AOC-MAC: A Novel MAC-layer Adaptive Operation Cycle Solution for Energy-awareness in Wireless Mesh Networks

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***Abstract*—In wireless mesh networks, mesh devices often have limited power budgets while performing complex and energy-consuming application tasks such as multimedia deliveries. In this context, reducing energy consumption is one of the main research concerns, yet most of the existing multimedia delivery schemes proposed for wireless mesh networks do not consider this factor. This paper presents AOC-MAC, an adaptive MAC-layer operation cycle management solution for high-quality multimedia transmissions over wireless mesh networks. AOC-MAC saves energy at mesh network devices by managing their sleep-periods in an innovative way while also maintaining high multimedia quality levels. AOC-MAC is deployed in conjunction with E-Mesh, an energy-aware routing mechanism, as part of an energy-aware cross-layer scheme. Network Simulator 3 (NS-3) simulation results show the balancing effect of obtaining energy savings and maintaining good multimedia quality levels by using AOC-MAC in comparison with the case when the standard IEEE 802.11s protocol is deployed.**

***Index Terms*—energy consumption, MAC-layer operation cycle management, multimedia streaming, wireless mesh networks**

I. INTRODUCTION

LATELY large-data delivery between wireless network devices puts enormous pressure on network resources. One of the typical examples of such delivery services is multimedia transmissions over wireless networks which have strict timing requirements to offer good user-perceived quality at remote devices. For such requirements, the network architecture and the corresponding delivery solutions must support high levels of quality-awareness, cost-effectiveness and service stability.

Wireless mesh is one of the latest common network architectures designed for such usage. A typical wireless mesh network is composed of multiple mesh points, classified as mesh clients, mesh routers and gateways according to their functionality. Mesh clients are usually pieces of personal electronic equipment such as laptops and/or smart mobile phones, which serve both as data senders and receivers. Mesh routers forward data traffic through the gateways, which may (but do not have to) be connected with the Internet. In a more general architecture, mesh clients could also act as mesh routers.

One of the key factors that affect data delivery quality is the data transmission capacity of the wireless mesh network, which closely relates to the life cycle of the power resources (usually batteries) of the mesh devices. It is clear that energy-saving at the mesh points is needed for offering the ability to maintain high-quality video delivery service. Mesh points unnecessarily spend energy in many situations in existing wireless mesh networks, especially when they are idle waiting for incoming traffic. Based on such background, the fundamental task to achieve energy-effectiveness is to reduce the excess and useless work periods and to allow the mesh points to have a longer off-time while also maintaining good Quality-of-Service (QoS) levels.

This paper presents AOC-MAC, a novel energy-aware adaptive operation cycle MAC-layer scheme, which saves energy at mesh network devices by managing their sleep periods at the MAC layer in an innovative way. AOC-MAC is deployed in conjunction with E-Mesh [1], an energy-aware routing algorithm in an energy-aware cross-layer solution for video delivery over wireless mesh networks, in order to provide fair trade-off between energy depletion on one side and network delivery performance and user-perceived quality on the other. 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 highly positive results.

The remainder of this paper is organized as follows. Section II summarizes some related works on wireless mesh networks with the main concern at the MAC layer. Section III presents the problem statement. Section IV describes the architecture and principle of the proposed solution AOC-MAC. Section V explains how the AOC-MAC mesh point operation cycle management scheme and E-Mesh work together. Section VI describes the settings of the simulation-based tests and discusses the relevant test results. The last section summarizes our work.

II. RELATED WORKS

As already mentioned, power resources at mesh devices are limited in many real-life cases and energy consumption

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management is considered very important in wireless networking in general and in wireless mesh network in particular, especially for multimedia deliveries [2].

Diverse energy-aware multimedia delivery solutions were proposed at different network layers from the MAC layer to the application layer, including cross-layer approaches [3][4][5][6][7][8]. Some existing energy-aware research works with specific focus on the MAC layer are discussed next.

The IEEE 802.11 standard [9] for wireless local area networks (WLANs) has already included a distributed MAC protocol which provides collision avoidance through various schemes such as handshake, back-off and carrier sensing. However this alone is not sufficient for the requirement of reasonable levels of QoS when IEEE 802.11 MAC protocol is deployed in wireless mesh networks, as the usage of hidden nodes and the interaction between multi-hop flows severely increase collision and cause higher latency. In [10] various solutions to improve QoS performance in wireless mesh networks with enhancements in retransmission and packet forwarding mechanisms are evaluated and proved to be effective for reducing end-to-end delay. Unfortunately these solutions work with single channel mesh networks only and further investigations in multi-channel mesh networks are essential.

