WETX: A Weighted Expected Transmission Routing Metric for Diversity in Wireless Sensor Networks

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***Abstract*—The expected number of transmission (ETX) metric represents the link quality for links in Wireless Sensor Networks (WSNs) that can vary for different radios. To adapt to these differences, radio diversity is a recent explored solution for wireless sensor networks. In this paper, we show that in a multi radio environment it is not enough to only choose a next hop based on link qualities as with the popular ETX metric. In such an environment, the cost of transmission and reception is radio specific, which needs to be considered when making a routing decision. Instead, we propose a scheme that explores the diversity in ETX over radios and therefore enables a node to choose an energy efficient link by considering a new metric $WETX$, for weighted ETX. We show by both analysis and simulation that our proposal can improve the energy consumption in a network and extend the network lifetime with up of 60%.**

Keywords: Wireless sensor networks; energy efficiency; ETX; $MIMO$; $SISO$

I. INTRODUCTION

Sensor nodes are characterized by having limited energy resources, which requires them to perform multi-hop communication in order to share information instead of using more costly direct communications [1]. With multi-hop communication a node uses less power to transmit data towards an intermediary node, used as a next hop to reach a collecting point further away. We refer to this collection point as the base station (BS) or a sink node. When sending data towards a BS, a node should choose its next hop so that the energy cost of delivering the packet to the BS is minimized.

Radio link qualities are affected by the environment and hence differ from one link to another. Sending a packet over a bad link requires more packet retransmissions until the packet is successfully received and hence has direct effect on energy consumption. The radio link qualities can fluctuate due to changes in the environment or external radio interference. State-of-the-art data collection protocols [2] are therefore designed to react to changes in network connectivity and repair their routing state accordingly. However, unless multiple alternative routes exist in the network, connection losses are unavoidable. Even if alternative routes exist, the re-routed traffic may cause network congestion and increased packet loss that can lead to more energy consumption.

In WSNs, using only one radio for communication may not effectively use the energy of nodes because of variation in link qualities that may only be present in this one radio for a specific environment. Therefore, the use of multiple radios [3] becomes beneficial in order to adapt to the fluctuation of link quality present at the different radios. Based on the possibility of equipping sensor nodes with multiple radios, we explore the diversity of link qualities from different radios to enhance the energy consumption over links. Specifically, in this paper, we show that in a multi radio environment it is not enough to only choose a next hop based on link qualities as with the popular ETX metric. In a multi radio environment, the cost of transmission and reception is radio specific, which needs to be considered when routing. We propose to do this with a new routing metric which weights the classic link quality metric ETX by the energy cost. By doing so, nodes decrease their energy consumption by avoiding bad links which leads to more retransmissions. We refer to this new metric as $WETX$(Weighted ETX) and show how this improves the energy efficiency of routing with up to 60% over using one single radio.

The rest of the paper is organized as follows. Section II reviews related work, Section III describes the system model and Section IV shows our proposed strategy. Section V shows the analytical results, while VI shows the simulation results of

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our new metric before we conclude in Section VII.

II. RELATED WORK

The use of multiple radios in data communication systems is a common technique referred to as multiple input multiple output ($MIMO$). We refer hereafter to some of recent works related to LAN for $MIMO$.

An example of recent wireless LAN standards utilizing $MIMO$ for improve range and data rates is $IEEE.802.11n$. However, the energy consumption of the currently available equipments is usually considered to be unacceptable for battery powered wireless sensor networks.

Implementation and analysis of range-diverse multiple radio communication are explored and compared with the state-of-the-art in [4] and [5]. In particular, [4] utilizes two radios, which differ in RF output power and energy consumed per bit. [5] discusses the use of sophisticated policies to decide when to switch to a different radio interfaces.

In the literature, a collection of metrics have been proposed to enhance routing performance. An interesting survey of routing metric in wireless mesh networks can be found in [6]. We review some of them in what follows, those of which are related to our work.

The authors in [7] proposed a routing metric for single-radio single-channel wireless networks, called the cumulative expected transmission count (ETX), which takes into account the link quality factor.

