

Energy Optimization based Path Selection Algorithm for IEEE 802.11s Wireless Mesh Networks

Martin M. Mhlanga, Thomas O. Olwal
Council for Scientific and Industrial Research,
Meraka Institute, Wireless Computing and Networking
Pretoria, South Africa
{mmhlanga, tolwal}@csir.co.za

Murimo B Mutanga, Mathew O. Adigun
University of Zululand
Department of Computer Science
Centre of Excellence, KZN
{bethelmutanga, profmatthewo}@gmail.com

Abstract—It is everyone’s dream to have network connectivity anywhere at all times. This dream can only be realized provided there are feasible solutions that are put in place for the next generation of wireless works. Wireless Mesh Networks (WMNs) configures itself and because of its cost effectiveness, it is therefore seen as a solution for the next generation networks. However, this field still has a lot of limitations and the main constrain is that the energy of the nodes is very limited, especially when the network is deployed in rural areas where electricity is a scares resource. This research therefore presents an energy optimization based path selection algorithm for IEEE 802.11s WMNs which is aimed at addressing the above mentioned constrains. As a newly proposed standard specifically designed for WMN, the IEEE 802.11s does not consider energy conservation as a priority in its protocol. As a result, the main goal for this research is that paths with enough energy for transmission in the network must be selected when transmitting packets. Our simulation results obtained from the experiments prove that there is a substantial increase with regard to the network’s operational time when energy is considered by the protocol used in IEEE 802.11s.

Wireless Mesh Networks; Hybrid Wireless Mesh Protocol; Energy-Aware, Optimization, Path Selection Algorithm; Path Selection Metric; IEEE 802.11s

I. INTRODUCTION

It is a dream for all people to have a network connection anywhere at all times. It is therefore imperative to have such a dream be realized for feasible solutions to the next generation wireless networking be implemented. A remarkable research study has been done in WMNs and in general ad hoc networks that led to important research contributions which include a lot of research in wireless networking protocols and theoretical capacity bounds. However, in WMNs there are still quite a number of important issues for instance in routing that are partially addressed or not addressed at all, e.g., scalability, network capacity, security and energy awareness [1]. In order to address these routing issues effectively, our work concentrates on routing mechanism executed in layer-2. Such a routing mechanism is called a mesh path selection and forwarding [2]. In layer-2 routing, a default and mandatory routing protocol called Hybrid Wireless Mesh Routing Protocol (HWMP) was designed by earlier researchers specifically for WMNs. The HWMP protocol is a combination of AODV and tree-based routing. The AODV protocol is designed to work on the network layer with the use of IP

addresses and hop count is used as a routing metric [2]. The HWMP protocol uses RM-AODV which works on the data link layer using MAC addresses and a radio-aware routing metric for path selection [1]. Another optional protocol that has been proposed is a layer-2 adaptation of OLSR called RA-OLSR [1], [2]. The OLSR protocol is proactive and AODV is reactive and when both protocols are combined it produces a hybrid protocol. However, HWMP does not regard energy conservation as a priority for WMN. This is proven by the fact that there is very little attention towards addressing energy-awareness problems in HWMP [3]. This is mainly caused by the assumption that the backbone routers for wireless mesh networks have been treated as if they have electric power supply and are also stationary and as a result are alleged not to have energy constraints [15]. However, when considering a situation where the mesh network is deployed in rural areas, the wireless mesh nodes would run out of energy in spite of being stationary. A WMN uses multiple nodes which are also referred to as multi hops. So as a multi hop it uses intermediate nodes to relay packets from the source to the destination. Because each node is responsible for the transmission of packets to other nodes in the network that also reduces the amount of energy used when transmitting. This is because of the shorter distance provided by the intermediate nodes in the network. However, the energy exhaustion of nodes when routing packets is the biggest intimidation to the necessary survivability of the network. As a result, this research proposes an energy-aware and optimizing path selection algorithm to be incorporated in the hybrid wireless mesh protocol (HWMP).

The rest of this paper is organized as follows: Section II and III discuss and analyze energy efficient routing protocols energy conserving routing metrics. Section IV, we present the algorithm design that we have adopted for this work. Section V presents random graphs that have been generated to analyze performance evaluation. Section VI concludes the paper.