Several other novel protocols are also proposed for solving some QoS performance issues of the IEEE 802.11 MAC protocol. For example, 2P [11] redesigns the CSMA/CA mechanism of the IEEE 802.11 MAC protocol to enable data transmission and reception along all links of a node simultaneously, making full use of the available channel capacity and supporting low-cost rural connectivity. The TDMA-mini-slot-based scheme proposed in [12] is another attempt to improve the performance of the IEEE 802.11 MAC protocol. It allocates channel resource in mini-slots synchronized within two-hop neighborhood mesh routers to avoid packet transmission corruption and provides priority access to cooperative communication by an instantaneous SNR-based helper selection algorithm in the case of faulty wireless channels. MAC-ASA [13] enhances end-to-end transmission throughput for both single-hop and multi-hop wireless mesh networks by combining distributed link scheduling algorithm and power control support for router-to-router communication together. It uses a modified version of the IEEE 802.11 CSMA/CA contention handling procedure within a TDMA-like protocol integrated to reduce transmission collision and enable data aggregation pipeline.

The related works listed above mainly concentrate on transmission performance in wireless mesh networks and take little consideration of the energy consumption of the mesh devices, which is definitely a noticeable factor when building a wireless mesh network infrastructure. In order to provide energy awareness, DSMA-S [14] is proposed with the usage of two out-of-band busy tone signals at the receiver side to indicate successful transmission and packet collision. Control and data packets are transmitted separately on the common wireless channel, which is divided into time-synchronized slots, to maximize channel efficiency. The busy tone signals are sensed only at the beginning of the time slots so that the idle listening state of mesh devices is reduced to save energy.

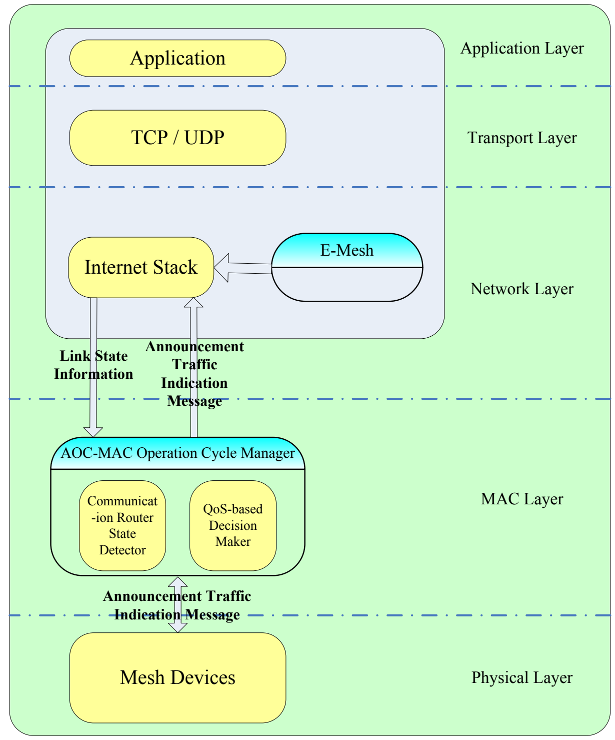

Fig.1. Architecture of AOC-MAC

Unfortunately, the works listed above have not been successful to consider the balance between energy consumption of mesh devices and the performance of data transmission in an innovative way. Moreover, lack of development friendliness occurs in some of those works.

III. Problem Statement

In this paper we attempt to get rid of the drawbacks of many existing works mentioned in section II and to solve the following problems:

- To save energy at mesh devices.
- To increase multimedia transmission performance.
- To maintain the balance between the two sides above during changes of network environments.

Hence the main contribution of this paper is listed as follows:

- An energy-aware scheme is provided for mesh devices.
- The data transmission performance of the wireless mesh network is guaranteed by the scheme while energy at mesh devices is saved.
- The energy-aware scheme adjusts the sleep/active periods of mesh devices at the MAC layer without touching the deployment of other layers. Hence the scheme is simple and easy to deploy.

