An Energy-aware Routing Algorithm for Quality-oriented Wireless Video Delivery

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***Abstract*—Energy consumption has been a critical factor for video services on mobile devices. Existing energy-aware video delivery solutions focus on reducing the energy consumption at either networks or mobile devices, at the expense of decreasing video quality. This article proposes E-Mesh, an energy-aware wireless routing algorithm which balances the need for energy saving with that of maintaining good quality of video content. E-Mesh is deployed at the network layer and works in conjunction with an innovative energy-aware MAC-layer duty cycle management scheme. Both simulation and perceptual testing were performed investigating the performance of E-Mesh. In particular, the impact of E-Mesh on content delivery data rate, network topology scale and device mobility were studied. Results demonstrate that E-Mesh obtains up to 23% energy savings at roughly the same content delivery quality level, in comparison with the state-of-the-art IEEE 802.11s routing protocol.**

***Index Terms*—energy consumption, routing protocols, multimedia communication, perceptual testing**

I. Introduction

OVER the past decades, the demand for supporting data communications has increased significantly. With the advances in wireless network technologies, usage of wireless devices has also increased rapidly, accompanied by growth in the data traffic associated with rich network services, such as video-related application services on mobile devices. High user Quality of Service/Experience (QoS/QoE) for such services is considered essential for their further development. However it is challenging to provide high quality video wireless services, as the network resources involved are often constrained. Energy consumption is another important issue, as often there are limited power budgets while performing complex and energy-consuming application tasks. It is clear that energy-saving in the network and at the level of mobile devices is needed for offering the ability to maintain high-quality video wireless delivery services. There is a need to find solutions to achieve energy-effectiveness while also maintaining good QoS/QoE levels for the wireless video services at different network layers [1-3].

This article introduces an energy-aware wireless routing algorithm E-Mesh [4] which works on top of the classic OLSR [5] protocol and makes use of a novel multiplication-based utility function when determining the best route for traffic delivery. This function combines utility components which reflect remaining energy level, transmission distance and network load. E-Mesh works in conjunction with AOC-MAC [6], an energy-aware router duty cycle management scheme in order to manage the sleep-periods of the network devices in a smarter way based on link-state communication condition and to reduce the energy consumption of routers by extending their sleep-periods. E-Mesh is illustrated and tested for quality-oriented energy-aware video deliveries over wireless mesh networks.

This article is organized as follows. Section II introduces several state-of-the-art related works on energy-efficient routing protocols. Section III presents the architecture of E-Mesh. Section IV and V introduces the simulation and perceptual test bed settings, respectively. Section VI presents and analyzes the simulation and perceptual test results. The last section concludes our work and presents future work plans.

II. Related Works

Routing protocols for mesh networks can be implemented with various technologies, among which the IEEE 802.11s routing protocol [7] is of particular interest. It defines the Hybrid Wireless Mesh Protocol (HWMP) as the key routing algorithm, employed by mobile devices to communicate with each other in a mesh manner and get access to the outside of the mesh network through gateway devices. It provides hierarchical schemes for data forwarding via a tree-like logical structure in mesh networks and on-demand routing schemes for addressing mobility.

Several research efforts have put in the design of advanced routing mechanisms with the goal to either increase delivery performance or encourage energy saving.

SOAR [8] is a proactive link-state-based routing protocol proposed for explicitly supporting multi-flow in wireless mesh networks. It attempts to improve the network throughput and fairness by introducing the following mechanisms: adaptively selecting forwarding paths to leverage path diversity and reducing duplicate transmissions; determining optimal forwarding nodes in terms of priority timer; local loss recovery to handle dropped packet detection and retransmission; adaptively controlling data sending rate according to network conditions. With these mechanisms, SOAR offers better

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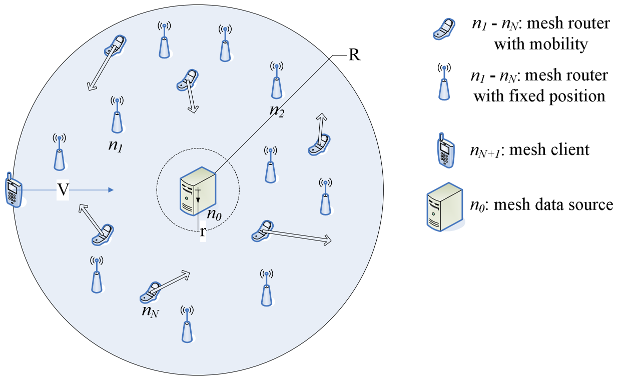

Fig.1. Wireless mesh network topology

tolerance on the instability of wireless network medium with the hop-by-hop data forwarding in comparison with traditional shortest-path routing protocols. The performance of SOAR is evaluated through simulations and real test-bed experiments for single-flow and multi-flow scenarios with various network topologies. Results show the SOAR achieves higher improvement on the network throughput under symmetric losses than asymmetric losses with single-flow scenarios, and significant improvement on the flow index fairness with multi-flow scenarios.

The multi-flow joint optimization routing algorithm proposed in [9] works as the key part of a cross-layer cross-overlay architecture. It provides fast information exchange during cross-layer parameter update in order to enable proactive traffic performance optimization using a mesh internetworking system with network centric computing. The routing algorithm gathers link-state information of multiple traffic flows from a global database deployed in the mesh internetworking system and makes a joint optimization to meet the constraint of every flow. Factors utilized in the joint optimization for route decision differ according to constraints of different flows. Examples of such factors include the end trip time over the link (for applications with strict end-to-end delay constraints) and the effective throughput of the flow (for applications with significant bandwidth demand constraints). The preferred routing choice is decided independently by each flow based on the result of the joint optimization using extensions of the Dijkstra's algorithm.

The authors of [10] present an enhanced version of the newly proposed IPv6-based routing protocol RPL [11] for sensor devices with constrained resources. The enhanced RPL offers QoS-aware support for multimedia services over original RPL networks in terms of delay, and also minimizes energy consumption and carbon footprint emissions. It achieves this by replacing the parent sensor node selection mechanism in the original RPL implementation with a new set of network metrics, such as delay constraint, battery consumption of potential parent nodes and type of root node energy sources.

EEQAR [12] is proposed as an energy-efficient QoS routing mechanism for wireless multimedia sensor networks. Based on cluster hierarchy of the network, EEQAR balances energy consumption of sensors by re-arranging the positions of sensors in the same cluster to change network structure, and establishing routing with an optimization factor table which

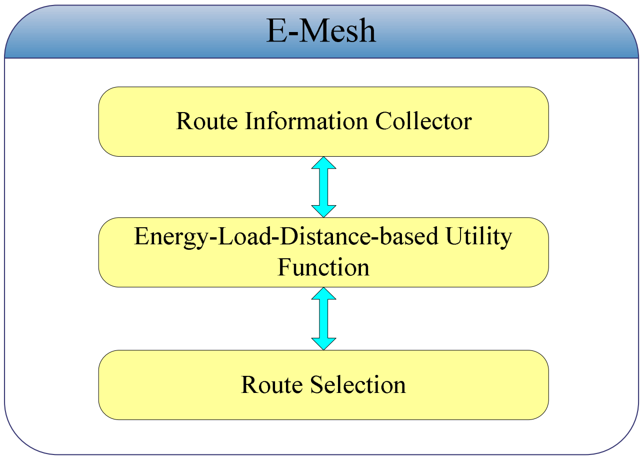

Fig.2. E-Mesh architecture

considers QoS trust value, energy level of sensor nodes and correlation between sensor nodes. Simulation results show that EEQAR performs high efficiency on network lifetime and QoS in wireless multimedia sensor network.

A routing metric based on an optimized queuing model that considers data rates, interference and packet loss for multi-hop wireless network is proposed in [13]. Cross-layer information from different OSI layers is considered, so the influence from interference is minimized. Nodes with higher capacity are with higher priority during routing so that load balancing could be optimized and streaming quality could be ensured.

ADHOP [14] is proposed as a routing algorithm with low overhead, which is adaptable to wireless mesh networks. It uses heuristic information metrics to support routing decisions based on residual energy demands. The network traffic load in the network is balanced among nodes using the energy metric without compromising communication. Each node in ADHOP network stores certain amounts of message between itself and other nodes in the network. Any changes in the network will be broadcasted by the nodes with adequate resources and all the other nodes update their local message. As a result, the routing table is updated efficiently.