The Weighted Cumulative Expected Transmission Time ($WCETT$) routing metric [8] was designed specifically for multi-radio multi-channel wireless networks. It calculates the Expected Transmission Time (ETT) of each hop and makes the routing decision based on the Cumulative ETT ($CETT$) and the channel diversity of each candidate route, which is characterized indirectly by the sum of $ETTs$ of hops operating at the Bottleneck frequency channel ($BETT$). The tradeoff between $CETT$ and $BETT$ is indicated by a weight β:

$$WCETT = (1-\beta) \times CETT + \beta \times BETT \tag{1}$$

The Metric of Interference and Channel switching cost (MIC) was designed to support load-balanced routing and to consider intra-flow and inter-flow interference, in addition to being isotonic [9]. The metric for a path p is defined as follows:

$$MIC(p) = \alpha \times \sum_{l \in p} IRU_l + \sum_{l \in p} CSC_i \tag{2}$$

where p represents a path in the network, l is a link in p, the parameter i is a node in the path, and α is a tunable parameter that enables the variance of weight given to the two components of MIC. The first component, IRU, considers inter-flow interference, while the second component, CSC, represents the level of intra-flow interference. The prior metrics are designed for mesh networks and there is no consideration of energy conservation.

Cooperative or virtual $MIMO$ scheme is used in WSNs applications where nodes group together to form virtual antenna arrays and transmit data cooperatively. An example of such schemes is discussed in [10] and [11]. They improve the reliability of links with employing antenna diversity with specific algorithms for their selection.

Our proposed scheme is different from the prior existing architectures as it uses a novel metric related to both the link quality and the energy cost to decide which radio and forwarder to use. To our best knowledge, we are the first proposing an energy efficient routing metric for multi radio WSNs.

III. SYSTEM MODEL

We assume a WSN consists of N sensors deployed in a field to continuously monitor an environment. We denote the i-th sensor node by n_i and the corresponding set of sensor nodes $S = \{n_1, n_2, ..., n_N\}$ where $|S| = N$. We make the following assumptions about sensor nodes and the network:

- Sensor nodes and the BS are all stationary after the deployment.
- Nodes with single input single output ($SISO$) are equipped with a single radio r_1 or r_2, while nodes with the $MIMO$ are equipped with multiple radios (in our case r_1 and r_2). We denote $E^{tx}_{r_1}$, $E^{tx}_{r_2}$ the energy of transmitting a packet for r_1 and r_2, respectively. Similarly, we denote $E^{rx}_{r_1}$, $E^{rx}_{r_2}$ the energy of reception a packet for r_1 and r_2, respectively.
- We denote the set of n_i neighbors by Ne_i. Each node n_i can reach its neighbor n_j ($n_j \in Ne_i$) with $E^{tx}_{r_1}$ or $E^{tx}_{r_2}$ for r_1 and r_2, respectively.
- Links are symmetric [12], i.e., if $n_i \in Ne_j$, then $n_j \in Ne_i$. Links are not perfect and they are characterized by a PRR (packet reception ratio), which reflects the link quality. The PRR is defined as the probability of a packet reception over a link. We assume that the PRR during the deployment is constant. We denote PRR_{r_1} and PRR_{r_2} the PRR of links for r_1 and r_2, respectively. We assume that the PRR of the link is symmetric. If n_i have a PRR $PRR_{r_1}(l)$ to its neighbor $n_j \in Ne_i$, then n_j have also the same $PRR_{r_1}(l)$ to its $n_i \in Ne_j$ using r_1.
- We focus in this work on collection applications, in which nodes use a collection tree protocol to send data toward a BS according to some routing metric. The metric in $SISO$ mode is the $ETX = \frac{1}{PRR}$ metric. The ETX [7] metric represents the expected number of transmission a node needs in order to successfully deliver a packet. It is to be noted that the state-of-the-art collection tree protocol (CTP) [13], [14] uses ETX to forward data.
- Nodes use infinite retransmissions to improve their packet delivery rate to the BS.

The objective of our proposed protocol is to reduce the energy consumption and extend the network lifetime when routing with multiple radios.

