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Cross-Layer Design for Energy Conservation in Wireless Sensor Networks

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***Abstract*—Wireless sensor networks (WSNs) require energy-efficient protocols to improve the network lifetime. In this work, we adopt a cross-layer strategy that considers routing and MAC layers jointly. At the routing layer, we propose balancing the traffic through the WSN. We show that sending the traffic generated by each sensor node through multiple paths instead of using a single path allows significant energy conservation. On the other hand, at the MAC layer, we propose to control the retry limit of retransmissions over each wireless link. We show that by efficiently adjusting the retry limit for each link, further energy conservation can be achieved, improving thus the network lifetime. A new analytical model for the joint optimization system is complemented by simulations in order to quantitatively evaluate the benefits of our proposal.**

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

I. INTRODUCTION

In order to minimize the energy consumption, extensive research has been conducted in the literature on designing energy efficient protocols at each layer aside. Regarding the MAC layer [1], the most common way to conserve energy consists in putting the transceiver and the processor of a sensor node into a low power sleep state when it is unused. As such, the wasted energy due to collisions, overhearing and idle listening is reduced. On the other hand, works in [2] [3] addressed the problem at the network layer by proposing new routing solutions that take into account the sleep state of some nodes.

In this paper, we propose a cross-layer strategy to improve the network lifetime by considering jointly the MAC and routing layers.

First, at the network layer, 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. 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. 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 [4]. 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.

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.

Second, at the MAC layer, we propose to adjust the retry limit of retransmissions over each wireless link according to its property and the required packet delivery probability. Usually, the MAC layer retransmits a packet whose transmission was not successful up to m times, where m is the same retry limit for all the wireless links. Instead, we suggest using different retry limits for different wireless links. Specifically, we propose a retransmission control mechanism that determines the appropriate retry limit of each link such that the probability of packet delivery over that link exceeds a pre-specified threshold (target per-hop success probability).

As a main contribution of our work, we show that by judiciously allocating the retry limit to each link, further energy conservation (around 5%) can be achieved compared to the basic load balancing routing scheme.

In [4], we have introduced the load balanced routing concept. In this paper, we rather address the energy conservation problem from a cross layer perspective. By investigating the MAC and the routing layers together, we expect achieving additional energy conservation.

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 with the retry limit control. Results are provided in section IV, where we evaluate the performance of our proposal. The article concludes with a summary of our contributions.

II. MODEL AND PROBLEM DESCRIPTION

This section describes the system model used in our analysis and formulates the general problem statement. We use similar notations as in our previous work [4], and present some of the equations from the model in [4] with brief explanations here for this paper to be self-contained.

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., $H^-(v) = V \backslash H^+(v)$.

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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 [5]. 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. Joint Optimization

In this subsection, we approach the efficient routing of reports to the sink node by balancing the traffic inside the network and by judiciously allocating the retry limit to each link. Hereafter, we assume that there is a retry limit on the number of retransmissions at the MAC layer. Accordingly, the MAC protocol retransmits a packet until its successful delivery or the retry limit m is reached. Usually, the same retry limit m is assigned to all the wireless links. Instead, we suggest using different retry limits for different wireless links. Thus, we associate to each link $(u, v) \in E$ a retry limit $m(u, v)$. Our objective is to determine the appropriate retry limit for each link $(u, v) \in E$ such that the probability of packet delivery over that link $P_{succ}(u, v)$ exceeds the target per-hop success probability Q_s. In other words, we aim at determining the optimal retry limit for each link that minimizes the energy consumption subject to the delivery probability constraint.

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.

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. $E(u, p)$ 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, denoted by $E(u)$, can be therefore expressed as follows:

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

where $E_{idle}(u)$ is the average amount of energy consumed by node u per unit of time during its idle state. 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:

$$\begin{array}{l} \min\limits_{\mathcal{W}, M} \left(\max\limits_{u \in V} E(u) \right) \\ \text{subject to} \\ \sum\limits_{p \in P(v)} w(p) = 1 \\ \forall (u, v) \in E, P_{succ}(u, v) \geq Q_s \end{array} \tag{5}$$

where $M = (m(u, v))_{(u,v) \in E}$.

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 and by judiciously allocating the retry limit to each link. This is achieved by determining the optimal set of vectors $(W(v))_{v \in V} = \mathcal{W}$ and M 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 when our cross layer design is applied. Once $E(u)$ is obtained for each node $u \in V$, we run a simple algorithm to derive the optimal routing set $\mathcal{W}$ and the corresponding optimal retry limit vector M that resolve the optimization problem of (5). As shown in (3), we need to calculate the elements $E_{idle}(u)$ and $E(u, p)$ in order to get $E(u)$.

