On Balancing Energy Consumption in Wireless Sensor Networks

Fatma Bouabdallah, Nizar Bouabdallah, and Raouf Boutaba

***Abstract*—Wireless sensor networks (WSNs) require protocols that make judicious use of the limited energy capacity of the sensor nodes. In this paper, the potential performance improvement gained by balancing the traffic throughout the WSN is investigated. We show that sending the traffic generated by each sensor node through multiple paths, instead of a single path, allows significant energy conservation. A new analytical model for load-balanced systems is complemented by simulation to quantitatively evaluate the benefits of the proposed load-balancing technique. Specifically, we derive the set of paths to be used by each sensor node and the associated weights (i.e., the proportion of utilization) that maximize the network lifetime.**

***Index Terms*—Energy conservation, load balancing, performance analysis, routing, wireless sensor networks (WSNs).**

I. INTRODUCTION

THE LIMITED energy capacity of sensor nodes dictates how communications must be performed inside wireless sensor networks (WSNs). WSN protocols must make judicious use of the finite-energy resources. Typically, sensor nodes avoid direct communication with a distant destination since a high transmission power is needed to achieve a reliable transmission [1], [2]. Instead, sensor nodes communicate by forming a multihop network to forward messages to the collector node, which is also called the sink node. In this regard, efficient routing in such multihop networks becomes crucial in achieving energy efficiency. In addition to using multihop communication for reducing the energy requirements for communication, an efficient routing protocol is needed to decrease the end-to-end energy consumption when reporting data to the sink node.

To improve the network lifetime, extensive research on designing energy-efficient medium-access control (MAC) protocols has been conducted in the literature [3]–[5]. Accordingly, the sensor nodes turn off some hardware components when they are unused. As such, the wasted energy due to idle listening to the medium is reduced. Indeed, a transceiver that constantly senses the channel will quickly deplete the sensor node energy and dramatically shorten the network lifetime. Thus, it is imperative that the idle sensor nodes enter sleep mode as often as possible [11]. However, each sensor node must coordinate with its neighbors to ensure communications when needed. To do so, the works in [3]–[10] suggested wake-up scheduling schemes at the MAC layer to activate sleeping nodes when needed. On the other hand, the works in [12] and [13] addressed the problem at the network layer by proposing new routing solutions that take into account the sleep state of some network nodes.

To date, much of the work on WSNs has focused on the energy minimization problem, taking into consideration the individual sensor node performance, i.e., finding methods that allow each sensor node to consume the minimum amount of energy subject to a given traffic load for handling. However, there has been little focus on how traffic is balanced throughout multihop WSNs and how it impacts the overall network lifetime.

In this paper, the use of multiple paths between each sensor node and the sink node is considered. It is shown that the network lifetime can be improved by efficiently routing (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 slowly and uniformly drain energy 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 always forwarding through the same path. In fact, always routing through the same path will quickly deplete the energy of the sensor nodes contained therein. The problem then consists of 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.

Using a classical contention-based access method to the data channel and the most commonly used acknowledgment (ACK) model to ensure reliable transmissions, a new analytical model is developed for calculating 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 and to relay the pass-through traffic of other sensor nodes. Moreover, to better evaluate the real behavior of WSNs, we consider the wasted energy due to retransmissions, overhearing, and idle listening, which is not the case in many models developed in the literature [13], [19]. Building on these results, we derive

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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 and varying network sizes. As a main contribution of our paper, we show that, by efficiently balancing the traffic inside the network, significant energy savings of up to 15% can be achieved, compared to the basic routing protocols.

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

II. RELATED WORK

To minimize the energy consumption in WSNs, several energy-efficient MAC protocols [3]–[5] and energy-efficient routing protocols [12], [13] have been proposed in the literature. These schemes aim at decreasing the energy consumption by using sleep schedules [14]. The key idea behind this concept is completely turning off some parts of the sensor circuitry (e.g., microprocessor, memory, and radio) when it does not receive or transmit data, instead of keeping the sensor node in the idle mode. This scheme simply attempts to reduce wasted energy due to idle listening, i.e., lost energy while listening to receive possible traffic that is not sent. To do so, the works in [3]–[10] suggest wake-up scheduling schemes at the MAC layer to activate sleeping nodes when needed. On the other hand, the works in [12] and [13] address the problem at the network layer by proposing new routing solutions that take into account the sleep state of some network nodes. Additional solutions for reducing energy consumption, based on congestion control, have also been proposed in [15] and [16]. These mechanisms aim at achieving further energy conservation by reducing the energy wastage resulting from the frequently occurring collisions in WSNs.

Although there is significant energy savings achieved by such schemes based on the sleep schedules, the WSN keeps sending redundant data. Typically, WSNs rely on the cooperative effort of the densely deployed sensor nodes to report detected events. As a result, multiple sensor nodes may report the same event. To further decrease energy consumption, we have proposed in [17] a MAC scheme that eliminates the transmission of useless redundant information by profiting from the spatial correlation between nodes, as in [18].

While the previous approaches are quite useful, the energy efficiency of these protocols can considerably be 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 for handling. However, there has been little focus on how traffic is balanced throughout multihop WSNs and how it impacts the network lifetime.

In view of this, significant energy savings can be achieved at the routing level when considering the multihop ability. Our work is motivated by the results presented in [19], where the authors investigated the problem of 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 the physical layer (i.e., power control), the MAC layer (i.e., transmission control), and the network layer (i.e., routing control). Specifically, regarding the network layer, the authors formulated the problem of multihop routing in the context of WSNs by considering the energy constraint required for reliable end-to-end transmission. Building on this formulation, the authors derived, for each sensor node, the path with the minimum energy consumption, assuming collision-free transmissions on the shared channel. This problem, which is also well known as the minimum total energy (MTE) routing problem, has extensively been addressed in the context of ad-hoc networks [20]–[22]. The MTE problem consists of finding the route that minimizes the total consumed energy between any pair of source and destination nodes.

Nevertheless, using the MTE routing, i.e., always routing through the path with the minimum energy consumption, will quickly deplete the energy of the sensor nodes contained therein. To address this issue, Kwon *et al.* [19] introduced the concept of routing packets such that energy consumption is balanced among multiple paths. However, in doing so, Kwon *et al.* considered a simplistic scenario such as that when the medium is slotted, i.e., for each transmission, all the network nodes are supposed to be in sleep state, except for the sender and receiver nodes. Thus, collision-free transmission is ensured. As such, the typical energy wasted by the sensor nodes due to collisions, overhearing, and idle listening was not considered.

In this paper, a general scenario with a conventional contention-based access method to the wireless channel is considered. We provide an in-depth analysis of load balancing through multihop WSNs. Although this work takes inspiration from [19], it differs in several ways. First, a more realistic scenario with multiple-access nodes competing to access the common wireless channel is considered. This reveals some of the major strengths of the WSN capabilities, e.g., the cooperative effort of the densely deployed sensor nodes to report detected events. It also allows for direct comparison with basic systems (i.e., where traffic balancing is not considered), without any additional assumptions, showing the clear benefit of load balancing. Our model indeed captures the real behavior of WSNs by considering the wasted energy due to retransmissions, overhearing, and idle listening. Second, this paper explores the impact of collisions and the unreliability of links on the energy consumption, considering the hidden-node problem that is typical in multihop networks. This paper shows how collisions (i.e., congestion) can be reduced through load balancing. In other words, this paper illustrates how spatial reuse of the wireless channel can be exploited to achieve additional energy conservation.

As an alternative to our multiple-path-routing approach for achieving load balancing, the works in [23]–[26] proposed instead the use of adaptive routing schemes, where the routing decisions are made on the fly by considering the current residual energy at the sensor nodes. These schemes balance between the MTE and the max-min residual energy routing [27], which selects the path whose minimum residual energy fraction after a packet delivery is the maximum. References [23]–[26] have the same design philosophy. They attempt to use the path with the minimum energy consumption while avoiding the nodes with small residual energy.

In our study, we opt for the preconfigured static routing, instead of the adaptive on-the-fly routing for three main reasons: First, in our study, the sensor nodes are not mobile. Hence, the network topology is static, as opposed to typical ad-hoc networks, where on-the-fly routing is required to adapt to the frequent topological changes.

The second reason behind using the preconfigured routing is the traffic pattern. In our study, we consider continuous-monitoring applications, where each node periodically reports its data to the sink node. The amount of information generated by each sensor node is therefore known *a priori*, as opposed to event-driven applications, where the generated information at each sensor node is not known *a priori* since it depends on the arbitrary occurrence of specific events. In such event-driven WSNs, it may be useful to make routing decisions on the fly for each occurring event by considering the current network state (i.e., the residual energy at each sensor node). However, this is not required in our targeted continuous-monitoring networks. To be more precise, it is not recommended for the third reason given here.

