Balancing Energy and Quality-awareness: A MAC-Layer Duty-Cycle Management Solution for Multimedia Delivery over Wireless Mesh Networks

Shengyang Chen, *Student Member, IEEE*, Zhenhui Yuan*, and Gabriel-Miro Muntean, *Member, IEEE*

Abstract—**Energy consumption has been a critical factor for mobile video applications. The quality of content delivery over wireless mesh networks consist of such devices is also considered important. Existing energy-aware research and industrial efforts focus on reducing high energy-consuming working periods of mesh devices, at the expense of decreasing the quality of video content. This article proposes an energy-quality-balanced solution AOC-MAC deployed at the MAC layer, working in conjunction with an energy-aware routing algorithm for wireless mesh devices. The simulation and perceptual test results are also presented in order to investigate the performance of the proposed solution. In particular, the impacts of content delivery data rate, mesh network topology scale and mesh device mobility are studied. Results demonstrate that AOC-MAC obtains up to 23% energy savings at roughly the same content delivery quality level, in comparison with the IEEE 802.11s MAC protocol.**

Index Terms—**energy consumption, MAC-layer duty cycle management, perceptual testing, wireless mesh networks.**

I. Introduction

OVER the past decades, the demand for support for data communications has increased significantly. With the advances in wireless mesh network technology, usage of wireless mesh devices has increased rapidly, accompanied by the growth of data traffic of high-level rich network services. High user Quality of Service/Experience (QoS/QoE) for such services is considered essential for further development of wireless mesh devices. It has been a challenge over the past years to provide high quality video-related mobile services with QoS/QoE provisioning over wireless mesh networks, as the network resources involved, such as channel bandwidth and signal strength, are often constrained. The energy consumption of wireless mesh devices is another important research issue nowadays, as they often have limited power budgets while performing complex and energy-consuming application tasks. 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 article presents the detailed principles of the energy-aware MAC-layer solution AOC-MAC previously introduced in [1]. AOC-MAC is an energy-aware mesh router duty cycle management scheme for high-quality video deliveries over wireless mesh networks. It manages the sleep-periods of mesh devices in smart manner based on link-state communication conditions, reducing the energy consumption of mesh routers by extending their sleep-periods. AOC-MAC works in conjunction with an innovative energy-aware network-layer routing algorithm E-Mesh [2], which extends the classic OLSR [3] routing algorithm. AOC-MAC informs E-Mesh about both connection condition and traffic delivery state and E-Mesh finds an optimal route for traffic delivery in terms of energy consumption level, network load and connection stability. This article extends [1] by presenting a real test bed environment and emulation-based tests performed for AOC-MAC evaluation. Subjective tests for assessing the delivered video quality levels have also been performed additionally and their extensive results are provided for further performance investigation. Detailed analysis was included regarding the effect of variations in network traffic load, router energy level and router communication distance on the performance of the proposed solution.

This article is organized as follows. Section II introduces several state-of-the-art related works on energy-efficient MAC protocols. Section III presents the architecture of the proposed solution AOC-MAC. Section IV and V introduces the simulation and perceptual test bed settings, respectively. Section VI presents and analyzes the simulation and perceptual

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Dr. S. Chen was with the Performance Engineering Laboratory, Dublin City University, Ireland and is now with Nuwave Ventures Ltd., Dublin, Ireland. E-mail: shengyang.chen5@mail.dcu.ie

Dr. Z. Yuan is the corresponding author of this article. He is with the Drone Research Group, Ministry of Education Key Frequency and Circuits Lab, School of Electronic and Information, Hangzhou Dianzi University, China. E-mail: yuanzhenhui@hdu.dedu.cn

Dr. G.-M. Muntean is with the Performance Engineering Laboratory, Dublin City University, Ireland., E-mail: gabriel.muntean@dcu.ie

test results. The last section concludes our work and presents future work plans.

II. Related Works

To adapt duty cycle for wireless devices to achieve optimal energy efficiency in terms of energy consumption and communication performance, various duty cycle management schemes have been proposed in the research literature. One of the earliest examples of synchronous duty cycle management schemes is S-MAC [4], which aims at reducing extra energy consumption caused by retransmission, overhearing and channel idle listening, at the cost of reducing pre-hop fairness and latency. S-MAC periodically listens the duty cycle of wireless mesh nodes whose radio access channels are inactivated for a fixed duration when idle and re-activated by messages notifying incoming packets. Synchronization of inactivated channel timer between neighboring nodes is done periodically by exchanging timestamps relatively. S-MAC obtains significant energy saving in the case with heavy traffic in which gaps between arriving packets are short. This benefit increases when the gaps between arriving packets become longer. However, S-MAC causes extra delay as the outgoing packets have to wait for the destination node to wake up, which might severely impact the QoS of time-sensitive applications.

To reduce the sleep-delay issue of S-MAC, diverse MAC-layer duty cycle management solutions were proposed, [5][6][7][8][9][10]. The disadvantages of these approaches include extra overhead, complexity and limited usability.

To solve the QoS performance issues specifically for wireless mesh networks using the IEEE 802.11 MAC protocol, several novel MAC protocols have been proposed in the research literature. One of the first MAC solutions for improving the QoS performance of single-channel wireless mesh networks is introduced in [11], including schemes for extending the contention window size, express forwarding and express retransmission based on CSMA/CA and TXOP [12] of the IEEE 802.11e MAC protocol. 2P [13] aims at improving the performance of the IEEE 802.11 MAC protocol by redesigning the CSMA/CA mechanism 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 DBTMA [14] protocol aims at solving the hidden/exposed terminal problem by using a pair of busy tones together with the RTS packets in order to provide protection from RTS packets collision. In [15], an advanced MAC-layer protocol used for parallelism packet transmission in wireless mesh networks is proposed as an extension of the Medium Access via Collision Avoidance with Enhanced Parallelism (MACA-P) [16] protocol. This protocol supports concurrent transmission by scheduling transmitting data packets and receiving ACK packets in the outgoing RTS packets to the neighbor mesh nodes. The MAC-layer scheme proposed in [17] aims at improving delay-constrained video streaming service quality in multi-hop wireless mesh networks. The scheme uses an algorithm to optimize different control parameters at mesh nodes together with an IEEE 802.11e HCCA-based [12] traffic scheduling mechanism. The TDMA-mini-slot-based scheme proposed in [18] improves the performance of the IEEE 802.11 MAC protocol in terms of the issues of packet loss, bandwidth decrease and transmission delay. This scheme allocates channel resource in mini-slots synchronized within two-hop neighborhood mesh nodes to avoid packet transmission corruption. It also provides priority access to extend cooperative communication to multi-hop cases by using an instantaneous SNR-based helper selection algorithm in the case of faulty wireless channels.