An energy-aware routing protocol for self-powered wireless mesh networks LPR is proposed in [15]. A novel energy flow model is introduced in LPR, which is based on interaction of communication and energy harvesting equipment hardware specification, high resolution, time-varying weather information. LPR balances the available energy budget across all the nodes in the network so that power failures are distributed among all participating parties.

In [16], a QoS-aware backup routing algorithm is proposed to work with an available bandwidth estimation mechanism to accommodate stable QoS for multimedia flows in mobile wireless mesh networks. The bandwidth estimation of any node in a network is based on the effective channel capacity and the total occupied bandwidth of this node and its neighbor nodes that share a common channel. The backup routing algorithm includes such information of the node into route calculation information packets to be broadcasted to neighboring nodes sharing the same channel for bandwidth estimation. Meanwhile, to reduce overhead caused by frequent route

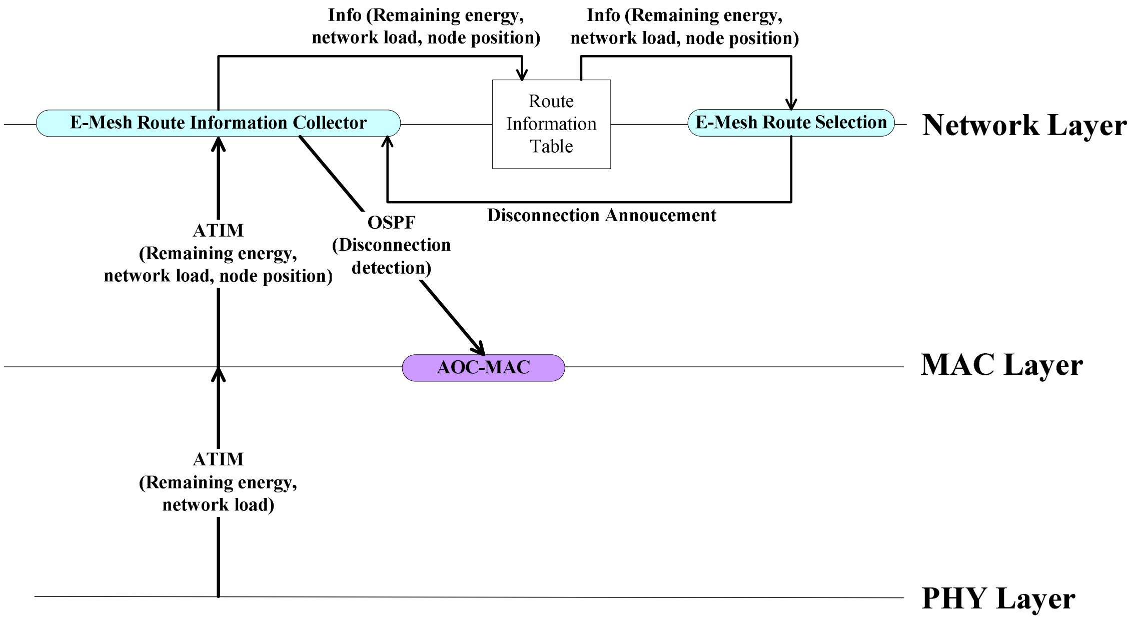

Fig.3. Network/device-condition-based information between different OSI layers

discovery in mobile wireless mesh networks with unstable link quality, a backup piggybacked path (whose available bandwidth is the second maximal among all the paths) is selected apart from the primary path when route is established after exchange of route request/reply messages between nodes, in order to provide more reliable connectivity. Multimedia stream are transmitted via the primary path by default unless it is disconnected, in which case the backup path is activated for transmission. Simulation-based results have proven that the backup routing algorithm successfully shortened the route establishment and re-built time, which is beneficial for real-time multimedia communications.

Recent research works focus more on allocating mesh network resources in a more efficient way. [17] presents a SPEA-based routing algorithm which considers shortest path, energy consumption, free-space loss and restrictions on delay and network bandwidth. The algorithm works in a distributed and multi-objective way as each mesh node in the algorithm is able to select any other nodes on its routing path. The complexity of the algorithm is independent from the number of mesh nodes so that it is suitable for large-scale mesh networks. Also, the algorithm is capable to handle both unicast and multicast schemes.

Despite of these and other research efforts, no solution balances well both energy saving and performance awareness.

III. Architectures of E-Mesh

This section presents proposed E-Mesh's architecture.

A. General Network Topology

Consider a wireless mesh network topology illustrated in Figure 1, in which the remote video server is a single mesh source node n_0. There are N mesh routers (n_1 to n_N) for data forwarding and at least one end user smartphone as the mesh client n_{N+1}. The position of each of these N routers is randomly distributed in a circular area with radius R. Some of the mesh routers move with a random velocity within the range of this circular area while others remain fixed. The mesh client n_{N+1} is moving with constant velocity when mobile, with its initial position at the edge of the circular area considered. The location of the mesh data source n_0 is fixed at the center of a circular area of consideration, as shown in Figure 1.

While the video content is being streamed from the remote server to the user device, the video data packets pass through multiple routers in the wireless mesh network along the delivery route. Depending on the traffic conditions and network topology variation in the wireless mesh network, this delivery route may change. The network operators of mesh routers desire to reduce the energy consumption on their network, while ensuring the QoS provisioning of the video streaming services. To achieve this, the network operators can deploy E-Mesh, which offers an innovative way to balance energy consumption, network load and connectivity for mesh routers during the video streaming service.

B. E-Mesh Architecture

E-Mesh is based on the following assumptions:

- The maximum communication ranges of the mesh nodes (i.e. mesh router, mesh data source and mesh client) are the same (defined as K).
- Each mesh node n_i has the capability to determine its position in terms of coordinate (X_i,Y_i) and to measure its remaining energy level E_i and traffic load L_i.
- The time for the client to get the information from the routers (such as their position and remaining energy level) is very short in comparison with data transmission time and the client movement time scale.

The block architecture of E-Mesh is illustrated in Figure 2 and contains the following three modules:

1) ***Route Information Collector***: obtains router information such as remaining energy on each router, instant traffic load on each router and distance vectors between routers.

TABLE 1 COMMON PARAMETERS USED IN E-MESH TESTING

Symbol	DESCRIPTION	Value (unit)
D_{min}	Minimum distance between the mesh client and each mesh router	0 (meter)
D_{max}	Maximum distance between the mesh client and each mesh router	150 (meters)
E_{max}	Maximum amount of remaining energy of each mesh router	100 (Joule)
L_{min}	Minimum network traffic load of each mesh router	0 (Mbps)
L_{max}	Maximum network traffic load passing each mesh router	2 (Mbps)
N	Number of mesh routers	20
T	The overall simulation time	200 (s)

2) ***Energy-Load-Distance-based Utility Function***: computes the utility function for all the mesh routers based on the information from the Route Information Collector module.
3) ***Route Selection***: establishes the best route for traffic delivery based on a sequence of energy-load-distance -aware utility values provided by the utility function.

B-1 Route Information Collector

This module is in charge of collecting network/ device-condition-based information from the mesh routers, including the remaining energy levels at each mesh router, current traffic load amount and distance between mesh routers, calculated using the position of each router. The information is used when computing by the utility function to assess the general condition of all the nodes in the wireless mesh network, in order to select the most suitable route for traffic delivery in terms of the least energy consumption on the mesh routers, optimal traffic load amount on the mesh routers and distance between routers within their maximum communication range.

The information is collected from the headers of the ATIM [7] packets sent by the PHY layer and forwarded by the MAC layer. The messages are stored and updated in a global route information table in which the utility function obtains the information as it needs. The process of the information collection is illustrated in Figure 3. The information of remaining energy and current network load of each mesh router is included in the ATIM packets by the PHY layer and sent to the MAC layer. After the MAC layer receives the packets, the information of (X, Y) position of each mesh router is added to the headers and the packets are forwarded to the network layer where E-Mesh obtains such information and stores them in the global route information table.

The duty cycle of each mesh router is controlled with the MAC-layer solution AOC-MAC, which periodically observes the communication states of the mesh routers included in the ATIM packets from E-Mesh and adjusts the length of the active periods of the mesh router in the duty cycle according to the communication states.