Performing on-the-fly routing for each generated information induces considerable exchange of signaling messages. This routing scheme requires global and online information about the network state in making routing decisions. In computer networks where packets are large, the small control packets may impose little overhead. However, in WSNs where the packet size is small, they constitute a large overhead. This can extremely be costly since a large amount of energy has to be spent to route the control packets.

In response to these challenges, we propose our preconfigured balanced routing scheme. From a performance evaluation perspective, we develop a model for energy consumption that captures the real behavior of WSNs, as opposed to previous works, where many simplistic assumptions have been considered.

III. MODEL AND PROBLEM DESCRIPTION

A. Network Model

We represent a WSN by directed graph $G(V, E)$, which is 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 $R_h(v)$ (which is also called the 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 node v, all the nodes inside its carrier-sensing range, which is denoted by $H(v)$, sense the channel to be busy and cannot access the medium. Hereinafter, we denote by $H^+(v) = H(v) \cup \{v\}$ and $H^-(v)$ the set of nodes that node v cannot hear, i.e., $H^-(v) = V \backslash H^+(v)$.

On the other hand, during the transmission of 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 $(v, u) \in E$. Note that, the proposed network model assumes the knowledge of sets $H(v)$ and $N_e(v)$ for each sensor node $v \in V$. To obtain such inputs in practice, we assume that the cartography of the sensor network is known in advance.

We represent the graph connectivity by a connectivity matrix. The connectivity matrix of $G(V, E)$ is a matrix whose rows and columns are labeled by the graph vertices V, with a 1 or a 0 in position (m, n), according to whether v_m and v_n are directly connected or not. In other words, placing 1 in position (m, n) means that v_m and v_n are within the transmission range of each other (i.e., the two nodes can communicate). In our study, all the sensor nodes periodically transmit their reports to the sink node, which is denoted by $\mathcal{S}$. Here, we target 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 graph $G(V, E)$ that connects v to sink node $\mathcal{S}$. The set of paths between 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 sensing data to the sink nodes. In our study, access to the medium among the competing nodes is arbitrated by the well-known IEEE 802.11-like sensor network protocol [28], [29]. The IEEE 802.11 distributed coordination function access method is based on the carrier-sense multiple-access/collision-avoidance (CSMA/CA) technique. Thus, considering IEEE 802.11 in the context of WSNs allows determining a general case study for all WSN protocols based on the CSMA/CA technique. Note that sensor medium access control [4] and timeout medium access control [5] are WSN MAC protocols that rely on the CSMA/CA technique to coordinate the access to the wireless channel between all competing nodes. Thus, our study also remains valid for those WSN MAC protocols.

According to the CSMA/CA technique, a host, wishing to transmit a frame, first senses channel activity until an idle period that is equal to distributed interframe space (DIFS) is detected. Then, to avoid collisions, the station waits for a random backoff interval before transmitting. The backoff time counter is decremented in terms of time slots as long as the channel is sensed to be free. The counter is suspended once a transmission is detected on the channel. It resumes with the old remaining backoff interval when the channel is sensed to be idle again for a DIFS period. The station transmits its frame when the backoff time becomes zero. If the frame is correctly received, the receiving host sends an ACK frame after a short interframe space (SIFS). If an ACK is not received by the sender within an ACK timeout, the transmitted frame is supposed to be lost (due to either collision or channel error).

In this case, the sending host attempts to send its frame again when the channel is free for a DIFS period augmented by the new backoff, which is sampled according to the binary exponential backoff (BEB) process. Specifically, for each new transmission attempt, the backoff interval is uniformly chosen from the range $[0, CW]$ in terms of time slots. At the first transmission attempt of a frame, CW is equal to the initial backoff window size $CW_{\min}$. Following each unsuccessful transmission, CW is doubled until a maximum backoff window size value $CW_{\max}$ is reached. Once the frame is successfully transmitted, the CW value is reset to $CW_{\min}$.

In our analysis, we assume that there is no limit on the number of retransmissions over a link. Hence, a packet is never discarded by a node and continues to be retransmitted until it is successfully delivered.

The procedure previously described is referred to as the basic access mode. An optional request-to-send (RTS)/clear-to-send (CTS) mechanism can also be used to avoid collision among data packets due to the hidden terminal problem [30], [31]. Using the RTS/CTS mechanism, collisions still occur but among the small RTS frames, instead of the relatively large data packets. However, the actual payload of a data packet in WSNs is usually small. For instance, the CC2420 low-cost transceiver [32] has a transmit buffer of 128 B and a data packet payload of 30–50 B. For this reason, the RTS/CTS mechanism is usually disabled in WSNs. Moreover, it was shown in [33] that RTS/CTS increases the overhead without really improving the network performance. In view of this, we consider the basic access mode, but the same study with slight modifications can easily be adapted to the case where the 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 a weight $w(p)$ to each path $p \in P(v)$, such that $\sum_{p\in P(v)} w(p) = 1$. 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 that go through 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 generated by either u or other sensor nodes and relayed by u to attain their final destination (i.e., the sink node). Rate $\lambda(u, v)$ can simply be 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 $1_{|(u,v)\in p}$ is the indicator function of the condition that link (u, v) belongs to 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 by considering the system working in the unsaturated regime, which is more likely the case of real WSNs. WSNs indeed produce light traffic, compared with 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 the average energy consumed by node u due to the successful delivery of a packet transmitted by v to the sink node through path p. $E(u, p)$ includes only the energy consumed in transmission or reception (i.e., it does not include the energy consumed by a sensor node during the idle state). The average amount of energy consumed by node u per unit of time due to the different transmissions inside the WSN, which is denoted by $E(u)$, can therefore be expressed as follows:

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

where $E_{\text{idle}}(u)$ is the average amount of energy consumed by node u per unit of time during its idle state. The lifetime of sensor node u is then given by

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

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 terms of energy consumption. The problem then consists of 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 therefore need to balance the energy consumption inside the network by efficiently routing 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 of the greediest sensor nodes to maximize the network lifetime.

C. Motivating Balanced Routing Through an Example

Consider the sample scenario shown in Fig. 1, where each sensor node among A, B, and C transmits r reports per unit of time to sink node $\mathcal{S}$. Nodes B and C directly transmit their data packets to $\mathcal{S}$ since $\mathcal{S}$ is within the B and C transmission ranges. On the other hand, node A has to transmit through B or C to reach $\mathcal{S}$.

We denote by $(1 - \beta(A, B))$ the packet delivery success probability from A to B. $\beta(A, B)$ represents the quality of the wireless link between nodes A and B. Assume that $\beta(A, B) = \beta(A, C) = \beta(B, \mathcal{S}) = \beta(C, \mathcal{S})$. As such, paths $p_1 = [A, B, \mathcal{S}]$

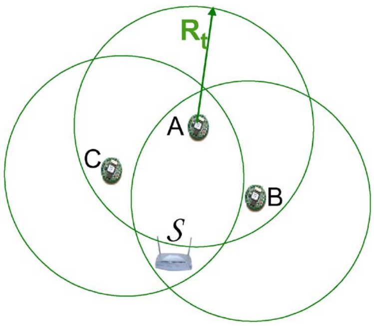


Fig. 1. Four-node example network.

and $p_2 = [A, C, \mathcal{S}]$ are equivalent in terms of the quality of the wireless links.

Assume that the routing layer chooses to use path p_1 to deliver packets from A to $\mathcal{S}$. As a result, node B transmits twice more packets than nodes A and C. Hence, node-B energy prematurely depletes, leading to a quick death of the network, although the remaining sensor nodes are still alive.

Alternatively, using our balanced routing method, node A fairly shares its generated traffic between intermediate nodes B and C. Specifically, as paths p_1 and p_2 have equivalent properties (i.e., same quality of the wireless links), node A sends exactly half of its traffic through each of the two possible paths. In doing so, the energy uniformly drains among nodes B and C, which improves the network lifetime, compared to the case where node A always transmits through the same path p_1.

It is worth noting that the proportions of utilization of concurrent paths p_1 and p_2, which are denoted by w_1 and w_2, respectively, depend on the paths' qualities. In the previous example, intermediate nodes B and C fairly share the traffic sent by node A (i.e., $w_1 = w_2 = 0.5$) since paths p_1 and p_2 have the same quality and this routing configuration maximizes the network lifetime.

Assume now that $\beta(A, B) = \beta(A, C)$ and $\beta(B, \mathcal{S}) < \beta(C, \mathcal{S})$. This means that $(B, \mathcal{S})$ is a better link than $(C, \mathcal{S})$ and that transmitting through B helps reduce the total number of retransmissions. Typically, a packet sent by node A requires less energy to be correctly delivered to node $\mathcal{S}$ when it is transmitted through p_1, instead of p_2. However, always routing through the path with minimum energy will quickly deplete the capacity of node B. Again, the traffic needs to be balanced among paths p_1 and p_2, and the tuple of weights (w_1, w_2) that maximizes the network lifetime depends on the quality of the wireless links (i.e., probability β).

