E-Mesh: An Energy-efficient Cross-layer Solution for Video Delivery in Wireless Mesh Networks

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***Abstract*—Devices in wireless mesh networks are often supplied with limited power resources, while also running complex applications with high energy requirements, such as high quality video deliveries over the network. Reducing energy consumption is a key factor when designing a solution for such scenarios. Some existing energy-aware video delivery solutions have been proposed for sensor networks, but they do not consider possible movement of devices and most of them are deployed at one network layer only. This paper presents E-Mesh, an energy-aware cross-layer solution for high quality multimedia deliveries over wireless mesh networks. The core idea of E-Mesh is to save energy at mesh network devices by managing their sleep-periods in a more smart way, while also trying to maintain high multimedia delivery quality. E-Mesh includes an innovative MAC-layer scheme for mesh device sleep period management and an energy-aware extension of the Optimized Link State Routing algorithm (OLSR). Network Simulator 3 (NS-3) simulation results show how important energy savings are obtained by using E-Mesh in comparison with the case when IEEE 802.11s mesh standard is employed, while maintaining good video quality levels.**

***Index Terms*—energy consumption, periodic structures, routing, wireless mesh networks**

I. Introduction

IN the modern society, large data delivery between wireless network devices puts an important pressure on network resources. For instance, it is expected that large amounts of continuous data such as multimedia streams to be transmitted through wireless network with strict timing requirements and support good user perceived quality at the remote device. In order to achieve this, the network architecture and the delivery solutions have to be capable of supporting and maintaining high throughput and low loss while cost-effectiveness and service stability are also essential factors to be considered.

In the quest for offering the features mentioned above, wireless mesh is one of the most widely-used network architectures. A typical wireless mesh network includes mesh clients, mesh routers and gateways, collectively called “mesh points”. Mesh clients are user electronic terminals such as laptops and/or smart mobile phones, which serve both as data sender and receiver. Mesh routers forward data traffic to and from the gateways, which may (but do not have to) be connected with the Internet. Often data (e.g. video) resides in servers, from which the wireless mesh network is used to deliver the content to the user mobile devices.

The quality of video delivery is strongly influenced by the data transport capacity of the wireless mesh network, which in turn depends on the life cycle of the power source of the battery-powered mesh devices. In order to be able to offer high-quality video delivery service for long periods of time, there is a need for a mechanism to save energy in the mesh points. In existing wireless mesh networks there are many situations in which the mesh points unnecessarily spend their energy like when they are idle long time waiting for incoming traffic. In this context, the fundamental task to achieve cost-effectiveness is to reduce the unnecessary work periods allowing the mesh points to sleep and save energy, while at the same time maintain good Quality-of-Service (QoS) levels. Another important aspect which needs to be considered for wireless mesh network data delivery is the collision avoidance supported by different MAC protocols so that the interfering mesh points avoid the transmission period of each other and therefore saving energy otherwise wasted.

This paper presents E-Mesh, an energy-efficient cross-layer solution for video delivery over wireless mesh networks which provides a good balance between energy saving on one side and network delivery performance and user perceived quality on the other side. E-Mesh includes a novel MAC layer mesh point operation cycle management scheme, which adaptively controls the sleep/awake pattern for each mesh point in order to save energy. It also makes use of an energy-aware extension of the classic Dijkstra routing algorithm which enables video data from the server to the mesh client to use an optimal path through the mesh network, in terms of energy consumption and QoS. The solution was modeled and tested in comparison with the standard IEEE 802.11s wireless mesh approach via simulations using Network Simulator 3 (NS-3), with quite positive results.

The rest of this paper is organized as follows. Section II discusses related works on various MAC and network layer energy-efficient solutions. Section III introduces the

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architecture of the wireless mesh network used by E-Mesh. Section IV explains principles behind the energy-aware extension for the routing algorithm and the mesh point operation cycle management mechanism. Section V describes the settings of the simulation-based tests and the test results and their analysis in comparison with IEEE 802.11s wireless mesh network. The last section summarizes our work and presents future work plans.

II. Related Works

A. *MAC layer Solutions*

As some mesh devices have limited amount of battery power supply, the energy consumption management is a key element in the wireless mesh network design. Next, MAC layer solutions are discussed among the research on energy-saving schemes.