II. ENERGY-AWARE AND EFFICIENT ROUTING PROTOCOLS.

Routing protocols with no means of optimizing energy have a tendency of using the same path for a longer period [5], [16]. The effect of using it for a longer period is that the energy of the nodes along the chosen path may be quickly exhausted. If the node’s energy is quickly exhausted that may result in the network being partitioned affecting the information delivery even though there might still be enough energy to some of the nodes. Therefore, energy should always be considered during

the design of a wireless mesh routing protocol. The amount of energy that is being consumed by the network also determines how long the network can work [17], [3]. In this research our findings suggest that the most valuable metric for routing protocol performance under the IEEE 802.11s is energy-awareness for network survivability. This consideration is more focused especially to networks that are to be deployed in rural areas. Energy-awareness routing guarantees that nodes with low energy in the network stay alive. A probability function in energy-aware routing is used as a means of choosing sub-optimal paths. This technique is also dependent on the amount of energy consumed in each path in the network [4]. The work in [5] states that choosing the shortest path might not be the best option as it may cause an energy dissipation of nodes in that path. An alternative to the use of a minimum path, multiple paths are available to route from the source node to the intended destination node. For the network lifetime to be prolonged, one among the many available paths is used with a certain probability. To advance the energy efficiency of an energy-unaware path localized rerouting techniques were proposed and presented in [4]. The above presented energy efficient routing protocol techniques can perform well in terms of energy conservation. To achieve that, neighborhood knowledge at nodes is required. The work presented in [6] shows that substantial amount of resources can be consumed in dynamic networks to update and gather the information for the node's neighbors.

III. ENERGY CONSERVING ROUTING METRICS

For a packet to decide on which path to choose whenever given multiple paths, [7] use the following metrics:

A. Residual Energy

Energy-aware routing regards the energy status of a node as the most imperative metric to be considered when selecting a route. The cost function applied for calculating the diversity of the approaches, which uses residual energy is:

$$f_i C_i^t = \frac{1}{C_i^t} \quad (1)$$

where f_i is the cost function and C_i^t is the remaining energy of node i at time t . In [8] proves that the design of the cost function has similar metric even though estimated by different functions. To eliminate the energy starving nodes from route selection, a Min-Max Battery Capacity Routing (MMBCR) was proposed. The work in [9] adopted the idea of using shortest path first until a certain amount of energy has been consumed before choosing an algorithm that has a power-aware. The battery capacity of the nodes determines how the Conditional MMBCR (CMMBCR) routing algorithm behaves.

B. Energy Drain Rate

The work in [10] presented an energy drain rate which represents the rate at which energy is being consumed, when network provisioning is increased with monitoring. In order to avoid node's failures that are caused by battery outage in a route and the lifetime of a node is known, the traffic passing through the node can be deviated. The research in [11] was

conducted to design a routing metric that is meant for predicting the lifetime of a battery. An exponential weighted moving average method was used to calculate the energy drain rate. For each second this method gives an approximation of the amount of energy dissipated. The fraction between the residual battery power (RBP) and drain rate (DR) represents the cost function at a node as follows:

$$C = \frac{RBP}{DR} \quad (2)$$

An analogue to MMBCR is the max-min algorithm which is the Minimum Drain Rate (MDR) mechanism responsible for the implementation for the cost function presented above. Other algorithms that share the same philosophy and objectives with CMMBR are found in the work done by [11] which provides an extension of the MDR algorithm to Conditional MDR.

C. Local Routing

In the work done in [7] and [12], reactive routing algorithms are denoted as global where all nodes take part when searching for a path, at the same time the source node and the intended destination node makes the decision to conclude. For a node to take part in the route searching process [12] gives authorization and as a result a broadcast is made to all the node about the decision making process. A criterion also exists which was designed to be used by the Local Energy-Aware Routing (LEAR) algorithm. This criterion is designed to provide a profile for the energy of the nodes where the intermediate nodes that are willing or reluctant to reply to route or to forward data traffic are defined. For a routing protocol performance to be improved it is therefore imperative to avoid exchanging control information regularly by applying the technique of shifting the accountability for reacting to changes in the energy budget of a node.

D. Transmission Power Model

Given a network graph, a routing algorithm basically entails searching for the best possible route where a vertex and an edge signifies a node and a wireless link respectively connecting two end nodes which are in the vicinity of each other's radio transmission range [13]. If the transmission power of a radio in a node is adjustable, the direct transmission range is adjustable together with the intermediate nodes. An increase in the communication range occurs when the transmission power is stronger while the number of hops are being reduced (hop count) to the destination. A lot of research has been conducted on transmission power adjustment in topology control for WMNs [14] and [15]. The main objective for this approach is to make sure that the network topology is kept connected while using minimal power. Transmission power control based energy efficient routing protocols are good in proving routes that uses minimal transmission power from a source to a destination node.

