H^+(v)$.

On the other hand, during the transmission of the node v, all the nodes residing in its transmission range, and thus representing its neighborhood denoted by $N_e(v)$, receive the signal from v with a power strength such that correct decoding is possible with high probability. A bidirectional wireless link exists between v and every neighbor $u \in N_e(v)$ and is represented by the directed edges (u, v) and $(v, u) \in E$.

We represent the graph connectivity by a connectivity matrix. The connectivity matrix of $G(V, E)$ is a matrix with rows and columns labeled by the graph vertices V, with a 1 or 0 in position (m, n) according to whether v_m and v_n are directly connected or not. In our study, all the sensor nodes transmit periodically their reports to the sink node, denoted by $\mathcal{S}$. We target here continuous-monitoring applications, which represent an important class of WSN applications. The average number of reports sent per unit of time by each sensor node v is denoted by $A(v)$. The transmitted packet by v can follow one of the possible paths in the graph $G(V, E)$ that connects v to the sink node $\mathcal{S}$. The set of paths between a vertex v and $\mathcal{S}$ is denoted by $P(v)$.

In WSNs, the reporting sensor nodes compete to access the common data channel to report their data information to the sink nodes. In our study, the access to the medium among the competing nodes is arbitrated by the well known IEEE 802.11-like sensor networks protocol [8] [9]. The IEEE 802.11 DCF access method is based on the CSMA/CA technique. In our analysis, we consider the basic access mode (i.e., DATA/ACK), but the same study with slight modifications can be simply adapted to the case where RTS/CTS option is enabled.

B. Problem Description

In this paper, we approach the efficient routing of reports to the sink node by balancing the energy consumption throughout the network. By doing so, we aim at improving the WSN lifetime. For each sensor node v, generated reports to the sink can follow one of the possible $|P(v)|$ paths. We associate to each path $p \in P(v)$ a weight $w(p)$, such that $\sum_{p \in P(v)} w(p) = 1$. The vector $W(v) = (w(p))_{p \in P(v)}$ represents the fraction of utilization of each path $p \in P(v)$ used to send the traffic from node v to the sink node.

The number of packets per unit of time going through the link $(u, v) \in E$ is denoted by $\lambda(u, v)$. It represents the rate of packets transmitted by node u to node v. These packets can be either generated by u or by other sensor nodes and relayed by u to attain their final destination (i.e., the sink node). The rate $\lambda(u, v)$ can be simply expressed as follows:

$$\lambda(u, v) = \sum_{k \in V} \sum_{p \in P(k)} w(p) \times A(k) \times 1\Big|_{(u,v) \in p} \tag{1}$$

where $1\Big|_{(u,v) \in p}$ is the indicator function of the condition that the link (u, v) belong to the path p. Moreover, the packet rate transmitted by node u is given by:

$$\lambda_u = \sum_{n \in N_e(u)} \lambda(u, n) \tag{2}$$

Note that (1) is derived considering the system working in the unsaturated regime, which is more likely the case of real WSNs. WSNs produce indeed light traffic compared to traditional wireless networks. Unless explicitly notified, we consider the WSN working under the unsaturated regime in the reminder of this paper.

Let us consider a path $p \in P(v)$. We denote by $E(u, p)$ the average energy consumed by the node u due to the successful delivery of a packet transmitted by v to the sink node through the path p. The average amount of energy consumed by node u per unit of time due to the different transmissions inside the WSN, denoted by $E(u)$, can be therefore expressed as follows:

$$E(u) = \sum_{v \in V} \sum_{p \in P(v)} w(p) \times A(v) \times E(u, p) \tag{3}$$

The lifetime of the sensor node u is then given:

$$T(u) = \frac{E_{init}}{E(u)} \tag{4}$$

where E_{init} is the initial amount of energy provided to each sensor node.