The S-MAC [1] protocol proposes to add energy-saving features to the typical MAC layer of wireless sensor network nodes, which also have limited power source as is the case of mesh devices. This new protocol implements a fixed duty cycle for each sensor node and maintains virtual clusters for them so that nodes in the same cluster adopt the same duty cycle schedule. Unfortunately S-MAC introduces additional delay and determines lower throughput, which make it not quite suitable for time-sensitive data delivery such as video. In order to solve the transmission delay issue of S-MAC, T-MAC [2] was proposed which redesigns the duty cycle as an adaptive active scheme, which makes sensor nodes transmit data in bursts of variable length and sleep between bursts. D-MAC [3] solves the issue of lower QoS levels of data delivery of S-MAC by introducing a data aggregation mechanism into the node duty cycle scheme to allow data to be delivered along the data gathering tree. It staggers the active schedule of nodes on the multi-hop path sequentially as a chain reaction and uses extra flags in the MAC header for handling request for the additional active schedule, adjusting the duty cycle under interference from sibling nodes. D-MAC is capable of reducing latency but it is only applicable under the specific data gathering tree scenario for unidirectional communication flow from multiple sources to a single sink. To get rid of this limitation, R-MAC [6] is put forward to provide the latency enhancement of S-MAC from a different point of view. It invents a small control frame as an event trigger along the data forwarding path to tell each node to wake up only in the data transmission period, instead of using RTS and CTS to negotiate the wake/sleep schedule. In this way it allows data delivery across multiple hops to finish in a single duty cycle, in which each node's downstream node could automatically wake up when the packet is ready to be sent to it. However R-MAC does not provide any transmission retry mechanisms, and when data packet loss occurs at one specific node on the data forwarding path, all nodes after it will receive nothing in that duty cycle, which wastes energy for idle-listening.

Other related works include P-MAC [4], X-MAC [5], RI-MAC [7] and LC-MAC [8], which provide various other improvements on S-MAC on different aspects such as traffic load. However most of them are specific to solutions for wireless sensor networks and may not be fully relevant to the wireless mesh networks.

B. *Routing Algorithms*

Routing plays an important role in improving wireless network efficiency. Classic routing algorithms like the Dijkstra's algorithm [9], the Optimized Link State Routing (OLSR) algorithm [10] and the Distance-Vector routing protocol [11] are being used frequently in various network scenarios and have significant benefits, although all of them have drawbacks on different aspects. For example, the Distance-Vector routing protocol is especially suitable for small-scale network topologies only due to its slow convergence usually unacceptable in large networks. The count-to-infinity problem is also notable.

Latest research has proposed more advanced routing-related algorithms. The A* algorithm [12] and the Recursive Best-First Search algorithm [13] have been proved to provide much better performance than the typical Dijkstra's algorithm when dealing with shortest-path problems for directed graph topologies, while the Simulated Annealing Arithmetic algorithm [14] offers better results for solving max-cut, knapsack, graph coloring and scheduling problems. The routing algorithm proposed in ENCARA [15] considers energy-related node characteristics in the routing process and differentiates nodes based on those characteristics while allocating energy of the nodes with strict energy constraints. However, since there are multiple parameters whose values are hard to be controlled in a reasonable range, the advanced algorithms listed above are too complicated to be used for solving routing problems. Consequently in this paper the OLSR algorithm, which is a typical example of usage of the Dijkstra's algorithm, was selected to be extended with energy-aware capabilities.

III. Solution Architecture

The E-Mesh network architecture contains one mesh source node which has the required data, N mesh routers for data forwarding and one mesh client. The position of each of these N routers is randomly distributed in a circular area with radius R. Some of the mesh routers will move with a random velocity inside the range of this circular area while others remain fixed. The mesh client is moving under a constant velocity, with its initial position to be set at the edge of the circular area. The location of the mesh data source is fixed at the center of a circular area of consideration. The architecture is shown in Fig.1.

Each router in the topology periodically goes to sleep and wakes up. The period for a router to go to sleep, to wake up, to listen to incoming signals and to transmit data is defined as the router's *operation cycle*. The operational cycle of the routers in the topology is controlled by the existing IEEE 802.11s DTIM beacon mechanism [16].