Diverse energy-related MAC solutions for wireless mesh networks are also proposed, considering the impact of access delay and packet collision on the energy consumption of wireless mesh devices. DSMA-S [19] is one of such examples proposed to solve the control packet collision problem. DSMA-S is based on the contention-based scheme in DBTMA and uses two out-of-band busy tone signals at the receiver node to indicate successful transmission and packet collision to other nodes. Meanwhile, control packets and data packets in DSMA-S are transmitted separately on the common wireless channel, which is divided into time-synchronized slots, to maximize the channel efficiency.

The energy-efficient wireless mesh node monitoring scheme proposed in [20] tries to ensure continuous and complete detection coverage for wireless mesh network intrusion and to save energy for the non-monitoring mesh nodes via duty cycle management. In this scheme, each node in the wireless mesh network is integrated with an intrusion detection engine for wireless link monitoring. A centralized and a distributed monitoring mesh node selection algorithm are proposed at the mesh gateway with trade-off between the time and message complexity for intrusion detection rate, respectively. Meanwhile duty cycle management schemes are used on the mesh nodes which are not selected as monitoring nodes, without affecting the intrusion detection process.

The characteristics of different mesh network design approaches are discussed in [21] based on various architectures. The work compares existing architecture designs of wireless mesh network and categorizes the designs based on environment. Characters such as routing mechanism, network management and network performance are investigated.

III. Architectures of AOC-MAC

This section presents the architecture of the proposed solution AOC-MAC.

A. General Network Topology

Consider the 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.

B. AOC-MAC Architecture

The block architecture of the proposed MAC-layer mesh router duty cycle management scheme based on the OSI

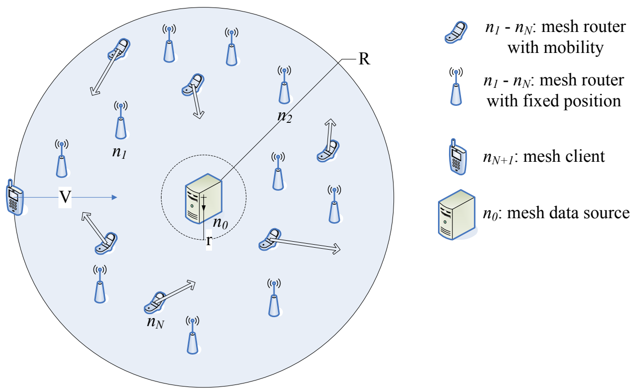

Fig.1. Wireless mesh network topology

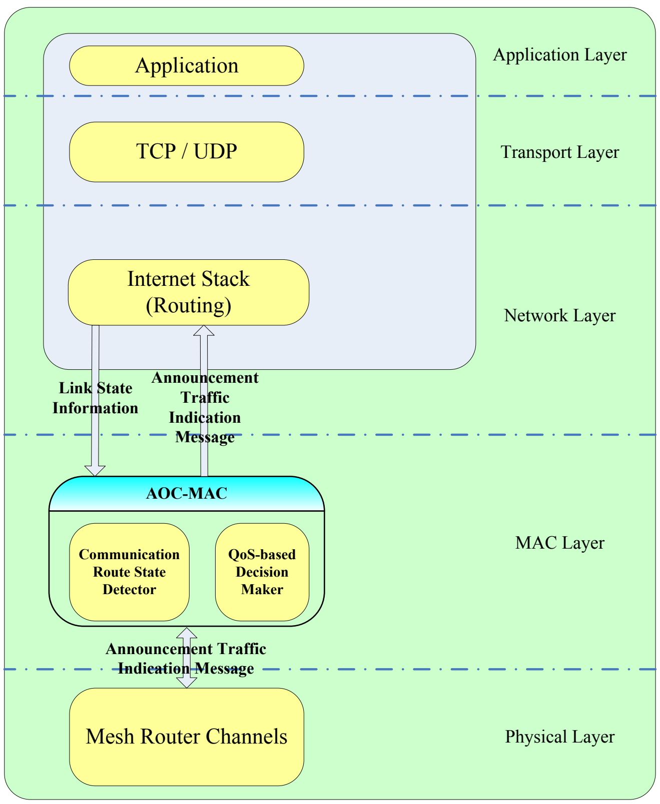

Fig.2. AOC-MAC architecture

network model is shown in Figure 2. AOC-MAC architecture is composed of the following two modules:

1) ***Communication Route State Detector***: periodically checks the communication states of the mesh routers. The communication states are obtained by using an external network-layer module which is in charge of routing during traffic delivery, based on a utility function with the energy consumption rate, the traffic load and the distance between mesh routers as the parameters [2].
2) ***QoS-based Decision Maker***: starts duty cycle adaptation based on the communication state detection result.

The ***Communication Route State Detector*** module defines functions to obtain link state information from the network layer (i.e. how many disconnections have happened during routing). The ***QoS-based Decision Maker*** module maintains a list of duty-cycle-related parameters and defines the function to

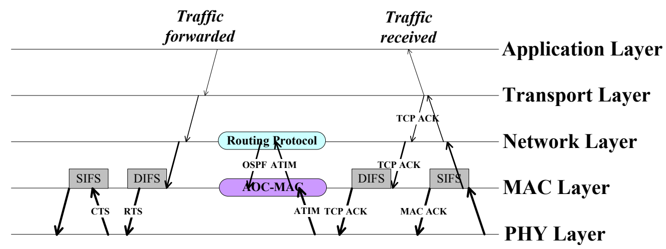

Fig.3. Network information exchange between different OSI layers

adjust the duty cycles of mesh routers according to the link state information stored in the ***Communication Route State Detector*** module.

The work flow in the AOC-MAC architecture involves interactions between interfaces in different OSI layers, as shown in Figure 3. At each mesh router, after receiving traffic sent from the mesh client or another mesh router, the physical channel state information is contained in the Announcement Traffic Indication Message (ATIM) [22] packet and sent to AOC-MAC. The sleep/wake-up states of wireless channels of the mesh router are independent from the network layer in general. However if AOC-MAC would co-operate with an energy-aware network-layer routing protocol (such as E-Mesh [2]), the performance in terms of balancing energy consumption and transmission performance of mesh routers can be further enhanced. For this reason, in AOC-MAC the sleep/wake-up states are indicated in the ATIM packets, which are forwarded to the routing protocols in the network layer. The network layer sends back the routing-protocol-based packets such as the Open Shortest Path First (OSPF) [23] packets to the MAC layer, informing the link state information during the routing process. AOC-MAC uses the 0-1 bit mesh power mode message included in the header of each ATIM packet to indicate the physical channel state (sleep/wake-up) for routing protocols. Meanwhile, AOC-MAC obtains the link state information from the OSPF packets sent by the routing protocols in order to check whether there are disconnections along the route between two mesh routers. The link state information is a binary field whose value of 0 represents no disconnection and 1 informs about a disconnection along the route. This field is included in the header of each OSPF packet at network layer.