The network lifetime is defined as the time spent from the deployment until the drain of the first sensor node. Hence, to maximize the network lifetime, we have to maximize the lifetime of the greediest node in the network in term of energy consumption. The problem consists then in minimizing the following function:

$$\max_{\mathcal{W}} T(u) = \min_{\mathcal{W}} \left(\max_{u \in V} E(u) \right) \tag{5}$$

Indeed, to maximize the network lifetime, we have to avoid the fast drain of sensor nodes with high energy consumption. We need therefore balancing the energy consumption inside the network by routing efficiently the data packets. This is achieved by determining the optimal set of vectors $(W(v))_{v \in V} = \mathcal{W}$ that enables to minimize the energy consumption by the greediest sensor nodes in order to maximize the network lifetime.

III. Analytical Model

In this section, we develop an analytical model to derive the energy $E(u)$ consumed by each node $u \in V$ per unit of time due to the different network transmissions according to a given routing set $\mathcal{W}$ (i.e., for a given set of vectors $(W(v))_{v \in V}$). Once $E(u)$ is obtained for each node $u \in V$, we run a simple

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algorithm to derive the optimal routing set $\mathcal{W}$ that achieves the objective function (5). In our analysis, we assume that there is no retry limit on the number of retransmissions at each link. Hence, a packet is never discarded by a node and continues to be retransmitted until being successfully delivered. As shown in (3), we need to calculate the elements $E(u,p)$ in order to get $E(u)$.

A. Calculation of $E(u,p)$

As explained before, $E(u,p)$, with $(u,v) \in V\backslash\{\mathcal{S}\}$ and $p \in P(v)$, is the average amount of energy consumed by node u due to the successful delivery of a packet from v to the sink node through the path p. To derive $E(u,p)$, we distinguish between two cases, according to whether the node u belongs to the path p or not.

1) Case 1: $u \in p$: In this case, node u is either the source or an intermediate node on the path p. The energy consumption at node u when forwarding a packet transmitted through p to the sink node is then the sum of the amounts of energy consumed in reception, transmission and idle states. Hence $E(u,p)$ can be written as follows:

$$E(u,p) = E(u,p)_{rec} + E(u,p)_{trans} + E(u,p)_{idle} \qquad (6)$$

a) Energy consumed in reception: $E(u,p)_{rec}$: This amount of energy corresponds to the following energy consumptions:

- Energy consumed at node u (if $u \neq v$, i.e., u is not the source of p) to receive the data packet from the previous node on the path p, denoted henceforth by $\#u-1$. It corresponds to the energy consumed by u while receiving the different node $\#u-1$ transmission attempts of the data packet. We recall that a transmission attempt from $\#u-1$ to u may be unsuccessful due to either collision or channel error. We denote by $\overline{N}_c(\#u-1,u)$ the average number of unsuccessful transmissions suffered by a packet sent from $\#u-1$ to u before being successfully transmitted. Hence, the energy consumed by u in reception while trying to receive a successful transmission of the data packet forwarded by $\#u-1$ is given by:

  $$(\overline{N}_c(\#u-1,u)+1) \times E^{rec}(data) \times 1\big|_{u\neq v}$$

  where $E^{rec}(data)$ is the energy consumed by a sensor node for the reception of a data packet. We note that in our study, we assume all the data packets (i.e., reports) sent by the different sensor nodes have the same size. Moreover, we assume that all the sensor nodes transmit at the same bit rate. These assumptions are typical of WSN applications.

  In turn, $\overline{N}_c(\#u-1,u)$ can be calculated as follows. Let $N_c(\#u-1,u)$ be a random variable representing the number of unsuccessful transmissions experienced by a packet before being successfully transmitted from $\#u-1$ to u. We denote by $\beta(\#u-1,u)$ the probability that a transmission attempt from $\#u-1$ to u be unsuccessful. $N_c(\#u-1,u)$ is a geometric random variable and thus we have:

  $$E[N_c(\#u-1,u)] = \overline{N}_c(\#u-1,u) = \frac{\beta(\#u-1,u)}{1-\beta(\#u-1,u)} \qquad (7)$$