IV. Architecture

The block architecture of the proposed cross-layer energy-aware solution is shown in Fig.1, involving an adaptive operation cycle management scheme deployed at the MAC layer which interacts with the E-Mesh routing scheme deployed at the network layer.

The operation cycle management scheme proposed by AOC-MAC is composed of two sub-modules:

1) Communication Route State Detector: periodically detects the communication state of mesh routers by interacting with the route selection component of the E-Mesh routing algorithm.
2) QoS-based Decision Maker: starts operation cycle adaptation based on the communication state detection result.

The work flow in the AOC-MAC architecture involves interactions between interfaces in different OSI layers, as shown in Fig.1. After regular communication with the transport layer in which the transmission protocols for high-quality videos are used, the energy-based routing algorithm in the network layer sends the essential link state information to the operation cycle management scheme which handles the sleep/wake-up periods of mesh devices by informing them the announcement traffic indication message.

By default, the operation cycle of all the mesh routers is controlled by the existing IEEE 802.11s DTIM beacon mechanism [15]. It defines a number of periodical beacon intervals within which traffic indication messages are exchanged to indicate different communication states such as pending traffic and re-instating stop flows and to guarantee the length of different operation cycle states (e.g. sleep/wake-up). The performance of this mechanism in terms of energy consumption and user-perceived quality is compared in Section V with AOC-MAC.

The detailed description of the operation cycle management scheme of AOC-MAC is presented next.

V. AOC-MAC Algorithm Description

This section describes the MAC-layer operation cycle management scheme of AOC-MAC and briefly introduces the E-Mesh energy-aware routing algorithm with which it works in conjunction. The following assumptions are made:

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

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

The operation cycle management scheme presented in AOC-MAC defines the active/inactive period of mesh routers in details and adaptively controls the length of the periods based on an advanced extension of the existing mechanism in E-Mesh.

The scheme uses the following parameters:

1) $\boldsymbol{S}$ – a set of mesh points (mesh routers and clients). 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 $\boldsymbol{S}$.
2) U – a counter of the frequency of the disconnection between the mesh client and any mesh router.

TABLE I
PSEUDO CODE FOR THE AOC-MAC ALGORITHM

```
U = 0
-----------------------------------------------
while (1)
{
    if in T_D, a mesh client disconnection is detected
    {
        U = U + 1;
    }
    if after T_D, U increases
    {
        if U >= TH_U
        {
            U = U – 1;
            T_A = T_A + ΔT_A;
        }
        else
            break;
    }
    else
    {
        if U > 0
        {
            U = U – 1;
            T_A = T_A – ΔT_A;
        }
        else
            break;
    }
}
```

3) TH_U – an upper threshold value of U until which the communication disruption is considered normal.
4) T_D – the time period in which the algorithm waits for the increase of U.
5) T_A – the ACTIVE time slot of the router in its operation cycle, waiting for data request from other mesh points. The rest of the operation cycle is the SLEEP period. It is clear that shorter T_A results in less energy consumption at the router.

The operation cycle adaptive management algorithm is described as follows:

1) At the initialization, U is set to 0 and the length of T_A is set by default. Meanwhile the communication route state detector starts keeping track of communication states for all the mesh points.
2) When the communication route state detector finds that there are no neighbor mesh points waking up for any mesh point in $\boldsymbol{S}$, 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, preventing severe decrement of the QoS level caused by over-extending the sleep period of mesh points.
4) When an event of 3) occurs, if after a period of time T_D, U does not increase, 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 its previous value.

The scheme is detailed in Table I in form of pseudo code.

By introducing this scheme, the operation cycle of each mesh point is able to be adaptive according to the change of network communication states, which is indicated in the link state information in the network layer. In return the change of the operation-cycle related states such as the value of U and T_A

TABLE II
COMMON PARAMETERS USED IN ALL FOUR 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	180 (meters)
V	Moving speed of the mesh client	2 (meters/s)
Thu	Data rate	1 (Mbps)

will be included in the announcement traffic indication message to be sent as feedback to the network layer for the routing algorithm to use. This information exchange process is working independently together with the regular mechanism of interaction between the network layer and the MAC layer in IEEE 802.11s.