IV. PROPOSED STRATEGY

Having multiple radios on a node enables it to choose the radio with the least cost when forwarding a packet. Thus, it will avoid an excessive number of retransmissions that can consume a considerable amount of energy if a radios link is bad. A simple version of such a routing metric would be to always let a node choose the radio with highest PRR (or lowest ETX) when forwarding. We refer to this strategy as R_{etx}. Furthermore, we refer to R_{r_1} and R_{r_2}, as the routing strategies when using only radio r_1 or r_2 for routing, respectively.

Fig. 1 illustrates the benefits of using R_{etx} over of R_{r_1} and R_{r2}. The figure shows the PRR of links between a number of nodes with two radios: r_1 and r_2. When routing with R_{etx}, the link of radio r_1 will be used to communicate between nodes n_1 and n_2, while the link r_2 will be used to communicate between the nodes n_2 and n_3. Hence the packet reliability is definitely better than if we were to route with R_{r_1} and R_{r_2}.

The benefit of using R_{etx} scheme becomes more interesting when some of the links in r_1 are much better than r_2 and vice versa, so that nodes will be able to use the best links available for each hop. Thus, it is more suitable in heterogenous environments where different radios are affected by different environmental characteristic, such as obstructions, local fading, or interference on a specific frequency. Specifically in industrial environments where radio interference sources may change position and obstructions to the line-of-sight between nodes are usually quite dynamic.

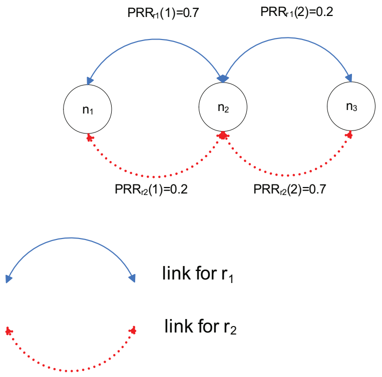

Fig. 1. PRR of the links in both radios r_1 and r_2.

A. Weighted ETX

To improve the energy consumption, we propose an optimized routing metric: a weighted ETX ($WETX$). We call the routing protocol using $WETX$ metric for R_{wetx}. In contrary to R_{etx}, R_{wetx} combines the transmission and reception costs of the radios with the ETX. $WETX$ is defined as the following.

$$WETX(j,k) = min(E^{tx}_{r_i} \times ETX_{r_i}(j,k) + E^{rx}_{r_i})$$

where $i = 1, 2$ and $n_j \in Ne_k$. For a link (j,k), $WETX(j,k)$ reflects the expected energy consumed when transmitting a packet over this link. It is important to note that $(E^{tx}_{r_i}, E^{rx}_{r_i})$ and ETX_{r_i} (the ETX at r_i), for $i = 1, 2$, are locally available at a node and hence do not incur any extra acquisition overhead.

At each node, R_{wetx} chooses the radio that has the minimum $WETX$ metric. Then, it uses this metric to select the next hop node that minimizes the sum of $WETX$ along the path to the final destination, when forwarding the packets.

To illustrate our idea, we refer to the same example shown in Fig. 1 where we let $(E^{tx}_{r_1}, E^{rx}_{r_1}) = (4, 1)$ energy units and $(E^{tx}_{r_2}, E^{rx}_{r_2}) = (1, 1)$ energy units. We believe that the transmision/reception cost of radios can be highly different in low power radio technologies, such as the case in Zigbee and bluetooth [15]. With $WETX$ each node will estimate the expected energy cost for each link and hence it will choose the link with the least energy cost. For the link $(1, 2)$, in the example, nodes n_1 and n_2 both estimate the cost $WETX(1, 2) = 4/0.7 + 1 = 6.71$ when using the link of r_1, and the cost $WETX(1, 2) = 6$ when using the link of r_2. Similarly, we have for the links $(2, 3)$, at nodes n_2 and n_3, $WETX(2, 3) = 21$ when choosing the link of r_1, $WETX(2, 3) = 2.4$, when choosing the link of r_2. Consequently, n_1 and n_2 choose r_2 as $6 < 6.71$, while n_2 and n_3 choose r_2 as $2.4 < 21$. Thus the energy gain for the link $(1, 2)$ when using R_{wetx} compared to R_{etx} is $1 - 6/6.71 = 10.58\%$.