The router operation cycle is composed of two states:

1) AWAKE: router listens to data request from outside for a

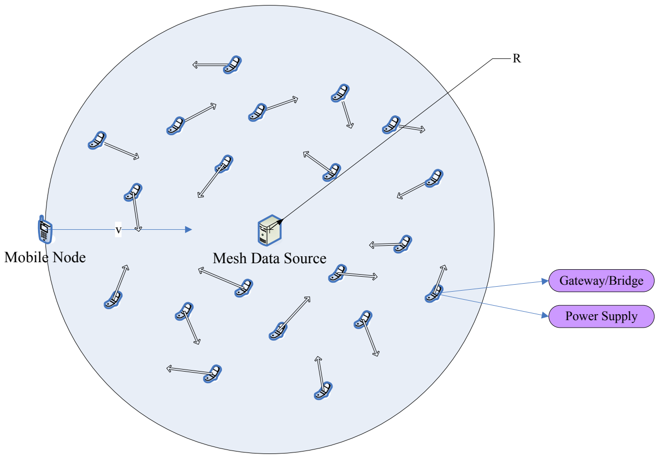

Fig.1. A typical mesh network topology

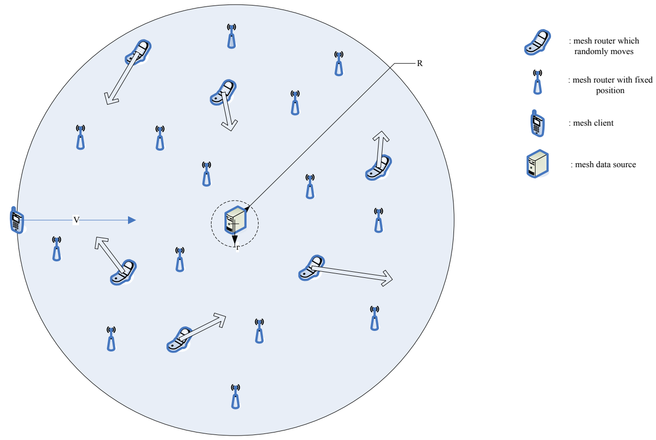

Fig.2. Architecture of the E-Mesh wireless mesh network topology

certain time period T_A. If in T_A the router has not received any incoming data requests, it goes into the SLEEP state. Otherwise it remains awake for data transmission and when it finishes it goes into the SLEEP state.

2) SLEEP: router is off and saves energy.

The length of T_A is flexible according to the communication state between mesh points in the topology. The mechanism to adaptively control the length of T_A is described in section IV.

IV. Algorithm Description

This section describes the two modules for energy-aware routing and MAC-layer operation cycle management. The algorithms are described based on the following assumptions:

1) The communication ranges of the mesh router, mesh data source and mesh client are the same.
2) The time for the client to get the information from the routers (such as position and remaining energy) is very short in comparison with the data transmission time and the time scale of the client movement.

A. Energy-Load-Distance-based Utility Function

Considering the network topology illustrated in Fig.2, each router n_i knows its local position in terms of the (X, Y) coordinates, its current network traffic load and its remaining energy levels. The remaining energy levels and network traffic load for each router are updated periodically.

For each router n_i, the Energy-Load-Distance-based utility function relies on the following components as described in equations (1), (2) and (3):

1) Remaining energy score $\boldsymbol{E(n_i)}$:

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

2) Distance score $\boldsymbol{D(n_i)}$:

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

3) Load score $\boldsymbol{L(n_i)}$:

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

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.

With these definitions, the utility function associated to route n_i is described as follows:

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

In equation (4) W_e, W_d and W_l are adaptive weight factors for $\boldsymbol{E(n_i)}$, $\boldsymbol{D(n_i)}$ and $\boldsymbol{L(n_i)}$, respectively. N represents the number of mesh routers.

B. Energy-aware Routing Algorithm

The mechanism used for energy-aware data routing in wireless mesh networks is an extension of the OLSR algorithm, which will be described next.

Define $\boldsymbol{S}$ as a set of mesh points (mesh data source, router and client). A neighbor mesh point of each mesh point n in $\boldsymbol{S}$ is defined as any mesh point in n's communication range not already contained in $\boldsymbol{S}$.

Suppose there are m mesh points in $\boldsymbol{S}$ ($1 <= m <=$ N + 2): $\boldsymbol{S} = \{n_1, n_2 \ldots\ldots n_m\}$. The algorithm detects all the neighbor mesh points of these m mesh points. Suppose mesh point n_x ($1 <= x <= m$) has y of these neighbor mesh points ($n_{x1}, n_{x2} \ldots\ldots n_{xy}$), some of which might also be neighboring other different mesh points n_z ($1 <= z <= m$ and y != z) in $\boldsymbol{S}$.