For an intuitive understanding of the aforementioned requirements, we give this simple example. Suppose that $\beta(B, \mathcal{S}) = 0.2$, $\beta(C, \mathcal{S}) = 0.5$, and $\beta(A, B) = \beta(A, C)$. In average, node B needs to transmit a packet $(1 + (\beta(B, \mathcal{S})/1 - \beta(B, \mathcal{S}))) = 1.25$ times to be correctly received by node $\mathcal{S}$. In the same way, node C needs to transmit a packet twice, in average, to be correctly received by node $\mathcal{S}$. To ensure a fair consumption of the energy at intermediate nodes B and C, w_1 and w_2 are given by resolving the following system:

$$\begin{cases} r \times 1.25 \times (w_1 + 1) = r \times 2 \times (w_2 + 1) \\ w_1 + w_2 = 1. \end{cases}$$

Hence, to maximize the WSN lifetime, $w_1 = 0.846$ and $w_2 = 0.154$ of the traffic must be transmitted through paths p_1 and p_2, respectively.

IV. ANALYTICAL MODEL

In this section, we develop an analytical model for deriving 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 can run a simple algorithm to derive the optimal routing set $\mathcal{W}$ that achieves objective function (5). As shown in (3), we need to calculate elements $E_{\text{idle}}(u)$ and $E(u, p)$ to obtain $E(u)$.

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

As explained before, $E(u, p)$, with $(u, v) \in (V \backslash \{\mathcal{S}\})^2$ and $p \in P(v)$, is the average amount of energy consumed by node u in transmission and reception due to the successful delivery of a packet from v to the sink node through path p. To derive $E(u, p)$, we distinguish between two cases, according to whether node u belongs to path p or not.

Case 1: $u \in p$: In this case, node u is either the source or an intermediate node on 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 and transmission. Hence, $E(u, p)$ can be written as follows:

$$E(u, p) = E(u, p)_{\text{rec}} + E(u, p)_{\text{trans}}. \tag{6}$$

Energy consumed in reception: $E(u, p)_{\text{rec}}$: This amount of energy corresponds to three energy consumptions.

1) 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 path p, which is denoted hereinafter 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

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

where $E^{\text{rec}}(data)$ is the energy consumed by a sensor node for the reception of a data packet. We note that, in our study, we assume that all the data packets (i.e., reports) sent by the different sensor nodes are of 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 is unsuccessful. $N_c(\#u-1,u)$ is a geometric random variable, and thus, we have

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

In the next section, we will show how to derive the probability $\beta(\#u-1,u)$.

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

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

where $\#k+1$ denotes the subsequent node to k on path p.

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

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

Note that, in our study, we assume that ACK frames are not subject to collision. To justify such assumption, let us first recall that following a correct transmission of a data packet through wireless link (u,v) (i.e., the data packet is correctly received by node v), the ACK message may not correctly be delivered to node u due to the reason given here.

- A collision occurs at node u when receiving the ACK message, i.e., the ACK signal overlaps with other transmissions at node u. This improbable event occurs when node v and a hidden node from v within the interference range of u (which is denoted hereinafter by n, $n\in H^{-}(v)\cap H(u)$) transmit at the same time. Note that such case happens if node n accesses the medium during the period of $\text{SIFS}+t_{\text{ACK}}$. In other words, if the backoff counter of node n expires during the $\text{SIFS}+t_{\text{ACK}}$ period of time, then a collision on the ACK frame is perceived by node u. Recall that, after the completion of u's DATA packet transmission, all the nodes in $H^{-}(v)\cap H(u)$ will resume their access after $\text{DIFS}+\text{Backoff}$ (see Section III-A). Therefore, an ACK's collision at u happens only if $\text{DIFS}+\text{Backoff}<\text{SIFS}+t_{\text{ACK}}$. Considering the scarcity of such event, we have neglected collisions on the ACK frames.

Energy consumed in transmission: $E(u,p)_{\text{trans}}$*:* This amount of energy corresponds to two energy consumptions.

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

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

where $E^{\text{trans}}(data)$ is the energy consumed by a sensor node for the transmission of a data packet.

2) 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

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

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 that are not necessarily intended for u, i.e., the 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 simply corresponds to nodes that jointly belong to 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 two energy consumptions at node u.

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

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

2) Energy consumed by node u while listening to the ACK frame sent by node k to node $\#k-1$ on 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 path p is given by

$$E(u,p)=\sum_{k\in Z(u,p)}\left[\left(\overline{N}_c(k,\#k+1)+1\right)\times E^{\text{rec}}(data)+E^{\text{rec}}(\text{ACK})\times 1_{\big|k\neq\text{source}(p)}\right]. \quad (10)$$

B. Calculation of $E_{\text{idle}}(u)$

It is the energy consumed by node u in the idle state and the energy dissipated by node u when it is neither transmitting nor receiving (i.e., while listening to the idle channel). $E_{\text{idle}}(u)$ can be expressed as follows:

$$\begin{aligned} E_{\text{idle}}(u) = 1 - &\sum_{v\in V}\sum_{p\in P(v)} w(p)\times A(v) \\ &\times \Bigg[\sum_{k\in Z(u,p)} \left[\overline{N}_c(k,\#k+1)T_{\text{data}} + T_{\text{ACK}}\times 1_{|k\neq v}\right] \\ &\quad + \left[\overline{N}_c(u,\#u+1)T_{\text{data}}+T_{\text{ACK}}\times 1_{|u\neq v}\right]\times 1_{|u\in p}\Bigg] \end{aligned} \tag{11}$$

where E^{idle} is the amount of energy consumed per unit of time by a sensor node in the idle state, and T_{data} and T_{ACK} are the transmission times of data reports and ACK messages, respectively. Note that (11) is always positive since we consider the unsaturated regime.

Finally, by substituting (6), (10), and (11) into (3), we obtain 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 be calculated to obtain $E(u)$ is $\beta(k,n)\forall(k,n)\in V^2$.

C. Calculation of $\beta(u,v)$

Let us consider edge $(u,v)\in E$. As stated before, $\beta(u,v)$ is defined as the probability of a transmission attempt from u to v to be unsuccessful due to either collision or channel error.

In our study, the access to the medium is arbitrated by the well-known IEEE 802.11-like sensor network protocol. In the following, we derive probability $\beta(u,v)$, considering the basic access mode case (i.e., Data/ACK). The same calculation methodology can simply be adapted to derive $\beta(u,v)$ in the RTS/CTS-based access mode case.

We note that various studies in the literature addressed the calculation of $\beta(u,v)$, considering simplistic assumptions and particular network topologies [34]–[36]. Specifically, Bianchi [36] assumed that the network operates under saturation conditions, i.e., the transmission queue of each node is assumed to be always nonempty. In addition, Bianchi [36] assumed that all the nodes are within each others' carrier-sensing range (i.e., no hidden terminals). Medepalli and Tobagi [34] and Garetto [35] extended the calculation of $\beta(u,v)$ for the multihop case with finite load. However, simplistic assumptions still need to be accounted for. For instance, the authors assumed that each node always transmits to the same neighbor, regardless of the packets' source and destination nodes. As such, each sensor node transmits through a single fixed route to the sink node, and all the routes to the sink form a set of trees where the root is the sink node and the sensors are the leaf nodes.

This assumption is impractical in WSNs, where routes change over time since the WSN topology changes, due to the drain of sensor nodes. In addition, the assumption considered in [34] is incompatible with the balanced routing philosophy, which allows the traffic generated by each sensor node to be bifurcated over different weighted routes to improve the network lifetime.

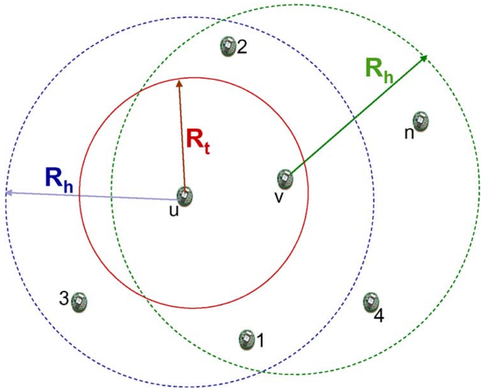


Fig. 2. Node n as a hidden node to node u.

To alleviate the aforementioned limitations, we recalculate $\beta(u,v)$, considering a general case by extending the works in [34] and [36]. We follow the same philosophy used in [34] and [36] since it yields very good results. This modeling approach dictates the consideration of the different events arbitrating the channel access for each node. The probabilities of these events are then related in terms of each other through fixed-point equations, which can be solved using numerical techniques. Due to the complexity of solving such equations, we provide hereinafter only the framework for deriving these equations. In the performance evaluation section, we instead use simulations to calculate $\beta(u,v)$.