B-2 Energy-Load-Distance-based Utility Function

The responsibility of the Energy-Load-Distance Utility Function module is to calculate the utility for each mesh router to enable choosing the next hop for the traffic from the neighbor mesh routers of the current mesh router. The neighbor mesh router with the optimal utility value will be selected as the next hop of the traffic and it will search for its next hop with the utility values of all its neighbor routes recalculated.

In the wireless mesh network topology shown in Figure 1, each mesh router n_i considers the following three key criteria for utility calculation: its local position in terms of the (X_i, Y_i) coordinates, its current network traffic load L_i and its remaining energy E_i. The remaining energy and network traffic load for each mesh router are updated periodically during the video streaming traffic delivery. Hence for each mesh router n_i, the Energy-Load-Distance-based utility function is shown in equation (4). It relies on the following components as described in equations (1), (2) and (3):

1) Remaining energy score $E(n_i)$:

$$E(n_i) = \frac{E}{E_{max}} \quad (1)$$

2) Distance score $D(n_i)$:

$$D(n_i) = \frac{D - D_{min}}{D_{max} - D_{min}} \quad (2)$$

3) Load score $L(n_i)$:

$$L(n_i) = \frac{L - L_{min}}{L_{max} - L_{min}} \quad (3)$$

In these functions E, D and L represent the current remaining energy, distance to the mesh client and traffic load of router n_i, which are obtained by the Router Information Collector. E_{max}, D_{max} and L_{max} represent the maximum value of remaining energy, distance to the mesh client and traffic load of router n_i, while D_{min} and L_{min} represent the minimum distance to the mesh client and traffic load of router n_i..

$$C(n_i) = \frac{L(n_i)^{W_l} * D(n_i)^{W_d}}{E(n_i)^{W_e}} \quad (1 <= i <= N) \quad (4)$$

In equation (4) W_e, W_d and W_l are adaptive weight factors for the utilities, respectively. The weights represent the importance of the different utilities in the route selection. The values of the weights are decided by the network operators of the mesh nodes in the wireless mesh network, depending on different possible demands on various situations. For example, the value of W_e is set higher in the case that the energy consumption is considered more important. On the other hand, if the network operator cares more about network load, the values of W_l can be set higher. As already mentioned, N represents the total number of mesh routers in the wireless mesh network.

B-3 Route Selection

Based on the utility calculation results provided by the Energy-Load-Distance Utility Function module, the Route Selection module is responsible for picking the mesh routers with the optimal utility values hop by hop, starting from the router closest to the remote server and ending at the router closest to the mesh client, to build the optimal traffic delivery route balancing the energy-load-distance criteria. The utility-optimal route is updated periodically by this module, according to the change of network conditions and routing device characteristics.

When no neighboring mesh routers are detected during the routing process, a disconnection announcement is made in the form of a 0-1 bit message (0 represents no disconnection and 1 represents disconnection) and sent to the Route Information Collector module. After receiving the disconnection announcement, the Route Information Collector module stores the 0-1 bit announcement message into the OSPF [18] packet headers before sending the OSPF packets to the MAC layer. The disconnection announcement is then used by the MAC-layer protocol as the link state information. This process is illustrated in Figure 3.

IV. SIMULATION TEST BED SETUP

A. Simulation Topology for E-Mesh

This section presents the detailed settings for the simulation-based testing. Modeling and simulation was performed using Network Simulator 3 (NS-3) [19] version 13, enhanced with an AOC-MAC model [6].

The wireless mesh network topology used in the simulation is illustrated in Figure 1, containing the following components:

- N mesh routers $\{n_1, n_2, \ldots n_N\}$ for data forwarding.
- Two mesh clients n_0 and n_{N+1}, n_0 is used as the user-required video source, i.e., the sender, and n_{N+1} works as the end user device, i.e., the receiver.

The positions of the N mesh routers are randomly distributed in a circular area with radius R.

B. Simulation Test Bed Setup for E-Mesh

In simulations the videos were transmitted using an extension of the EvalVid model [20], a tool-set used for measuring video quality during transmission through real-time or simulation networks. In order to avoid unnecessary ICMP traffic during transmission, EvalVid obtains video information by parsing the trace file of the video frames which are generated by the mp4trace tool inside. After transmission, QoS parameters such as frame loss rate, end-to-end delay, cumulative jitter and several video quality measurement matrices are generated as output for user-perceived video quality evaluation.

To study the performance of E-Mesh within different wireless mesh network environments, separate test scenarios were performed to study the impact of different weigh factor settings in the E-Mesh utility function [4] and different settings of mesh router mobility. Each scenario includes a specific experimental setup based on the topology illustrated in Figure 1. The performance of E-Mesh is evaluated in terms of the following parameters on each mesh router, in comparison with the performance of the IEEE 802.11s routing protocol:

- Average energy consumption rate
- QoS parameters such as video packet loss rate and network throughput
- Video quality assessment parameters

Tests are initialized with the parameters listed in Table 1.

The energy model used in both scenarios is an extension of the energy model provided by NS-3, which measures the power of mesh devices by multiplying two main factors:

1) Voltage: The voltage is set in the initialization stage of the topology with a fixed value 3.0 V.
2) Radio current intensity: NS-3 supports five different working states of each mesh device in the physical layer. In each of them the mesh device has associated different current intensities. Our extended energy model includes an additional SLEEP state, relevant to our research:
   a) IDLE: the device is idle (current intensity I = 426μA)
   b) CCA_BUSY: the device has sensed the medium busy through the CCA mechanism (I = 426μA)
   c) TX: the device is sending a packet (I = 17.4mA)
   d) RX: the device is receiving a packet (I = 19.7mA)
   e) SWITCHING: the device is switching to another channel if it is multi-channel (I = 426μA)
   f) SLEEP: the device is off (I = 20uA)

The transmission quality is estimated in terms of the PSNR value of the received data stream, which translates the effect of bit rate and loss on user perceived quality according to the formula [21] presented in equation (5). The relationship between various PSNR values and the corresponding user perceived quality levels is illustrated as associated by the ITU T. P.800 standard [22].

$$PSNR = 20\,log_{10}\left(\frac{MAX\_Bitrate}{\sqrt{(EXP\_Thr - CRT\_Thr)^2}}\right) \quad (5)$$

In equation (5), *MAX_Bitrate* is the average bit rate of the data stream transmitted, *EXP_Thr* is the average throughput expected to be obtained and *CRT_Thr* is the actual measured average throughput. According to the parameter settings presented in Table 1, the value of *MAX_Bitrate* and *EXP_Thr* in equation (4) is 2 Mbps during simulation.

The following test scenarios are designed for E-Mesh:

- *Scenario B1*: the traffic load weight W_l is set as 1.0, 2.0, 3.0 and 4.0.
- *Scenario B2*: the remaining energy weight W_e is set as 1.0, 2.0, 3.0 and 4.0.
- *Scenario B3*: the mesh router distance weight W_d is set as 1.0, 2.0, 3.0 and 4.0.

For each E-Mesh scenario, testing was based on the following two settings of mesh router mobility cases:

- *Case 1*: All the N mesh routers $\{n_1, n_2, \ldots n_N\}$ were allocated with fixed positions, which were uniformly distributed in the range of [0, 2π] with in the circular area. The position of mesh client n_0 was at the center of the circular area, remaining fixed. The mesh client n_{N+1} moves from the boundary of the circular area towards n_0, with a constant speed 2.0 m/s.
- *Case 2*: The mesh routers were allocated with an initial random pause period between [0, 2] (seconds), a random movement direction value between [0, 2π] and a random speed value between [1.0, 2.0] (m/s) towards this direction until it reaches the boundary of the mesh network with range R, as shown in Figure 1. The mesh

(a) Source video frame (b) Received video frame

Fig.6. An example of the quality of the original and received video clips (images from "*Back to the Future*" Courtesy of Universal Studios Licensing LLC)

Fig.4. Experimental real-life test-bed topology - Principle

client n_{N+1} was allocated with a constant speed 2.0 m/s from at the boundary towards the mesh client n_0 located and fixed at the center of the circular area.