The authors in [3] show that radio diversity can be used as a solution in order to overcome to the problem of mixture of environments that can be present in the same application. An example of such scenario may be tracking elderly for health care applications, where patients can change environments (inside a building, amusement park, etc). In such an application our proposal may be used to support two kinds of traffic in the network: traffic that needs to be delivered reliably and not. Indeed the position of patients, for example, might be monitored reliably for quick intervention in case of emergency. However other patient measurements (such as temperature) might not necessarily be sent reliably. Consequently an energy efficient way for delivery could be used in order to extend the network lifetime.

TABLE I
ROUTING STRATEGIES.

R_{r_i}	Routing using $SISO$ on $r_i, i = 1, 2$.
R_{etx}	Routing using $MIMO$ with the ETX metric.
R_{wetx}	Routing using $MIMO$ with the $WETX$ metric.

V. ANALYTICAL RESULTS

In order to compare the different strategies, we derive an analytical model of their energy consumptions in a chain topology. We consider a chain or a path of L links rooted at a BS (see Fig. 2). Note that the topology considered in this analysis is similar to the one in SAFESPOT project [16], where a large number of nodes may be deployed along a roadside for traffic monitoring and safety. In Fig. 2, l is the number of the link in the chain and it represents the link between nodes n_l and n_{l+1}. In this analysis, we assume the sender consumes energy for the (re)transmitted packets, the receiver consumes energy for the successful data received, and we consider a free energy consumption at the BS as it is not energy constrained. We calculate the energy spent by a node at level l of the chain, $1 \leqslant l \leqslant L$, as E_{r_i}, E_{etx}, and E_{wetx}, for each strategy R_{r_i}, R_{etx}, and R_{wetx},$i = 1, 2$, respectively as follows.

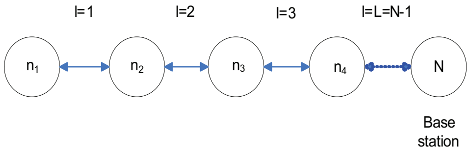

Fig. 2. Path of L links rooted at the BS.

$$E_{r_i}(l) = \begin{cases} \frac{E^{tx}_{r_i}}{PRR_{r_i}(l)} + E^{rx}_{r_i}, & \text{if } l < L \\ \frac{E^{tx}_{r_i}}{PRR_{r_i}(l)}, & \text{if } l = L \end{cases} \tag{3}$$

$$E_{etx}(l) = \begin{cases} \frac{E^{tx}_{r_1}}{PRR_{r_1}(l)} + E^{rx}_{r_1}, & \text{if } PRR_{r_1}(l) > PRR_{r_2}(l) \\ & \text{and if } l < L \\ \frac{E^{tx}_{r_1}}{PRR_{r_1}(l)}, & \text{if } PRR_{r_1}(l) > PRR_{r_2}(l) \\ & \text{and if } l = L \\ \frac{E^{tx}_{r_2}}{PRR_{r_2}(l)} + E^{rx}_{r_1}, & \text{if } PRR_{r_1}(l) \leq PRR_{r_2}(l) \\ & \text{and if } l < L \\ \frac{E^{tx}_{r_2}}{PRR_{r_2}(l)}, & \text{if } PRR_{r_1}(l) \leq PRR_{r_2}(l) \\ & \text{and if } l = L \end{cases} \tag{4}$$

$$E_{wetx}(l) = \begin{cases} min(\frac{E^{tx}_{r_1}}{PRR_{r_1}(l)} + E^{rx}_{r_1}, & \text{if } l < L \\ \quad \frac{E^{tx}_{r_2}}{PRR_{r_2}(l)} + E^{rx}_{r_2}) & \\ min(\frac{E^{tx}_{r_1}}{PRR_{r_1}(l)}, \frac{E^{tx}_{r_2}}{PRR_{r_2}(l)}), & \text{if } l = L \end{cases} \tag{5}$$

We then calculate the total energy consumed for all packets generated by nodes TE_{r_i}, TE_{etx} and TE_{wetx} for each strategy R_{r_i}, R_{etx} and R_{wetx}, respectively as follows.