- The second amount of energy consumed by node u in reception is the energy consumed while overhearing unintended data transmissions. It corresponds to the data transmissions not intended to node u and performed by nodes inside its carrier sensing range while relaying the packet transmitted on the path p to its final destination. Such set of nodes is denoted $Z(u,p) = \{k \in V / k \in H(u) \cap p\}$. Each node $k \in (Z(u,p)\backslash\{\#u-1\})$ transmissions are overheard by node u and induces the following energy consumption at u:

  $$\big(\overline{N}_c(k,\#k+1)+1\big) \times E^{rec}(data)$$

  where $\#k+1$ denotes the subsequent node to k on the path p.
- The third amount of energy consumed by node u in reception is the energy spent to receive an ACK frame from the next node (downstream node) on the path p (i.e., from node $\#u+1$), or while overhearing unintended ACK frames sent by the other intermediate nodes on the path p.

Hence the total amount of energy consumed by node u in reception, during the delivery of a packet to the sink node through the path p, is given by:

$$E(u,p)_{rec} = \sum_{k\in Z(u,p)} \left[\begin{array}{c} (\overline{N}_c(k,\#k+1)+1) \times E^{rec}(data) \\ +E^{rec}(ACK) \times 1\big|_{k\neq v} \end{array} \right] \qquad (8)$$

b) Energy consumed in transmission: $E(u,p)_{trans}$: This amount of energy corresponds to the following energy consumptions:

- Energy consumed by node u during the different attempts to transmit successfully the data packet to node $\#u+1$. It is simply given by:

  $$\big(\overline{N}_c(u,\#u+1)+1\big) \times E^{trans}(data)$$

  where $E^{trans}(data)$ is the energy consumed by a sensor node for the transmission of a data packet.
- Energy consumed by node u (if $u \neq v$, i.e., u is not the source of p) to transmit an ACK frame to node $\#u-1$.

The total amount of energy consumed by node u in transmission is therefore given by:

$$E(u,p)_{trans} = \big(\overline{N}_c(u,\#u+1)+1\big) \times E^{trans}(data) + E^{trans}(ACK) \times 1\big|_{u\neq v} \qquad (9)$$

c) Energy consumed in idle state: $E(u,p)_{idle}$: It is the energy consumed by node u while listening to the idle channel. It is the energy consumed in backoff and during the different DIFS and SIFS periods spent by node u while attempting to transmit the packet to $\#u+1$. $E(u,p)_{idle}$ can be expressed as follows:

$$E(u,p)_{idle} = \left[\begin{array}{c} b(u,\#u+1) + (DIFS+SIFS) \\ \times \big((\overline{N}_c(u,\#u+1)+1\big) \end{array} \right] \times E^{idle} \qquad (10)$$

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where E^{idle} is the amount of energy consumed per unit of time by a sensor node in the idle state and $(b(u, \#u+1)$ is the average total time spent by node u in backoff when attempting to transmit a packet to $\#u+1$. $b(u, \#u+1)$ can be expressed as follows:

$$b(u, \#u+1) = \begin{bmatrix} \frac{CW_m}{2} \times \beta^m(u, \#u+1) \\ + \sum_{i=0}^{m-1} \frac{CW_i}{2} \times \beta^i(u, \#u+1) \times \\ (1-\beta(u, \#u+1)) \end{bmatrix} \times Slot \tag{11}$$

where m is the number of backoff stages in the BEB, $CW_i = 2^i CW_{\min}$ (i.e., $CW_m = CW_{\max}$) and $Slot$ is the duration of a backoff slot. Note that in the expression (11), we assume as in [10] that a packet is never discarded by a node and continues thus to be retransmitted until being successfully delivered (i.e., there is not a retry limit).

2) Case 2: $u \notin p$: In this case, we calculate the energy possibly consumed by u due to the successful delivery of a packet through path p although $u \notin p$. It is the energy that u may consume due to the reception of signals, which are not necessarily intended to u, i.e., signals transmitted by neighboring nodes to u that participate in forwarding the data packet on p. To calculate this amount of energy, let us consider again the set $Z(u,p) = \{k \in V / \ k \in H(u) \cap p\}$. This set of nodes corresponds simply to nodes that are jointly belonging to the path p and within the node u carrier sensing range. These nodes, whose transmissions are heard by node u, participate in the transmission of the data packet through p. Specifically, each node $k \in Z(u,p)$ induces the following energy consumption at node u:

- Energy consumed by node u while overhearing the different transmission attempts of the data packet from node k to the node $\#k+1$ of the path p. This amount of energy can be expressed as follows:

$$\left(\overline{N}_c(k, \#k+1) + 1\right) \times E^{rec}(data)$$

- Energy consumed by node u while listening to the ACK frame sent by node k to node $\#k-1$ on the path p, if k is not the source of p.