Fig.5. Experimental real-life test-bed topology used - Deployment

V. Perceptual Test Bed Setup

The simulation-based tests described in the previous sections have provided performance evaluation for E-Mesh in terms of energy consumption rate, transmission QoS parameters (e.g. loss rate, delay) and estimated transmission quality. Although PSNR was used in the simulation-based tests to estimate user perceived quality, quality evaluation based on actual measurements and perceptual testing were performed in order to confirm the simulation results. For this purpose, a real-life test-bed with an E-Mesh prototype has been set-up.

Several video clips were transmitted for performance evaluation. The delivered video clips were saved at the mesh client device and were evaluated using objective and subjective video quality assessment metrics.

A. General Topology

Prototyping of E-Mesh was done using the NS-3 Tap Bridge [23] mechanism, provided as a particular NS-3 module. This enables the integration of real-life Internet hosts into NS-3 simulations. The experimental test-bed topology is illustrated in Figure 5, and consists of a multimedia server, a client machine and a "Bridge" host set in between the server and client. The multimedia server and client are installed with one single Ethernet card. The "Bridge" is installed with two Ethernet cards *Eth0* and *Eth1*, connected to the multimedia server and client using Ethernet cables, respectively. The NS-3 implementation of E-Mesh is deployed at the "Bridge" host, in which the NS-3 server node in the simulation topology is connected with the multimedia server host and the NS-3 client node in the simulation topology is connected with the client host, using the Tap Bridge module. This ensures that the solution implementation has impact on the traffic delivery from the multimedia server host to the client host. Figure 5 further presents the photo of the test-bed based on the topology illustrated in Figure 4.

B. Equipment and Software Specifications

The hardware equipment involved in the tests is listed below:

- Multimedia server host: a desktop with Ubuntu 12.04, Intel Core i7-3770 at 3.48GHz and NetXtreme BCM5722 Gigabit Ethernet PC card
- Client host: a desktop with Ubuntu 12.04, Intel Core i7-3770 at 3.48GHz and NetXtreme BCM5722 Gigabit Ethernet PC card
- "Bridge" host: a desktop with Ubuntu 12.04, Intel Core i7-3770 at 3.48GHz and two Ethernet cards:
  - NetXtreme BCM5722 Gigabit Ethernet PC
  - 82579LM Gigabit Network Connection
- 2 KRONE PremisNET CATEGORY 5e Ethernet cables

The software used in the tests is listed below:

- Video LAN Client (VLC) [24]: an open-source video player supporting multiple operating systems and most of the existing codecs. VLC is deployed at both the multimedia server host and the client host, used for

TABLE 2 ENERGY CONSUMPTION RATES, TRAFFIC LOSS RATES AND PSNR VALUES WITH DIFFERENT SETS OF THE THREE UTILITIES FOR 802.11S AND E-MESH

E-Mesh Utility Function Weight Factor		Energy Consumption Rate (Joule/s)				Loss Rate (%)				PSNR (dB)			
		802.11s		E-Mesh		802.11s		E-Mesh		802.11s		E-Mesh	
		Sta	Mov	Sta	Mov	Sta	Mov	Sta	Mov	Sta	Mov	Sta	Mov
Traffic Load	1.0	23.98	24.9	20.71	22.16	2.984	3.113	4.057	4.386	30.5	30.14	27.84	27.16
	2.0	23.98	24.9	21.55	22.88	2.984	3.221	4.057	4.467	30.5	29.84	27.84	26.99
	3.0	23.98	24.9	22.07	23.36	2.984	3.306	4.057	4.514	30.5	29.61	27.84	26.91
	4.0	23.98	24.9	22.40	23.74	2.984	3.353	4.057	4.546	30.5	29.49	27.84	26.85
Remaining Energy	1.0	23.98	24.9	20.71	22.16	2.984	3.113	4.057	4.386	30.5	30.14	27.84	27.16
	2.0	23.98	24.9	19.53	20.66	2.984	3.251	4.057	4.496	30.5	29.76	27.84	26.94
	3.0	23.98	24.9	17.78	18.4	2.984	3.362	4.057	4.572	30.5	29.47	27.84	26.79
	4.0	23.98	24.9	15.12	16.66	2.984	3.449	4.057	4.627	30.5	29.24	27.84	26.69
Mesh Router Distance	1.0	23.98	24.9	20.71	21.66	2.984	3.113	4.057	4.386	30.5	30.14	27.84	27.16
	2.0	23.98	24.9	20.56	21.49	2.984	3.297	4.057	4.502	30.5	29.64	27.84	26.93
	3.0	23.98	24.9	20.45	21.35	2.984	3.426	4.057	4.587	30.5	29.3	27.84	26.77
	4.0	23.98	24.9	20.38	21.28	2.984	3.503	4.057	4.633	30.5	29.11	27.84	26.68

video traffic sending and receiving.

- MSU Video Quality Measurement Tool [25]: an objective video quality assessment software which supports most of the objective video quality assessment metrics such as PSNR, MSE, VQM and MSSSIM. It requires the original video and the delivered video to be simultaneous inputs of the video quality assessment metrics.

C. *Video Clip*

The video clip selected for transmission is a sequence from the "Back to the Future" with the following parameters: size: 250 MB, duration: 25 minutes and 29 seconds, encoding codec: MPEG-4, bit rate: 1339 Kbps, resolution: 1280×720, frame rate: 23.976 fps and color space: YUV. Illustrations of frames from the source and received video clips, respectively are presented in Figure 6.

D. *Experimental Scenarios*

To investigate the video transmission quality of E-Mesh, the following test cases are designed:

- *Case B1*: The video clips are delivered from the multimedia server host to the client host. The corresponding NS-3 E-Mesh scenario *B1* is deployed and simulated on the "Bridge" host, with different settings of the traffic load weight and the mesh router mobility set to as follows:
  - Static: mesh routers have fixed positions.
  - Randomly Moving: mesh routers are moving with uniformly distributed speeds and directions.
- *Case B2*: The video clips are delivered from the multimedia server host to the client host. The corresponding NS-3 E-Mesh scenario *B2* is deployed and simulated on the "Bridge" host, with different settings of the remaining energy and the mesh router mobility set to as follows:
  - Static: mesh routers have fixed positions.
  - Randomly Moving: mesh routers are moving with uniformly distributed speeds and directions.
- *Case B3*: The video clips are delivered from the multimedia server host to the client host. The corresponding NS-3 E-Mesh scenario *B3* is deployed and simulated on the "Bridge" host, with different settings of the mesh router distance weight and the mesh router mobility set to as follows:
  - Static: mesh routers have fixed positions.
  - Randomly Moving: mesh routers are moving with uniformly distributed speeds and directions.

E. *Objective Quality Assessment*

Despite the fact that PSNR [26] is not a standard video quality metric and has some limitations in terms of its accuracy, as it is widely used for subjective video quality assessment, PSNR was selected as the objective video quality assessment metric for the delivered video quality measurement of E-Mesh. This makes the comparison between the results easier. The delivered video quality is affected by QoS parameters such as packet loss and end-to-end delay. In general, higher traffic throughput and lower loss indicate better received video quality. Figure 6 illustrates the quality of the original and received videos affected by the QoS parameters.

F. *Subjective Quality Assessment*

PSNR was used for measuring the received video quality in the real-life experimental tests, as there are reports that the PSNR-based objective video quality assessment does not correlate perfectly with the user perceived quality from human vision, which behaves non-linearly. This section presents the investigation of the performance of E-Mesh using subjective video quality assessment. MOS [22] was selected as the subjective video quality metric. The MOS quality scale is from 1 to 5, where a value of 1 indicates "bad" quality and a value of 5 indicates "excellent" quality. Test video sequences are transmitted from the multimedia server host to the client host, over the "Bridge" host where the prototyping of E-Mesh is deployed within NS-3. The delivered video clips are obtained based on the same test cases described in the objective video quality assessment in section VI B.

The subjective tests were done in a separate room without any disturbance from outside. 20 users (12 males and 8 females) were invited to watch the video clips received in the test cases.

The age of users was distributed between 24 to 40 years old. The occupations of the users include technicians, students, business people, engineers, etc. The users watched the video clips in different order and after watching each video clip, they rated clip's perceived quality based on the MOS metric by filling a questionnaire presented on paper. During the subjective test, any video clip presented to a user will never repeat to the same user, in order to prevent user boredom according to the ITU-T Rec. P.913 [27].

