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An Energy-Efficient Hybrid Wireless Mesh Protocol (HWMP) for IEEE 802.11s Mesh Networks

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Abstract— **The existing path selection scheme in IEEE 802.11s for wireless mesh networks is Hybrid Wireless Mesh Protocol (HWMP). The main routing metric of HWMP is called airtime metric, which is dependent on packet error rate and transmission bitrate. HWMP does not take energy efficiency into consideration despite its importance for mobile nodes and other nodes which are battery driven. In our proposed energy-efficient HWMP (eHWMP) scheme, in addition to airtime metric, we incorporate per-hop delay and residual energy into the routing metric in order to increase energy efficiency without jeopardizing end-to-end delay performance. Preliminary simulation results show that eHWMP achieves our objective by increasing network lifetime without causing significant effects on end-to-end delay and throughput as compared to the traditional HWMP.**

Index Terms—*Energy-efficient, HWMP, routing, wireless mesh networks.*

I. Introduction

The recently published IEEE 802.11s Wireless Mesh Networking standard by the 11s Task Group in September 2011 defines Hybrid Wireless Mesh Protocol (HWMP) as the default path selection scheme for Wireless Mesh Networks (WMNs). The WMN is a distributed network comprised of wireless nodes that connect among themselves in the absence of fixed network infrastructure. IEEE 802.11s aims to construct WMNs based on the traditional IEEE 802.11 standard. The standard defines Medium Access Control (MAC) protocol and physical layer specifications to support multi-hop mesh networks. One of the main features being introduced in the standard is HWMP, in which a hybrid path selection scheme is applied to the data link layer, and it is based on MAC addresses. An upper layer of a node may therefore see any destination nodes in a WMN as its direct neighbors; but in fact, the destination node may be multiple hops away. Hence, the routing information could be processed faster in data link layer and relief the processing workload of the upper layers.

HWMP enables a source node to choose the best possible path to its destination node. The main intrinsic characteristic is that, there are three operating modes, namely proactive tree-based, reactive and hybrid path selection approaches. The proactive tree-based approach elects a root node, which has all the path information toward any destinations; while the rest of the nodes send packets to the root node. Every node constantly broadcast path maintenance message. The reactive approach enables a node to broadcast path request message, which establishes path, only when it needs to send packets; while the destination node replies with a path response message to the source node upon receiving the path request message The hybrid approach applies both proactive and reactive approaches independently or concurrently; for instance, the proactive tree-based and reactive approaches are suitable for networks with high and low traffic loads, respectively [1].

HWMP computes a metric called airtime, which is based on hop count and frame error rate. Airtime metric reflects the amount of channel resources, such as bandwidth, being consumed by transmitting a frame over a particular link.

While IEEE 802.11s is expected to become a popular standard, there has been lack of energy consideration in HWMP. This paper provides a next-level of enhancement on HWMP in which metric such as residual energy and per-hop-delay, is incorporated into the routing metric in order to achieve energy efficiency. This enhancement brought about by energy-efficient HWMP (eHWMP) could prolong network lifetime without significantly effects on the network wide performance, such as end-to-end delay.

The rest of this article is organized as follows. Section 2 presents related work on energy-efficient hybrid routing schemes. Section 3 discusses eHWMP and how it has been applied to reduce energy consumption without jeopardizing end-to-end delay. Section 4 presents simulation setup and results. Finally, section 5 presents conclusion and future work.

II. Related Work

This section presents related work on the traditional energy-efficient hybrid routing schemes in mesh networks.

A. Energy-effiicient Hybrid Routing Schemes

There are four main challenges associated with achieving energy efficiency in hybrid routing schemes as follows:

1) Different levels of residual energy among nodes: Using hybrid routing, nodes in a network may be grouped into clusters. Each cluster is comprised of a clusterhead and member nodes. Clusterhead, which serves as a local point of process that collects packets from member nodes and sends them to base station, is expected to incur higher energy consumption.Hence, nodes with higher residual energy may be

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elected as clusterheads. [2] address this challenge by rotating the role of clusterhead among nodes in a cluster.