A. Calculation of $E(u,p)$: Joint Optimization of MAC and Routing layers

In this subsection, we extend the analytical model of [4] to support the retry limit constraint. To do so, we define $S_{p,u}$ as the probability that a node u on the path p relays to the sink node the packet sent by $source(p)$. It is worth noting that intermediate node u on p can properly relay a packet sent by $source(p)$ only if the packet is correctly delivered to u through the downstream links. Specifically, let $h_{p,u}$ denote the number of hops separating $source\,(p)$ from u, then $S_{p,u}$ is given by:

$$S_{p,u} = \begin{cases} 1 & \text{if} \quad h_{p,u} = 0, \\ \prod\limits_{k \in F_{p,u}} P_{succ}\,(k, \#k+1) & \text{otherwise,} \end{cases} \tag{6}$$

where $F_{p,u} = \{k \in p \mid 0 \leq h_{p,k} < h_{p,u}\}$ and $\#k+1$ denotes the next node relative to k on the path p. Let us now calculate the average amount of energy consumed by node u in reception or transmission due to the transmission of a packet through the path p: $E\,(u,p)$. Hence $E(u,p)$ can be written as follows:

$$E(u,p) = E(u,p)_{rec} + E(u,p)_{trans} \times 1\big|_{u \in p} \tag{7}$$

1) $E(u,p)_{rec}$:: It is the energy that u may consume due to the reception of signals, which may be or not 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 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:

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

  where $E^{rec}(data)$ is the energy consumed by a sensor node for the reception of a data packet. In turn, $\overline{N}_c(\#u-1, u)$ is the average number of retransmissions which can be calculated as follows.

  $$\begin{aligned}&\overline{N}_c(k, \#k+1) = \\ &\sum_{n=1}^{m(k,\#k+1)-1} \Big[n \times \beta_n(k, \#k+1)^{n-1} \times (1 - \beta_n(k, \#k+1)) \Big] \\ &\quad + m\,(k, \#k+1) \times \beta_{m(k,\#k+1)}(k, \#k+1)^{m(k,\#k+1)}\end{aligned} \tag{8}$$

  where $\beta_n(k, \#k+1)$ is the probability of unsuccessful transmission at the backoff stage n.
- 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.

However, each node $k \in Z(u,p)$ causes the above energy consumption at node u only if the packet passing through p is successfully delivered to k. Hence, the total amount of energy consumed by node u in the reception mode due to the transmission of a packet through the path p is given by:

$$E(u,p)_{rec} = \sum_{k \in Z(u,p)} S_{p,k} \left[\begin{array}{l} \overline{N}_c(k, \#k+1) \times E^{rec}(data) \\ +E^{rec}(ACK) \times 1\big|_{k \neq source(p)} \end{array} \right] \tag{9}$$

2) $E(u,p)_{trans}$:: 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:

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

  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 $u \neq source(p)$) to transmit an ACK frame to node $\#u-1$.

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

$$E(u,p)_{trans} = S_{p,u} \left[\begin{array}{l} \overline{N}_c(u, \#u+1) \times E^{trans}(data) \\ +E^{trans}(ACK) \times 1\big|_{u \neq source(p)} \end{array} \right] \tag{10}$$

It is easy to see that the only unknown variable that remains to calculate in order to get $E(u)$ is $\beta(k,n)$ and its elements $\beta_i(k,n)$, $\forall\ (k,n) \in V$ and $\forall\ 0 \leq i \leq m\,(k,n)$. These variables will be determined by means of simulations as it will be shown in the next section.

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

It is the energy consumed by node u in the idle state. It is the energy dissipated by node u when it is not transmitting neither receiving (i.e., while listening to the idle channel). $E_{idle}\,(u)$ can be expressed as follows:

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

where E^{idle} is the amount of energy consumed per unit of time by a sensor node in the idle state, 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.

IV. PERFORMANCE EVALUATION

In this section, we evaluate the efficiency of our proposed scheme. We first analyze the results regarding our balanced routing algorithm when there is no retry limit on the number of retransmissions at the MAC layer. Then, we investigate the effect of retransmission control at the MAC layer on the energy efficiency.