Let us consider Fig. 2. A transmission from node u is unsuccessfully received by node v if one or more of four events occur.

1) A: A packet error occurs during the transmission on wireless link (u,v).
2) B: One or more sensor nodes, within both the carrier-sensing ranges of u and v, transmit in the same backoff slot as u.
3) C: Node u transmits while v is already busy with the transmission of hidden nodes from u. For instance, assume that node n is transmitting a packet to node v, as shown in Fig. 2. Node n is outside the carrier-sensing range of node u (i.e., n is a hidden node from u). As such, node u still senses the channel to be idle and can transmit a packet to v during node-n transmission. If this happens, the newly arriving packet from u cannot be received by v since it is already busy. Effectively, the packet from u to v experiences a collision.
4) D: Node v receives transmissions from hidden nodes from u, whereas the transmission of the latter is still in progress. Typically, if, during the packet transmission from u to v plus SIFS (also called the vulnerable period), node n transmits a packet to any of its neighboring nodes, the receiving node v will not return an ACK frame to u. Node u therefore considers the packet as unsuccessfully transmitted and schedules for a retransmission later. We note that, in our analytical model, we do not consider the signal capture property.

Note that, according to events C and D, the collision perceived by node u results from the overlap of DATA packets emanating from u and one hidden node from u (denoted by n). However, focusing on each event separately allows us to identify the differences between both events. In fact, considering event C, the transmitted packet by node u collides at node v with an in-progress transmission of a node n hidden from u. In other words, node u transmits to node v, which is already occupied by a transmission from a node $n \in H^-(u)$ such that v is within its interference range (i.e., $n \in H^-(u) \cap H(v)$). On the other hand, according to event D, node u starts correctly transmitting to node v, but before the completion of the packet transmission, a collision occurs at node v due to the transmission of a node $n \in H^-(u) \cap H(v)$. Specifically, this event occurs if any node $n \in H^-(u) \cap H(v)$ accesses the medium during the vulnerable period $T_V (T_V = (T_{\text{data}} + \text{SIFS})/Slot)$. We can see that such event is not considered in C.

Based on the aforementioned analysis and assuming the independence of the different events leads to failed transmission, the probability that node u successfully transmits to v can be written as follows:

$$1-\beta(u,v) = (1-\Pr\{A\})(1-\Pr\{B\})(1-\Pr\{C\})(1-\Pr\{D\}) \tag{12}$$

where $\Pr\{A\} = l(u,v)$, with $l(u,v)$ being the packet error rate on link (u,v). In the following, we provide the details on computing the probabilities of events B, C, and D.

1) Calculation of $\Pr\{B\}$:

Theorem 1: For every $u \in V$ and $v \in N_e(u)$, the probability $\Pr\{B\}$ that one or more nodes in $H(u) \cap H^+(v)$ transmit in the same backoff slot used by u for transmission to v is given by

$$\Pr\{B\} = 1 - \prod_{k \in H(u) \cap H^+(v)} (1 - \Gamma_k \Psi_k \rho_k) \tag{13}$$

where

$$\begin{aligned}\Gamma_k &= \Pr\{\text{node-}k \text{ backoff timer expires in a given backoff} \\ &\qquad \text{slot} | \text{node } k \text{ is in backoff}\} \\ \Psi_k &= \Pr\{\text{node } k \text{ is in backoff} \\ &\qquad | k \text{ has a packet to transmit}\}\end{aligned}$$

and $\rho_k = \max(1, \sum_{n \in N_e(k)} \lambda(k,n) \times E[T(k,n)])$ indicates the server utilization of node k, with $E[T(k,n)]$ being the average service time of a packet transmitted by k to n. $E[T(k,n)]$ is defined as the time spent by a packet since it reaches the head of line of the transmission queue of k until the end of its successful transmission to n.

Proof 1:

$$\begin{aligned}\Pr\{B\} = 1 - \Pr\{&\text{no node in } H(u) \cap H^+(v) \\ &\text{accesses the channel in a given backoff slot} | \text{node} \\ &u \text{ accesses the channel in that backoff slot}\}.\end{aligned} \tag{14}$$

Let us consider sensor node $k \in H(u) \cap H^+(v)$. For the sake of simplicity, we denote by $\mathcal{X}$, $\mathcal{Y}$, $\mathcal{Z}$, and $\mathcal{Q}$ the following events:

$$\begin{aligned}\mathcal{X} &= \{\text{node } k \text{ accesses the channel in a given backoff slot}\} \\ \mathcal{Y} &= \{\text{node } u \text{ accesses the channel in that backoff slot}\} \\ \mathcal{Z} &= \{k \text{ has a packet to transmit}\} \\ \mathcal{Q} &= \{\text{node} k \text{ is in backoff}\}.\end{aligned} \tag{15}$$

Then, we have

$$\begin{aligned}\Pr\{\mathcal{X}|\mathcal{Y}\} &= \Pr\{\mathcal{X}, \mathcal{Z}, \mathcal{Q}|\mathcal{Y}\} \\ &= \Pr\{\mathcal{X}|\mathcal{Q}, \mathcal{Z}, \mathcal{Y}\} \times \Pr\{\mathcal{Q}, \mathcal{Z}|\mathcal{Y}\} \\ &= \Pr\{\mathcal{X}|\mathcal{Q}, \mathcal{Z}, \mathcal{Y}\} \times \Pr\{\mathcal{Q}|\mathcal{Z}, \mathcal{Y}\} \times \Pr\{\mathcal{Z}|\mathcal{Y}\} \\ &= \Pr\{\mathcal{X}|\mathcal{Q}\} \times \Pr\{\mathcal{Q}|\mathcal{Z}, \mathcal{Y}\} \times \Pr\{\mathcal{Z}\} \\ &= \Gamma_k \times \Pr\{\mathcal{Q}|\mathcal{Z}, \mathcal{Y}\} \times \rho_k \\ &\simeq \Gamma_k \Psi_k \rho_k.\end{aligned} \tag{16}$$

Note that event $\{\mathcal{Q}|\mathcal{Z}, \mathcal{Y}\}$ means that all the nodes in $H(k)$ are not transmitting. Moreover, since $k \in H(u)$, event $\{\mathcal{Q}|\mathcal{Z}, \mathcal{Y}\}$ only needs the nodes in $H(k) \cap H^-(u)$ not to be in the transmission state. In (16), we assume that $\Pr\{\mathcal{Q}|\mathcal{Z}, \mathcal{Y}\} \simeq \Pr\{\mathcal{Q}|\mathcal{Z}\} = \Psi_k$. Later, we will show how to derive Ψ_k. Substituting (16) into (14), we obtain (13), which concludes the proof. ■

We highlight that, to express the probability Γ_k that a sensor node k transmits in a randomly chosen backoff slot, given that k is in backoff, we use the well-known result of [36], which was also used in [34], as follows:

$$\Gamma_k = \frac{2(1-2\beta_k)}{W(1-2\beta_k) + \beta_k(W+1)\left(1-(2\beta_k)^m\right)} \tag{17}$$

where m is the number of backoff stages (i.e., $CW_{\max} = 2^m CW_{\min}$), and $W = CW_{\min}$. Moreover, β_k is the probability that a transmission attempt of node k is unsuccessful and is given by

$$\beta_k = \frac{1}{\lambda_k} \sum_{n \in N_e(k)} \lambda(k,n) \times \beta(k,n). \tag{18}$$

It is worth noting that (17) has been derived in [36] for the case of a single-hop network. In [34], Medepalli and Tobagi used (17) in the context of multihop networks and showed that good results can still be obtained.