VI. Result Analysis

A. E-Mesh Simulation Test Result Analysis

The network traffic load and remaining energy on the mesh routers and the distance between mesh routers in the mesh network are considered as the three key parameters in the E-Mesh routing utility function. This section studies how the E-Mesh performance is affected by these parameters.

In the simulation-based tests, the weight of the network traffic load, remaining energy and router distance in the E-Mesh utility function are controlled by the weight factor W_l, W_e *and* W_d, respectively. The influence of each parameter was tested separately with various values varied from 1.0 to 4.0, representing the exponentially growth of the importance of the weight in the E-Mesh routing utility function. For tests of each parameter, the values of the other two parameters were set to 1.0 by default and remained fixed.

Note the energy consumption rates in the tests were average rates of all the mesh routers in the considered network, not just the ones along the selected path, as the path can dynamically vary during testing.

The test results for the three parameters were summarized in Table 2 and analyzed as follows.

Static Mesh Routers

As shown in Table 2, when considering the influence of **network traffic load**, the average energy consumption rates of the IEEE 802.11s routing protocol remain the same, as HWMP is used as the default protocol without the influence from the E-Mesh utility function. On the other hand, the energy consumption rates of E-Mesh slightly increase along with the increase of W_l, which results in deviations of selecting the active neighboring mesh routers with higher traffic load during the routing process, regardless of the remaining battery energy on those routers. With the value of W_l set to 1.0, 2.0, 3.0 and 4.0, E-Mesh has achieved approximately 13.64%, 10.13%, 7.96% and 6.59% energy savings in comparison with the IEEE 802.11s routing protocol, respectively.

The frame loss rates slightly increase along with the increase of the value of W_l, as higher value of W_l indicates higher importance of traffic load during mesh router selection and results in higher chance of traffic overloading and packet drop. With the value of W_l set to 1.0, 2.0, 3.0 and 4.0, E-Mesh has experienced approximately 4.32%, 7.94%, 10.79% and 12.36% increase of the average frame loss rate in comparison with the IEEE 802.11s routing protocol, respectively. The PSNR values decrease along with the increase of the value of W_l for E-Mesh, as higher value of W_l indicates higher chance of packet drop and results in transmission quality decline. With different values of W_l, the transmission quality of E-Mesh remains roughly the same level in comparison with the IEEE 802.11s routing protocol, with approximately 0.4dB, 0.7dB, 0.9dB and 1.0 dB decrease.

It is clear that with static mesh routers, E-Mesh achieves considerable energy savings in comparison with the IEEE 802.11s routing protocol, while maintaining roughly the same quality level with different values of W_l. The energy saving benefit of E-Mesh decreases along with the increase of the value of W_l, but still remains at a good level. When the increase of W_l exceeds a certain limit, the energy saving benefit does not overcome the quality decrease any more.

When considering the influence of **remaining energy** which indicates energy consumption rate, the average energy consumption rates of the IEEE 802.11s routing protocol remain fixed. The average energy consumption rates of E-Mesh slightly decrease along with the increase of the value of W_e, as higher value of W_e indicates deviations of selecting mesh routers with more remaining energy during routing process. With the value of W_e set to 1.0, 2.0, 3.0 and 4.0, E-Mesh has achieved approximately 13.64%, 18.56%, 25.85% and 36.54% energy savings in comparison with the IEEE 802.11s routing protocol, respectively.

The frame loss rates of E-Mesh increase along with the increase of the value of W_e. With the value of W_e set to 1.0, 2.0, 3.0 and 4.0, E-Mesh has experienced approximately 4.32%, 8.95%, 12.67% and 15.58% increase of the average frame loss rate in comparison with the IEEE 802.11s routing protocol, respectively. The PSNR values decrease along with the increase of the value of W_e for E-Mesh while the PSNR values of the 802.11s routing protocol remain the same. With different values of W_e, the transmission quality of E-Mesh decrease for 0.4dB, 0.8dB, 1.0dB and 1.3dB in comparison with the IEEE 802.11s routing protocol.

It is clear that with the static mesh routers, the energy saving benefit of E-Mesh increases along with the increase of the value of W_e, as energy is considered with higher weight during the routing process. In this case, E-Mesh achieves considerable energy savings in comparison with the IEEE 802.11s, while the transmission quality level remains approximately the same.

When considering the influence of **distance between mesh routers**, the average energy consumption rates of the IEEE 802.11s routing protocol do not change while the average energy consumption rates of E-Mesh decrease along with the increase of the value of W_d, as higher value of W_d indicates lower transmission power. With the value of W_d set to 1.0, 2.0, 3.0 and 4.0, E-Mesh has achieved approximately 13.64%, 14.26%, 14.72% and 15.01% energy savings in comparison with the IEEE 802.11s routing protocol, respectively. The frame loss rates of E-Mesh slightly increase along with the increase of the value of W_d while the frame loss rates of the IEEE 802.11s routing protocol stay in the same level. With the value of W_d set to 1.0, 2.0, 3.0 and 4.0, E-Mesh has experienced approximately 4.32%, 10.49%, 14.81% and 17.39% increase of

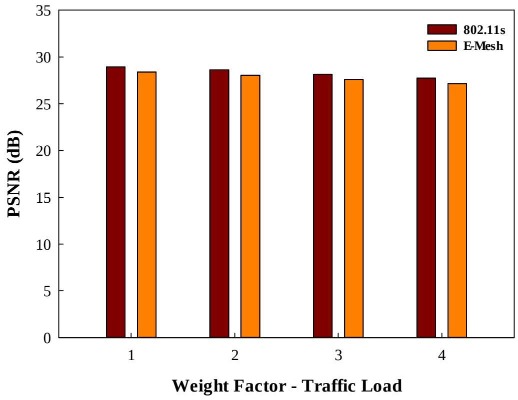

Fig.7. PSNR achieved using 802.11s and E-Mesh with variable weights on traffic load when the mesh routers are static

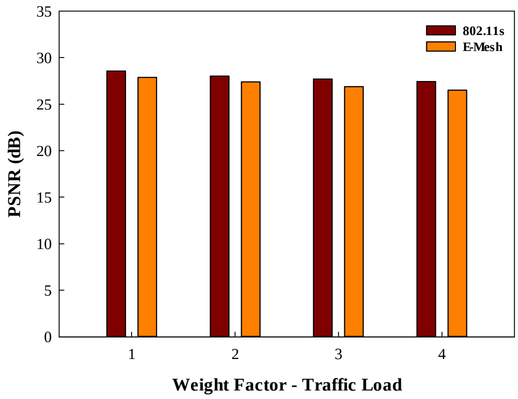

Fig.8. PSNR achieved using 802.11s and E-Mesh with variable weights on traffic load when the mesh routers are moving

the average frame loss rate in comparison with the IEEE 802.11s routing protocol, respectively.

The PSNR values of E-Mesh slightly decrease along with the increase of the value of W_d, but roughly remain at a stable level. With the value of W_d set to 1.0, 2.0, 3.0 and 4.0, the transmission quality of E-Mesh remains roughly the same level in comparison with the IEEE 802.11s routing protocol, with approximately 0.4dB, 0.8dB, 1.2dB and 1.4dB decrease.

It is clear that with static mesh routers, E-Mesh achieves better energy savings in comparison with the IEEE 802.11s routing protocol, which increases along with the increase of the value of W_d, while maintaining roughly the same transmission quality levels.

Moving Mesh Routers

As shown in Table 2, when considering the influence of **network traffic load**, the average energy consumption rates of the IEEE 802.11s routing protocol still remain the same, without the influence from the E-Mesh utility function. The energy consumption rates of E-Mesh slightly increase along with the increase of the value of W_l. With the value of W_l set to 1.0, 2.0, 3.0 and 4.0, E-Mesh has achieved approximately 11.01%, 8.11%, 6.18% and 4.66% energy savings in comparison with the IEEE 802.11s routing protocol, respectively. The frame loss rates of E-Mesh slightly increase along with the increase of the value of W_l. With the value of W_l set to 1.0, 2.0, 3.0 and 4.0, E-Mesh has experienced approximately 8.11%, 10.14%, 11.26% and 12.05% increase of the average frame loss rate in comparison with the IEEE 802.11s routing protocol, respectively. The PSNR values of E-Mesh decrease along with the increase of the value of W_l. With different values of W_l, the transmission quality of E-Mesh remains roughly at the same level in comparison with the IEEE 802.11s routing protocol, recording approximately 0.7 dB, 0.8dB, 0.9dB and 1.0dB decreases, respectively.