The results presented hereafter are derived using both analytical and simulation approaches. A simulation model has been developed using ns-2 [6] in order to calculate the probability of unsuccessful transmission on each link (i.e., β) according to the

Transmission range	12 m
Hearing Range	24 m
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

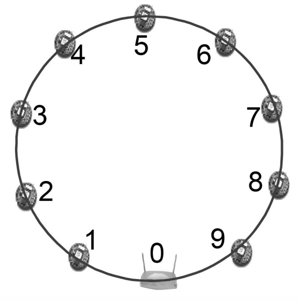


Fig. 1. The ring wireless sensor network.

routing configuration $\mathcal{W}$ and the retry limit vector M. Then, the analytical framework of section III is used to calculate the energy consumption at each node.

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 one of the existing sink nodes over several hops. 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.

A. Evaluation Results of the Balanced Routing Scheme

In this subsection, we analyze the gain that can be introduced by our balanced routing scheme without retry limit control. To achieve this, we use the simple networks shown in Fig. 1. In our study, we use the hop-based spanning trees (HST) [7] and ETX-based spanning trees (ETX) [8] 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 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.

Considering 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.

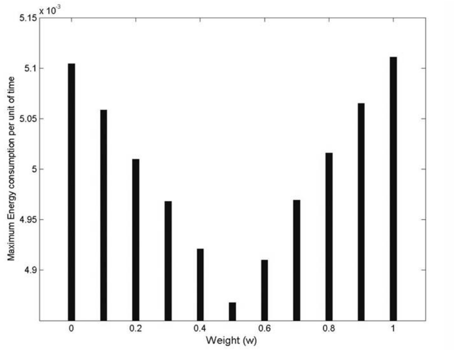


Fig. 2. The maximum sensor node consumption as a function of the weight w.

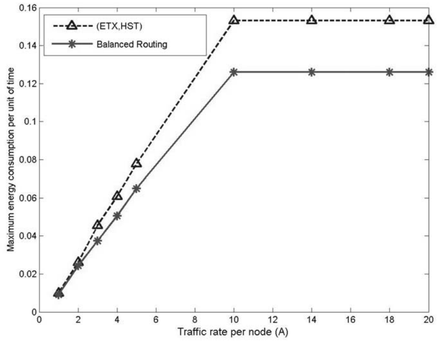


Fig. 3. Comparison of the energy consumption between our balanced routing scheme and the basic schemes (ETX & HST) in the ring topology.

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 2 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 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 3 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 3 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.

B. Results of Joint Optimization of MAC and Routing layers

Now, we evaluate the use of retry limit control in terms of energy efficiency. To achieve this, let us consider the simple WSN shown in Fig. 4. Sensor nodes 1 and 4 reports their data to sink nodes 2 and 4, respectively.

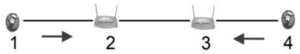


Fig. 4. Simple WSN Example.

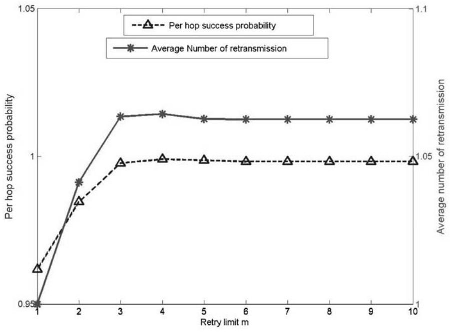


Fig. 5. The average number of retransmissions $\overline{N}_c$ vs. the per-hop success probability P_{succ}.

Figure 5 shows the average number of retransmissions $\overline{N}_c$ and the per-hop success probability P_{succ} as function of the retry limit m. As expected, the per-hop success probability P_{succ} increases with m since more opportunity is given to each packet to be correctly delivered. In this case, where A is set equal to 1 packet/s, P_{succ} reaches its maximum ($\simeq 1$) as soon as m exceeds 3. Similarly, increasing m increases the average number of retransmission $\overline{N}_c$. When m surpasses 3, $\overline{N}_c$ becomes constant since all generated packets are successfully delivered.

Figure 6 shows the average number of successfully received packets per unit of time (i.e., goodput) and the probability of unsuccessful transmission attempt β as function of the retry limit m, in the saturated regime. Figure 6 reveals that the goodput increases with m. When m exceeds 7, the goodput becomes constant. In this range of m, the maximum goodput is reached. However, rising m reduces also β since packets are provided more opportunity to be successfully transmitted.

In order to get more insight regarding the energy conservation achieved by the use of the retry limit allocation, let us revisit the simple example of Fig. 1, where all the nodes transmit through the shortest path at rate a 0.9 report/s. Specifically, assume that node 5 transmits always through node 6.