We also recall that, in our analysis, we assume that the network is operating in the unsaturated regime since the traffic load in WSNs is usually light, compared with that in classic wireless networks. Typically

$$\sum_{n \in N_e(k)} \lambda(k,n) \times E\left[T(k,n)\right] < 1 \qquad \forall\, k \in V.$$

Calculation of $\Pr\{C\}$: The probability $\Pr\{C\}$ that node v is already busy when it receives a transmission from

u can be written as follows:

$$\begin{aligned}\Pr\{C\} &= \Pr\{\text{node } v \text{ is already busy}|\text{node } u \text{ accesses}\\ &\qquad \text{the channel to transmits to } v\}\\ &= \Pr\{\text{node } v \text{ is busy only due}\\ &\qquad \text{to nodes hidden from } u\}\\ &= \Pr\{\text{node } v \text{ is busy only due to nodes hidden from}\\ &\qquad u \mid v \text{ is busy}\} \times \Pr\{v \text{ is busy}\}. \end{aligned} \tag{19}$$

The first element of the expression of $\Pr\{C\}$ is typically the fraction of access attempts from only the nodes hidden from u to all the nodes in $H^+(v)$. Hence, we obtain

$$\begin{aligned}&\Pr\{\text{node } v \text{ is busy only due to}\\ &\quad \text{nodes hidden from } u|v \text{ is busy}\}\\ &= \frac{\left[1 - \prod_{k\in H^-(u)\cap H(v)} (1-\alpha_k)\right] \prod_{k\in H^+(u)\cap H^+(v)} (1-\alpha_k)}{\left[1 - \prod_{k\in H^+(v)} (1-\alpha_k)\right]}\end{aligned} \tag{20}$$

where α_k is the probability that node k transmits on the medium in a given slot. To derive α_k, let us define the following events:

$$\begin{aligned}\mathcal{X} &= \{\text{node } k \text{ backoff timer expires in a given slot}\}\\ \mathcal{Y} &= \{\text{node } k \text{ is in backoff}\}\\ \mathcal{Z} &= \{k \text{ has a packet to transmit}\}.\end{aligned}$$

Then, α_k can be expressed as follows:

$$\begin{aligned}\alpha_k &= \Pr\{\mathcal{X}|\mathcal{Y}\} \times \Pr\{\mathcal{Y}\}\\ &= \Pr\{\mathcal{X}|\mathcal{Y}\} \times \Pr\{\mathcal{Y}|\mathcal{Z}\} \times \Pr\{\mathcal{Z}\}\\ &= \Gamma_k \Psi_k \rho_k\end{aligned} \tag{21}$$

where $\Psi_k = \Pr\{\mathcal{Y}|\mathcal{Z}\}$ is the fraction of time that node k spends in backoff when attempting to successfully transmit a packet. Ψ_k is simply given by

$$\Psi_k = \frac{b_k}{E[T_k]} \tag{22}$$

where $E[T_k] = (1/\lambda_k)\sum_{n\in N_e(k)} \lambda(k,n) \times E[T(k,n)]$ is the average service time of a packet successfully transmitted by node k. Moreover, $b_k = (1/\lambda_k)\sum_{n\in N_e(k)} \lambda(k,n) \times b(k,n)$ is the average total time spent by node k in backoff when attempting to successfully transmit a packet, where $b(k,n)$ is the average total time spent by node k in backoff when attempting to transmit a packet to n.

The second element of the expression of $\Pr\{C\}$ can be written as follows:

$$\begin{aligned}\Pr\{v \text{ is busy}\} &= 1 - \Pr\{v \text{ is not busy}\}\\ &= 1 - \prod_{k\in H^+(v)} \delta(v,k)\end{aligned} \tag{23}$$

where $\delta(v,k)$ is the probability that v is not occupied by a transmission from k. $\delta(v,k)$ is given by

$$\begin{aligned}\delta(v,k) = 1 - \sum_{n\in N_e(k)} \lambda(k,n) \times \left(\overline{N}_c(k,n) + 1\right)\\ \times T_{\text{data}} - \sum_{n\in N_e(k)} \lambda(n,k) \times T_{\text{ACK}}\end{aligned} \tag{24}$$

where T_{data} and T_{ACK} are the transmission times of a data packet and an ACK frame, respectively.

Finally, substituting (20) and (23) into (19), we obtain the expression of $\Pr\{C\}$.

Calculation of $\Pr\{D\}$*:* We denote by $T_V = (T_{\text{data}} + \text{SIFS})/Slot$ the vulnerable period of time, which is expressed in terms of backoff slots, during which the transmission of a hidden node from u and within the carrier-sensing range of v prevents the success of the in-progress transmission from u to v. Hence, the probability $\Pr\{D\}$ that node v receives transmissions from hidden nodes from u while the transmission of node u is still in progress can be derived as follows:

$$\begin{aligned}\Pr\{D\} &= 1 - \Pr\{\text{no node in } H^-(u)\cap H(v)\\ &\qquad \text{transmits during } T_V \text{ slots}\}\\ &= 1 - \prod_{k\in H^-(u)\cap H(v)} (1-\alpha_k)^{T_V}.\end{aligned} \tag{25}$$

Finally, substituting (13), (19), and (25) into (12), we obtain the expression of $\beta(u,v)$. We can see that the only remaining unknown variable that needs to be calculated to be able to compute $\beta(u,v)$ is $E[T(k,n)]$, i.e., the average time taken in successfully transmitting a packet from node k to n.

D. Calculation of $E[T(k,n)]$

To derive $E[T(k,n)]$, we extend the average cycle analysis proposed in [34] to handle the case in which a node can transmit to all its neighbors. Accordingly, $E[T(k,n)]$ is expressed as follows:

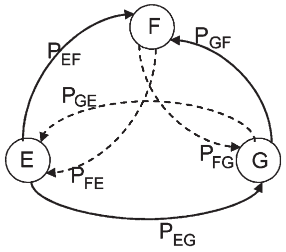
$$E\left[T(k,n)\right] = d(k,n) + b(k,n) + s(k,n) + c(k,n). \tag{26}$$

Here, $d(k,n)$ is the average time taken by a successful transmission attempt of a packet from k to n. $d(k,n)$ can simply be given by

$$d(k,n) = d = \text{DIFS} + T_{\text{data}} + \text{SIFS} + T_{\text{ACK}}. \tag{27}$$

$b(k,n)$ is the average total time spent by node k in backoff when attempting to transmit a packet to n and can be expressed as follows:

$$\begin{aligned}b(u,\#u+1) = \Bigg[&\frac{CW_m}{2} \times \beta^m(u,\#u+1)\\ &+ \sum_{i=0}^{m-1} \frac{CW_i}{2} \times \beta^i(u,\#u+1)\\ &\times (1-\beta(u,\#u+1))\Bigg] \times Slot\end{aligned} \tag{28}$$



(a)

$$\begin{pmatrix} P_E & P_{EF} & P_{EG} \\ P_{FE} & P_F & P_{FG} \\ P_{GE} & P_{GF} & P_G \end{pmatrix}$$

(b)

Fig. 3. Markovian chain. (a) The state transition diagram. (b) The transition probability matrix.

where we recall that 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. Recall that, in (28), we assume, as in [36], that a packet is never discarded by a node and thus continues to be retransmitted until being successfully delivered (i.e., there is no retry limit). $s(k,n)$ is the average time taken by the successful transmissions of other nodes in $H(k)$ during the service of node k packet to node n. $c(k,n)$ is the average time taken by the unsuccessful transmissions, regardless whether k is involved or not, which suspend the transmission of node k to n.

To derive $s(k,n)$ and $c(k,n)$, let us consider the state transition diagram of the Markov chain and its associated transition probability matrix shown in Fig. 3, where states E, F, and G are defined here.

1) E: {A successful transmission is made by node k to $n|\mathcal{X},\mathcal{Y}$.
2) F: {Unsuccessful transmission is made in $H^+(k)|\mathcal{X},\mathcal{Y}$.
3) G: {successful transmission is made by nodes other than k in $H^+(k)|\mathcal{X},\mathcal{Y}$.

Here, $\mathcal{X}$ and $\mathcal{Y}$ represent the following events:

$$\mathcal{X} = \{\text{at least one node in } H^+(k) \text{has attempted to transmit}\}$$
$$\mathcal{Y} = \{\text{node } k \text{ has a packet to transmit to } n \text{ in its queue head}\}.$$

As shown in Fig. 3, $P_{i,j}$ is the transition probability from states i to j, and P_i is the probability of remaining in the same state i, following a new transmission attempt by the nodes in $H^+(k)$. In our case, we have $P_{i,j} = P_j \forall i,j \in \{E,F,G\}$ since the probability of visiting state j, following the next transmission attempt by nodes in $H^+(k)$, does not depend of the current system state. We denote by N_F the random variable representing the number of unsuccessful transmissions made before a successful transmission is achieved again by node k to node n. It is the number of times that state F is visited between two successive visits of state E. Hence, $c(k,n)$ is given by

$$c(k,n) = E[N_F] \times d. \tag{29}$$

In the same way, we obtain

$$s(k,n) = E[N_G] \times d \tag{30}$$

where N_G is the random variable representing the number of times that state G is visited between two successive visits of state E. In other words, $E[N_G]$ is the average number of successful transmissions done by other nodes in $H(k)$ during the service of a packet from k to n.

