Energy Aware Routing in IEEE 802.11s Wireless Mesh Networks

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Keywords: IEEE 802.11s WMNs, HWMP, Airtime Link Metric, Energy Aware Routing, QoS.

Abstract: Wireless Mesh Networking is a continuous growing technology that can be used used for several application scenarios, such as military tactical operations, etc. in next generation wireless networks. The IEEE 802.11s Standard defines the procedures that wireless nodes follow in order to interconnect and create a Wireless Local Area Network (WLAN) mesh network. It, also, defines the routing protocol and the metric that are used by a IEEE 802.11s mesh network to route data. However, although the energy consumption of mesh nodes is a crucial parameter for the network's lifetime in specific purpose operations (e.g. military and health) the default metric proposed by the standard doesn 't take into account the energy of the nodes. In this paper, a new energy - aware routing metric for the IEEE 802.11s mesh networks has been implemented. Simulation results showed that the proposed metric prolongs the lifetime of a WMN in comparison with the the default metric used by IEEE 802.11s Standard while causing a little higher total delay in the network.

1 INTRODUCTION

Wireless Mesh networking is a promising solution for next generation wireless networks that envisages supplementing wired infrastructure with a wireless backbone for providing Internet connectivity to mobile nodes (MNs) or users in residential areas and offices, and could be called the Web-in-the-sky (Nandiraju et al., 2007). Wireless Mesh Networks (WMNs) attract more and more the attention of the research community due to their low cost implementation and robustness. Mesh networking is considered the most appropriate technology for Military/Government wireless networks (Shyy, 2006). However, in these networks several factors should be taken into acount, such as mobility, QoS support, power management etc.

IEEE developed an amendment of the IEEE 802.11 Standard, namely the IEEE 802.11s Standard (802.11s 2011/D12.0, 2011), for mesh networking in Wireless Local Area Networks (WLANs). The aforementioned Standard defines the Hybrid Wireless Mesh Protocol (HWMP) as the path selection protocol used by IEEE 802.11s WMNs. The default metric of HWMP is the Airtime Link Metric (ALM) which does not take into account the energy of the nodes in the network and thus, the routing mechanism is not energy - efficient.

In this paper, we deal with problems caused by nodes that suffer from energy exhaustion and we propose an energy aware routing metric that can address connectivity problems in IEEE 802.11s networks. This energy aware metric is used by HWMP routing protocol instead of the airtime link metric. In particular, the proposed metric takes into account the residual energy of nodes and selects the route that is made up by nodes with the maximum residual energy in the mesh network. Thus, nodes with low energy levels do not participate in the routing procedure and remain operational for longer periods of time. This results in the prolonging of the network lifetime.

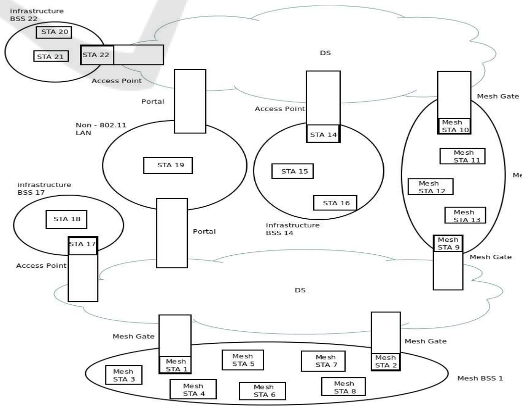

Figure 1: An IEEE 802.11s Architecture.

The rest of the paper is organized as follows: The basic components of an IEEE 802.11s WMN archi-

Zogkou M., Sgora A. and Vergados D..
Energy Aware Routing in IEEE 802.11s Wireless Mesh Networks.
DOI: 10.5220/0004634302150220
In *Proceedings of the 10th International Conference on Signal Processing and Multimedia Applications and 10th International Conference on Wireless Information Networks and Systems* (WINSYS-2013), pages 215-220
ISBN: 978-989-8565-74-7

tecture are presented in Section 2, while Section 3 describes briefly the HWMP, defined in IEEE 802.11s Standard. Section 4 overviews several existing routing metrics in WMNs, while in Section 5 the proposed energy - aware routing metric is presented. Simulation results are discussed in Section 6. Finally, Section 7 concludes the paper.