2) Higher energy consumption of nodes closer to base station: Energy consumption of nodes physically closer to base station is higher compared to other nodes because they tend to have higher amount of traffic load. [3] address this challenge by using flat routing, which establishes multiple routes, among nodes nearer to the base stationin order toprevent only certain nodesare selected to forward packets to the base station which may incur higher energy consumption.

3) Dynamic traffic load: Energy consumption of a network with different levels of traffic loads is affected by the choice of routing approaches. In other words, different routing approaches may be used for different levels of traffic loads in order to reduce energy consumption. [4] address this challenge by establishing new routes in wireless sensor networks using reactive routing and proactive routing. When traffic load is low, reactive routing is applied and nodes without traffic may choose not to involve in routing. Since constant route maintenance is not necessary, it reduces energy consumption. When traffic load is high, proactive routing is applied by base station to construct a routing tree from the base station to all wireless sensor nodes. This reduces routing overhead and route discovery cost, and so it reduces energy consumption.

4) Achieving balance between end-to-end energy consumption and residual energy of nodes: Achieving a balance between end-to-end energy consumption and residual energy of nodes helps to prolong a network lifetime. A route that is comprised of nodes with higher residual energy may not provide lower end-to-end energy consumption. Likewise, a route with lower end-to-end energy consumption may be comprised of nodes with lower residual energy level, and hence, using this route may even exhaust its residual energy. [5] address this challenge by introducing a hybrid routing scheme to prolong network lifetime. When all the nodes of a candidate route have sufficient amount of residual energy, it chooses a route with the lowest end-to-end energy consumption; otherwise, it chooses a route that avoids nodes with comparatively lower residual energy.

Our proposed scheme is addressing the challenge of different levels of residual energy among nodes, in which, eHWMP takes into consideration the residual energy level of nodes before choosing the best possible path.

III. ENERGY-EFFICIENT HYBRID WIRELESS MESH PROTOCOL

The purpose of our enhancement in this work is to incorporate residual energy levels of intermediate nodes into the consideration of next-hop selection in order to provide energy efficiency, while the QoS performance, particularly end-to-end delay, is well taken care of.

Traditionally, HWMP chooses the shortest path from a source node to its destination node in wireless mesh networks. While this may reduce end-to-end delay, the shortest path may not provide energy efficiency. This is because a path may be comprised of nodes with low residual energy levels, and so any link breakages may incur routing overhead, which may further deplete the residual energy. In addition to the original airtime metric, we incorporate residual energy level and per-hop delay into the reward function in order to achieve higher energy efficiency without significant effects on end-to-end delay. The airtime metric represents the link condition (i.e. bandwidth) that reflects the amount of channel resources being consumed by transmitting a frame over a particular link between a node pair. Higher airtime metric indicates that higher channel resource is consumed using that particular link to transmit a frame, and vice-versa. Per-hop delay is the time duration being incurred to send a packet to the next-hop node.

Our proposed scheme incorporates residual energy and per-hop delay into the existing routing metric called airtime metric A^t, which is the airtime of a link at time t, The routing cost is calculated using Equation (1) as follows:

$$C^t = \omega_1\left(\frac{A^t}{A^t_{max}}\right) + \omega_2\left(\frac{d^t}{d^t_{max}}\right) + \omega_3\left(1 - \frac{r^t}{r_{init-max}}\right) \quad (1)$$

where d^t is the per-hop delay of a link at time t, r^t is the residual energy of a node at time t, and $r_{init-max}$ is the initial energy level of the node with the highest initial energy level. Note that, the weight factors are ω_1 , ω_2 and ω_3 where $\omega_1 + \omega_2 + \omega_3 = 1$. The denominators A^t_{max} and d^t_{max} are used to normalize the respective A^t and d^t values, and there are three main steps to calculate each of them.

Firstly, the smoothed average values (or denominators) of airtime of the link A^t_{avg} and per-hop delay d^t_{avg} at time t are calculated using exponential moving average. Both A^t_{avg} and d^t_{avg} are calculated in the same way, and we show how to calculate A^t_{avg} in this paper. The A^t_{avg} is updated as time goes by. Denote the learning rate by $0 \leq \alpha_1 \leq 1$, the updated smoothed average value at time $t+1$ (or A^{t+1}_{avg}) is calculated using Equation (2) as follows:

$$A^{t+1}_{avg} = \alpha_1 A^t + (1-\alpha_1)A^t_{avg} \quad (2)$$

where higher α_1 value indicates higher dependency on the current airtime value of the link and lower α_1 value indicates higher dependency on the smoothed average airtime value of the link at time t.