By default, the duty cycle of all routers in the wireless mesh network is controlled by the existing IEEE 802.11s DTIM beacon mechanism [22]. 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 states of the duty cycle of the mesh nodes (e.g. sleep/wake-up). The wake-up time of each mesh router is defined as the Mesh Awake Window in the 802.11s beacon frame. The sleep time of each mesh router is defined as the rest part of the beacon interval apart from the wake-up time. In the AOC-MAC algorithm, the default lengths of the sleep/wake-up periods of mesh routers defined in DTIM are used as the initial duty cycle states of them. The lengths of these periods are adaptively changed during traffic transmission using the AOC-MAC algorithm.

B-1 Communication Route State Detector

The basic functionality of this module is to gather the route/connection state information via feedback messages from the network layer module, in order for AOC-MAC to make decisions on how the duty cycles of the mesh routers are adjusted. It includes a *disconnection counter DCount* which calculates the number of disconnections occurred during the mesh router duty cycle adjustments. The disconnection occurs during the traffic data forwarding between routers when some of the routers are asleep. Suppose data packets are forwarded in the mesh network from router A to router B, which is in the sleeping state extended by AOC-MAC. As the channels of router B are inactive, no data packet from router A is received. As mentioned, the disconnections are recorded and included in the headers of the link state information packets sent by the routing protocols in the network layer. If such disconnections happen frequently in the mesh network, the quality of the traffic delivery in the entire mesh network decreases. As a result, the duty cycles of the mesh routers need to be increased in order to maintain good traffic delivery quality. A threshold value of the disconnection number is defined. In general, a higher threshold value indicates lower requirement on service quality level.

The detection on communication (disconnection) states and the calculation of disconnection numbers is done periodically by AOC-MAC. The length of the interval between two detections is determined according to the frequency of the change of the wireless mesh network topology, which corresponds to the mobility of the mesh routers and the mesh clients. In this thesis, in the AOC-MAC experiments, the length of this interval is set to 20 seconds which proves to be satisfactory according to the test results illustrated in Section VI. The value of the disconnection counter is used as one of the key parameters of the QoS-based Decision Maker module, together with the length of the interval between two detections.

B-2 QoS-based Decision Maker

In each communication state detection period, the duty cycle (the active period) of each mesh router is lengthened or shortened depending on the value of the disconnection counter from the Communication Route State Detector module. When the value of the disconnection counter is smaller than the threshold value set in the Communication Route State Detector module according to the demand on service quality level from the end user, the duty cycle of the mesh routers is decreased in length in order to save energy. Once the value of the counter exceeds the threshold, indicating possible decrease on traffic delivery service quality due to too many disconnections, the duty cycle of the mesh routers is reversed to their original lengths to maintain good service quality levels. This adjustment of mesh router duty cycles is performed during the entire duration of traffic delivery.

The AOC-MAC decision making algorithm is briefly described in Table 1 in form of a pseudo code, and makes use of the following parameters:

1) ***S*** – a set of mesh points (mesh routers and clients). A neighbor mesh point of each mesh point *n* in ***S*** is defined as any mesh point in *n*'s communication range not already in ***S***.
2) *U* – a counter of the frequency of the disconnection between the mesh client and any mesh router.
3) TH_U – an upper threshold value of *U* up to which the communication disruption is considered normal.