$$TE_{r_i} = \sum_{l=1}^{l=L} l \times (E_{r_i}(l)) \tag{6}$$

$$TE_{wetx} = \sum_{l=1}^{l=L} l \times (E_{etx}(l)) \tag{7}$$

$$TE_{wetx} = \sum_{l=1}^{l=L} l \times (E_{wetx}(l)) \tag{8}$$

Fig. 3 shows the average energy consumed in the network with the different strategies with L. The results show that the performance of R_{r_1} compared to R_{r_2} depends on the links quality PRR (the energy consumption of R_{r_1} and R_{r_2} crosses each other with an increasing of L due to the PRR being a uniform random distribution at each radio). However, R_{etx} and R_{wetx} performs basically equal and better than both R_{r_1} and R_{r_2}. The superiority observed in R_{etx} and R_{wetx} (they perform equal in this figure) compared to R_{r_1} and R_{r_2} is due to the fact of avoiding bad links in R_{etx} and R_{wetx} schemes, respectively.

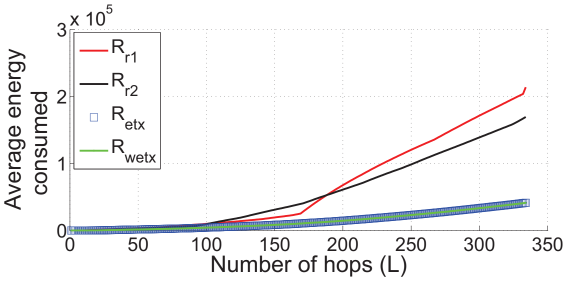

Fig. 3. Average energy consumed over the network with varying L.

To see the difference between R_{etx} and R_{wetx}, we vary the transmission and the reception cost for one of the radios, for example r_1. Fig. 4 shows the average energy consumed over the network with varying $E^{tx}_{r_1}$. The results shows that as the $E^{tx}_{r_1}$ increases, the energy consumption observed for R_{r_1} and R_{etx} increases. Indeed, the energy consumption of R_{r_1} is directly related to $E^{tx}_{r_1}$. On the other hand, E_{etx} increases because R_{etx} chooses the best PRR between r_1 and r_2, which may be chosen from the links of r_1. However, we also observe that R_{wetx} converges to use the link of r_2 in high $E^{tx}_{r_1}$ because the cost of transmitting from links of r_1 becomes very high. The results show that R_{wetx} considers the whole energy cost to transmit packets, and therefore it consumes less energy. The same behavior is observed when varying $E^{rx}_{r_1}$(see Fig. 5).

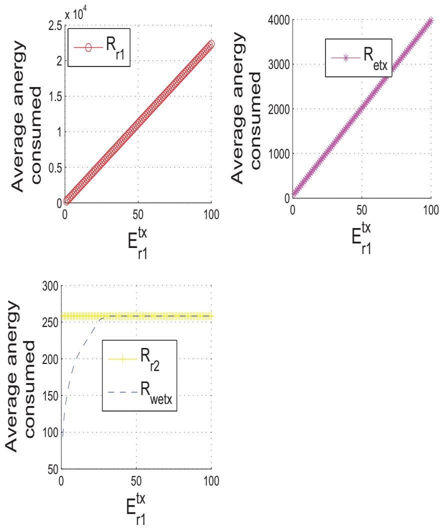

Fig. 4. Average energy consumed over the network with varying E^{tx}_{r1}.

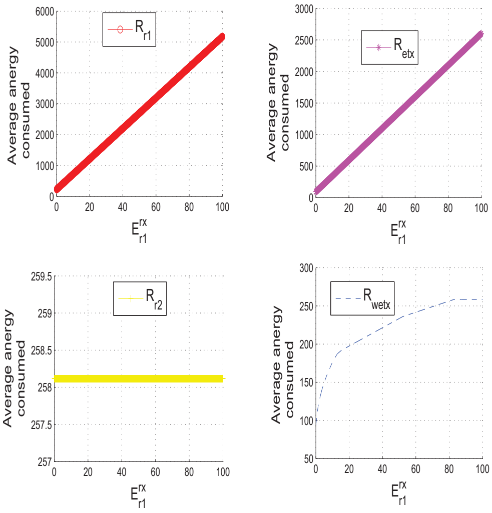

Fig. 5. Average energy consumed over the network with varying $E_{r_1}^{rx}$.