IV. ALGORITHM DESIGN AND DEVELOPMENT

As stated in the literature that all nodes that are used frequently along discovered paths to provide connectivity for longer durations may lead to a more graceful degradation of the network resulting in network partitioning. To help solve the problem of network partitioning, we therefore proposed an energy optimization based path selection algorithm for the IEEE 802.11s HWMP. The proposed algorithm will result in an unbiased energy spending among the nodes which also maximizes the network lifespan. When given multiple paths to choose from during the routing process, choose the path that will help prolong the network lifetime. In order to ensure that networks with low-energy nodes are kept alive. The HWMP protocol does not use the one good path it has discovered for every transmission; instead a set of good paths are kept in its routing table and one good path is chosen among the many available paths based on a probabilistic fashion. Therefore, different paths are used at different times instead of using the single path for all the transmissions in the network and in return energy depletion in certain nodes is avoided to avoid network partitioning. The protocol has the following three phases which have been used in [7]:

A. The Setup Phase

The connection is initiated by the source node and before the request could be sent, the energy cost field is set to zero as:

$$Cost(n_S) = 0 \quad (3)$$

where n_S and n_D represents the source node and the destination node respectively. The request is forwarded by the intermediate node to its immediate neighbors, which satisfies the conditions:

$$\begin{aligned} d(n_i, n_S) &\geq d(n_j, n_S) \\ d(n_i, n_D) &\leq d(n_j, n_D) \end{aligned} \quad (4)$$

where $d(n_i, n_j)$ is the distance calculated between n_i and n_j . After receiving the request, the energy metric is then calculated by the neighbor node and added to the total energy cost of the path:

$$J_{n_j, n_i} = Cost(n_i) + Metric(n_j, n_i) \quad (5)$$

It should be noted that paths with high costs are discarded while paths with low costs are added to the forwarding denoted as FT_j of n_j .

$$FT_j = \{i \mid J_{n_j, n_i} \leq \alpha \cdot (\min J_{n_j, n_k})\}, \quad (6)$$

where α is a constant and $\min J_{n_j, n_k}$ is the minimum energy costs in joules between node j and node k . The probability of choosing paths with low costs is denoted as P_{n_j, n_i} while the costs are inversely proportional to the probability as given by:

$$P_{n_j, n_i} = \frac{1J_{n_j, n_i}}{\sum_{k \in FT_j} 1J_{n_j, n_k}} \quad (7)$$

In order for a packet to get to the intended destination the standard energy cost is computed by node n_j using the neighbors in the forwarding table and the associated cost is given by:

$$Cost(n_j) = \sum_{i \in FT_j} P_{n_j, n_i} J_{n_j, n_i} \quad (8)$$

It should be noted that the average cost $Cost(n_j)$ is sent in the ‘‘Cost’’ field of the request packet and the intermediate nodes forward it towards the source node as in equation (4).

B. Path Selection Algorithm.

When considering a network graph that is modeled as $G(N, A)$, where all the set of nodes are represented by N while the set of all directed links (i, j) , are represented by A , with $i, j \in N$. Let S_i represent all the set of nodes that can be reached by node i using a dynamic transmission range of power level P . We can assume that if $j \in S_i$ then link (i, j) exists. Assume node i is assigned an initial battery energy level denoted as E_i . Suppose $Q_i^{(c)}$ is the generation information rate at node i that belongs to commodity $c \in C$, where all the set of commodities are represented by C . A commodity refers to goods that flow over the entire network originating from sources and destinations that are different. The transmission energy required node i to its neighboring node j is denoted by e_{ij} . The information transmission rate of commodity c from node i to node j is called the flow $q_{ij}^{(c)}$ [16] and [17]. Let the aggregate flows over the entire network be Q_i and q_{ij} for all commodities as given by:

$$Q_i = \sum_{c \in C} Q_i^{(c)}, \quad (9)$$

and

$$q_{ij} = \sum_{c \in C} q_{ij}^{(c)}. \quad (10)$$

For every c commodity, information is generated at the set of origin nodes as given by $O^{(c)}$:

$$\text{i.e., } O^c = \{i \mid Q_i^{(c)} > 0, i \in N\}, \quad (11)$$

and a set of destination nodes D^c that is responsible in making sure that any node is reached for a successful transfer of commodity c . For a given flow $q = \{q_{ij}\}$, the lifetime of node i depends on the initial energy denoted as E_i , the transmission energy between link i and j denoted as e_{ij} and the flow q_{ij} . Such relationship is defined as follows:

$$T_i(q) = \frac{E_i}{\sum_{j \in S_i} e_{ij} \sum_{c \in C} q_{ij}^{(c)}} \quad (12)$$