Secondly, due to the unpredictable nature of the airtime of the link A^t_{avg} and per-hop delay d^t_{avg} values, it is necessary to incorporate the variance of these values into Equation (2). The variance of the airtime value of the link V^{t+1}_A is updated as time goes by. Denote the learning rate by $0 \leq \alpha_2 \leq 1$, the updated smoothed average value at time $t+1$ (or V^{t+1}_A) is calculated using Equation (3) as follows:

$$V^{t+1}_A = \alpha_2 V^t_A + (1-\alpha_2)|A^{t+1}_{avg} - A^t| \quad (3)$$

where higher α_2 value indicates higher dependency on the current variance of the airtime value of the link and lower α_2 value indicates higher dependency on the difference between smoothed average airtime value of the link at time $t+1$ and the airtime of the link at time t. Note that, the variance of the per-hop delay V^{t+1}_d is updated in the same way.

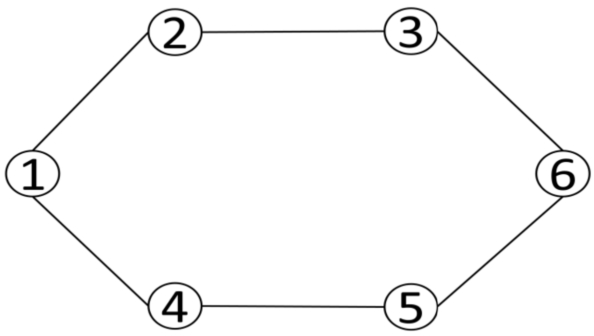

Fig. 1. Network Topology.

Thirdly, the denominator A_{max}^{t} is calculated using Equation (4) as follows:

$$A_{max}^{t+1} = A_{avg}^{t+1} + kV_{A}^{t+1} \quad (4)$$

where $k \geq 1$ is a constant value. Higher k value reduces the occurrence of $A^{t} > A_{max}^{t}$ in which $C^{t} > 1$ may occur. For simplicity, this paper adopts the assumption of $A^{t} = A^{t-1}$ if $A^{t} > A_{max}^{t}$.

IV. Simulation Experiments, Results and Discussions

This section presents simulation setup, performance metrics, as well as simulation results and discussions.

A. Simulation Setup

The purpose of the simulation is to show the enhancement on energy-efficiency brought about by the eHWMP using routing cost C^{t}. Fig. 1 shows the network topology under investigation.

The simulation parameters are shown in Table 1. Generally speaking, node 1 sends a single CBR traffic from source node 1 to destination node 6 via different paths, specifically, 1−2−3−6 (P1) and 1−4−5−6 (P2), which are decided by HWMP and eHWMP. The simulation duration is for 1000 seconds. The initial energy levels of node 2 and node 3 are 25mAh and the initial energy levels for the other nodes are 50mAh.

TABLE I. Simulation Parameters.

Categories	Description	Value
Traffic	Type	Constant Bit Rate (CBR)
	Data packet size	1024 Bytes
	Transmission Power	265 mA
	Receiving Power	130 mA
	Idle Power	95 mA
	Sleep Mode Power	2 mA
Routing	Weight ω_1	0.1
	Weight ω_2	0.1
	Weight ω_3	0.8
	Learning rate α_1	0.5
	Learning rate α_2	0.5
	Constant k	1

B. Performance Metrics

We compare network performance achieved by both HWMP and eHWMP. The network performance metrics are as follows:

- *Residual energy* is the remaining energy level of each node upon completion of a simulation run.
- *Average end-to-end delay* is the average time incurred for data packets to traverse along a path from node 1 to destination node 6. This includes queuing, processing, transmission and propagation delays.
- *Network lifetime* is the operating duration until the first node exhausts its energy.

Generally speaking, higher residual energy level, lower average end-to-end delay and higher network lifetime are favorable.