For each of the neighbor mesh points of all the mesh points in $\boldsymbol{S}$, there are two possibilities for the mesh client (which is a mesh point in $\boldsymbol{S}$) to communicate with it: if it is in the mesh client's communication range, the client could set up direct communication with it, otherwise the client chooses one or more routers in $\boldsymbol{S}$ as intermediate nodes. Either way there is a route established from the client to this neighbor mesh point. In fact there are multiple possible routes from the mesh client to any of these mesh points in $\boldsymbol{S}$.

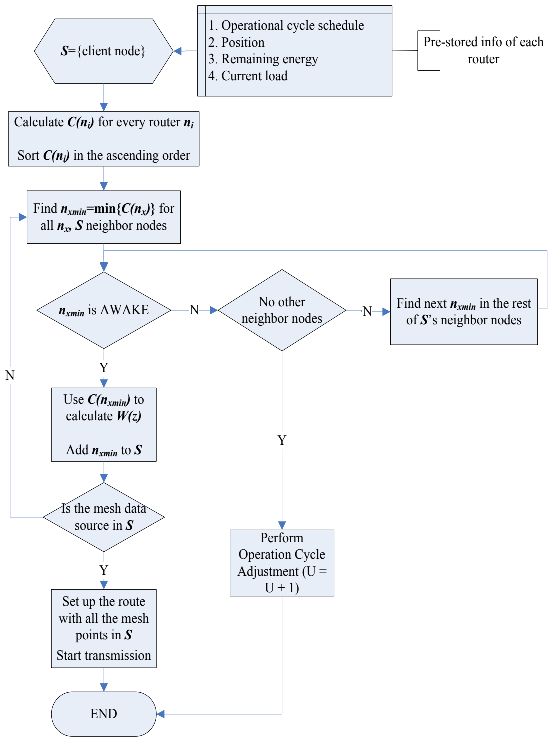

Fig.3. Energy-aware Routing Algorithm in E-Mesh

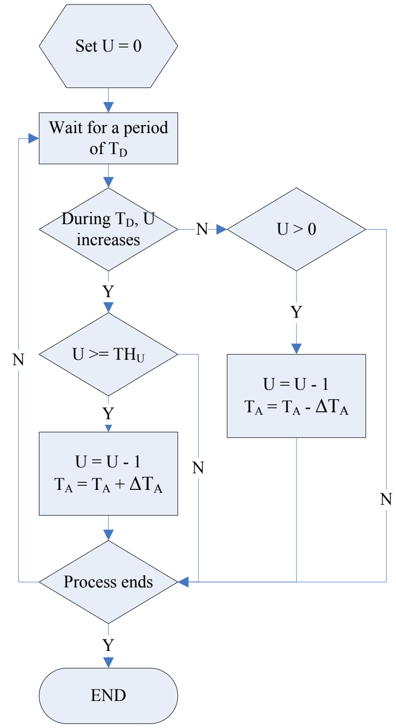

Fig.4. Adaptive Operation Cycle Management in E-Mesh

Suppose there are z nodes (n_{x1}, n_{x2} …… n_{xz}) on any one of these routes from the mesh client to mesh point n_x ($1 <= x <= m$) in ***S***. The concept of *routing weight factor* ***W(z)*** is introduced as the sum of the utility function values ***C(n***$_{xz}$***)*** computed for the z nodes on this route. n_{xmin} is defined as the neighbor mesh point of any node $n_{x'}$ in those z nodes which has associated the minimum value of ***C(n***$_{xz}$***)***. In this context, the routing weight factor is described as follows:

$$W(z) = \min(\sum_{i=1}^{z} C(n_{xi}), W(n_{xmin}) + C(n_{xmin})) \quad (5)$$

With the above definitions, the process of data forwarding path generation from the source to the client is listed below:

1) The algorithm starts when ***S*** contains the mesh client only.
2) The Energy-Load-Distance-based Utility Function periodically calculates the route selection utility ***C(n)*** for every mesh router n in the topology and searches for the mesh router n_{xmin} which has the minimum value of ***C(n)*** in the communication range of all the mesh points in ***S***.
3) If n_{xmin} is in AWAKE state, the routing weight factor from the client to n_{xmin} is computed and n_{xmin} is added to ***S***. If n_{xmin} is in AWAKE state, alternative mesh points in ascending order of ***C(n)*** are sought and this step is repeated. If no other mesh point can be found, the Communication Route State Detector in the MAC-layer router operation cycle management scheme notifies this situation to the QoS-based Decision Maker and waits until the next period of ***C(n)*** calculation comes.
4) If a new mesh point is added to ***S***, the algorithm checks if ***S*** contains the mesh data source. If so, it establishes the route with all the mesh points in ***S***, using the mesh client as the start point and the mesh data source as the end point. Once the route has been set up, the algorithm waits for the next period of ***C(n)*** calculation.

Fig.3 presents the diagram which details the energy-aware routing algorithm.

C. MAC-layer-based Adaptive Management of Router Operation Cycle

The router operation cycle management scheme presented in E-Mesh defines the time periods of AWAKE and SLEEP states of mesh routers in details and adjusts them in a different and more intelligent way in comparison with the DTIM beacon mechanism in the standard IEEE 802.11s.

The algorithm uses the following parameters:

1) *U* – a measurement of how many times the mesh client is unable to communicate with any router.
2) TH_U – an upper threshold value of *U* until which the communication disruption is considered normal.
3) T_D – the time period in which the algorithm waits for the increase of *U*.

The router operation cycle adaptive management algorithm is described as follows:

1) At the initialization, *U* is set to 0.
2) When the Communication Route State Detector finds that all the mesh points in ***S*** are unable to find any awake neighbor mesh points, *U* is incremented by 1.
3) When the value of *U* exceeds TH_U, the length of T_A is increased by ΔT_A (e.g. 0.5 times the original value) by the QoS-based Decision Maker.
4) When an event of 3) occurs, if after a period of time T_D, *U* does not increase again, it is decreased by 1. *U* has a lower limit of 0.
5) Every time when *U* decreases, the value of T_A is reverted to the value before its last increase.

The algorithm is detailed in Fig.4.

V. Simulation-Based Testing and Result Analysis

A. Topology and Scenarios

This section presents the detailed settings for the

TABLE I
COMMON PARAMETERS USED IN BOTH SCENARIOS

Symbol	Quantity	Value
N	Number of mesh routers in the wireless mesh network topology	20
R	Radius of the circular coverage area of the wireless mesh network topology	200 (meters)
V	Moving speed of the mesh client	2 (meters/s)
Thu	Data rate	2 (Mbps)

TABLE II
ADDITIONAL PARAMETERS USED IN THE E-MESH SCENARIO

Symbol	Quantity	value
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	10 (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)
t	The operation cycle period of a mesh router	10 (s)
T	The overall simulation time	200 (s)
T_A	The SLEEP period in the operation cycle	2.5 (s)
T_D	A certain time period	10 (s)
TH_U	Threshold value of U in the operation cycle handling mechanism	10
W_d	Weight factor for the distance score	0.1
W_e	Weight factor for the energy score	0.2
W_l	Weight factor for the traffic load score	0.1

TABLE III
RELATIONSHIP BETWEEN PSNR AND USER PERCEIVED QUALITY LEVELS

Symbol	User Perceived Quality Level	Value
>37	Excellent	Imperceptible
31-37	Good	Perceptible but not annoying
25-31	Fair	Slightly annoying
20-25	Poor	Annoying
<20	Bad	Very annoying

TABLE IV
COMPARISON BETWEEN 802.11S AND E-MESH IN TERMS OF ENERGY CONSUMPTION, AVERAGE THROUGHPUT, LOSS RATE AND AVERAGE PSNR FOR DIFFERENT DATA RATES

Data Rate (Mbps)	Energy Consumption (Joule/s)		Average Throughput (Mbps)	
	802.11s	E-Mesh	802.11s	E-Mesh
1	0.718	0.673	0.945	0.876
2	1.124	0.635	1.965	1.927
5.5	0.747	0.607	4.533	3.771
Data Rate (Mbps)	**Loss Rate (%)**		**Average PSNR (dB)**	
	802.11s	E-Mesh	802.11s	E-Mesh
1	2.708	5.758	31.471	24.514
2	1.761	3.700	36.532	29.420
5.5	9.703	16.944	20.853	11.618

simulation-based testing. Modeling and simulation was performed using NS-3 version 11.