B. E-Mesh Energy-aware Routing Algorithm

The previously introduced energy-aware routing algorithm E-Mesh is used along with the newly proposed AOC-MAC in this paper. E-Mesh is an extension of the classic OLSR algorithm based on a utility function which introduces energy, transmission range and user-perceived quality as the extra link state information and treats the interactive effects of them as the most prior factors during the optimized route selection process. The route selection process involves the periodical update of the link state information and the searching steps for the corresponding link-state-optimal mesh routers. Once a link-state-optimal mesh router is found, it is selected to be the last mesh point along the data transfer route and the algorithm starts to look for the next link-state-optimal router according to the updated link state information, until the sender mesh client is included in the route. The route selection process is repeated periodically during the change of the mesh network structure to assure the optimization of route at any time.

The algorithm works together with AOC-MAC by controlling the increment of U during the update process of the exchanged link state information among mesh routes. Meanwhile, it obtains the announcement traffic indication message from MAC layer to update the route selection priority and to adjust the link state information accordingly.

VI. SIMULATION-BASED TESTING AND RESULT ANALYSIS

A. Topology and Scenarios

This section presents the detailed settings for the simulation-based testing. Modeling and simulation was performed using NS-3 version 13.

The network topology used in simulation contains the following components:

- N mesh routers for data forwarding.
- Two mesh clients, one with the user-required video source, i.e., the sender, and the other working as user's terminal, i.e., the receiver.

The position of each of these N routers is randomly distributed in a circular area with radius R.

Based on this topology, the following four test scenarios are designed for video transmission performance and energy consumption assessment:

TABLE III
ADDITIONAL PARAMETERS USED IN THE AOC-MAC SCENARIOS

Symbol	Quantity	value
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_{max}	Maximum network traffic load passing each mesh router	1 (Mbps)
t	The operation cycle period of a mesh router	10 (s)
T	The overall simulation time	200 (s)
T_A	The ACTIVE period in the operation cycle	2.5 (s)
T_D	A certain time period	20 (s)
TH_U	Threshold value of U in the operation cycle	10

- Scenario 1: The standard IEEE 802.11s protocol is deployed with all mesh routers are in fixed positions.
- Scenario 2: The standard IEEE 802.11s protocol is deployed with all mesh routers move with random speed and direction inside the circular area.
- Scenario 3: AOC-MAC is deployed with all mesh routers are in fixed positions.
- Scenario 4: AOC-MAC is deployed with all mesh routers move with random speed and direction inside the circular area.

In all the scenarios the receiver mesh client moves with a constant velocity from at the edge towards the center of the circular area where the sender mesh client is located and fixed. All the scenarios are initialized with the parameters listed in Table II and the two AOC-MAC-related scenarios are additionally initialized with the parameters listed in Table III.

The default maximum communication range of mesh points in the IEEE 802.11s wireless mesh network topology is closely relevant to the default propagation model used during data delivery. In our four scenarios this range is estimated as 150 meters using the NS-3 log-distance propagation loss model [16]. The estimation is based on the relationship between the maximum communication range of the mesh point and its maximum transmission power level [17].

The video transmitted in both scenarios is set with the following parameters by default:

- Size: 18.4 Mbytes
- Duration: 666 seconds
- Encoding codec: MPEG4
- Bit rate: 220 Kbps
- Resolution: 352×288 (pixels×pixels)
- Frame rate: 30 fps
- Color space: YUV

In simulations the video is transmitted using an extension of the EvalVid model [18], 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.