TABLE 1 AOC-MAC DECISION MAKING 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;
    }
}
```

4) T_D – a 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. Note that shorter T_A results in lower router energy consumption.

The biggest concern for the performance of the QoS-based Decision Maker module is the impact of the ping-pong effect caused by the back-forth adjustment of the mesh router duty cycle. AOC-MAC is aware of the extra overhead in the mesh network from the frequent change of mesh router duty cycle, which results in jitter and delay. However, the ping-pong effect does not affect the energy consumption rate on mesh routers, which is considered more important by the network operators. The impact on the service quality of the ping-pong effect does not overcome the benefit of energy saving from reducing duty cycles of mesh routers by AOC-MAC.

IV. SIMULATION TEST BED SETUP

A. Simulation Topology for AOC-MAC

This section presents the detailed settings for the simulation-based testing. Modeling and simulation was performed using Network Simulator 3 (NS-3) [24] version 13.

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

- *N* mesh routers $\{n_1, n_2, ...n_N\}$ 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 AOC-MAC

In simulations the videos were transmitted using an extension of the EvalVid model [25], 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

TABLE 2 COMMON PARAMETERS USED IN AOC-MAC TESTING FOR DATA RATE IMPACT INVESTIGATION

Symbol	Quantity	Value
N	Number of mesh routers in the wireless mesh network	20
R	Radius of the circular coverage area of the wireless mesh network	180 (meters)
V	Moving speed of the mesh client n_{N+1}	2 (meters/s)
E	Initial battery energy of each mesh router	100 (Joule)
T	The overall simulation time	200 (s)
t	The SLEEP period of a mesh router	7.5 (s)
T_A	The WAKE-UP period of a mesh router	2.5 (s)
T_D	The period in which the algorithm waits for the increase of *DCount*	20 (s)
TH_{DC}	Threshold value of *DCount*	10

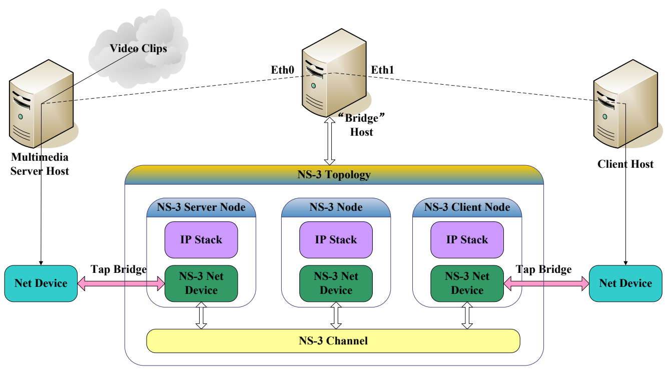

Fig.4. Experimental real-life test-bed topology used

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 AOC-MAC in wireless mesh networks with variable conditions, separate test scenarios were performed to study the impact of traffic level, number of routers and router mobility. In each scenario, the performance of AOC-MAC was evaluated and compared against the standard IEEE 802.11s MAC protocol and the synchronous duty cycle management scheme S-MAC [4]. The implementation of the IEEE 802.11s MAC protocol was included in the existing modules of NS-3. S-MAC was deployed via a brief implementation in NS-3. The performance of the AOC-MAC duty-cycle management mechanism is evaluated in terms of the following parameters on each mesh router:

- Average energy consumption rate
- QoS parameters such as frame loss rate and end-to-end delay
- Video quality assessment parameters

The following test scenarios are designed for AOC-MAC:

Scenario A1: traffic data rate: 1.0, 2.0, 5.5 and 11 Mbps.

Scenario A2: number of mesh routers: 10, 20, 30, 40, and 50.

Scenario A3: mesh router mobility is set to static and mobile.

The two mobility cases of mesh routers are described as follows:

- Case 1: All the N mesh routers $\{n_1, n_2, ...n_N\}$ 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} was moving 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 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.

Tests are initialized with the parameters listed in Table 2.

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

V. PERCEPTUAL TEST BED SETUP

In this context, the simulation-based tests described in the previous sections have provided performance evaluation for AOC-MAC in terms of energy consumption rate, transmission QoS parameters (e.g. loss rate, delay) and estimated transmission quality. Although quality metrics such as MSSSIM and PSNR were used in the simulation-based tests, quality evaluation based on actual measurements and perceptual evaluation performed is to confirm the simulation results. For this purpose, a real-life test-bed has been set-up and prototyping of AOC-MAC has been done.

This section introduces the perceptual test bed used for the performance evaluation of AOC-MAC in terms of the video delivery quality. Several video clips are transmitted for performance evaluation. The delivered video clips are saved at the mesh client device and evaluated using objective and subjective video quality assessment metrics.

A. General Topology

Prototyping of AOC-MAC is done using the NS-3 Tap Bridge [26] mechanism, which is provided as a particular NS-3 module. This enables the integration of real-life Internet hosts into NS-3 simulations.

Using the NS-3 Tap Bridge module, the experimental test-bed topology is illustrated in Figure 4, and consists of a multimedia server, a client host machine and a "Bridge" host

TABLE 3 VIDEO PARAMETERS IN AOC-MAC TESTING FOR DATA RATE IMPACT INVESTIGATION

Video	Title	Size (Mbytes)	Duration (seconds)	Encoding Codec	Bit Rate (Kbps)	Resolution (pixels×pixels)	Frame Rate (fps)	Color Space
1	Cartoon	25	666	MPEG4	308	352×288	30	YUV
2	The Simpsons	50	399	MPEG4	1026	576×240	25	YUV
3	Jurassic Park	137.5	841	MPEG4	2000	1920×1040	23.976	YUV
4	Back to the Future	250	1529	MPEG4	1339	1280×720	23.976	YUV

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

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

set in between the server host and the client host. The multimedia server host and the client host are installed with one single Ethernet card. The "Bridge" host is installed with two Ethernet cards *Eth0* and *Eth1*, connected to the multimedia server host and the client host using Ethernet cables, respectively. The NS-3 implementation of AOC-MAC 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) [27]:

VLC is 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 video traffic sending and receiving.

- MSU Video Quality Measurement Tool [28]:

MSU is an objective video quality assessment software which supports many 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 Sequences

As presented in Section IV, the simulation-based tests of AOC-MAC have investigated the impact of different data rates on performance, involving video streams with different parameters. Accordingly, for the experimental test of AOC-MAC in this chapter, four video sequences are used as the original video source stored in the multimedia server host, with the characteristics illustrated in Table 3.

D. Experimental Scenarios

To investigate the video transmission quality of AOC-MAC, the following test cases are designed:

- *Case A1*: The four video clips are delivered from the multimedia server host to the client host, offering different data rates. The corresponding NS-3 AOC-MAC scenario *A1* are deployed and simulated on the "Bridge" host.
- *Case A2*: The video sequence 2 in Table 3 is delivered from the multimedia server host to the client host. The corresponding NS-3 AOC-MAC scenario *A2* is deployed and simulated on the "Bridge" host, with different settings of mesh router numbers.
- *Case A3*: The video sequence 2 in Table 3 is delivered from the multimedia server host to the client host. The corresponding NS-3 AOC-MAC scenario *A3* is deployed and simulated on the "Bridge" host, with different settings of mesh router mobility.

E. Objective Quality Assessment

PSNR [29] and the Multi-scale Structural Similarity (MSSSIM) metric [30] are the selected objective video quality assessment metrics in the AOC-MAC test scenarios. The delivered video quality is affected by QoS parameters such as packet loss and end-to-end delay. In general, higher throughput and lower loss indicate better received video quality, but this is not guaranteed. Figure 6 illustrates the quality of the original and received videos affected by the QoS parameters.

F. Subjective Quality Assessment

In previous sections, objective video quality assessment metrics such as PSNR and MSSSIM are used for measuring the received video quality for the real-life experimental tests. However, the results from the objective video quality assessment metrics do not correlate perfectly with the user perceived quality from human vision, which behaves non-linearly. This section presents the investigation of the performance of AOC-MAC using subjective video quality assessment. MOS [31] is selected for the subjective video quality measurement. The quality scale for MOS is introduced with the value 5 indicating the "excellent" quality and 1 indicating the "bad" quality. The same four video sequences listed in Table 3 are transmitted from the server host to the client host, over the "Bridge" host where the prototyping of AOC-MAC 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 each user is distributed between 24 to 40 years old. The occupations of the users include technicians, students, business people, engineer, etc. Each user was required to watch the video clips received in each test case in the order which the cases are described in section IV. After watching all the received video clips, each user was asked to rate the quality of each video clips based on the MOS metric by filling a questionnaire presented to the subjects on papers, which was handed out to the user before watching the video clips. 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 ITU-T Rec. P.911 [32].

Based on the set-up regulated above, video clips received using the prototyping of AOC-MAC are evaluated by users.

VI. Result Analysis

A. AOC-MAC Simulation Test Result Analysis

A-1 Impact of Traffic Data Rate on AOC-MAC Performance

This test was done in order to investigate the impact of various traffic data rate from the sender node on AOC-MAC performance. A data rate which exceeds the standard bandwidth of mesh network causes severe data packet drop and decreases QoS. Also, high data rate requires frequent packet transmissions in the mesh network and the mesh routers are obliged to stay awake longer, increasing energy consumption.

As indicated in section IV B, each mesh router in the network can be deployed with static position or with mobility. In this test, each mesh router was allocated with a uniformly distributed random mobility. At the initialization of the mesh network topology, each mesh router pauses for a random time value between [0, 2] (seconds) and chooses a random direction value between [0, 2π] and then moves with 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. When each mesh router reaches the boundary, it pauses again with a new random time between [0, 2] (seconds) and repeats the process above. The mesh client n_{N+1} moves with a constant speed 2.0 m/s from at the boundary towards the center of the wireless mesh network circular area where the mesh client n_0 is located and fixed.

The test was initialized with the parameters listed in Table 2.

The impact of four different data rates: 1) 1.0 Mbps; 2) 2.0 Mbps; 3) 5.5 Mbps and 4) 10.0 Mbps were investigated in this test, involving four corresponding test videos with the parameters listed in Table 3.

The results of the data rate impact study are shown in Table 4. Note that the energy consumption rates of the IEEE 802.11s MAC protocol, S-MAC and AOC-MAC on mesh routers increase along with the increase of traffic data rate, as higher data rate leads to more frequent transmissions and shorter sleep-periods of the mesh routers. With a 1-Mbps data rate, AOC-MAC has obtained 20.23% decrease in the energy consumption rate in comparison with IEEE 802.11s MAC protocol, but the energy saving benefit is 18.63% less than that of S-MAC. With a 2-Mbps data rate, AOC-MAC has obtained 17.03% and 5.44% energy savings on mesh routers in comparison with IEEE 802.11s MAC and S-MAC, respectively. In this case the energy savings of AOC-MAC and S-MAC are approximately the same. With a 5.5-Mbps data rate, the energy saving of AOC-MAC is approximately 16.37% and 10.81% lower than those of IEEE 802.11s MAC and S-MAC, respectively. With a 10-Mbps data rate, AOC-MAC saves 14.2% more energy than the IEEE 802.11s MAC protocol and 11.18% than S-MAC. It is clear that in data transmission scenarios at low data rates, AOC-MAC provides energy saving benefit compared against the IEEE 802.11s MAC protocol, but the performance of S-MAC in terms of energy savings is better. However, the energy saving benefit of S-MAC decreases severely in at high data rates, while AOC-MAC saves more energy.

The frame loss rates when using IEEE 802.11s MAC, S-MAC and AOC-MAC increase along with the increase of traffic data rate, as higher data rate causes higher chances for data packet collisions and drops during traffic delivery. With a 1-Mbps data rate, the average frame loss rate of AOC-MAC has increased to approximately 4.4% in comparison with the 3.7% rate of the IEEE 802.11s MAC protocol and the 3.95% rate of S-MAC. With a 2-Mbps data rate, AOC-MAC has obtained 4.58% average frame loss rate in comparison with the 4.06% rate of IEEE 802.11s MAC and the 4.293% rate of S-MAC, respectively. With a 5.5-Mbps data rate, the average frame loss rate of AOC-MAC has increased with 5.21% in comparison with 4.65% of the IEEE 802.11s MAC and 4.89% rate of S-MAC. With a 10-Mbps data rate, AOC-MAC has obtained 5.99% average frame loss rate in comparison with 5.34% of IEEE 802.11s MAC and 5.64% of S-MAC, respectively. Although AOC-MAC increases slightly the frame loss rate in comparison with IEEE 802.11s MAC and S-MAC, the value remains at a normal level for wireless communications.