2 THE IEEE 802.11s ARCHITECTURE

The basic component of an IEEE 802.11s architecture is the mesh station (STA), i.e an autonomous station that implements the mesh functionalities, such as formation of the mesh BSS, path selection, and forwarding. The mesh facilities are available to the mesh STAs that belong to a Mesh Basic Service Set (MBSS).

Mesh STAs within the MBSS can communicate with each other either directly, or through other mesh STAs. Communication with nodes outside the MBSS can be achieved through the Distribution System (DS).

A mesh STA that can also provide access to one or more DSs, via the wireless medium (WM) for the MBSS is called mesh gate. Once an MBSS contains a mesh gate that connects it to the IEEE 802.11 DS, the MBSS can be integrated with other infrastructure Basic Service Sets (BSSs) too, given that their Access Points (APs) connect to the same DS.

When a MBSS accesses the IEEE 802.11 DS through its mesh gate, the MBSS can be integrated with a non-IEEE-802.11 LAN. Whereas the portal integrates the IEEE 802.11 architecture with a non-IEEE-802.11 LAN, the mesh gate integrates the MBSS with the IEEE 802.11 DS.

Figure 1 depicts an IEEE 802.11s Architecture.

3 THE HYBRID WIRELESS MESH PROTOCOL (HWMP)

The default routing protocol defined in IEEE 802.11s Specification is the HWMP, which is operated on the Data Link Layer and therefore it uses the MAC addresses for routing. Also, the specification defines the ALM as the default metric used by the HWMP for path selection. The ALM reflects the total channel resources consumed by the transmission of a frame over a particular link and is given by the following equation.

$$c_a = \left[O + \frac{B_t}{r}\right]\frac{1}{1-e_f} \qquad (1)$$

where, O and B_t are constants listed in Table I and the input parameters r and e_f are the data rate in Mbps and the frame error rate for the test frame size B_t respectively.

Table 1: Airtime Cost Constants.

Parameter	Recommended Value	Description
O	Varies depending on the PHY	Channel access overhead, which includes frame headers, training sequences, access protocol frames, etc.
B_t	8192	Number of bits in test frame

HWMP operates in two different routing modes: the “on - demand” and the “tree-based proactive” modes.

In the “on - demand” mode, whenever a mesh STA needs to establish a routing path to a destination mesh STA, it broadcasts a Path Request (PREQ) message to all its neighbors having specified the sequence number, the address of the destination mesh STA, and the ALM metric initialized to the initial value of the active path selection metric. Upon receiving a PREQ, if the node that received the PREQ is not the destination mesh STA acts as follows: First, it creates a path to the source mesh STA if no path exists, or it updates its current path in two cases: 1) if the sequence number of the PREQ is greater than the last one; 2) if the sequence number is the same with its current path but propagates a better metric for the path. Then, it calculates its routing metric and updates the PREQ with the cumulative metric. The updated PREQ is forwarded to all its neighbors. This procedure is repeated until the PREQ reaches its destination. When the destination mesh STA receives the PREQ, it creates or updates its routing path to the source node and it sends unicast Path Reply (PREP) message back to the source mesh STA.

In the “tree-based proactive” mode, there are two mechanisms, namely, the proactive PREQ and the proactive RANN (Root ANNouncement). The proactive PREQ mechanism creates paths from the mesh STAs to the root, using only group-addressed communication. The RANN mechanism creates paths between the root and each mesh STA using acknowledged communication.

It should be noted that on-demand and proactive modes can be used concurrently, because the proactive modes are extensions of the on-demand mode.

4 WMNS' ROUTING METRICS

Although the ALM takes into account the transmission rate, as well as, the transmission error rate, since it does not define any load mechanism it can route traffic to congested areas (Islam et al., 2010). Also, the fact that the ALM is unaware of intra-flow interference has a significant effect on the network performance in Multi-Channel Multi-Radio WMNs (Bin Ngadi et al., 2012). Furthermore, issues such as energy and security are not considered. However, although extensive research carried out for the design of new metrics very few works have focused on the path selection mechanism for IEEE 802.11s WMNs.