Fig. 6 shows the average energy consumed with varying both $L = \{1, ..., 500\}$ and $E_{r_1}^{tx} = \{1, ..., 5\}$. Fig. 7 shows the energy consumed ratio of R_{wetx} over R_{etx} and $R_{r_i}, i = 1, 2$ when varying both L and $E_{r_1}^{tx}$. The energy consumed ratio of R_{wetx} over R_{r_i} is $ratio_{R_{ri}} = \frac{TE_{wetx}}{TE_{r_i}}, i = 1, 2$, while the energy consumed ratio of R_{wetx} over R_{etx} is $ratio_{R_{etx}} = \frac{TE_{wetx}}{TE_{etx}}$, and the energy gain $g(ratio) = 1 - ratio$, where $ratio \in \{ratio_{R_i}, ratio_{R_{etx}}\}, i = 1, 2$. We observe that for $E_{r_1}^{tx} = 1$, R_{wetx} performs better than R_{r_1} and R_{r_2} and equal to R_{wetx}. The variation shown in Fig. 6 and Fig. 7 is due to variation in the random PRR for r_1 and r_2, as have already been shown in Fig. 3. We also observe that the bigger E_{r1}^{tx} is, the smaller ratio over both (R_{etx}, R_{r_1}), and the bigger ratio over R_{r_2}. The maximum gain ratio observed is around 98% over R_{r_2}, when $E_{r_1}^{tx} = 1$. This gain decreases as $E_{r_1}^{tx}$ increases, as shown in Fig. 4. However, the gain ratio is around 80% and 40% for R_{etx} and R_{r_1}, respectively, when $E_{r_1}^{tx} = 5$ energy unit. These gain ratios increase as the $E_{r_1}^{tx}$ increases, as shown in Fig. 4. Note that R_{wetx} achieves an increased energy saving over R_{etx} with the number of hops because at each link in the chain there is an additional energy benefit, as have already shown in the example of Fig. 1.

In the proposition 5.1 hereafter we infer the performance of R_{wetx} in a point to point communication, which is a generalization of collection communication.

Proposition 5.1: in a general topology, if a node n_i has a packet to send to the n_j $(i, j = \{1, ..., N\}$ and $n_i, n_j \in S)$, then $TE_{wetx} <= TE_{etx}$, and $TE_{wetx} <= TE_{r_i}$, $i = 1, 2$. In other worlds, R_{wetx} performs always better than R_{r_i}, $i = 1, 2$ and R_{etx}.

Proof: we prove this proposition by reductio ad absurdum for $TE_{wetx} <= TE_{etx}$ and the demonstration is the same for $TE_{wetx} <= TE_{r_i}, i = 1, 2$. We assume $TE_{wetx} > TE_{etx}$. We denote $S_{path} = \{path_k\}, k \geq 1$ the set of all possible paths from n_i to the n_j. We denote $path_{wetx}$ and $path_{etx}$ the paths of the packet toward the n_j when using R_{wetx} and R_{etx}, respectively. By definition of R_{wetx}, the node n_i will choose the path that has the minimum energy consumption to the n_j, so $path_{wetx} = min(\{path_k\}), k \geq 1$. Therefore, as $path_{etx} \in S_{path}$, then $TE_{wetx} \leq TE_{etx}$, which is contradictory to the first assumption. ■

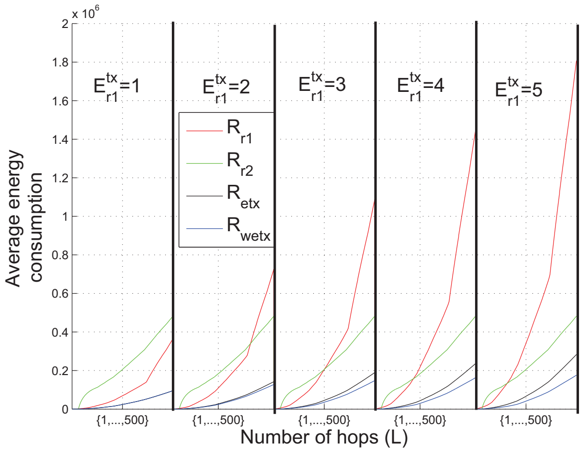

Fig. 6. Average energy consumed over the network with varying $E_{r_1}^{tx}$ and L.