The end-to-end delays of the three MAC schemes decrease along with the increase of traffic data rate, as higher data rates are associated with shorter sleep-periods of mesh routers and result in lower latency. With a 1-Mbps data rate, the average

TABLE 4 EFFECT OF TRAFFIC DATA RATE ON AOC-MAC PERFORMANCE

Data Rate		802.11s	S-MAC	AOC-MAC
Energy Consumption (mWatts)	1 Mbps	21.4	13.89	17.07
	2 Mbps	24.9	20.79	19.66
	5.5 Mbps	29.5	27.66	24.67
	10 Mbps	31.4	30.33	26.94
Frame Loss (%)	1 Mbps	3.702	3.954	4.395
	2 Mbps	4.057	4.293	4.586
	5.5 Mbps	4.645	4.887	5.206
	10 Mbps	5.338	5.644	5.987
End-to-end Delay (Seconds)	1 Mbps	1.50	1.67	1.80
	2 Mbps	1.43	1.61	1.73
	5.5 Mbps	1.38	1.50	1.61
	10 Mbps	1.35	1.42	1.49
MSSSIM	1 Mbps	0.772	0.723	0.706
	2 Mbps	0.754	0.707	0.683
	5.5 Mbps	0.712	0.691	0.677
	10 Mbps	0.697	0.685	0.671

end-to-end delay of AOC-MAC has experienced approximately 19.7% and 8.22% increase in comparison with IEEE 802.11s MAC and S-MAC, respectively. With a 2-Mbps data rate, AOC-MAC has experienced 20.87% and 7.7% increase of end-to-end delay in comparison with IEEE 802.11s MAC and S-MAC, respectively. With a 5.5-Mbps data rate, the average end-to-end delay of AOC-MAC has experienced approximately 16.78% and 7.47% increase in comparison with IEEE 802.11s MAC and S-MAC, respectively. With a 10-Mbps data rate, AOC-MAC has experienced 10.49% and 5.27% increase of average end-to-end delay in comparison with IEEE 802.11s MAC and S-MAC, respectively. It is clear that when the traffic data rate increases, the values of end-to-end delay of the three MAC schemes become closer.

The video quality is estimated in terms of MSSSIM measured by using MSU. Note how the MSSSIM values of IEEE 802.11s MAC, S-MAC and AOC-MAC decrease with the increase of the traffic data rate. With a 1-Mbps data rate, the average MSSSIM value of AOC-MAC has experienced approximately 8.55% decrease in comparison with IEEE 802.11s MAC, and approximately 2.35% decrease in comparison with S-MAC. With a 2-Mbps data rate, AOC-MAC has experienced 9.42% and 3.4% decrease of the average MSSSIM value in comparison with IEEE 802.11s MAC and S-MAC, respectively. With a 5.5-Mbps data rate, the average MSSSIM value of AOC-MAC has experienced approximately 4.92% decrease in comparison with IEEE 802.11s MAC, and approximately 2.03% decrease in comparison with S-MAC. With a 10-Mbps data rate, AOC-MAC has experienced 3.73% and 2.04% decrease of the average MSSSIM value in comparison with IEEE 802.11s MAC and S-MAC, respectively. Note that the decrease of data transmission QoS in terms of MSSSIM is less obvious when the data rate is higher.

Test results indicate that both the energy saving benefit of AOC-MAC and the consequent decrease in QoS (i.e. frame loss, delay, MSSSIM) are less obvious at higher traffic data rates, in comparison with IEEE 802.11s MAC and S-MAC. However, regardless of the traffic data rate, the energy saving benefit overcomes the QoS decrease.

TABLE 5 EFFECT OF MESH ROUTER NUMBER ON AOC-MAC PERFORMANCE

Mesh Routers		802.11s	S-MAC	AOC-MAC
Energy Consumption (mWatts)	10	26.12	23.48	22.24
	20	24.9	20.79	19.66
	30	23.43	19.62	18.84
	40	22.06	18.75	17.53
	50	20.98	18.42	17.07
Frame Loss (%)	10	4.796	5.025	5.238
	20	4.057	4.293	4.586
	30	3.547	3.725	4.028
	40	3.249	3.396	3.712
	50	3.122	3.247	3.537
End-to-end Delay (Seconds)	10	1.324	1.516	1.664
	20	1.433	1.608	1.729
	30	1.527	1.679	1.763
	40	1.589	1.726	1.782
	50	1.631	1.747	1.793
MSSSIM	10	0.665	0.602	0.588
	20	0.754	0.707	0.683
	30	0.819	0.781	0.767
	40	0.874	0.836	0.817
	50	0.908	0.869	0.841

A-2 Mesh Router Number Impact on AOC-MAC Performance

This test was done in order to investigate how different numbers of mesh routers included in the network affect AOC-MAC performance. The settings of mesh router mobility used in section IV B were used in this test. The traffic data rate was set to 2.0 Mbps and the video number 2 in Table 3 was selected as the corresponding source video. The number of mesh routers was varied from 10 to 50 with a step of 10 mesh routers in each test. The other settings related to the mesh network topology have remained the same as shown in Table 2.

The estimation and measurement results of the impact of the number of mesh routers are shown in Table 5. Note how the energy consumption rates on the mesh routers when IEEE 802.11s MAC, S-MAC and AOC-MAC are employed decrease along with the increase of number of mesh routers, as less mesh routers require to be in the wake-up state for longer in order to maintain wireless connectivity. With 10 mesh routers, AOC-MAC has obtained 14.85% decrease of energy consumption rate in comparison with IEEE 802.11s MAC, and 5.28% decrease of energy consumption rate in comparison with S-MAC. With 20 mesh routers, AOC-MAC obtains 21.04% and 5.44% energy savings in comparison with IEEE 802.11s MAC and S-MAC, respectively. With 30 mesh routers, AOC-MAC saves approximately 19.59% and 3.97% more energy in comparison with IEEE 802.11s MAC and S-MAC, respectively. With 40 mesh routers, AOC-MAC provides 20.53% and 6.51% energy savings in comparison with IEEE 802.11s MAC and S-MAC, respectively. With 50 mesh routers, the energy saving of AOC-MAC is approximately 18.64% and 7.33% higher than that of IEEE 802.11s MAC and S-MAC, respectively.

The frame loss rates of IEEE 802.11s MAC, S-MAC and AOC-MAC decrease along with the increase in the number of mesh routers, as less mesh routers with mobility cause more

TABLE 6 EFFECT OF MESH ROUTER MOBILITY ON AOC-MAC PERFORMANCE

Average Values	Case 1			Case 2		
	802.11s	S-MAC	AOC-MAC	802.11s	S-MAC	AOC-MAC
Energy Consumption (mWatts)	23.98	19.75	18.81	24.9	20.79	20.66
Frame Loss (%)	2.984	3.112	3.413	4.057	4.293	4.586
End-to-end Delay (Seconds)	1.356	1.445	1.538	1.433	1.608	1.732
MSSSIM	0.784	0.718	0.696	0.754	0.707	0.683
Standard Deviation	Case 1			Case 2		
	802.11s	S-MAC	AOC-MAC	802.11s	S-MAC	AOC-MAC
Frame Loss	1.806	1.784	1.713	1.896	1.897	1.864
End-to-end Delay	0.489	0.487	0.486	0.537	0.535	0.539
MSSSIM	0.141	0.176	0.183	0.153	0.178	0.185