Let Q denote the following event:

$$Q = \{\text{state } E \text{ is left between two successive visits of state } E\}.$$

Hence, based on [37], we have

$$\Pr\{N_F = i|Q\} = \begin{cases} 1 - r_F, & \text{if } i = 0 \\ r_F \times (h_F)^{i-1} \times (1 - h_F), & \text{otherwise} \end{cases}$$

where r_F and h_F are given by

$$\begin{cases} r_F = \eta_F + \eta_G (1 - P_G)^{-1} P_{G,F} \\ h_F = P_F + P_{F,G} (1 - P_G)^{-1} P_{G,F} \end{cases}$$

with

$$\begin{aligned} \eta_F &= \Pr\{\text{The system leaves state } E \text{ to } F \mid \\ &\qquad \text{the system has left state } E\} \\ &= \frac{P_F}{1 - P_E} \\ \eta_G &= 1 - \eta_F = \Pr\{\text{The system leaves state } E \text{ to } G | \\ &\qquad \text{the system has left state } E\}. \end{aligned}$$

Hence, we obtain

$$E[N_F|Q] = \sum_{i=1}^{+\infty} i \times r_F \times (h_F)^{i-1} \times (1 - h_F) = \frac{P_F}{P_E (1 - P_E)}.$$

Then, we have

$$E[N_F] = E[N_F|Q] \times \Pr\{Q\} = E[N_F|Q] \times (1 - P_E) = \frac{P_F}{P_E}. \tag{31}$$

In the same way, we also obtain

$$E[N_G] = \frac{P_G}{P_E}. \tag{32}$$

According to (31) and (32), we need to derive probabilities P_E, P_F, and P_G to derive $E[N_F]$ and $E[N_G]$. To achieve this, let us define the probabilities $\theta(k,n)$ and $\theta(k)$ as follows:

$$\begin{aligned} \theta(k,n) &= \Pr\{\text{node } k \text{ successfully transmits in a given} \\ &\qquad \text{slot to node } n |\ k \text{ has a packet to transmit} \\ &\qquad \text{to } n \text{ in its queue head}\} \\ &= (1 - \beta(k,n)) \times \Gamma_k \times \Psi(k,n) \end{aligned} \tag{33}$$

where

$$\Psi(k,n) = \frac{b(k,n)}{E\left[T(k,n)\right]}. \tag{34}$$

Moreover, $\theta(k)$ is defined as

$$\begin{aligned}\theta(k) &= \Pr\{\text{node } k \text{ successfully transmits in a given slot}| \\ &\qquad\qquad k \text{ has a packet to transmit}\} \\ &= \frac{1}{\lambda_k} \sum_{n \in N_e(k)} \lambda(k,n) \times \theta(k,n). \end{aligned} \tag{35}$$

Let us now derive the probability P_F that an unsuccessful transmission is made in $H^+(k)$, given that at least one node in $H^+(k)$ has attempted to transmit and that node k has a packet to transmit to n in its queue head. Let $\mathcal{Z}$ denote the following event:

$$\mathcal{Z} = \left\{\text{successful transmission is made in } H^+(k)\right\}.$$

Hence, P_F can be written as follows:

$$\begin{aligned} P_F &= 1 - \frac{\Pr\{\mathcal{Z}, \mathcal{X}|\mathcal{Y}\}}{\Pr\{\mathcal{X}|\mathcal{Y}\}} \\ &= 1 - \frac{\Pr\{\mathcal{X}|\mathcal{Z}, \mathcal{Y}\} \times \Pr\{\mathcal{Z}|\mathcal{Y}\}}{\Pr\{\mathcal{X}|\mathcal{Y}\}} \\ &= 1 - \frac{\Pr\{\mathcal{Z}|\mathcal{Y}\}}{\Pr\{\mathcal{X}|\mathcal{Y}\}} \\ &= 1 - \frac{\theta(k,n) + \sum\limits_{m \in H(k)} \theta(m) \times \rho_m}{1 - \left[\Gamma_k \times \Psi(k,n) \times \prod\limits_{m \in H(k)} (1 - \alpha_m)\right]}. \end{aligned} \tag{36}$$

In the same way, we obtain P_G given by

$$P_G = \frac{\sum\limits_{m \in H(H)} \theta(m) \times \rho_m}{1 - \left[\Gamma_k \times \Psi(k,n) \times \prod_{m \in H(k)} (1 - \alpha_m)\right]}. \tag{37}$$

Finally, P_E is simply given by $P_E = 1 - P_F - P_G$. Then, substituting (27)–(30) into (26), we obtain the expression of $E[T(k,n)]$.

V. PERFORMANCE EVALUATION

In this section, we present the performance evaluation results. We first analyze the results regarding our balanced routing algorithms. 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 [38] to calculate the probability of unsuccessful transmission on each link (i.e., β) according to the routing configuration. Then, the analytical framework in Section IV-A-1. is used to calculate the energy consumption at each sensor node.

TABLE I
PARAMETER SETTING

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}

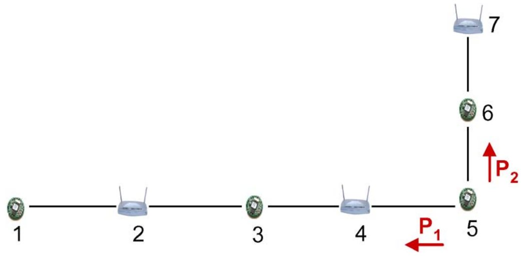


Fig. 4. Simple seven-node multihop WSN.

In our study, we use the hop-based spanning trees (HSTs) [39], [40] and expected transmission count (ETX)-based spanning trees (ETX) [41] as baselines to which the balanced routing improvements can 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 the hop count. This technique may lead to the use of slow 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 periodically reports with rate A the local data to one of the existing sink nodes over several hops. At each hop, the traffic originating from the local sensor must be merged with route-through traffic. The access to the data channel is arbitrated by the IEEE 802.11-like sensor network protocol. The parameters setting in our analysis are listed in Table I.

A. *Impact of the Routing Decision on the Quality of the Wireless Links and the Energy Consumption*

In this section, we use a simple seven-node multihop WSN, as shown in Fig. 4, to illustrate the impact of the traffic distribution inside the network on the packet delivery success probability over the WSN links and on the energy efficiency. Recall that the increase in the probability of a failed transmission $\beta(u,v)$ on a link (u,v) increases the number of retransmissions, which amplifies the energy wastage.

In Fig. 4, the distance between consecutive nodes is fixed to 10 m, the transmission range of each sensor node is 12 m, and the carrier-sensing range is 24 m. Nodes 2, 4, and 7 play the

TABLE II
COLLISIONS AND ENERGY CONSUMPTION IN A SEVEN-NODE MULTIHOP WSN

	Using P1	Using P2
Node 1 consumption (J)	0.0178	0.0176
Node 3 consumption (J)	0.0068	0.0066
Node 5 consumption (J)	0.0009	0.0006
Node 6 consumption (J)	0.0003	0.0006
$\beta(1,2)$	0.0145	0
$\beta(5,4)$	0.4667	0

role of sink nodes. Assume that only nodes 1 and 5 monitor the supervised area and periodically send their reports to one of the sink nodes with rates $A = 20$ reports/s and $A = 0.5$ reports/s, respectively. Straightforwardly, node 1 reports its data to sink node 2, and node 5 can report its data to either node 4 or node 7.

One can presume that node-5 reporting through either $p_1 = [5,4]$ or $p_2 = [5,6,7]$ is always performed without any collisions with regard to the transmissions of node 1. In other words, one may think that transmitting through route $p_1 = [5,4]$ or $p_2 = [5,6,7]$ is collision free since nodes 4–7 are outside the carrier-sensing range of sender node 1. Hence, *a priori* reporting of node-5 data to sink node 4 is a better choice since node 5 is only at one hop from node 5 and sink node 7 is at two hops from node 5. This, however, is untrue, as shown in Table II, which reports the results regarding collisions and energy consumption according to whether path p_1 or p_2 is adopted by node 5 to report its data to one of the sink nodes.

Specifically, if node 5 reports its data to sink node 7, collision-free transmission is ensured in all the WSN links, as shown in Table II. However, if node 5 chooses to communicate with sink node 4, wireless links (1, 2) and (5, 4) suffer from a serious problem of collision, as will be explained here.

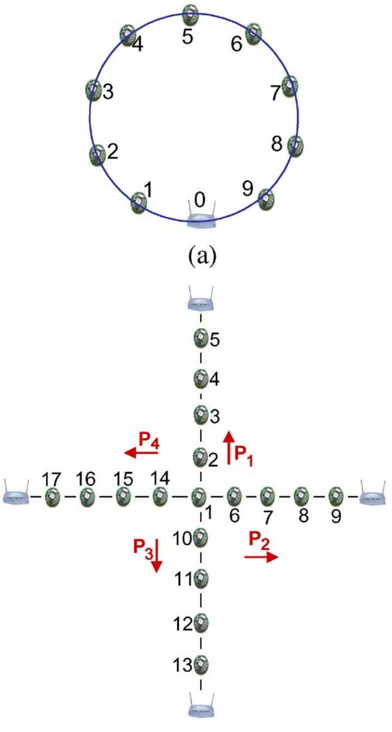
Although node 5 is outside the carrier-sensing ranges of both sender node 1 and receiver node 2, a node-1 transmission can fail due to collision caused by node-5 transmission. How can this happen?

It is worth noting that a collision may occur on link (1, 2) (i.e., at receiver node 2) only due to the transmissions of the hidden node 4. However, in our scenario, node 4 is a sink node and does not generate reports. Nevertheless, it transmits ACK frames to node 5. These ACK frames can overlap with node-1 transmissions at receiver node 2, thus causing collisions. In particular, node-1 transmission to node 2 fails in one of two cases.