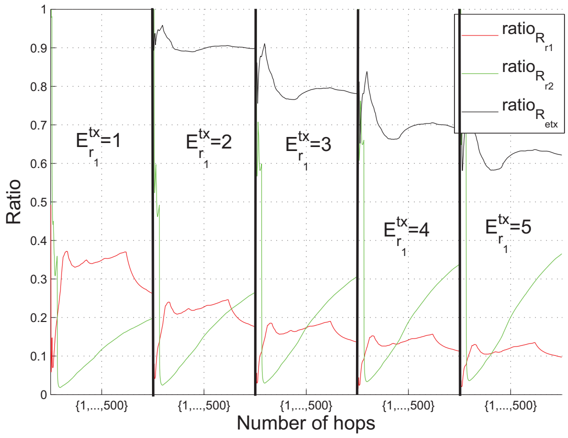

Fig. 7. Energy consumed ratio of R_{wetx} over R_{ri} and R_{etx} with varying $E_{r_1}^{tx}$ and L.

VI. SIMULATION RESULTS

To validate our results, we build an event driven simulator in Matlab, which simulates the different strategies. We consider a continuous monitoring application, in which data is generated periodically at a predefined frequency. In our simulation, we assume an underlying Low Power Listening LPL [17], [18] link layer. We denote the average energy consumption when a packet is transmitted successfully, when the packet transmission failed, and when the packet is received for each radio

$i = 1, 2$ by $E^{stx}_{r_i}$, $E^{ftx}_{r_i}$, and $E^{rx}_{r_i}$, respectively, as follows:

$$E^{stx}_{r_i} = (LPL/2 \times I^{tx}_{r_i} + delay \times I^{rx}_{r_i}) \times V \qquad (9)$$

$$E^{ftx}_{r_i} = LPL \times I^{tx}_{r_i} \times V \qquad (10)$$

$$E^{rx}_{r_i} = (sample/2 + delay) \times I^{rx}_{r_i} \times V \qquad (11)$$

Based on equations (9) and (10), the average energy consumed when transmitting a packet over a link with $PRR_{r_i}(l)$ is

$$\mathrm{E}^{tx}_{r_i}(l) = E^{ftx}_{r_i} \times (\frac{1}{PRR_{r_i}(l)} - 1) + E^{stx}_{r_i} + E^{rx}_{r_i},\ i = 1, 2 \qquad (12)$$

where LPL is the low power listening interval, $I^{tx}_{r_i}$ is the radios current draw when transmitting, $I^{rx}_{r_i}$ is the radios current draw when receiving, V is the voltage, $sample$ is the time it takes for a node to check the channel for activity, and $delay$ is a constant time, in which the radio is kept on after reception or transmission.

The simulation parameters are presented in Tab. II together with additional radio parameters. It is to be noted that the parameters of the radio reflects the characteristics of our hardware platform $Opal$ [3] supporting two radios r_1 and r_2 for $RF230$ [19] and $RF212$ [20], respectively. The following results are simulated in a grid topology of 4×4 nodes.

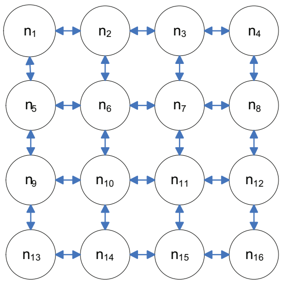

Fig. 8. Grid topology of 16 nodes.

TABLE II
SIMULATION PARAMETERS.