Under flow q model, the system lifetime can therefore be defined as the time it takes for the first battery to run out of energy among all nodes in N . Because of its equivalence, the system lifetime can also be presented as the minimum lifetime over all nodes, i.e.,

$$T_{\text{sys}}(q) = \min_{i \in N} T_i(q) \quad (13)$$

$$\min_{i \in N} \frac{E_i}{\sum_{j \in S_i} e_{ij} \sum_{c \in C} q_{ij}^{(c)}}$$

Our aim therefore is to find the flow that can help in maximizing the network lifespan under the conditions of flow conservation. Maximizing the lifetime of a network has been made clear in [5], [16] and can be invoked as:

$$\text{Maximize } T_{\text{sys}}(q) = \min_{i \in N} \frac{E_i}{\sum_{j \in S_i} e_{ij} \sum_{c \in C} q_{ij}^{(c)}} \quad (14)$$

$$\text{subject to } q_{ji}^{(c)} \geq 0, \forall i \in N, \forall j \in S_i, \forall c \in C,$$

$$\sum_{j: i \in S_j} q_{ji}^{(c)} + Q_i^{(c)} = \sum_{k \in S_i} q_{ik}^{(c)}, \forall i \in N - D^{(c)}, \forall c \in C$$

The c commodity of flow conservation condition at node i applies to each commodity separately and can be formulated as linear programming problem. Consequently the following is the linear programming problem which is equivalent to the problem of maximizing the network lifetime. This modeling applies if and only if the generation rate of information $Q_i^{(c)}$ is given at the set of origin nodes $O^{(c)}$ and the set of destination nodes $D^{(c)}$ for each commodity c .

$$\text{Maximize } T$$

$$\text{subject to } \hat{q}_{ji}^{(c)} \geq 0, \forall i \in N, \forall j \in S_i, \forall c \in C,$$

$$\sum_{j \in S_i} e_{ij} \sum_{c \in C} \hat{q}_{ij}^{(c)} \leq E_i, \forall i \in N, \quad (15)$$

$$\sum_{j: i \in S_j} \hat{q}_{ji}^{(c)} + TQ_i^{(c)} = \sum_{k \in S_i} \hat{q}_{ik}^{(c)}, \forall i \in N - D^{(c)}, \forall c \in C$$

where $\hat{q}_{ij}^{(c)} = Tq_{ij}^{(c)}$ represents the quantity of data of commodity c transmitted from node i to node j until time T . An energy-aware link cost metric for path selection (EAPM) was used to find a cost function that will provide the best possible path to help maximize the network lifetime. The metric is an extremely significant module of the protocol because the protocol uses it to evaluate routes. The EAPM

metric denoted as J_{ij} was presented in [5], [7] and [16] and is adopted for this research to use it for routes evaluation before choosing a path. The metric is represented as:

$$J_{ij} = \frac{e_{ij}^{x_1} E_i^{x_3}}{R_i^{x_2}}. \quad (16)$$

When the energy-aware link cost metric J_{ij} is calculated three parameters should be considered for link (i, j) . Where, e_{ij} is the amount of transmission energy consumed over the link, E_i represents the initial energy of node i , R_i is the residual energy at the transmitting node i . Parameters x_1 , x_2 and x_3 represent weighting factors that are non-negative for each variable in equation (16). The EAPM metric will be evaluated and compared with three other metrics which have been widely used in WMNs. The following are the names of the metrics that EAPM will be evaluated against: ETX, Airtime Link Metric, and the last metric is the Multi-metric. The airtime link metric is a way of calculating the amount of channel resources consumed when transmitting a frame over a particular wireless link. The proposed Multi-metric consist of interference and mesh point's transmitting capability in wireless environment based on residual bandwidth, Frame Delivery Ratio (FDR), and mesh point's load, with a huge overhead. The ETX metric, or Expected Transmission Count, is a measure of the quality of a path between two nodes in a wireless packet data network. It is used extensively in mesh networking algorithms