One of the first metrics designed for WMNs is the Expected Transmission Count (ETX) metric (Campista et al., 2008) that calculates the expected number of transmissions required to successfully send a packet over the link, including retransmissions. However, ETX does not take into account either the packet size or the bandwidth of the links. Therefore, it increases the control overhead, which results in low network performance. In order to confront the above shortcomings, the Expected Transmission Time (ETT) (Draves et al., 2004) has been introduced that considers also and the throughput into its calculation. Koksal and Balakrishnan (2006) also proposed two variations of the ETX metric that estimate the losses by means of the bit error probability: the modified Expected Number of Transmissions (mETX), and the Effective Number of Transmissions (ENT).

Mhatre et al. (2007) proposed the Expected Throughput (ETP) metric, which measures the expected throughput of the link. Also, Passos et al. (2006) proposed the Minimum Loss (ML) metric that calculates the delivery ratio and selects the route with the lowest end - to - end loss probability by multiplying the delivery ratios of the links across the path. Especially, for IEEE 802.11s WMNs Islam et al. (2010) proposed the Expected Forwarding Time (EFT). EFT calculates the end - to - end delay that a packet experiences on its way to the destination and selects the path that has the lowest end - to - end delay to route packets.

Furthermore, for multi-channels WMNs also several metrics have been proposed. Draves et al. (2004) proposed the Weighted Cumulative ETT (WCETT) metric that tries to find paths with less intra-flow interference and channel diversity. However, WCETT does not guarantee the selection of the shortest path and does not take into account inter - flow interference. Thus, the selected routing paths may suffer from congestion. Another metric, that aims to limit the interference levels on a WMN, is the Metric of Interference and Channel-switching (MIC) (Yang et al., 2005). MIC is based on the ETT metric and takes into account the inter - flow interference by calculating the number of nodes that interfere. Subramanian et al. (2006) proposed the iAWARE metric that combines the interference ratio (IR) with the ETT metric. More specific, the interference experienced by links is given by the fraction of ETT, calculated for a link, to the interference ratio of the same link. The Signal to Noise Ratio (SNR) and Signal to Interference and Noise Ratio (SINR) are used for the calculation of the interference variations.

All the metrics mentioned above do not consider energy constraints. The Expected Transmission Energy (ETE) (Jin et al., 2011) was introduced for implementation in wireless mesh sensor networks (WMSNs). The aforementioned metric takes into account the energy distribution in the network aiming to examine the routes that are selected when ETE metric is in use. In addition, a threshold has been introduced aiming in avoiding the calculation of the metric by nodes with residual energy below the threshold. The calculation of the metric is given below.

$$c'_a = \left[O_{c_\alpha} + O_p + \frac{B_t}{r} + \sum_{i=1}^{n_j} \frac{E_{init}}{100E_i}\right] \frac{1}{1-e_{pt}} + \frac{\sum_{i=1}^{n_j} \frac{E_{ic}}{E_{init}}}{n_j} \tag{2}$$

Where, E_i is the residual energy of node i after the completion of the transmission, E_{i_c} is the energy consumption of node i, n is the number of nodes that consist the network and n_j is the number of nodes along the route that has been selected. The O_{c_α} and O_p are constants used in older versions of the 802.11s Specification to describe the channel and the protocol overhead, respectively.

Table 2 gathers the above metrics that have been proposed for use in WMNs.

5 THE PROPOSED METRIC

The proposed metric takes into account the residual energy of a node by calculating the total energy consumed by a node whenever it is in one of the following states:

- IDLE: During this state the nodeis idle.
- CCA_BUSY: During this state the node is busy.
- TX: During this state the node only transmits packets.
- RX: During this state the node only receives packets.
- SWITCHING: During this state the node switches from one channel to another.

Table 2: Existing Routing Metrics.