It is noted that with moving mesh routers, the energy saving benefit of E-Mesh in comparison with the IEEE 802.11s routing protocol is less obvious than with static mesh routers, and decreases along with the increase of the value of W_l.

When considering the influence of **remaining energy** which indicates energy consumption rate, the average energy consumption rates of E-Mesh decrease along with the increase of the value of W_e, while the average energy consumption rates of IEEE 802.11s routing protocol remain fixed. With the value of W_e set to 1.0, 2.0, 3.0 and 4.0, E-Mesh has achieved approximately 11.01%, 17.03%, 25.11% and 33.09% energy savings in comparison with the IEEE 802.11s routing protocol, respectively. The frame loss rates of E-Mesh slightly increase along with the increase of the value of W_e. With the value of W_e set to 1.0, 2.0, 3.0 and 4.0, E-Mesh has experienced approximately 8.11%, 10.82%, 12.69% and 14.05% increase of the average frame loss rate in comparison with the IEEE 802.11s routing protocol, respectively. The PSNR values of E-Mesh decrease along with the increase of the value of W_e and the PSNR values of the IEEE 802.11s routing protocol remain the same. With different values of W_e, the transmission quality of E-Mesh was approximately 1 dB lower than the IEEE 802.11s routing protocol.

Note that E-Mesh achieves significant energy savings in comparison with the IEEE 802.11s routing protocol, regardless of the mesh router mobility. The energy saving benefit of E-Mesh increases along with the increase of the value of W_e, while the QoS level of E-Mesh decreases with moving mesh routers in comparison with static mesh routers, but still remains at a good level.

When considering the influence of **distance between mesh routers**, the average energy consumption rates of the IEEE 802.11s routing protocol remain the same while the energy consumption rates of E-Mesh slightly decrease along with the increase of the value of W_d. With the value of W_d set to 1, 2, 3 and 4, E-Mesh has achieved approximately 13.01%, 13.69%, 14.26% and 14.54% energy savings in comparison with the IEEE 802.11s routing protocol, respectively. The frame loss rates of E-Mesh slightly increase along with the increase of the value of W_d. With the value of W_d set to 1.0, 2.0, 3.0 and 4.0, E-Mesh has experienced approximately 7.51%, 10.96%, 13.06% and 14.19% increase of the average frame loss rate in comparison with the IEEE 802.11s routing protocol, respectively. The PSNR values of E-Mesh decrease along with the increase of the value of W_d. With the value of W_d set to 1.0, 2.0, 3.0 and 4.0, the transmission quality of E-Mesh remains

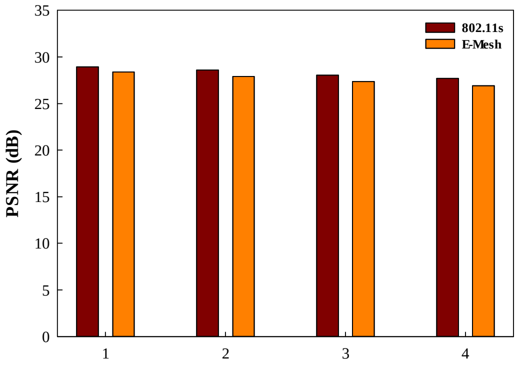

Fig.9. PSNR achieved using 802.11s and E-Mesh with variable weights on remaining energy when the mesh routers are static

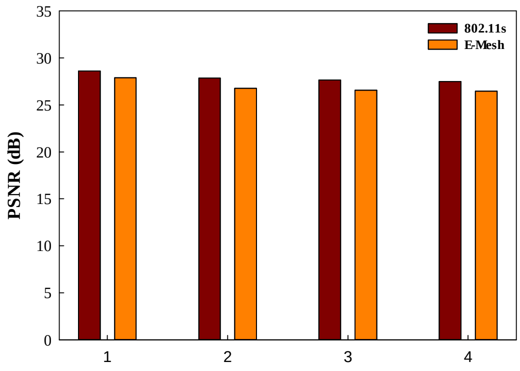

Fig.10. PSNR achieved using 802.11s and E-Mesh with variable weights on remaining energy when the mesh routers are moving

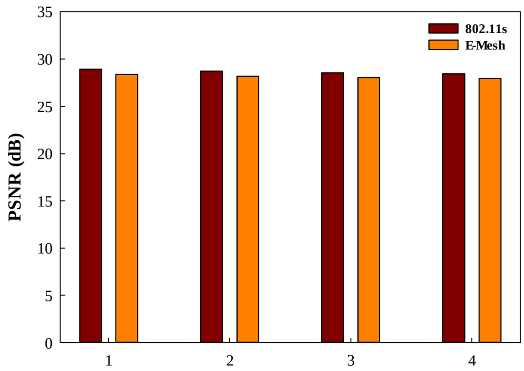

Fig.11. PSNR achieved using 802.11s and E-Mesh with variable weights on mesh router distance when the mesh routers are static

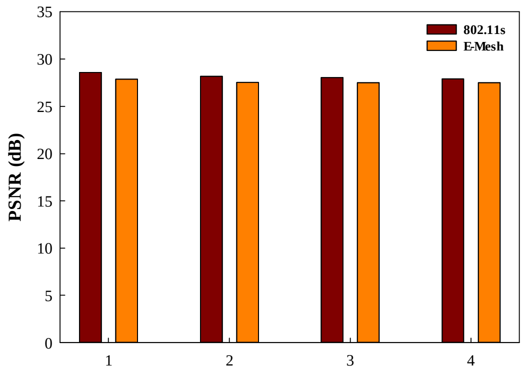

Fig.12. PSNR achieved using 802.11s and E-Mesh with variable weights on mesh router distance when the mesh routers are moving

roughly the same level in comparison with the IEEE 802.11s routing protocol, with approximately 0.7dB, 0.9dB, 1.1dB and 1.2dB decrease.

Note that with moving mesh routers, the energy saving benefit of E-Mesh in comparison with the IEEE 802.11s routing protocol is roughly the same with than when static mesh routers are considered, regardless of the value of W_d.

B. Objective Test Result Analysis

Figure 7 and Figure 8 illustrate the measured PSNR results of the received videos for the E-Mesh experimental test case B-1 with different weights on the traffic load, when the mesh routers are static and moving, respectively. In Figure 7, when the mesh routers are static, the PSNR of the received video slightly decreases along with the increase of the traffic load weight factor value, but in general it remains at a stable level. In this case, the PSNR of the received video using E-Mesh has decreased approximately 1.9%, 1.95%, 1.85% and 2.09% with the traffic load weight factor value 1.0, 2.0, 3.0 and 4.0, respectively, in comparison with IEEE 802.11s.

In Figure 8, when the mesh routers are moving, the PSNR of the received video again slight decreases along with the increase of the traffic load weight factor value. In this case, the PSNR of the received video using E-Mesh has decreased approximately 2.4%, 2.17%, 2.96% and 3.35% with the traffic load weight factor value 1.0, 2.0, 3.0 and 4.0, respectively, in comparison with the IEEE 802.11s routing protocol. In general, the average PSNR of the received video is lower when the mesh routers are moving, in comparison with when the mesh routers are static, as the mobility of mesh routers decreases the stability of the network connectivity. With the traffic load weight factor value 1.0, 2.0, 3.0 and 4.0, the PSNR of the received video using the IEEE 802.11s routing protocol is roughly 1.21%, 2.1%, 1.56% and 1.08% lower when the mesh routers are moving, while the PSNR of the received video using E-Mesh is roughly 1.76%, 2.32%, 2.68% and 2.39% lower when the mesh routers are moving.

Figure 9 and Figure 10 illustrate the measured PSNR results of the received videos for the E-Mesh experimental test case B-2 with different weights on the remaining energy of mesh routers, when the mesh routers are static and moving, respectively. In Figure 9, when the mesh routers are static, the PSNR of the received video slightly decreases along with the increase of the remaining energy weight factor value, but in general it remains at a stable level. In this case, the PSNR of the received video using E-Mesh has decreased approximately 1.9%, 2.32%, 2.46% and 2.89% with the remaining energy weight factor value 1.0, 2.0, 3.0 and 4.0, respectively, in comparison with the IEEE 802.11s routing protocol.