Hence, the total amount of energy consumed by node u, which does not belong to p, due to the transmission of a packet through the path p is given by:

$$E(u,p) = \sum_{k \in Z(u,p)} \begin{bmatrix} (\overline{N}_c(k, \#k+1) + 1) \times E^{rec}(data) \\ + E^{rec}(ACK) \times 1\big|_{k \neq source(p)} \end{bmatrix} \tag{12}$$

Finally, by substituting (6) and (12) in (3), we get the amount of energy $E(u)$ consumed by each node $u \in V$ per unit of time due to the different network transmissions according to a given routing set $\mathcal{W}$. It is easy to see that the only unknown variable that remains to calculate in order to get $E(u)$ is $\beta(k,n) \ \forall \ (k,n) \in V$, which will be determined by means of simulations as it will be shown in the next section.

IV. Performance Evaluation

In this section, we evaluate the efficiency of our proposed scheme. We study the impact of traffic balancing on both the packet delivery success probability over the WSN links and on the energy consumption at each sensor node. Building on these results, we provide the optimal routing configuration that maximizes the network lifetime using simple illustration networks. The results are derived using both analytical and simulation approaches. A simulation model has been developed using ns-2 in order to calculate the probability of unsuccessful transmission on each link (i.e., β). Then, the analytical framework of section III is used to calculate the energy consumption at each node.

In our study, we use the hop-based spanning trees (HST) [11] [12] and ETX-based spanning trees (ETX) [13] as baselines to which the balanced routing improvements could be compared. Both baselines take advantage of the global information of the network state to make routing decisions. Specifically, the HST protocol uses flooding to select the shortest path in terms of hop count. This technique may lead to use long and unreliable links. The ETX protocol alleviates this issue since it takes into account the quality of the wireless links in the routing operation. Typically, each link in the network is assigned an ETX cost metric to indicate its quality.

In our model, the sensor nodes achieve continuous monitoring of the supervised area. Each sensor node reports periodically with a rate A the local data to the sink node over several hops. At each hop, the traffic originating from the local sensor must be merged with route thru traffic. The access to the data channel is arbitrated by the 802.11-like sensor networks protocol. The parameters setting in our analysis are listed in table I.

Transmission range	12 m
Hearing Range	24 m
Packet length	30 bytes
IFQ length	65 packets
Transmit power	24.75 mW
Receive power	13.5 mW
Idle power	13.5 mW
Sleep power	15 μW
Initial energy per node	1 J
Transmission bit rate	40 kbs^{-1}

TABLE I
Parameters setting

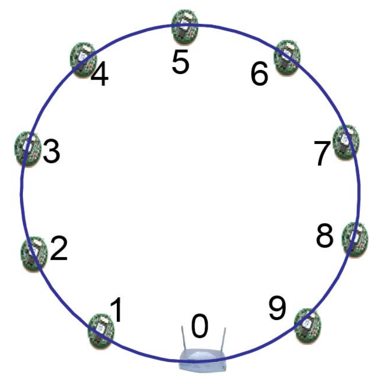

Fig. 1. The ring wireless sensor network.

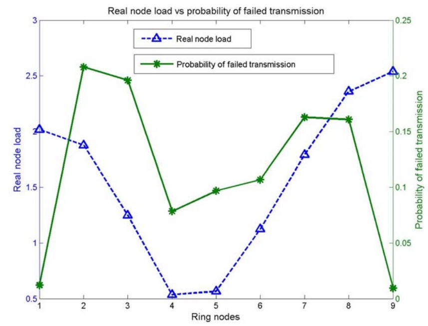

Fig. 2. Real node load vs. the probability of failed transmission.