Figures 7 and 8 compare the energy consumption per node as well as the achieved per-hop success probability, respectively, for three various values of the vector M. In the first configuration of M, denoted Optimal configuration, the retry limit is allocated such that all the links satisfy the desired per-hop success probability $Q_s = 95\%$. In other words, for each link (u, v), $m(u, v)$ takes the minimum value that achieves the desired per-hop success probability Q_s. The second configuration of M used in our experiment is called Under-Optimal configuration. In this case, the achieved per-hop success probability over each link is less than Q_s. The last configuration of M considered in our experiments is called Over-Optimal configuration. In this case, the achieved per-hop success probability over all the links is much greater than Q_s.

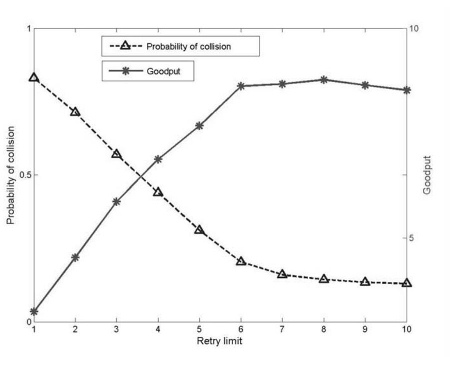


Fig. 6. Collision probability vs. the average number of successfully received packets per unit of time A_{sat}.

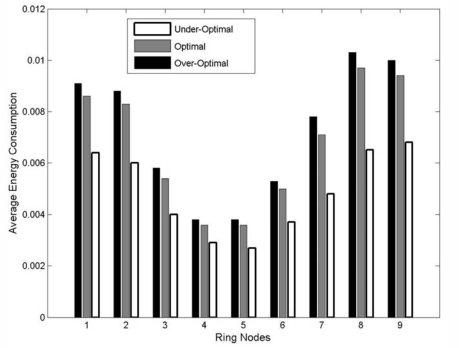


Fig. 7. Comparison of the energy consumption per node for the Under-Optimal, Optimal and Over-Optimal configurations.

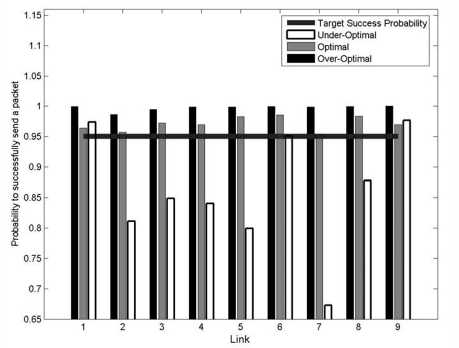


Fig. 8. The per-hop success probability achieved by the Under-Optimal, Optimal and Over-Optimal configurations.

As expected, Fig. 7 shows that the Under-Optimal configuration achieves the lowest energy consumption but the worst per-hop success probability (see Fig. 8). The desired reliability is not satisfied. In contrast, the Over-Optimal configuration achieves the best per-hop success probability and the highest energy consumption. On the other hand, using the Optimal configuration reduces the energy consumption compared to the Over-Optimal configuration while respecting the target per-hop success probability at each link.

Figure 9 shows the maximum sensor node consumption in the WSN as a function of w. For each weight w, the optimal configuration M is considered. Similar to the basic case of balanced routing scheme without retry limit control, we can observe that the minimal energy consumption is obtained when the traffic is fairly shared between the two ring sides.

Figures 10 shows the gain introduced by the retry limit

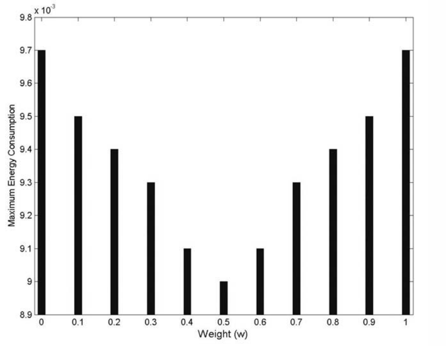


Fig. 9. The maximum sensor node consumption as a function of w. For each w, the Optimal configuration is considered.