C. Simulation Results and Discussions

This section presents the network performance achieved by both HWMP and eHWMPin the aspects of network lifetime, percentage of times in which path with higher residual energy is chosen, average end-to-end delay, and average throughput.

1)Netwotk lifetime: Fig.2 shows the network lifetimes of HWMP and eHWMP. When packet arrival rate is below 5 packets per second (packets/s), or, low traffic load, the difference of network lifetime between HWMP and eHWMP are below 25s. Lower traffic load allows nodes to operate in idle mode more often than transmit mode; hence, the energy consumption for both schemes are almost the same. When the packet arrival rate is 5−30 packets/s, the difference of network lifetime between HWMP and eHWMP becomes larger. The highest improvement of eHWMP over HWMP is at 15packets/s, in which there is 8% improvement. This indicates that eHWMP has choosen the path with higher residual energy level (i.e. P2), hence nodes with lower energy level are less likely to be chosen. Hence, these nodes consume lesser energy

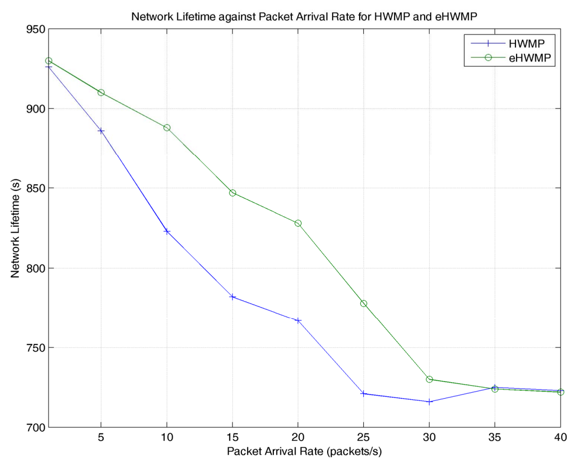

Fig. 2. Network lifetime against packet arrival rate

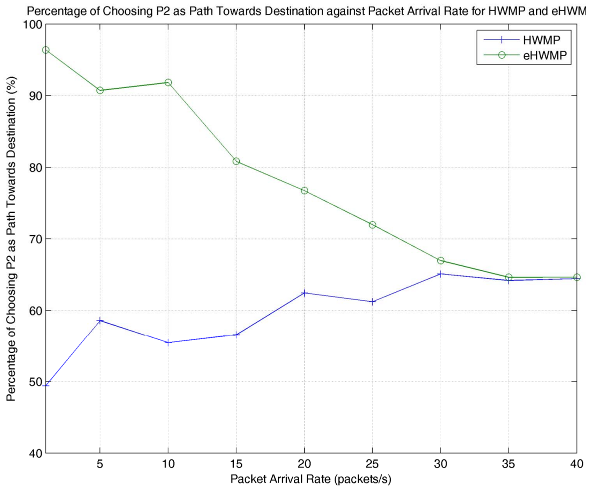

Fig.3. Percentage of choosing P2 as path towards destination against packet arrival rate

and prolong the network lifetime. When packet arrival rate is more than 30 packets/s, the traffic load is higher; hence nodes along the initially chosen path (P2) consume higher energy level than nodes along P1. When the residual energy levels of node 4 and node 5 (along P2) are similar to or lower than node 2 and node 3, node 1 changes the path to node 6 from P2 to P1. So, the energy consumption, and hence network lifetime, of both paths is similar; as shown in Fig. 2.

2) Percentage of choosing P2 as path towards destination: Fig. 3 shows the preferences of node 1 choosing a path towards node 6 for HWMP and eHWMP. When packet arrival rate is less than 30 packets/s, eHWMP has a high preference of choosing P2 as the path towards its destination. The percentage of choosing P2 is higher than 70% as compared to choosing P1. This is due to the higher residual energy level of node 4 and node 5 as compared to node 2 and node 3. While in HWMP scheme, in which path selection is solely base on airtime, the preferences of choosing P2 is from 49% to 52%. When the packet arrival rate is more than 30 packets/s, the percentage of choosing P2 for both schemes are similar. This is due to the residual energy levels of node 4 and 5 becomes lower or similar to node 2 and 3. In this case, path selection is depending more on airtime and per-hop delay since the residual energy factor is similar for both paths. Hence, the percentage of choosing P1 and P2 are similar for HWMP and eHWMP.