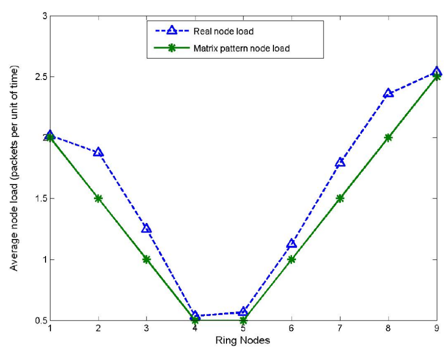

Fig. 3. Real node load vs. matrix pattern node load.

To exhibit the gain that can be introduced by our balanced routing scheme, we use the simple ring WSN shown in Fig. 1. The sensor nodes form a ring, which can be representative of U building. The distance between consecutive sensor nodes is fixed to $10\ m$. The sink node, denoted by node 0, is positioned between sensor nodes 1 and 9. It is at equal distance $5\ m$ from both nodes 1 and 9. The sensor nodes report their data to the sink node. In this case, both HST and ETX routing schemes dictate transmitting through the shortest path. Particularly, node 5 can use one of the possible two routes. Assume that node 5 transmits always through node 6. As a result, all the nodes of the right half of the ring will consume more energy than their counterparts of the left half of the ring. Typically, node 9 has the highest burden since it deals with the maximum route thru traffic. This results in a shorter lifetime for this node, which yields to loss of coverage when node 9 depletes its energy, leading thus to the premature WSN death.

These results are reported in Figs. 2, 3 and 4. In this case, each sensor node generates periodically 0.5 report/s to the sink node. Figure 2 shows that going closer to the sink node, the probability of failed transmission increases progressively. This results in an increase of the number of retransmissions.

An exception is observed at nodes 1 and 9. They represent relatively low failed transmission probabilities. This is simply because they do not have hidden nodes that disturb their transmissions to the sink node. In contrast, the remaining sensor nodes suffer from hidden nodes that disturb their transmissions. For instance, when transmitting to node 1, node 2 suffers from transmissions done by the hidden node 8.

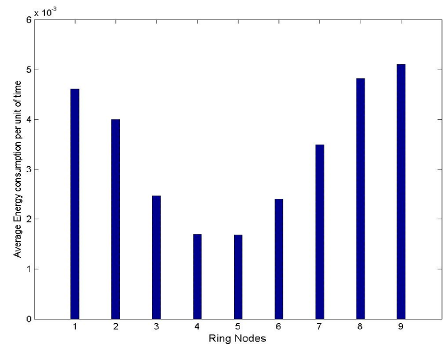

Fig. 4. Average energy consumption for each ring node.

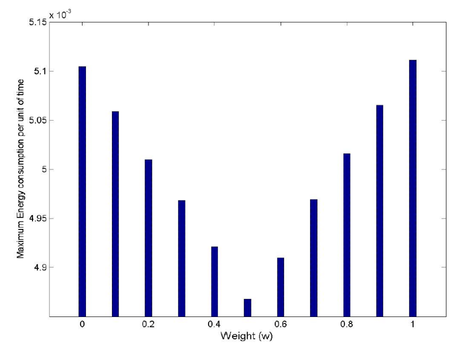

Fig. 5. The maximum sensor node consumption as a function of the weight w.

Although node 9 has the lowest unsuccessful transmission probability and thus the lowest number of required retransmissions, it has the maximum energy consumption (see Fig. 4). This is because it handles excessive route thru traffic, which dominates the fact that the other nodes need much more retransmissions.

For instance, node 9 has to transmit and relay a total number of 2.5 reports per unit of time to the sink node. We refer to this rate as the matrix pattern node load. Node 9 needs to transmit a packet $(1+\beta(9,0)/(1-\beta(9,0))) = 1.001$ times to be correctly received by the sink node. Hence, in average, node 9 transmits $2.5 \times 1.001 = 2.5025$ packets per unit of time to the sink node. We refer to this rate as the real node load as opposed to the matrix pattern node load (see Fig. 3).