1) Node 1 transmits while node 2 is already overhearing an ACK frame transmitted from nodes 4 to 5.
2) Sink node 4 acknowledges node 5 while the transmission of node 1 to node 2 is still in progress.

Typically, if node 1 transmits at t_1 a report to node 2, Δ units of time after a data transmission from 5 to 4 (i.e., $t_1 = t_5 + \Delta$), with $\Delta \in [\text{SIFS}, T_{\text{data}} + \text{SIFS} + T_{\text{ACK}}]$, the node-1 transmission fails. The ACK frame sent by node 4 to node 5 will overlap at node 2 with the data packet sent by node 1, and a collision is pronounced by node 2 at exactly $t_1 + \Delta'$, where $\Delta' = \max(T_{\text{data}} + \text{SIFS} - \Delta, 0)$.

This example is an illustration of the unforeseen collisions that may occur in multihop networks due to the well-known hidden-node problem [42]. This example shows that routing through the shortest path does not always lead to the most energy-efficient consumption since the HST routing method may lead to excessive energy wastage due to collisions. The ETX routing protocol alleviates the HST limitation since it is able to detect the aforementioned anomaly and therefore chooses node 7, instead of node 4, as a sink node for sensor node 5.



(a)

(b)

Fig. 5. Network topologies. (a) The ring topology. (b) The bus/star topology.

B. Evaluation Results of the Balanced Routing Scheme

In this section, we analyze the gain that can be introduced by our balanced routing scheme over the basic routing schemes. To achieve this, we use the simple networks shown in Fig. 5. These topologies are sufficient to reveal many of the general challenges.

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

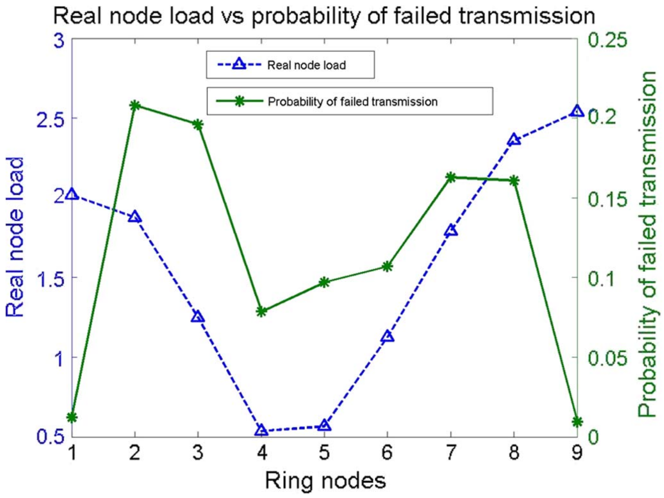


Fig. 6. Real node load versus the probability of failed transmission.

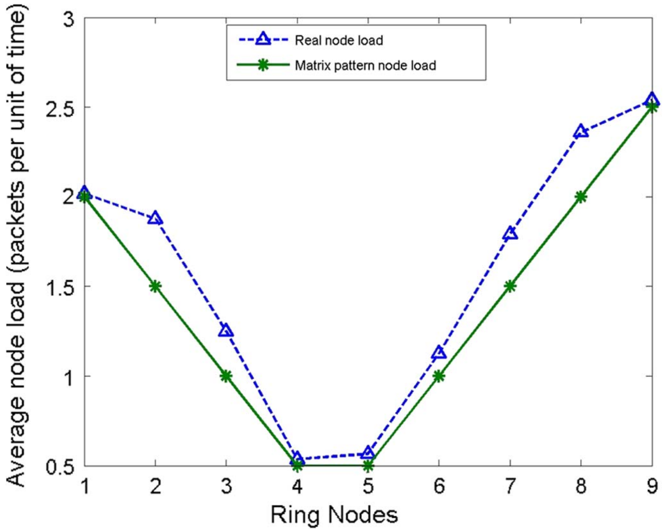


Fig. 7. Real node load versus matrix pattern node load.

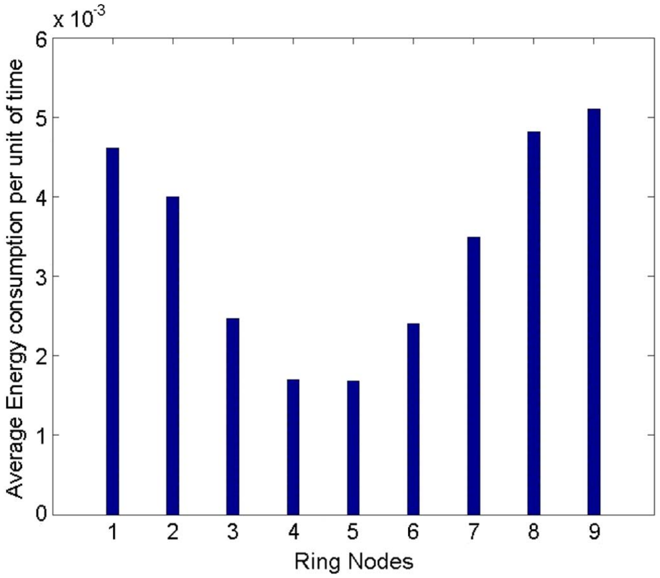


Fig. 8. Average energy consumption for each ring node.

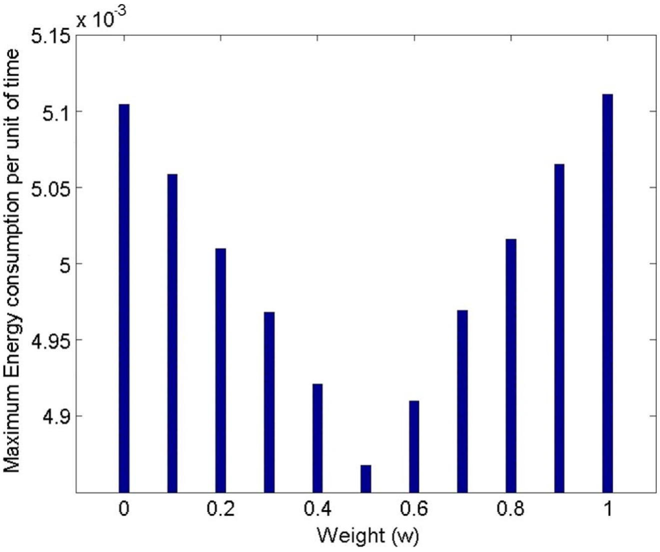


Fig. 9. Maximum sensor node consumption as a function of weight w.

These results are shown in Figs. 6–8. In this case, each sensor node periodically generates 0.5 report/s to the sink node. Fig. 6 shows that, going closer to the sink node, the probability of failed transmission progressively increases. This results in an increase in 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.

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. 8). 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 $1/(1-\beta(9,0)) = 1.001$ 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. 7). Node 8 needs, in average, to transmit a packet $1/(1-\beta(8,9)) = 1.191$ times to be correctly received by node 9. As such, node 8 suffers from much more retransmissions than node 9, even if the total number of transmitted packets per unit of time by node 8, i.e., $2 \times 1.191 = 2.382$, is smaller than that by node 9. As a result, node 9 more quickly depletes its energy than node 8, causing 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.

Fig. 9 shows the maximum sensor node consumption in the WSN (i.e., $\max_{u\in V} E(u)$) as a function of w. We can observe

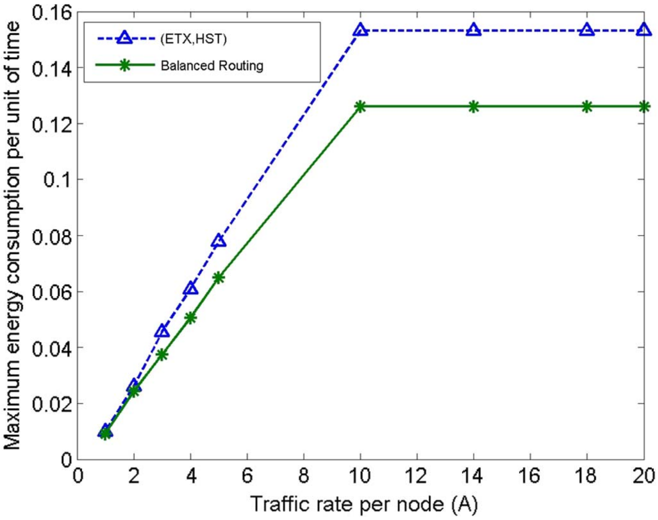


Fig. 10. Comparison of the energy consumption between our balanced routing scheme and the basic schemes (ETX and HST) in the ring topology.

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 nodes 1 and 9 have equivalent energy consumption.