Metric	Path Selection Criterion
EFT	end - to - end delay for all routing paths
ETX	forward and reverse delivery ratios of the link
ETT	forward and reverse delivery ratios of the link, throughput
ML	packet delivery ratio, end-to-end loss probability
WCETT	end - to - end delay and channel diversity
MIC	forward and reverse delivery ratios of the link, throughput, inter -flow interference
ETP	expected throughput of the link
mETX	losses by means of the bit error probability
ENT	losses by means of the bit error probability
iAWARE	intrerference ratio, forward and reverse delivery ratios of the link, throughput
ETE	transmission rate, transmission error rate, energy consumption rate of nodes in the network

More specifically, for each node n_i the residual energy $R(n_i)$ is computed as:

$$R(n_i) = E_{current}(n_i) - E_{con}(n_i) \tag{3}$$

where $E_{current}(n_i)$ and $E_{con}(n_i)$ denote the current energy of the node n_i and the energy consumed by the node n_i, respectively. At the beginning, the current energy is set to the initial energy of the node.

Since the consumed energy of each node n_i depends on the state that the node is (i.e. IDLE, TX, RX, CCA_BUSY, SWITCHING), we use the following equation to determine its consumed energy:

$$E_{con}(n_i) = Current(n_i) * Voltage(n_i) * Duration \tag{4}$$

where $Current(n_i)$ is the current in Ampere and depends on the state in which the node n_i is, $Voltage(n_i)$ voltage is the supply voltage in Volts and $Duration$ is the interval that passed since the last energy update.

For each node n_i an energy cost function $C(n_i)$is assigned that is given by:

$$C(n_i) = \frac{E_{init}(n_i)}{R(n_i)} \tag{5}$$

Thus, the total energy cost for a route p from source node n_S to destination node n_D , is given by:

$$E_p = \sum_{n_i \in p,\, n_i \neq n_D} C(n_i) \tag{6}$$

The selected route l will be the one that satisfies the following property:

$$E_l = min\{E_p : p \in V\} \tag{7}$$

where V is the set of all the possible routes.

6 SIMULATION RESULTS

The proposed metric (denoted as energy in the following figures) was evaluated using the simulation software ns-3 (http://www.nsnam.org) and its performance was compared only against the ALM (denoted as airtime in the following figures) since important implementation details, as well as, simulation parameters for the ETE metric are not given. Also the authors consider that a node consumes energy only when it transmits or receives data .

We set up our simulation by constructing a grid topology with N x N mesh STAs. The distance between two neighboring mesh STAs in the grid was set to 120 m. In our simulations we generated four UDP traffic flows among 4 nodes in the network. Figure 2 shows an illustrative example for the case of a 3 x 3 grid topology. Each simulation run consisted of 10 iterations, each having the same pair of sender-destination. Details concerning the simulation parameters are given in Table 3.

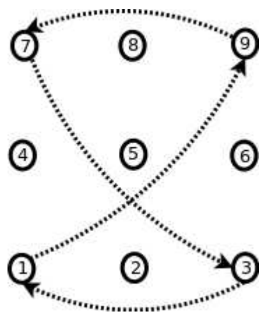

Figure 2: A 3 x 3 grid topology.

Table 3: Simulation Parameters.

Parameter	Value
N	2, 3, 4, 5, 6 and 8
Initial Energy (E_{init})	33 Joules
Interval	0,1 sec
Data rate	150 kbps
Packet size	1024 bytes
Propagation loss model	log-distance
Transmission power	18 dbm
Simulation time	25000 sec

The residual energy of a node is calculated by the energy that consumes whenever it is in one of the states described above. The supply voltage of each node is set to 3 Volts, while the Duration is set to 1sec. For each state different current has been set. Table 4 summarizes the current of a node for each state.

Table 4: Energy consumption for each state.

State	Current (Ampere)
IDLE	0.00426
CCA_BUSY	0.00426
TX	0.0174
RX	0.0194
SWITCHING	0.00426

We used three different quantitative measures (network lifetime, delay and the Packet Delivery Fraction (PDF)) to compare the performance of the three routing metrics. It should be noted that the reactive mode of the HWMP protocol was used for path selection, which implies the absence of a root node in the mesh network used in our simulation scenarios. Also, as the network lifetime we consider the time that the first node of the network ran out of energy.