In Figure 10, when the mesh routers are moving, the PSNR of the received video again slight decreases along with the

TABLE 3 PSNR VALUES WITH 802.11S AND E-MESH

E-Mesh Test Cases			PSNR (dB)			
			802.11s		E-Mesh	
			Static	Moving	Static	Moving
E-Mesh Utility Function Weight Factor	Traffic Load	1.0	28.87	28.42	28.31	27.75
		2.0	28.44	27.82	27.89	27.24
		3.0	28.01	27.54	27.47	26.69
		4.0	27.63	27.28	26.99	26.37
	Remaining Energy	1.0	28.87	28.42	28.31	27.75
		2.0	28.45	27.69	27.74	26.59
		3.0	27.91	27.45	27.19	26.44
		4.0	27.58	27.35	26.73	26.26
	Mesh Router Distance	1.0	28.87	28.42	28.31	27.75
		2.0	28.59	28.02	28.04	27.41
		3.0	28.42	27.88	27.82	27.34
		4.0	28.27	27.72	27.79	27.37

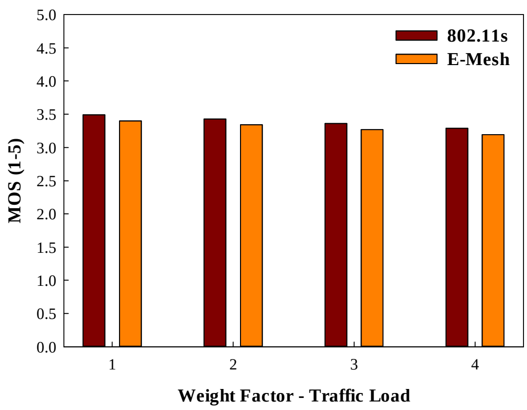

Fig.13. MOS achieved using 802.11s and E-Mesh with variable weights on traffic load when the mesh routers are static

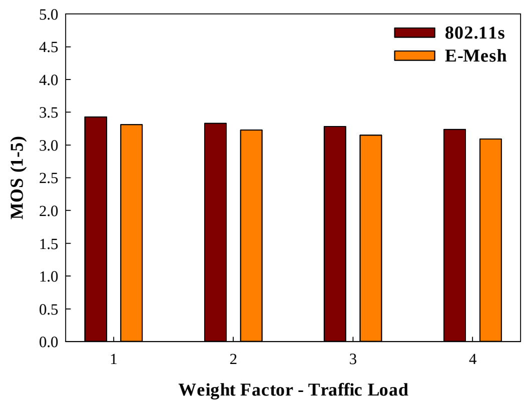

Fig.14. MOS achieved using 802.11s and E-Mesh with variable weights on traffic load when the mesh routers are moving

increase of the remaining energy weight factor value. In this case, the PSNR of the received video using E-Mesh has decreased approximately 2.4%, 3.84%, 3.83% and 3.82% with the remaining energy w eight factor value 1.0, 2.0, 3.0 and 4.0, respectively, i n comparison with the IEEE 802.11s routing protocol. In general, the average PSNR of the received video is lower when the mesh routers are moving, in comparison with when the mesh routers are static. With the remaining energy weight factor value 1.0, 2.0, 3.0 and 4.0, the PSNR of the received video using the IEEE 802.11s routing protocol is roughly 1.21%, 2.59%, 1.46% and 0.79% lower when the mesh routers are moving, while the PSNR of the received video using E-Mesh is roughly 1.76%, 4.08%, 2.85% and 1.75% lower when the mesh routers are moving.

Figure 11 and Figure 12 illustrate the measured PSNR results of the received videos for the E-Mesh experimental test case B-3 with different weights on the mesh router distance, when the mesh routers are static and moving, respectively. In Figure 11, when the mesh routers are static, the PSNR of the received video slight decreases along with the increase of the mesh router distance weight factor value, but in general it remains at a stable level. In this case, the PSNR of the received video using E-Mesh has decreased approximately 1.9%, 1.88%, 1.86% and 1.76% with the mesh router distance weight factor value 1.0, 2.0, 3.0 and 4.0, respectively, in comparison with the IEEE 802.11s routing protocol. In Figure 12, when the mesh routers are moving, the PSNR of the received video again slight decreases along with the increase of the mesh router distance weight factor value. In this case, the PSNR of the received video using E-Mesh has decreased approximately 2.4%, 2.27%, 1.89% and 1.45% with the mesh router distance weight factor value 1.0, 2.0, 3.0 and 4.0, respectively, in comparison with the IEEE 802.11s routing protocol. In general, the average PSNR of the received video is lower when the mesh routers are moving, in comparison with when the mesh routers are static. With the mesh router distance weight factor value 1.0, 2.0, 3.0 and 4.0, the PSNR of the received video using the IEEE 802.11s routing protocol is roughly 1.21%, 1.88%, 1.79% and 1.9% lower when the mesh routers are moving, while the PSNR of the received video using E-Mesh is roughly 1.76%, 2.27%, 1.82% and 1.61% lower when the mesh routers are moving.

The measured PSNR values of the received videos for E-Mesh test cases are concluded in Table 3. Although the PSNR values demonstrate the decrease of received video quality when E-Mesh is deployed, good level of energy saving is achieved in comparison with the IEEE 802.11s routing protocol, according to the simulation test results presented in section VI A.

C. *Subjective Test Result Analysis*

Figure 13 and Figure 14 illustrate the measured MOS results of the received videos for the E-Mesh experimental test case B1

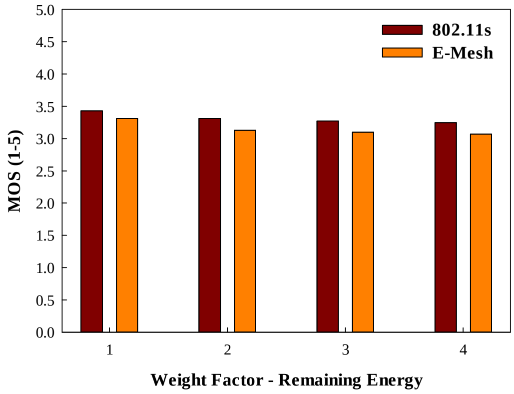

Fig.15. MOS achieved using 802.11s and E-Mesh with variable weights on remaining energy when the mesh routers are static

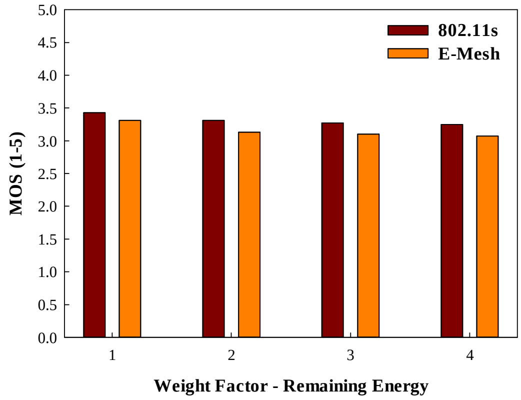

Fig.16. MOS achieved using 802.11s and E-Mesh with variable weights on remaining energy when the mesh routers are moving

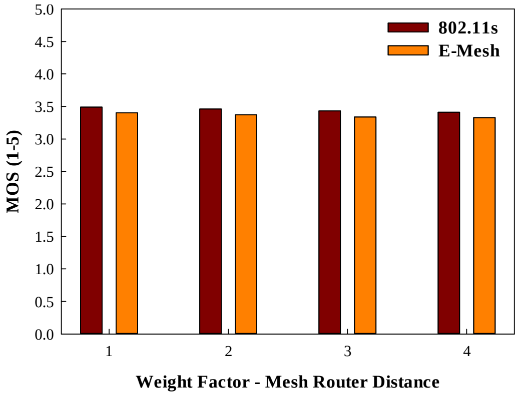

Fig.17. MOS achieved using 802.11s and E-Mesh with variable weights on mesh router distance when the mesh routers are static