Two simulation scenarios are considered with the same topology, as shown in Fig.2. Each scenario contains one mesh source node which has the required video source, *N* mesh routers for data forwarding and one mesh client. The position of each of these *N* routers is randomly distributed in a circular area with radius *R*. All the mesh routers keep moving under random velocity and direction inside the range of the circular area. The mesh client is moving under a constant velocity, with its initial position to be set at the edge of the circular area. The location of the mesh data source is fixed at the center of the circular area of consideration. The first scenario uses the standard IEEE 802.11s protocol, while the second one has the proposed E-Mesh solution deployed. Both scenarios are initialized with the parameters listed in Table I. In the E-Mesh scenario, the additional parameters listed in Table II are used.

B. Simulation-based Energy Models

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.
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)

C. Results Analysis

As shown in Fig.5, 6 and 7, during the simulation the energy consumption in the E-Mesh scenario experiences a significant decrease of 13.3% in comparison with the value computed in the IEEE 802.11s scenario, while the throughput remains roughly the same. Although the loss rate increases with approximately 1.94% during the simulation, the value remains at a normal level for wireless communications.

The video quality is estimated in terms of the Peak Signal-to-Noise Ratio (PSNR), which translates the effect of bit rate and loss on user perceived quality according to the formula [17] presented in equation (6). Table III indicates the relationship between various PSNR values and the corresponding user perceived quality levels as associated by the ITU T. P.800 standard [18].

$$PSNR = 20\,log_{10}\left(\frac{MAX\_Bitrate}{\sqrt{(EXP\_Thr - CRT\_Thr)^2}}\right) \quad (6)$$