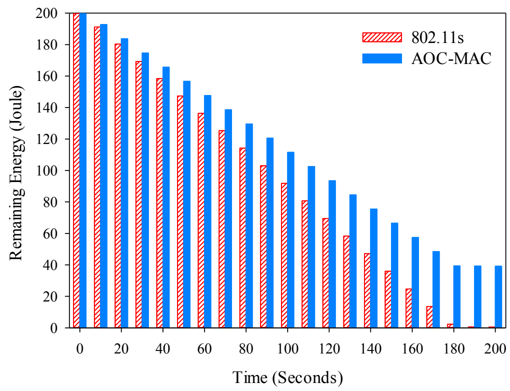

Fig.2. Remaining energy levels when the mesh routers are in fixed position

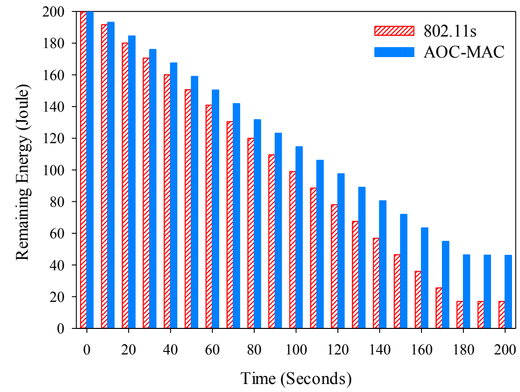

Fig.3. Remaining energy levels when the mesh routers are randomly moving

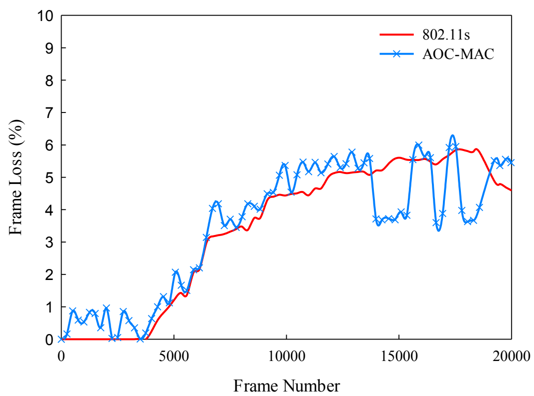

Fig.4. Frame loss rate when the mesh routers are in fixed position

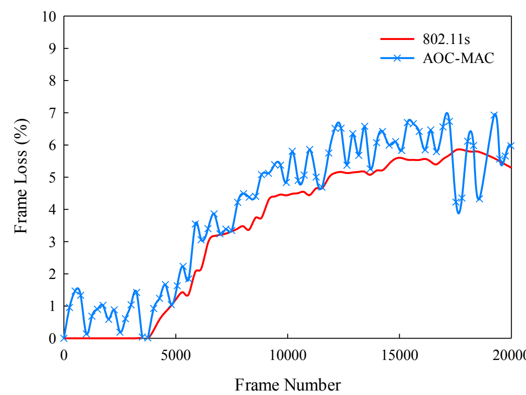

Fig.5. Frame loss rate when the mesh routers are randomly moving

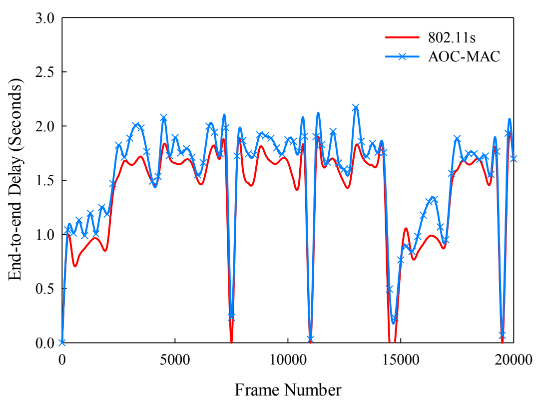

Fig.6. End-to-end delay when the mesh routers are in fixed position

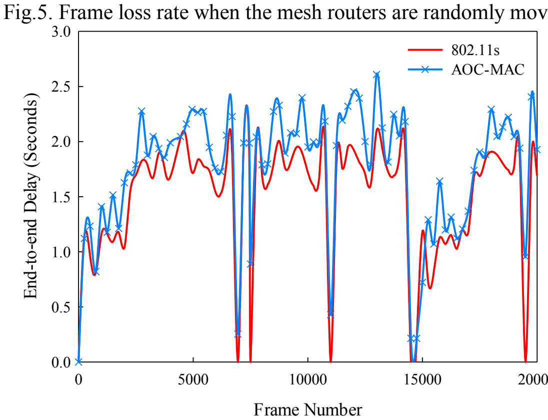

Fig.7. End-to-end delay when the mesh routers are randomly moving

B. Results Analysis

As shown in Fig.2 and Fig.3, the energy consumption in scenario 3 (AOC-MAC) experiences a significant decrease of 19.76% in contrast with scenario 1 (802.11s), whereas the energy saving rate from scenario 2 (802.11s) to 4 (AOC-MAC) is roughly 19.35%. Although the frame loss rate increases approximately from 3.5 % to 3.7% from scenario 1 to 3 and roughly from 3.7% to 4.4% from scenario 2 to 4, as seen in Fig.4 and Fig.5, the value remains at a normal level for wireless communications. The end-to-end delay of scenario 3 has an increase of 12.7% in contrast with scenario 1, whereas the percentage of increase is 6.65% from scenario 2 to 4 as shown in Fig.6 and Fig.7.