unstable wireless connectivity and higher chances of packet drop. With 10 mesh routers, the average frame loss rate of AOC-MAC is 5.24% in comparison with 4.8% of IEEE 802.11s MAC and 5.03% of S-MAC. With 20 mesh routers, AOC-MAC has obtained 4.58% average frame loss rates in comparison with 4.06% average frame loss rate of IEEE 802.11s MAC and 4.293% of S-MAC. With 30 mesh routers, the average frame loss rate of AOC-MAC is approximately 4.03% in comparison with 3.55% of IEEE 802.11s MAC and 3.73% of S-MAC. With 40 mesh routers, AOC-MAC has obtained 3.72% average frame loss rates in comparison with 3.25% of IEEE 802.11s MAC and 3.4% of S-MAC. With 50 mesh routers, the average frame loss rate of AOC-MAC has increased to approximately 3.54% in comparison with 3.12% average frame loss rate of IEEE 802.11s MAC and 3.25% of S-MAC. Note that with the increase in the number of mesh routers, frame loss rates of the three schemes tend to be closer.

The end-to-end delays of the three MAC schemes increase along with the increase in the number of mesh routers, but in general remains at good levels. The MSSSIM values when IEEE 802.11s MAC, S-MAC and AOC-MAC are employed are also shown in Table 5. Note the MSSSIM values increase with the increase in the traffic data rate, but in general remain at good level. The results presented indicate that although AOC-MAC results in slight QoS decrease in comparison with IEEE 802.11s MAC and similar quality level with S-MAC regardless of the number of mesh routers, there is a significant energy saving benefit.

A-3 Mesh Router Mobility Impact on AOC-MAC Performance

This test was done in order to investigate the impact of mesh router mobility on AOC-MAC performance. Different mobility settings of mesh routers result in different network structures in different periods, in which the condition of traffic delivery changes and the sleep/wake-up periods of mesh router change accordingly, affecting the throughput during traffic delivery and the energy consumption of mesh routers.

Two mesh router mobility test cases were introduced in this test, involving the mesh nodes illustrated in Figure 1:

- 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} was moving 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 the mobility parameters described in section IV B, starting from a random pause period between [0, 2] (seconds) and continuing to move with a random direction value between [0, 2π] and a random speed value between [1.0, 2.0] (m/s) until the boundary of the mesh network with range R is reached, as shown in Figure 1. The mesh 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.

In this test, the traffic data rate was set to 2.0 Mbps and the video sequence 2 in Table 3 was selected as the corresponding source video. The number of mesh routers was set to 20. The rest settings related to the mesh network topology remained the same as shown in Table 2.

The results of the mesh router mobility impact study are shown in Table 6 in terms of the average value of the results and the standard deviation of the QoS parameters:

- Energy consumption: In case 1 when the mesh routers are static, the energy savings of AOC-MAC in comparison with the IEEE 802.11s and S-MAC are approximately 21.56% and 4.76%, respectively. In case 2 when the mesh routers are randomly moving, the energy savings of AOC-MAC in comparison with the IEEE 802.11s is approximately 17.03%, while the energy consumption rates of AOC-MAC and S-MAC are approximately the same. The average energy consumption rate of AOC-MAC in case 1 is 8.95% lower than in case 2.
- Frame loss: The average frame loss rate of AOC-MAC has increased to 3.41% in comparison with the 2.98% rate of the IEEE 802.11s MAC protocol and the 3.11% rate of S-MAC in case 1, respectively. In case 2, the average frame loss rate of AOC-MAC has increased to 4.59% in comparison with the 4.06% rate of the IEEE 802.11s MAC protocol and the 4.29% rate of S-MAC, respectively. The average frame loss rate of AOC-MAC in case 1 is 25.58% lower than in case 2.

TABLE 7 PSNR AND MSSSIM VALUES WITH 802.11S, S-MAC AND AOC-MAC

			802.11s	**S-MAC**	**AOC-MAC**	**802.11s**	**S-MAC**	**AOC-MAC**
			PSNR (dB)			**MSSSIM (0-1)**		
Test Case A-1	Data Rate (Mbps)	**1**	28.63	28.06	27.14	0.768	0.731	0.712
		2	27.84	27.34	26.77	0.748	0.704	0.692
		5.5	26.66	26.22	25.67	0.709	0.695	0.682
		10	25.45	24.97	24.46	0.702	0.691	0.677
Test Case A-2	Number of Mesh Routers	**10**	26.38	25.98	25.62	0.670	0.605	0.593
		20	27.84	27.34	26.77	0.760	0.707	0.683
		30	29.00	28.58	27.90	0.823	0.781	0.767
		40	29.77	29.38	28.61	0.880	0.830	0.811
		50	30.11	29.77	29.03	0.874	0.858	0.833
Test Case A-3	Mesh Router Mobility	**Static**	30.50	30.14	29.34	0.748	0.704	0.692
		Mobile	27.84	27.34	26.77	0.734	0.689	0.683

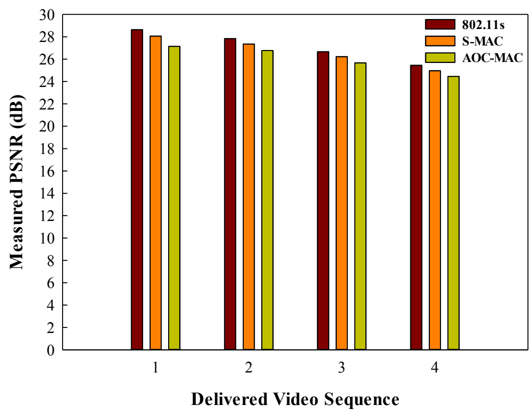

Fig.7. PSNR achieved using 802.11s, S-MAC and AOC-MAC with variable data rates

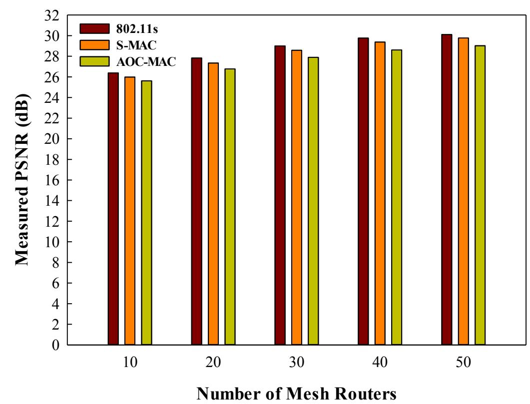

Fig.8. PSNR achieved using 802.11s, S-MAC and AOC-MAC with variable mesh router numbers

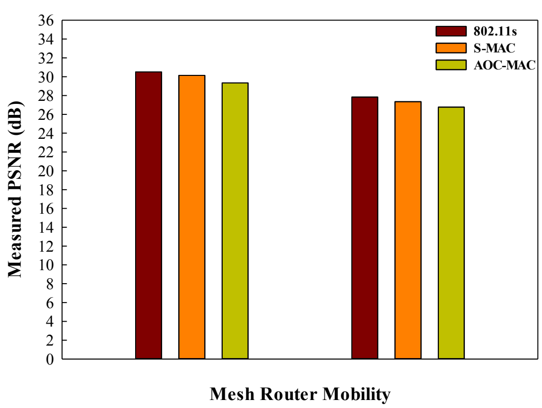

Fig.9 PSNR achieved using 802.11s, S-MAC and AOC-MAC with variable mesh router mobility

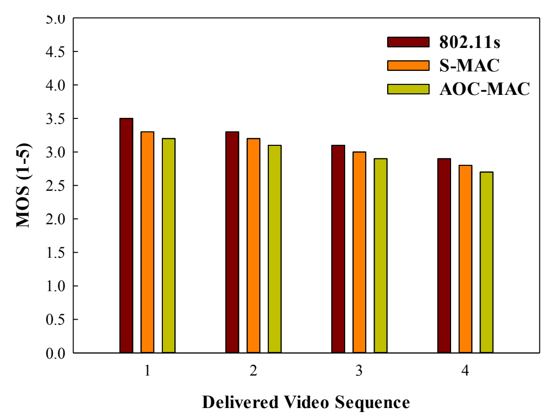

Fig.10. MOS achieved using 802.11s, S-MAC and AOC-MAC with variable data rates

- End-to-end delay: In case 1 when the mesh routers are static, the end-to-end delay of AOC-MAC has approximately 13.42% increase in comparison with the IEEE 802.11s and 6.44% increase in comparison with S-MAC. In case 2 when the mesh routers are randomly moving, the end-to-end delay of AOC-MAC has approximately 17.03% and 7.71% increase in comparison with the IEEE 802.11s and S-MAC, respectively. The average end-to-end delay of AOC-MAC in case 1 is 11.2% lower than in case 2.
- Quality: In case 1 when the mesh routers are static, the average MSSSIM value of AOC-MAC has approximately 11.22% decrease in comparison with the IEEE 802.11s and 3.06% decrease in comparison with S-MAC. In case 2 when the mesh routers are randomly moving, the end-to-end delay of AOC-MAC has approximately 9.41% and 3.39% decrease in comparison with the IEEE 802.11s and S-MAC, respectively. The average MSSSIM value of AOC-MAC in case 1 is 1.87% higher than in case 2.

Test results indicate that AOC-MAC achieves better performance in terms of both energy savings and QoS levels in the case when the mesh routers are with fixed position in comparison with the case when mesh routers are with random mobility, as indicated by the standard deviations of the results included in Table 6. The standard deviation of energy consumption rate is not presented as the energy is dropping almost linearly. AOC-MAC deployed at mesh routers with mobility results in higher standard deviation on frame loss, end-to-end delay and video quality, representing lower stability. It is clear that fixed mesh routers reduce the frequency of mesh network topology change, indicating more stable network connectivity during traffic delivery. However, the effect of mesh router mobility on transmission quality is not obvious, according to Table 6.