V. SIMULATION AND RESULTS

In this section, graphs for the results are generated to evaluate how the proposed energy optimization based path selection algorithm performs. NS-2 was used to simulate the algorithm and a 1500m x 1500m grid was used as the field configurations with 81 static mesh nodes ranging from 9 to 81 nodes. The range of up to 250m can be covered by each node in the network. The carrier frequency that was used is 2.4 GHz. An assumption is made that the omni-directional antennas used are placed at a height of 1.5m higher than a node and possessing a 0dB gain. The protocol used in this simulation is HWMP which is a default protocol for WMNs. A fixed number of packet sizes (512-bytes) are used by the experiments with a changing of pause times. Fixed nodes and a packet rate of 4 packets per seconds are used in this simulation. The maximum run time for the simulation was set to be 15 minutes (900 seconds) of simulated time. Constant bit rate (CBR) was used as a traffic source to generate the data traffic for this experiment. The following performance metrics are considered for this experiment and their analysis:

A. Network Lifetime

The work done in [15] presents the network lifetime as the time it takes for the network to be active before the first node disconnects. Each of the network instance's lifetimes is considered. We had to vary the number of nodes in the network

in order to run the tests for the network lifetime. Figure 1 below, shows the network topology. Figure 2 shows a comparison of the number of nodes alive versus the simulation time in a network of 81 nodes for the four metrics, simulated with 30 traffic connections. A successful transmission of 1024 packets was sent with 512 bytes of data. This serves as a proof that EAPM has more network lifetime compared to the other metrics evaluated in this experiment. This is due to the fact that EAPM considers energy when selecting an optimal path while the other metrics considers issues like the mesh point's transmitting capability in a wireless mesh environment.

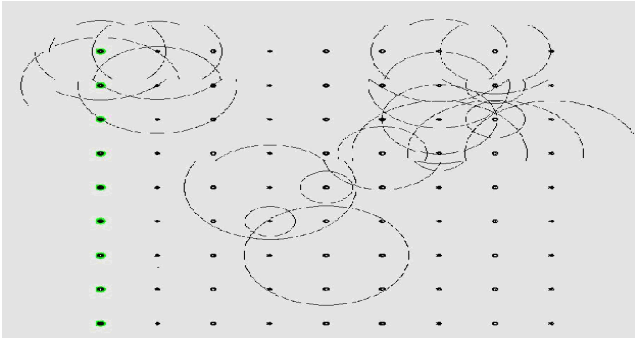


Figure 1: Network Topology of HWMP during RREQ and RREP

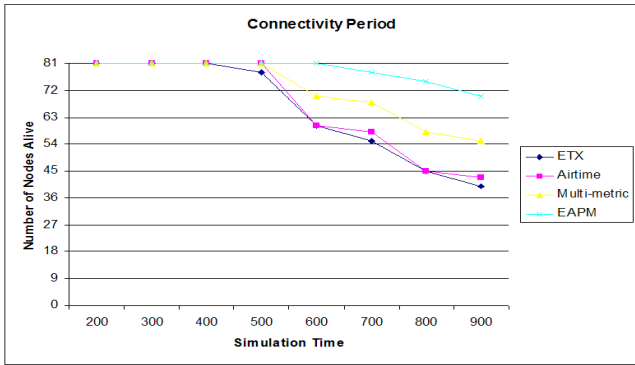


Figure 2: Performance comparisons of the number of nodes alive versus simulation time (sec) for a 81-nodes network

B. Energy Efficiency

The main purpose for this experiment is to figure out how best our algorithm can serve energy in the network. We denote energy efficiency as ξ and it is given by:

$$\xi = \sum_{i=1}^n \left\{ \left[\frac{J_{pi}}{S_{pi} J_{ij}} \right] / n \right\} \quad (17)$$

where J_{pi} denotes the energy path costs, S_{pi} denotes the selectivity of the path pi and the link cost metric denoted as J_{ij} . n is the total number of nodes in the network. After the execution of the algorithm $\xi = 0$ where full energy is used for transmission by each node, it is regarded as the worst case scenario. The network saves more energy if the energy

efficiency value is higher. It is impossible to reduce transmission energy to a 0 value and in practice the value of $\xi \leq 1$ stands even though the reality says ξ cannot be equal to 1, when you consider maintaining connectivity in the network.