The video quality is estimated in terms of the Multi-scale Structural Similarity (MSSSIM) metric [19], measured by using the MSU video quality measurement tool. The MSSSIM values of the IEEE 802.11s and AOC-MAC scenarios are shown in Fig.8 and Fig.9. Scenario 3 experiences a 15.6% quality decrease in contrast with scenario 1 as measured by MSSSIM and the corresponding quality decrease from scenario 2 to 4 is 8.6%, but in general the quality is still at good quality level.

The comparison of test results of the four scenarios is provided in Table IV in terms of the average value of the results and the standard deviation of the QoS parameters. The standard deviation of energy consumption rate is not presented as Fig.2 and Fig.3 imply that the energy is dropping almost linearly. Results in Table IV clearly indicate that when AOC-MAC is introduced into the case that the mesh routers are moving, the QoS parameters such as frame loss, end-to-end-delay and average throughput experience a slight increase while the energy consumption rate remains

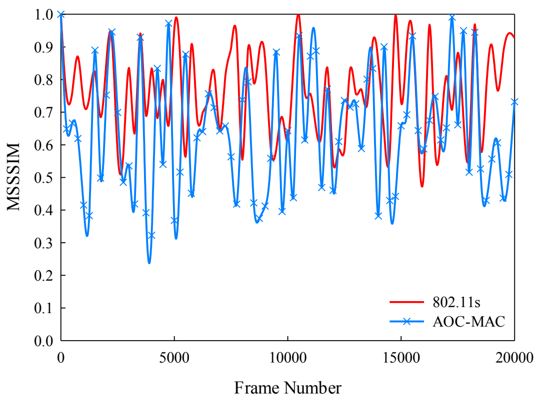

Fig.8. MSSSIM values (compared with the original video) when the mesh routers are in fixed position

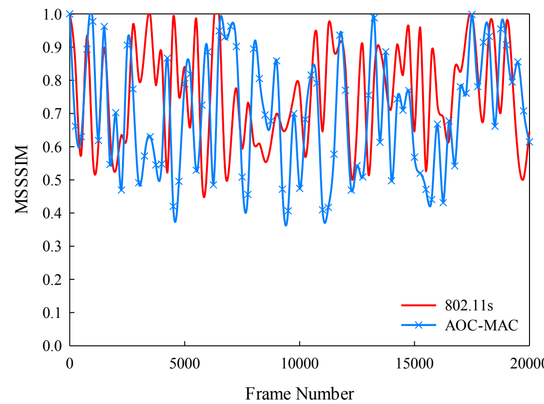

Fig.9. MSSSIM values (compared with the original video) when the mesh routers are randomly moving

TABLE IV
COMPARISON BETWEEN 802.11S AND AOC-MAC IN TERMS OF AVERAGE QOS PARAMETER VALUES AND STANDARD DEVIATION

Average Values	Mesh routers in fixed position		Mesh routers randomly moving	
	802.11s	AOC-MAC	802.11s	AOC-MAC
Energy Consumption (Joule/s)	1.098	0.881	1.059	0.854
Frame Loss (%)	3.485	3.731	3.709	4.404
End-to-end Delay (Seconds)	1.364	1.538	1.504	1.604
Average Throughput (Mbps)	0.935	0.893	0.943	0.917
MSSSIM	0.781	0.659	0.771	0.705
Standard Deviation	**Mesh routers in fixed position**		**Mesh routers randomly moving**	
	802.11s	AOC-MAC	802.11s	AOC-MAC
Frame Loss	1.865	1.709	1.946	1.962
End-to-end Delay	0.496	0.498	0.537	0.539
Average Throughput	0.089	0.085	0.045	0.021
MSSSIM	0.130	0.186	0.142	0.171

approximately at the same level. AOC-MAC in this case results in smaller standard deviation on throughput and video quality, representing higher stability.

VII. CONCLUSIONS AND FUTURE WORK

This paper proposes AOC-MAC, a novel energy-aware adaptive operation cycle management scheme at the MAC layer, which saves energy at mesh network devices by better managing their sleep-periods. AOC-MAC is deployed as part of an energy-aware cross-layer solution for video delivery over wireless mesh networks. Simulation-based testing shows how AOC-MAC improves energy consumption in comparison with the standard IEEE 802.11s, balancing high level of energy-saving with little video transmission quality decrease.