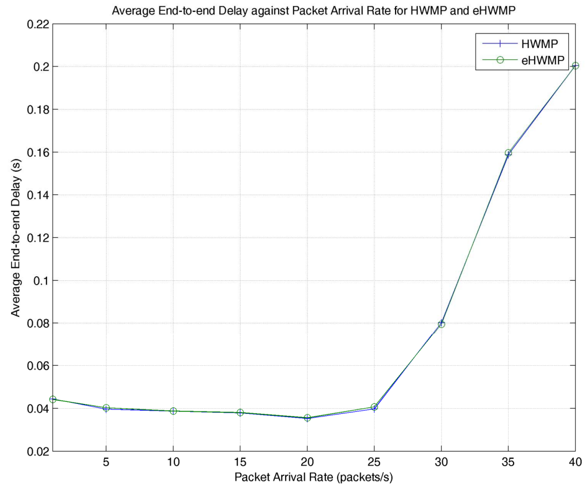

Fig.5. Average end-to-end delay against packet arrival rate

3) Average residual energy-level of intermediate node: Fig.4 shows the average residual energy level of intermediate nodes (nodes 4 and node 5) upon completion of a simulation run. When the packet arrival rate is less than 30packets/s, the average residual energy level for eHWMP is lower than HWMP upon completion of simulation. This is due to the

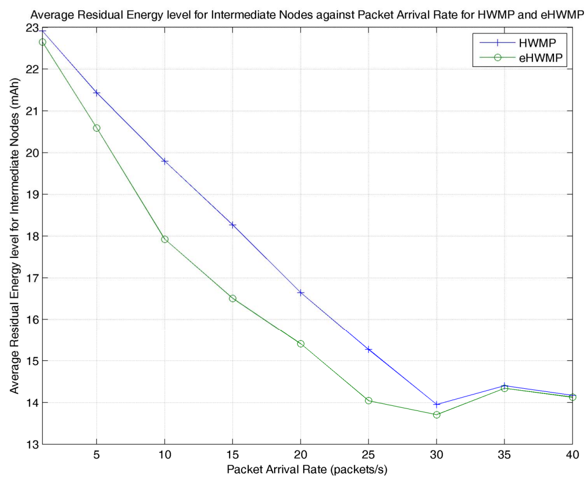

Fig.4. Average residual energy level for intermediate nodes against packet arrival rate

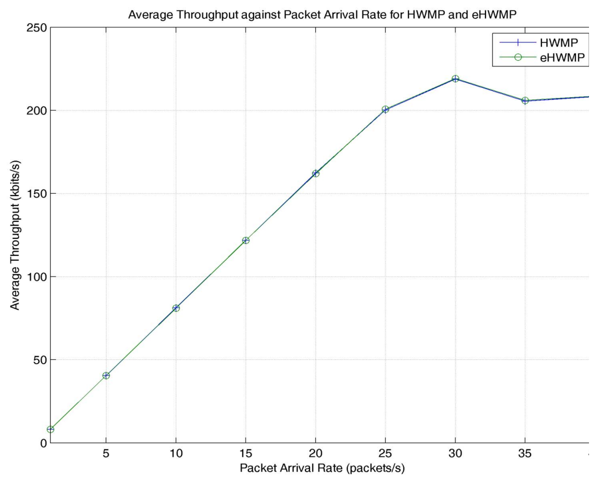

Fig.6. Average throughput against packet arrival rate

selection of P2 as the path to node 6; hence, node 4 and node 5 transmit more packets and consume more energy. When packet arrival rate is more than 30 packets/s, the residual energy level for HWMP and eHWMP become similar. This is due to the path selection trends which are similar for both schemes, hence, the energy consumption of node 4 and node 5 are similar for HWMP and eHWMP.

4) Average end-to-end delay: Fig. 5 shows the average end-to-end delay of packets from node 1 to node 6. The average end-to-end delay for both schemes increase with the packet arrival rate. The average end-to-end delay of eHWMP is similar to HWMP. Fig. 5 shows that eHWMP has successfully increased the network lifetime without jeopardizing end-to-end delay of the network.