In equation (6), *MAX_Bitrate* is the average bit rate of the

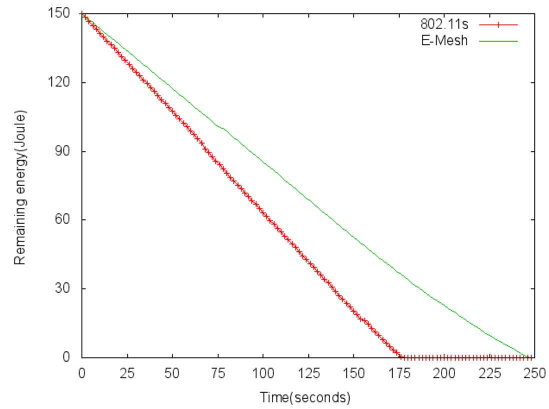

Fig.5. Remaining energy levels

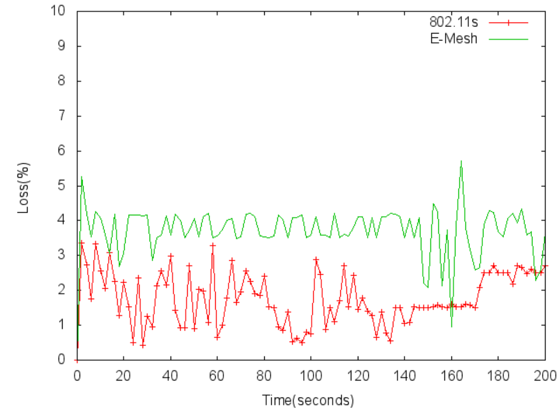

Fig.6. Loss rate

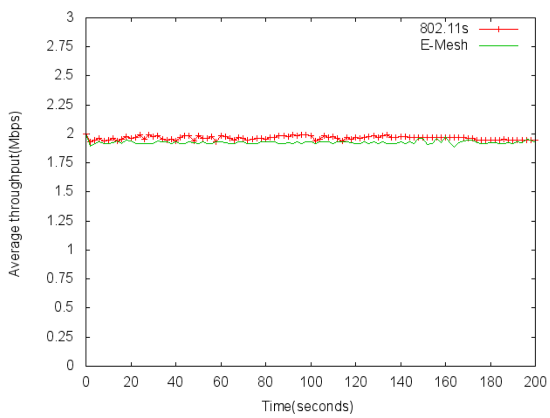

Fig.7. Average throughput

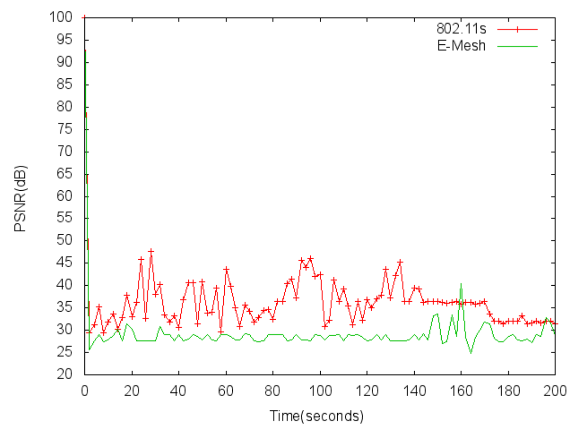

Fig.8. PSNR

data stream transmitted, *EXP_Thr* is the average throughput expected to be obtained and *CRT_Thr* is the actual average measured throughput.

According to Table I, the value of *MAX_Bitrate* and *EXP_Thr* in equation (9) is 2 Mbps during simulation, therefore using the results shown in Fig.7, the PSNR values are computed and shown in Fig.8.

Fig.8 indicates that the quality of the E-Mesh-based video delivery scenario has decreased with approximately 5 dB in comparison with that obtained in the IEEE 802.11s scenario, but it is still close to the "Good" level of user perceived quality according to Table III.

Testing results were also generated for the two scenarios with three different data rates supported by the IEEE 802.11s standard. Table IV shows the energy consumption and delivery performance parameters for both E-Mesh and IEEE 802.11s mesh networks with data rates of 1, 2 and 5.5 Mbps. The table presents the results computed for the payload only, removing the influence of overhead delivery.

When the data rate is 1 Mbps, the IEEE 802.11s scenario has a throughput of 0.945 Mbps and E-Mesh has the throughput of 0.876 Mbps. Due to the expected increase of loss from 2.71% to 5.76% caused by the increase in router nodes' sleep time, the average PSNR decreases for the E-Mesh in comparison with IEEE 802.11s roughly 6 dB. In this case there is about 6.3% reduction in the energy consumption rate, which is – as expected - the lowest in the three cases.

In the 2 Mbps data rate case, a significant 43.51% reduction in the energy consumption rate is obtained by the E-Mesh scenario in comparison with the IEEE 802.11s scenario, which is the highest in the three cases. Meanwhile the throughput obtained by the E-Mesh scenario is 1.927 Mbps, which is roughly the same as the 1.965 Mbps obtained in the IEEE 802.11s scenario, but with a better jitter 0.013 versus 0.016 in the IEEE 802.11s case. The loss rate of the IEEE 802.11s scenario decreases from 2.71% to 1.76% in comparison with the case of 1 Mbps data rate, with the decrease on the loss rate for the E-Mesh scenario from 5.76% to 3.7%. The PSNR value of the E-Mesh scenario has an approximately 6 dB decrease in comparison with that of the IEEE 802.11s scenario, but remaining around the 31-dB threshold between the "Fair" and "Good" user perceived quality levels, according to Table III.

In the 5.5 Mbps data rate case, the reduction of energy consumption has dropped, but it is still 18.74%. The throughputs of the IEEE 802.11s and E-Mesh cases are 4.533 Mbps and 3.771 Mbps respectively, and both scenarios experience significant loss rates, which determine severe reductions in PSNR levels. It is clear that a 5.5 Mbps data rate, which is typically achieved in single hop IEEE 802.11b networks, is too optimistic for both multi-hop scenarios considered here and trading video quality for energy savings does not help. However, error concealment methods can be used in conjunction with E-Mesh-based video delivery to reduce the negative effect of loss in the user perceived quality.

VI. Conclusions and Future Work

This paper proposes E-Mesh, an energy-aware cross-layer video delivery solution for wireless mesh networks. It includes energy-efficient router operation cycle management scheme and an energy-related enhancement of a classic routing algorithm. Simulation-based testing shows how our scheme improves energy consumption in comparison with the standard IEEE 802.11s while trades energy-saving with video transmission QoS with less than 20% of quality decrease.

To get better effect of saving energy and improvement of QoS, the future work includes the enhancement of the routing algorithm and a more effective adaptive operation cycle management mechanism. Also to consider real time usage, there are possible improvements on introducing real time video streams into the network scenario, with different protocols such as RTP or RTSP.

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