REFERENCES

[1] S.Chen, G.-M. Muntean, "E-Mesh: An Energy-efficient Cross-layer Solution for Video Delivery in Wireless Mesh Networks", *IEEE BMSB*, Seoul, Korea, Jun. 2012, pp.1-7

[2] G.-M. Muntean, P. Perry, L. Murphy, "Objective and Subjective Evaluation of QOAS Video Streaming over Broadband Networks", *IEEE Transactions on Network and Service Management*, vol. 2, no. 1, November 2005, pp. 19-28

[3] J. Adams, G.-M. Muntean, "Power Save Adaptation Algorithm for Multimedia Streaming to Mobile Devices," *IEEE International Conf. on Portable Information Devices*, Orlando, Florida, USA, 2007

[4] M. Kennedy, H. Venkataraman, G.-M. Muntean, "Battery and Stream-aware Adaptive Multimedia Delivery for Wireless Devices", *IEEE Local Computer Networks Conf. (LCN)*, Oct. 2010, pp. 843 –846

[5] A.-N. Moldovan, C. H. Muntean, "Subjective Assessment of BitDetect-a Mechanism for Energy-aware Multimedia Content Adaptation," *IEEE Trans. Broadcasting*, vol. 58, no. 3, Sep. 2012, pp. 480–492

[6] A. N. Moldovan, A. Molnar , C. H. Muntean, "EcoLearn: Battery Power Friendly e-Learning Environment for Mobile Device Users", in "Learning-Oriented Technologies, Devices and Networks", A. Lazakidou and I. Omary (Eds), *Lambert Academic Publishing*, 2011, pp.273-296

[7] Y. Song, B. Ciubotaru, and G.-M. Muntean, "A Slow-start Exponential and Linear Algorithm for Energy Saving in Wireless Networks", *IEEE BMSB*, 2011, pp. 1-5.

[8] S.Chen, G.-M. Muntean, "An Energy-aware Multipath-TCP-based Content Delivery Scheme in Heterogeneous Wireless Networks", *IEEE Wireless Communications and Networking Conference (WCNC)*, Shanghai, China, April 2013, pp.1-6

[9] IEEE P802.11, The Working Group for Wireless LANs. http://grouper.ieee.org/groups/802/11/.

[10] M. Benveniste, "A Distributed QoS MAC Protocol for Wireless Mesh", *SENSORCOMM*, Cap Esterel, France, Aug 2008, pp. 788-795

[11] B. Raman, K. Chebrolu, "Design and Evaluation of a new MAC Protocol for Long-Distance 802.11 Mesh Networks", *MOBICOM*, Cologne, Germany, Aug-Sept 2005, pp. 156-169

[12] H. Jiao, Frank Y. Li, "A Mini-Slot-based Cooperative MAC Protocol for Wireless Mesh Networks", *IEEE Globecom Workshops*, Miami, USA, Dec 2010, pp. 89-93

[13] R. Santamaria, O. Bourdeau, T. Anjali, "MAC-ASA: A New MAC Protocol for WMNs", *ICCCN*, Hawaii, USA, Aug 2007, pp. 973-978

[14] F. Huang, Y. Yang, "Energy Efficient Collision Avoidance MAC Protocol in Wireless Mesh Access Networks", *IWCMC*, Hawaii, USA, Aug 2007, pp.272-277

[15] Joseph D. Camp, Edward W. Knightly, "The IEEE 802.11s Extended Service Set Mesh Networking Standard", *IEEE Communications Magazine*, vol.46, no.8, Aug. 2008, pp. 120-126

[16] Ns3::LogDistancePropagationLossModel Class Reference, Network Simulator 3 [Online]. Available: http://www.nsnam.org/docs/release/3.13/doxygen/classns3_1_1_log_distance_propagation_loss_model.html

[17] Theodore S. Rappaport (1991, May 10). Wireless Communications: Principles and Practice, 2nd Edition, CA: Prentice Hall, 2002, pp. 70-73

[18] J.Klaue, B.Rathke, A.Wolisz, "EvalVid – A Framework for Video Transmission and Quality Evaluation", *Performance TOOLS 2003*, Urbana, USA, Sept. 2003, pp. 255-272

[19] Z.Wang, E.P.Simoncelli, A.C.Bovik, "Multi-scale Structural Similarity for Image Quality Assessment", *Proc. IEEE Asilomar Conf. Signals. Syst. Comput.* Nov. 2003, pp. 1398-1402