Fig. 10 shows a comparison of the energy consumption with our routing scheme for 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. Fig. 10 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 and 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.

It is worth noting that the studied scenario represents the worst case regarding the gain that can be achieved by our proposed solution. As previously explained, the greediest nodes 1 and 9 do not suffer from the hidden-node problem, which limits their energy wastages. Adding hidden nodes to nodes 1 and 9 increases the gain achieved by our solution. In our study, the worst case is considered to show that, in spite of the disadvantageous conditions, our method always achieves sensible gain.

Let us now consider the network topology in Fig. 5(b). As before, each sensor node periodically reports its data with a rate of $A = 0.5$ report/s to one of the four sink nodes. According to the HST and ETX schemes, the sensor nodes always transmit according to the shortest path. Particularly, node 1 has to choose among the four possible paths. When our balanced routing scheme is considered, the traffic generated by node 1 is balanced among the four possible paths.

Table III reports the maximum sensor node consumption in the WSN for various values of vector $W = (w_1, w_2, w_3, w_4)$. We can again observe that the minimal consumption is obtained when the traffic generated by node 1 is fairly distributed among the four possible paths (i.e., $W = (0.25, 0.25, 0.25, 0.25)$).

TABLE III
MAXIMUM ENERGY CONSUMPTION FOR VARIOUS VALUES OF W

W	$Max\ E(u)$
$(1, 0, 0, 0)$	0.0036
$(0.5, 0, 0.5, 0)$	0.0032
$(0.4, 0.2, 0.2, 0.2)$	0.0031
$(0.1, 0.4, 0.1, 0.4)$	0.0031
$(0.2, 0.3, 0.2, 0.3)$	0.0030
$(0.1, 0.3, 0.3, 0.3)$	0.0030
$(0.25, 0.25, 0.25, 0.25)$	0.0029

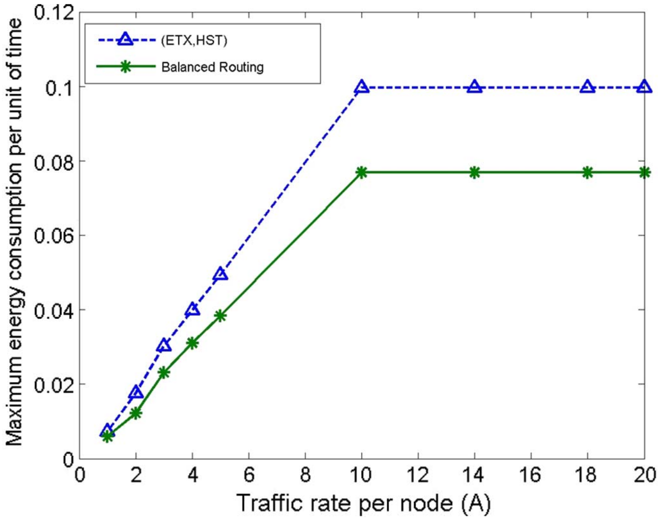


Fig. 11. Comparison of the energy consumption between our balanced routing scheme and the basic schemes (ETX and HST) in the bus/star topology.

TABLE IV
MAXIMUM ENERGY CONSUMPTION FOR VARIOUS VALUES OF W

W	$Max\ E(u)$
$(1, 0, 0, 0)$	0.0039
$(0.5, 0, 0.5, 0)$	0.0034
$(0.4, 0.2, 0.2, 0.2)$	0.0034
$(0.2, 0.3, 0.2, 0.3)$	0.0032
$(0.25, 0.25, 0.25, 0.25)$	0.0032
$(0.1, 0.4, 0.1, 0.4)$	0.0031
$(0.1, 0.3, 0.3, 0.3)$	0.0030

Fig. 11 shows the gain introduced by our routing schemes, compared with the basic schemes (HST and ETX), as a function of traffic rate A. We can observe that up to 15% of the energy conservation can be achieved by efficiently balancing the traffic inside the WSN.

Let us now suppose that node 5 more frequently reports its data to the sink node than the other sensor nodes in the WSN. For instance, assume that node 5 generates data at a rate of 0.8 report/s. In this case, the optimal energy consumption is obtained for $W = (0.1, 0.3, 0.3, 0.3)$, as shown in Table IV. Indeed, as path p_1 already handles more traffic, compared to paths p_2, p_3, and p_4, due to the excessive transmission of node 5, node 1 needs to transmit less traffic through p_1 to fairly balance the traffic inside the WSN. This example is introduced to show that the optimal routing configuration depends on not only the WSN topology but also the pattern of traffic exchanged between the sensor nodes.

To conclude this paper, let us compare our balanced routing with the basic schemes using the arbitrary meshed network in Fig. 12. We assume that only node 1 periodically generates packets to sink node S at a rate of 0.5 report/s. The remaining

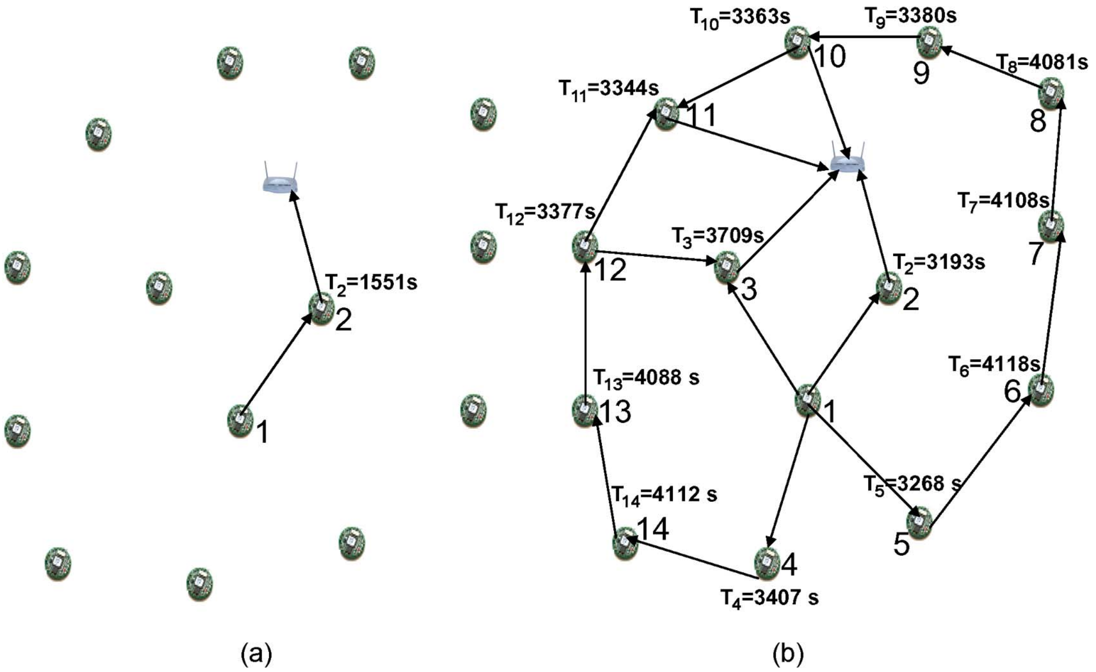


Fig. 12. Comparison of the energy consumption between our balanced routing scheme and the (ETX and HST) schemes in a meshed network topology.

sensor nodes participate only in the routing operations. Each sensor node has initial energy $E_{\text{init}} = 1$ J.

Fig. 12 shows the results provided when using the basic routing schemes and the balanced routing scheme. We can observe that the routes used in balanced routing are more spread out than those used in 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 twice as long as that of the basic schemes, which is 1551 s. This is a typical example of the gain introduced by the balanced routing, which avoids energy wastage due to useless nodes, i.e., sensor nodes that are not completely used before the network death, even if they still have available energy in their batteries.

VI. CONCLUSION

Operating on limited battery capacity imposes the use of energy-efficient protocols. The objective of such protocols can be formulated as follows: Minimize the total amount of energy consumed by the network in forwarding a packet between any pair of nodes. We have shown in this paper that such objective does not necessarily maximize the network lifetime since the network death can happen while several sensor nodes still have plenty of their capacities (i.e., the useless-node problem). The key idea is therefore to profit from the total available energy resource in the network before its death. To achieve this, we have proposed a load-balanced routing scheme. We have shown that this scheme better fits WSNs, compared with on-the-fly routing schemes in the context of continuous-monitoring applications. Moreover, considering load-balanced routing, we derived the optimal routing configuration that maximizes the network lifetime. To do so, we developed an analytical model for evaluating the energy consumption at the sensor nodes. The model captures the real behavior of WSNs since it takes into account the wasted energy due to idle listening, overhearing, and retransmissions. We have shown that significant improvements can be made by our routing scheme in terms of the network lifetime. Future research directions will be the adaptation of our preconfigured routing scheme to handle event-driven or on-demand reporting applications.

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