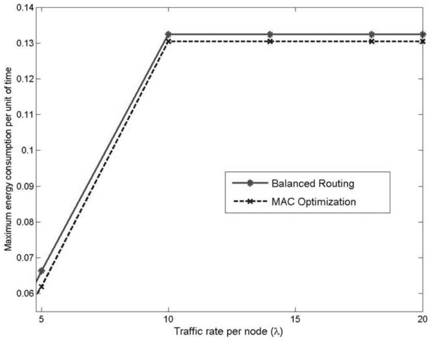
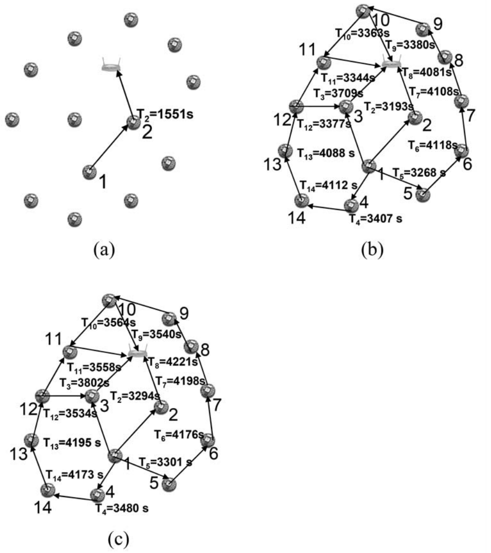


Fig. 10. The gain introduced by our balanced routing scheme with retry limit control compared to the case when the balanced routing scheme is applied without any retry limit control: Ring topology.

control mechanism over the basic balanced routing case when the ring topology is used. We can see that controlling the retry limit enables further energy conservation compared to the basic balanced routing scheme.

To conclude this paper, let us compare the network lifetime when the HST routing, the basic balanced routing and the control retry limit aware balanced routing are used in the arbitrary mesh network of Fig. 11. We assume that only node 1 generates packets periodically to the sink node S at a rate 0.5 report/s. The remaining sensor nodes participate only in the routing operations. Each sensor node has initial energy $E_{init} = 1J$. Two main conclusions can be drawn based on these results:

- First, balanced routing enables significant improvement of the network lifetime compared to classic HST routing. We can observe that the routes used in balanced routing are more spread out than those of the HST routing. The balanced routing benefits from the total available energy resource in the network, whereas the HST scheme uses only a small subset of the sensor nodes' energies. The network lifetime obtained by our basic balanced routing scheme is 3193 s, which is more than two times as long as 1551 s of the HST scheme.
- Second, enabling the control retry limit mechanism achieves further improvement in the network lifetime as shown in Fig. 11.



(a)

(b)

(c)

Fig. 11. Comparison of the network lifetime when the HST routing, the basic balanced routing and the control retry limit aware balanced routing are used in an arbitrary mesh network.

V. CONCLUSION

Conceiving energy-efficient protocols is a critical issue in energy-constrained wireless sensor networks. In this paper, we proposed a cross-layer design that considers the joint optimization of MAC and routing layers. With regard to the routing layer, 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, we propose sending the traffic generated by each sensor node through multiple paths instead of using a single path. On the other hand, at the MAC layer, we proposed to efficiently allocate the retry limit for each wireless link such that the delivery probability satisfies a target per-hop success probability. We developed an analytical model to quantitatively evaluate the actual energy consumption at the sensor nodes according to a given routing configuration. Our model captures the real behavior of WSNs by considering the wasted energy due to idle listening, overhearing and retransmissions. We showed that by efficiently balancing the traffic inside the network and by judiciously allocating the retry limit to each link, further energy conservation is achieved.

REFERENCES

[1] K. Kredo II, P. Mohapatra, *Medium access control in wireless sensor networks*, Computer Networks, Vol. 51, Issue 4, pp. 961–994, March 2007.
[2] R. C. Shah, H. M. Rabaey, *Energy aware routing for low energy ad hoc sensor networks*, IEEE WCNC, Orlando, FL, USA, March 2002.
[3] J. Chang and L. Tassiulas, *Maximum lifetime routing in wireless sensor networks*, IEEE/ACM Transactions on Networking, Vol. 12, Issue 4, pp. 609–619, August 2004.
[4] F. Bouabdallah, N. Bouabdallah, and R. Boutaba, *Load-Balanced Routing Scheme for Energy-Efficient Wireless Sensor Networks*, IEEE GLOBECOM 2008, New Orleans, LA, USA, December 2008.
[5] *Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications*, ISO/IEC IEEE 802.11 Standard, 1999.
[6] The Network Simulator—ns-2. [Online]. Available: http://www.isi.edu/nsnam/ns.
[7] D. B. Johnson, D. A. Maltz and J. Broch, *DSR : The dynamic source routing protocol for multihop wireless ad hoc networks*, in Ad Hoc Networking, edited by Charles E. Perkins, Chapter 5, pp. 139–172, Addison-Wesley, 2001.
[8] D. Couto, D. Aguayo, J. Bicket and R. Morris, *A high-Throughput Path Metric for Multi-Hop Wireless Routing*, in Proc. ACM MOBICOM, 2003.