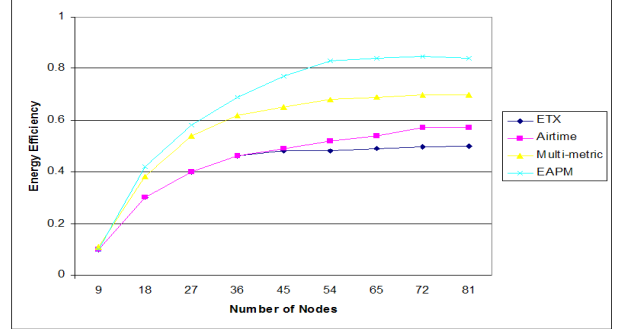


Figure 3: Performance comparison of energy efficiency versus the number of nodes based on the four evaluated metrics.

Figure 3 depicts a comparison of energy efficiency versus the number of nodes based on the four evaluated metrics. When the network has fewer nodes e.g., 9 to 18 nodes, the network doesn't perform well in terms of energy efficiency as the average energy efficiency is below 0.5. This implies that less than 50% of the energy is saved. This kind of connectivity is caused in sparsely populated networks. However, as the number of nodes increases in the network, the energy efficiency rises to 50% and above for most of the networks as shown by the simulation graph. This is due to the fact that the network nodes are densely populated and as a result nodes lessen their transmission energy by a larger margin which ensures connectivity to the most nearest neighbors.

C. Packet Delivery Ratio

The purpose of this experiment was to determine the capabilities of the network to deliver the data packets that are sent from source to the intended destination node [14]. All the packets that are generated and delivered successfully by the nodes are measured to determine the percentage of PDR. If the network has a total failure then PDR is at 0% and if PDR is at 100% then it means all the data packets in the network were successfully delivered. This experiment shows that a network topology that is too dense, the average node degree is high resulting in multiple routes which helps reduce network partitioning and ensuring the ability to deliver packets to their destination [14]. A node degree refers to the number of connections or edges the node has to other nodes. The proposed EAPM metric provides better data delivery rate ratio than Multi-metric, Airtime Link Metric and ETX.

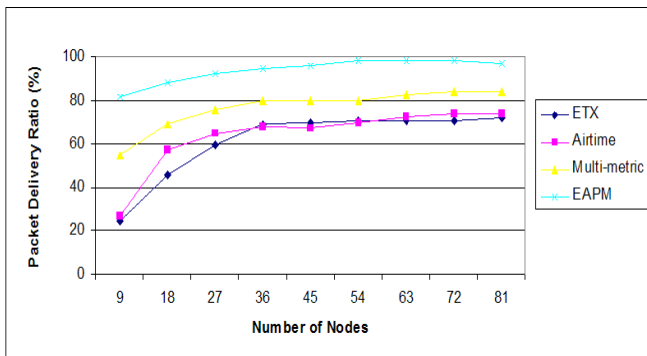


Figure 4: Performance comparison of packet delivery ratio versus number of nodes of all four metrics

VI. CONCLUSION AND FUTURE WORK

Considering a Wireless Mesh Networks (WMNs) to be deployed in power constrained rural areas, the energy used by the wireless nodes is a very limited resource that should be used efficiently. When routing packets from the source to the destination node, energy exhaustion of nodes is what remains to be the main threat to the basic availability of the network. The main goal of this research therefore is to minimize the total transmission energy consumed for a packet to reach the intended destination. However, the usual approach of selecting the shortest path when routing packets may drain out the energy of the nodes along the chosen paths. Using this kind of an approach may halt the delivery information in the long run causing network partitioning even though there are network nodes with enough energy for transmission. Therefore we introduced an energy optimization based path selection algorithm for IEEE 802.11s WMNs that will maximize the network lifetime. The proposed energy optimization based path selection algorithm provides a balanced energy spending among nodes which therefore maximizes the network lifetime. The balanced energy spending will reduce the amount of workload which is usually given to other nodes which are unfairly burdened to support many packet-relaying functions. A simulation was used to test the performance of our solution in this research. A test-bed implementation using the MERAKA test-bed should be conducted as future work. We also plan to do a cross-layer routing approach (layer-2 and layer-3) instead of the one layer that we are focusing on for this work. We also plan to consider doing an experiment on packet delivery ratio.

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