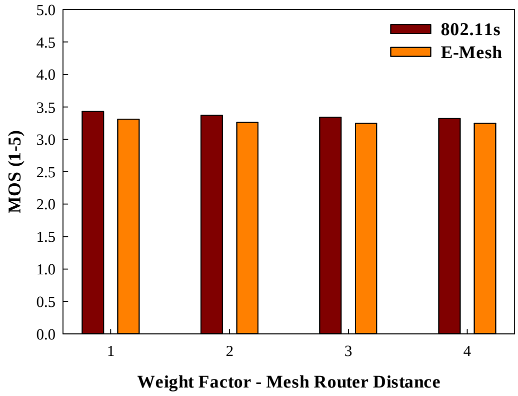

Fig.18. MOS achieved using 802.11s and E-Mesh with variable weights on mesh router distance when the mesh routers are moving

with different weights on the traffic load, when the mesh routers are static and moving, respectively. In Figure 13, when the mesh routers are static, the MOS of the received video slight decreases along with the increase of the traffic load weight factor value, but in general it remains at a stable level. In this case, the MOS of the received video using E-Mesh has decreased approximately 2.58%, 2.62%, 2.68% and 3.04% with the traffic load weight factor value 1.0, 2.0, 3.0 and 4.0, respectively, in comparison with the IEEE 802.11s routing protocol. In Figure 14, when the mesh routers are moving, the MOS of the received video again slight decreases along with the increase of the traffic load weight factor value. I n this case, the MOS of the received video using E-Mesh has decreased approximately 3.5%, 3%, 3.96% and 4.63% with the traffic load weight factor values of 1.0, 2.0, 3.0 and 4.0, respectively, in comparison with IEEE 802.11s. In general, the average MOS of the received video is lower when the mesh routers are moving, in comparison with when the mesh routers are static, as the mobility of mesh routers decreases the stability of the network connectivity. With the traffic load weight factor values of 1.0, 2.0, 3.0 and 4.0, the MOS of the received video using IEEE 802.11s is roughly 1.72%, 2.92%, 2.38% and 1.52% lower when the mesh routers are moving, while the MOS of the received video using E-Mesh is roughly 2.65%, 3.29%, 3.67% and 3.13% lower when the mesh routers are moving.

Figure 15 and Figure 16 illustrate the measured MOS results of the received videos for the E-Mesh experimental test case B2 with different weights on the remaining energy of mesh routers, when the mesh routers are static and moving, respectively. In Figure 15, when the mesh routers are static, the MOS of the received video slight decreases along with the increase of the remaining energy weight factor value, but in general it remains at a stable level. In this case, the MOS of the received video using E-Mesh has decreased approximately 2.58%, 3.21%, 3.29% and 4.26% with the remaining energy weight factor value 1.0, 2.0, 3.0 and 4.0 , respectively, in comparison with IEEE 802.11s. In Figure 16, when the mesh routers are moving, the MOS of the received video slight decreases again along with the increase of the remaining energy weight factor value. In this case, the MOS of the received video using E-Mesh has decreased approximately 3.5%, 5.44%, 5.2% and 5.54% with the remaining energy weight factor values of 1.0, 2.0, 3.0 and 4.0, respectively, in comparison with IEEE 802.11s. In general, the average MOS of the received video is lower when the mesh routers are moving, in comparison with when the routers are static. With the remaining energy weight factor values 1.0, 2.0, 3.0 and 4.0, the MOS of the received video using the IEEE 802.11s routing protocol is roughly 1.72%, 3.5%, 2.1% and 1.22% lower when the mesh routers are moving, while the MOS of the received video using E-Mesh is roughly 2.65%, 5.72%, 4.02% and 2.54% lower when the routers are moving.

Figure 17 and Figure 18 illustrate the measured MOS results of the received videos for the E-Mesh experimental test case B3

TABLE 4 MOS VALUES WITH 802.11S AND E-MESH

E-Mesh Test Cases			MOS (1-5)			
			802.11s		E-Mesh	
			Static	Moving	Static	Moving
E-Mesh Utility Function Weight Factor	Traffic Load	1.0	3.49	3.43	3.40	3.31
		2.0	3.43	3.33	3.34	3.23
		3.0	3.36	3.28	3.27	3.15
		4.0	3.29	3.24	3.19	3.09
	Remaining Energy	1.0	3.49	3.43	3.40	3.31
		2.0	3.43	3.31	3.32	3.13
		3.0	3.34	3.27	3.23	3.10
		4.0	3.29	3.25	3.15	3.07
	Mesh Router Distance	1.0	3.49	3.43	3.40	3.31
		2.0	3.46	3.37	3.37	3.26
		3.0	3.43	3.34	3.34	3.25
		4.0	3.41	3.32	3.33	3.25

with different weights on the mesh router distance, when the mesh routers are static and moving, respectively. In Figure 17, when the mesh routers are static, the MOS of the received video slight decreases along with the increase of the mesh router distance weight factor value, but in general it remains at a stable level. In this case, the MOS of the received video using E-Mesh has decreased approximately 2.58%, 2.6%, 2.62% and 2.35% with the mesh router distance weight factor value 1.0, 2.0, 3.0 and 4.0, respectively, in comparison with the IEEE 802.11s routing protocol. In Figure 18, when the mesh routers are moving, the MOS of the received video again slight decreases along with the increase of the mesh router distance weight factor value. In this case, the MOS of the received video using E-Mesh has decreased approximately 3.5%, 3.26%, 2.69% and 2.21% with the mesh router distance weight factor value 1.0, 2.0, 3.0 and 4.0, respectively, in comparison with the IEEE 802.11s routing protocol. In general, the average MOS of the received video is lower when the mesh routers are moving, in comparison with when the mesh routers are static. With the mesh router distance weight factor value 1.0, 2.0, 3.0 and 4.0, the MOS of the received video using the IEEE 802.11s routing protocol is roughly 1.72%, 2.6%, 2.62% and 2.64% lower when the mesh routers are moving, while the MOS of the received video using E-Mesh is roughly 2.65%, 3.26%, 2.69% and 2.4% lower when the mesh routers are moving.

The measured MOS values of the received videos for E-Mesh test cases are concluded in Table 4. Although the MOS values demonstrate the decrease of received video quality when E-Mesh is deployed, good level of energy saving is achieved in comparison with the IEEE 802.11s routing protocol, according to the simulation test results presented in section VI B.

VII. CONCLUSIONS AND FUTURE WORK

This paper presents an energy-aware network-layer routing algorithm E-Mesh for the purpose of energy saving and maintaining good application service quality levels for devices in wireless mesh networks. The performance analysis of E-Mesh was performed via simulations using NS-3 and real-life experimental tests using objective and subjective quality assessment metrics. Simulation models and prototypes for E-Mesh were developed and used for testing.

E-Mesh was analyzed in terms of energy consumption rate, QoS and video-related transmission quality. Comparison was made between an IEEE 802.11s multi-router mesh network with E-Mesh deployed and another mesh network with the same parameter settings but without E-Mesh. Performance analysis was investigated with the impact of various settings of the traffic load, remaining energy and mesh router distance weight factors in the E-Mesh utility function introduced.

Simulation-based test results of E-Mesh show that when the mesh routers are static, E-Mesh achieves up to a significant 22.9% energy saving, in return of a 9.65% increased loss and a 0.7-dB decreased PSNR, in comparison with the IEEE 802.11s routing protocol, with various settings of traffic load, remaining energy and mesh router distance weight factors. When the mesh routers are moving, E-Mesh achieves up to 19.8% energy saving, in return of a 13% increased loss and a 1-dB decreased PSNR, in comparison with the IEEE 802.11s routing protocol, with various settings of traffic load, remaining energy and mesh router distance weight factors. Experimental test results of E-Mesh show that approximately the same video transmission quality level is achieved in comparison with the IEEE 802.11s routing protocol, but while achieving important energy saving.

As for all algorithms E-Mesh has an overhead, especially in terms of energy consumption, data proces sing and storage; however this overhead is distributed equally across all mesh network nodes and therefore when selecting one or another path in terms of E-Mesh's utility, this overhead will not influence the algorithm behavior.

Future work will include extension of E-Mesh to involve application layer and as part of the evaluation comparisons with existing adaptive energy aware solutions [2, 28] will be performed. E-Mesh's scalability issues will also be considered.

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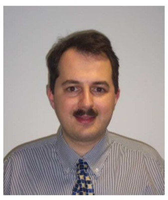

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