On the other hand, node 8 needs in average to transmit a packet $(1+\beta(8,9)/(1-\beta(8,9))) = 1.191$ times to be correctly received by node 9. As such, node 8 suffers from much more retransmissions than node 9. Even though, the total number of transmitted packets per unit of time by node 8, $2 \times 1.191 = 2.382$ is smaller than the one transmitted by node 9. As a result, node 9 depletes more quickly its energy than node 8, causing thus a premature death of the WSN.

To overcome this limitation, we adopt our balanced routing scheme. Accordingly node 5 transmits a fraction w of its traffic through node 6 and the remaining part $(1-w)$ through node 4. The other nodes of the network keep transmitting through the shortest path.

Figure 5 shows the maximum sensor node consumption in

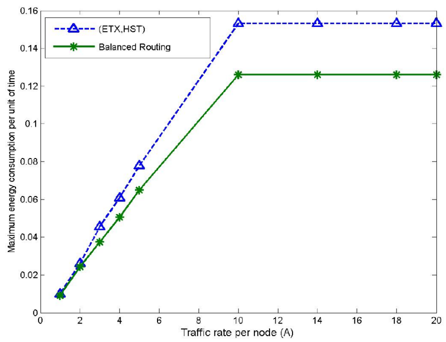

Fig. 6. Comparison of the energy consumption between our balanced routing scheme and (ETX & HST) schemes in the ring topology.

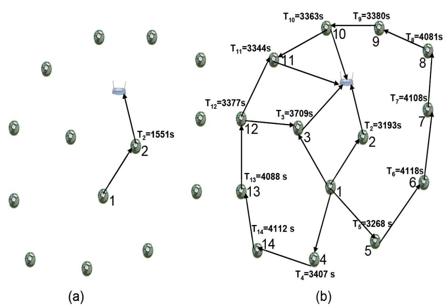

Fig. 7. Comparison of the energy consumption between our balanced routing scheme and (ETX & HST) schemes in a meshed network topology.

the WSN (i.e., $\max_{u \in V} E(u)$) as a function of w. We can observe that the minimal consumption is obtained when the traffic is fairly shared between the two ring sides. In this case, the traffic is efficiently balanced inside the network and the nodes 1 and 9 have equivalent energy consumption.

Figure 6 compares the energy consumption with our routing scheme to the cases where HST and ETX schemes are considered. The optimal routing configuration (i.e., $w = 0.5$) is used when our balanced routing scheme is considered. Figure 6 reveals that the gain achieved by our scheme increases with the rate of traffic A generated by each sensor node. When A gets high values, the energy consumption as well as the achieved gain become constant. In this range of A, the traffic is generated at each sensor node in a saturated manner in which as soon as a packet is transmitted, another is waiting in line.

To conclude this paper, let us compare our balanced routing with the basic schemes using the arbitrary meshed network of Fig. 7. We assume that only node 1 generates packets periodically to the sink node $\mathcal{S}$ at a rate 0.5 report/s. The remaining sensor nodes participate only in the routing operations. Each sensor node has initial energy $E_{init} = 1J$.

Figure 7 shows the results provided when using the basic routing schemes and the balanced routing scheme, respectively. We can observe that the routes used in balanced routing are more spread out than those of the basic routing. The balanced routing benefits from the total available energy resource in the network, whereas the basic schemes use only a small subset of the sensor nodes' energies. The network lifetime obtained by our scheme is $3193\ s$, which is more than two times as long as $1551\ s$ of the basic schemes. This is a typical example of the gain introduced by the balanced routing, which avoid energy wastage due to nodes useless, i.e., sensor nodes not completely used before the network death even if they still have available energy in their batteries.

V. Conclusion

Conceiving energy-efficient protocols is a critical issue in energy-constrained wireless sensor networks. In this paper, we showed that a life-optimal routing algorithm must take advantage of the total available energy resources in the network before its death. To achieve this, a load balanced routing scheme was proposed. We showed through simple examples that by efficiently balancing the traffic inside the network, the network lifetime can be significantly improved.

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