5) Throughput: Fig. 6 shows the throughput performandce of sending packets from node 1 to node 6. When packet arrival rate is less than 30 packets/s, the throughput for both schemes increase with packet arrival rate. When the packet arrival rate is 35 packets/s, the throughput for both schemes has dropped for 13kbit/s due to high amount of packet loss, in which more packet drops are observed at source node and intermediate nodes since the nodes could not transmit all packets at such high paket arrival rate and a large amount of packets are dropped. Fig. 6 shows that eHWMP has successfully increased network lifetime without jeopardizing throughput performance.

V. Conclusions and Future Work

From the discussion, we observe that eHWMP outperform the original HWMP in the aspects of network lifetime without jeopardizing end-to-end delay and throughput performances. Further work can be done to determine the optimum value of various variables in eHWMP, namely ω_1, ω_2, ω_3, α_1, $\alpha_2$and k. Further works can also be done to implement eHWMP in a wireless mesh network platform to investigate real-life problems of eHWMP implementation, such as the effect of weather and temperature on energy efficiency achieved by eHWMP. The implementation of eHWMP in extreme temperature may effects energy efficiency. Energy may be used to operate fan or cooler in high temperature conditions to reduce the operating temperature of a node, hence, the idle mode energy consumption maybe similar or higher than operating in transmission mode. It is important to take this effect into consideration when implementing eHWMP in wireless mesh networks.

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References

[1] Ming Ann Ng, Kok-Lim Alvin Yau and David Chieng, 2012. “Issues and Challenges of Energy-efficient Hybrid Routing Schemes: A Review”, Journal of Applied Sciences,12:2096-2106.DOI:10.3923/jas.2012.2096.2106

[2] Tabibzadeh M, Sarram M, Adibnia F. Hybrid routing protocol for prolonged network lifetime in large scale wireless sensor network. Proceeding of the International Conference on Information and Multimedia Technology, 2009 (ICIMT '09), Jeju Island, South Korea, 16–18 December 2009; 179–183.

[3] Priyankara S, Kinoshita K, Tode H. A clustering/multi-hop hybrid routing method for wireless sensor networks with heterogeneous node types. IEEE GLOBECOM Workshops 2010; 207–212, DOI: 10.1109/GLOCOMW.2010.5700311.

[4] Figueiredo CMS, Nakamura EF, Loureiro AAF. An event-detection estimation model for hybrid adaptive routing in WSNs. Proceeding of the IEEE International Conference of Communications, 2007 (ICC '07), Glasgow, Scotland, 24–28 August 2007; 3887–3894.

[5] Cano JC, Kim D. Investigating performance of power-aware routing protocols for mobile ad hoc networks. Proceeding of the International Mobility and Wireless Access Workshop, 2002 (MobiWac 2002), Texas, USA, 12 October 2002; 80–86.

[6] IEEE P802.11s. Part 11: IEEE Standard for Information Technology— Telecommunications and information exchange between systems— Local and metropolitan area networks— Specific requirements: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications Amendment 10: Mesh Networking, September 2011.

[7] Garroppo RG, Giordano S. Implementation Frameworks for IEEE 802.11s System. Computer Communications.;33(3), February 2010; 336-349.

[8] Hiertz GR, Denteneer D, Max S, Taori R, Cardona J, Berlemann L, Walke, B. IEEE 802.11s: The WLAN mesh standard. IEEE Wireless Communications 2010; 17(1): 52–67.

[9] Hiertz GR, Zang YP. IEEE 802.11s: WLAN Mesh Standardization and High Performance Extensions. IEEE Network; 22(3), May 2008; 12-19.

[10] Uludag S, Imboden T, Akkaya K. A taxonomy and evaluation for developing 802.11-based wireless mesh network testbeds. International Journal of Communication Systems 2011. DOI: 10.1002/dac.1299.

[11] Lin YD, Chang SL, et al.. Indoor Deployment of IEEE 802.11s mesh network: Lessons and Guidelines. Ad Hoc Network; 9(8), November 2011; 1404-1413.