Parameter	**value**
$delay$	20ms
$sample$	50ms
LPL	random in $[100, 1000]$ ms
$I^{tx}_{r_1}$	24 mA
$I^{tx}_{r_2}$	16mA
$I^{rx}_{r_1}$	9mA
$I^{rx}_{r_2}$	15mA
packet delay for r_1	20ms
packet delay for r_2	20ms
V	3 volts
Packet transmission period	10s

Fig. 9 shows the network lifetime defined as when the first node dies, versus different initial energy of nodes in point to point communication. In this scenario, there is only one source (node n_{16}) and one destination (node n_1). We used different seed for each run with all the protocols and used random LPL for nodes. The results obtained are averaged for 50 times and they show clearly the benefit of using the $WETX$ metric in WSNs and confirms the superiority in the network lifetime of R_{wetx} over R_{etx}, R_{r_1} and R_{r_2}.

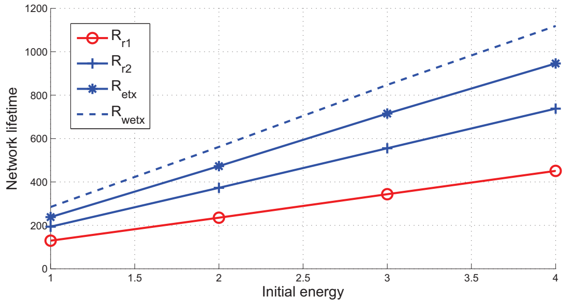

Fig. 9. Network lifetime when node n_{16} is periodically generating data.

We use the same configuration as before but in this scenario all the nodes in the network are involved in the periodic data reporting toward the BS. Fig. 10 shows the network lifetime with different initial energy of nodes and Fig. 11 shows the remaining energy when the first node dies. As expected, the figure shows that with R_{wetx} there is an effective use of energy. The gain ratio increases for higher initial energy of nodes. Form Fig. 10 we observe that the maximum ratio gain observed of the network lifetime for R_{wetx} over R_{etx}, R_{r_2} and R_{r_1} is around 16%, 34% and 60%, respectively. Note that Fig. 11 shows that R_{wetx} achieves a small gain, around 1.5%, in remaining energy compared to R_{etx} because the remaining energy is taken when the the firs node dies. Therefore, as R_{wetx} lives longer than R_{etx}, it consumes an additional energy before the first node dies. Similar results for different topologies are obtained but we leave them out due to space limitation.

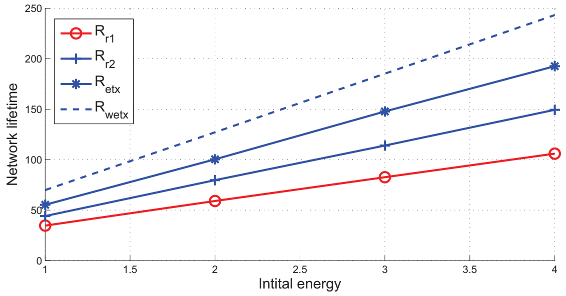

Fig. 10. Network lifetime when all nodes are periodically generating data.

VII. CONCLUSIONS AND FUTURE WORK

In this paper, we explored how to minimize the energy consumption when using multiple radios for routing in WSNs. We proposed a weighted metric $WETX$, which represents the expected energy consumed when transmitting a packet over a

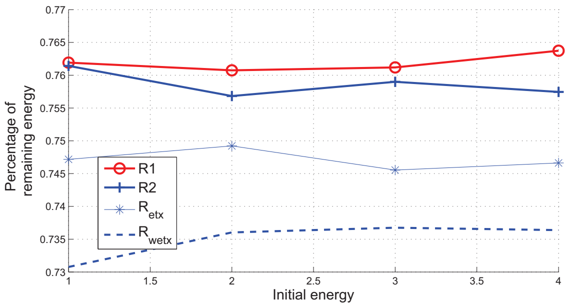

Fig. 11. Remaining energy when all nodes are periodically generating data.

link, and compared it with the state-of-the-art ETX metric for single and multiple radios. We developed an analytical model which we used to compare the different strategies and prove the benefits of our scheme in any topology. We also built an event driven simulator for the different strategies to validate the performance of the proposed scheme.

In the future, we plan to explore a higher number of radios, implement a load balancing metric that uses topology-based LPL [21] in top of $WETX$ to extend the network lifetime. We also plan to validate the results in our testbed, which supports nodes with dual radios.

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