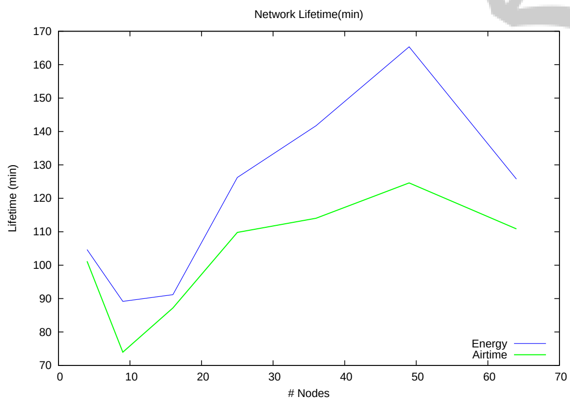

Figure 3: Lifetime vs # Nodes.

Figure 3 illustrates the network lifetime for each metric that was applied in the HWMP. As Figure 3 depicts, the proposed metric outperforms the ALM regarding the network lifetime. When the ALM metric is applied in the HWMP, energy constraints are not taken into account for the forwarding of data. Thus, the energy of the nodes along that path is depleted at shorter time.

In terms of the total delay that the network experiences, as shown in figure 4, the ALM metric achieves lower delay in comparison with the proposed one. Since the proposed metric considers the energy constraints it should select longer routes than ALM, leading to a slightly increase in terms of delay.

The last measure that was used for the comparison of the three metrics is the Packet Delivery Fraction (PDF), which denotes the percentage of the successfully delivered packets. As shown in figure 5, the PDFs for both merics are quite identical.

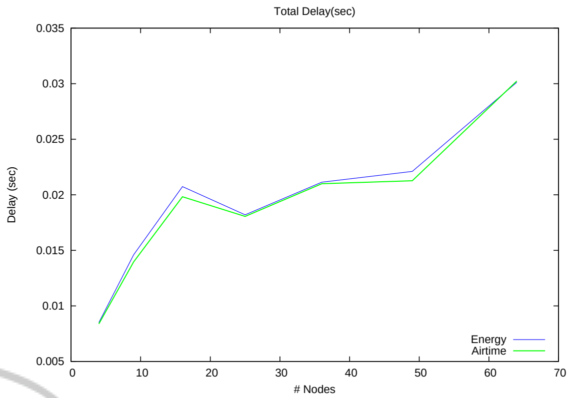

Figure 4: Total Delay vs # Nodes.

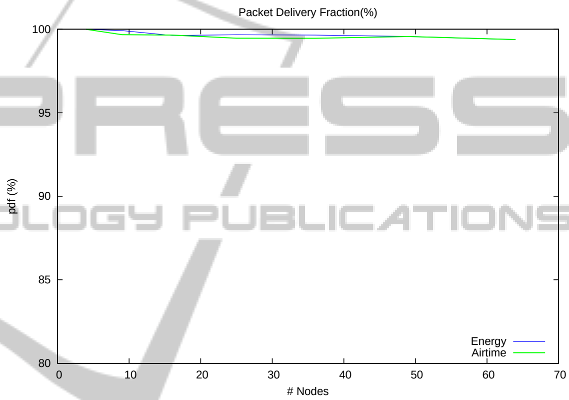

Figure 5: Packet Delivery Fraction vs # Nodes.

7 CONCLUSIONS

In this paper, we have proposed a new routing metric that was incorporated with the HWMP, in place of the ALM, and applied in a WMN. The proposed metric calculates an energy cost function by taking into account the residual energy of nodes in the network and selects the path that minimizes the aforementioned cost function. Simulation results showed that the proposed metric prolongs the lifetime of a WMN in comparison with the ALM, while causing a little higher total delay in the network.

ACKNOWLEDGEMENTS

This work was carried out during the tenure of an ERCIM ”Alain Bensoussan” Fellowship Programme.

The research leading to these results has received funding from the European Union Seventh Framework Programme (FP7 2007-2013) under grant agreement no 246016.

This work is also partly supported by UPRC (University of Piraeus Research Center).

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