B. AOC-MAC Perceptual Test Result Analysis

B-1 Objective Test Result Analysis

The measured PSNR and MSSSIM values of the received videos for the three test cases are presented in Table 7. Figure 7 also illustrates the PSNR values measured in test case A-1 and shows that the video delivered with AOC-MAC has slightly lower average PSNR in comparison with IEEE 802.11s MAC and S-MAC with different data rates (1 Mbps, 2 Mbps, 5.5 Mbps and 11 Mbps). For example, when the video sequence 1 in Table 3 is delivered, PSNR of AOC-MAC has decreased by 5.2% and 3.3% in comparison with IEEE 802.11s MAC and S-MAC, respectively. Similar results are obtained for MSSSIM, suggesting 7.3% and 2.6% decrease of the received video quality when AOC-MAC is used in comparison with IEEE 802.11s MAC and S-MAC, respectively.

PSNR results measured in test case A-2 are illustrated in Figure 8 which shows the increase in average PSNR of the received videos along with the increase of the number of mesh routers in the simulated mesh network. For different mesh router numbers, the average PSNR of the received videos using AOC-MAC has decreased in comparison with IEEE 802.11s MAC and S-MAC. For instance, when 20 mesh routers are used, the average PSNR of the received videos using AOC-MAC has decreased 3.8% and 2.1% compared against IEEE 802.11s MAC and S-MAC, respectively. Similarly, the average MSSSIM of the received videos increases along with the increase of the number of mesh routers in the simulated mesh network. Also, MSSSIM of AOC-MAC decreases in comparison with the other two MAC protocols. For instance, the decrease of the average MSSSIM of the received videos using AOC-MAC is roughly 10.1% in comparison with IEEE 802.11s MAC and 3.4% in comparison with S-MAC.

Figure 9 illustrates PSNR values measured in test case A-3 and shows that when the mesh routers are randomly moving, the video delivered with the three MAC solutions has lower average PSNR than when the mesh routers are static. When IEEE 802.11s MAC is used, the PSNR of the received video has an 8.7% decrease when the mesh routers are randomly moving compared against when the mesh routers are static. When S-MAC is used, the PSNR of the received video experiences a 9.3% decrease when the mesh routers are randomly moving compared against the static case. When AOC-MAC is used, the PSNR of the received video has a 8.6% decrease when the mesh routers are randomly moving compared against when they are static. In general, AOC-MAC has approximately 3.8% and 2.7% lower average PSNR in comparison with IEEE 802.11s MAC and S-MAC when the mesh routers are static, respectively. When the mesh routers are moving, AOC-MAC has approximately 3.8% and 2.1% lower average PSNR in comparison with IEEE 802.11s MAC and S-MAC, respectively. A similar comparison can be made in terms of MSSSIM. When IEEE 802.11s MAC is used, the MSSSIM of the received video has a 1.87% decrease when the mesh routers are randomly moving compared against when the mesh routers are static. When S-MAC is used, the MSSSIM of the received video has a 2.13% decrease when the mesh routers are randomly moving compared against when the mesh routers are static. When AOC-MAC is used, the MSSSIM of the received video has a 2.89% decrease when the mesh routers are randomly moving compared against when the mesh routers are static. In general, AOC-MAC has approximately 7.5% and 1.7% lower average MSSSIM in comparison with IEEE 802.11s MAC and S-MAC when the mesh routers are static, respectively. When the mesh routers are moving, AOC-MAC has approximately 8.3% and 2.3% lower average MSSSIM in comparison with IEEE 802.11s and S-MAC, respectively.

TABLE 8 MOS VALUES WITH 802.11S, S-MAC AND AOC-MAC

		802.11s	**S-MAC**	**AOC-MAC**
		MOS (1-5)		
Test Case A-1 Data Rate (Mbps)	**1**	3.5	3.3	3.2
	2	3.3	3.2	3.1
	5.5	3.1	3.0	2.9
	10	2.9	2.8	2.7
Test Case A-2 Number of Mesh Routers	**10**	3.1	3.0	2.9
	20	3.3	3.2	3.1
	30	3.5	3.4	3.3
	40	3.6	3.5	3.4
	50	3.7	3.6	3.5
Test Case A-3: Mesh Router Mobility	**Static**	3.8	3.7	3.5
	Mobile	3.3	3.2	3.1

Although the received video quality is slightly lower on comparison with IEEE 802.11s MAC and S-MAC, AOC-MAC achieves significant energy savings on mesh routers according to the test results presented in section VI A.

B-2 Subjective Test Result Analysis

Figure 10 illustrates the average MOS values measured for test case A-1, which shows that video delivered with AOC-MAC has slightly lower average MOS in comparison with IEEE 802.11s MAC and S-MAC with different data rates (1 Mbps, 2 Mbps, 5.5 Mbps and 10 Mbps). When the video sequence 1 to 4 in Table 3 is delivered, the average MOS of AOC-MAC has decreased by approximately 8.57% and 3.03%; 6.06% and 3.12%; 6.45% and 3.33% and finally 3.45% and 3.57% in comparison with IEEE 802.11s MAC and S-MAC, respectively. Also, Figure 10 shows the decrease of MOS along with the increase of the data rate of the delivered video.

The average MOS values measured in test case A-2 are illustrated in Figure 11, which shows the increase of the average MOS of the received videos along with the increase of the number of mesh routers in the simulated mesh network. For different mesh router numbers, the average MOS of the received videos using AOC-MAC has decreased in comparison with IEEE 802.11s MAC and S-MAC. When 10, 20, 30, 40 and 50 mesh routers are set in the simulated mesh network, the average MOS of the received videos using AOC-MAC has decreased 6.45% and 3.33%; 6.06% and 3.13%; 5.71% and 2.94%; 5.56% and 2.86%; and finally 5.41% and 2.78%

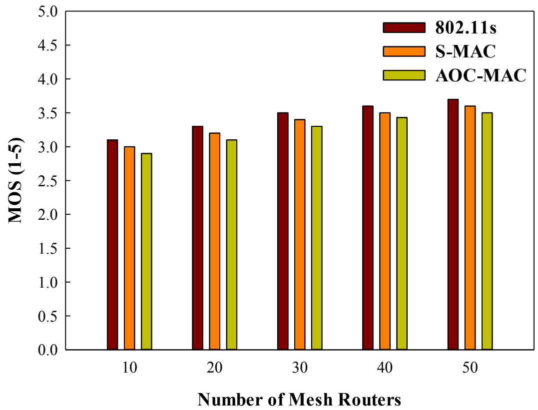

Fig.11. MOS achieved using 802.11s, S-MAC and AOC-MAC with variable mesh router numbers

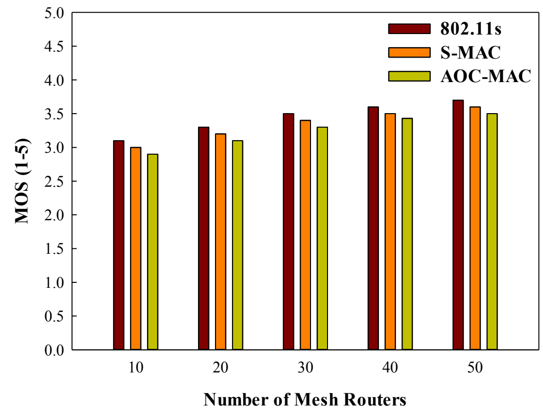

Fig.12. MOS achieved using 802.11s, S-MAC and AOC-MAC with variable mesh router mobility

compared against the IEEE 802.11s MAC protocol and S-MAC, respectively. Also, Figure 11 shows the decrease of MOS along with the increase of the video data rate. It is clear that the impact of AOC-MAC on the decrease of received video quality is less significant with higher number of mesh routers.

Figure 12 illustrates the MOS values measured in test case A-3, which shows that when the mesh routers are randomly moving, the video delivered with the three MAC solutions has lower average MOS than when the mesh routers are static. When IEEE 802.11s is used, the MOS of the received video has a 13.16% decrease when the mesh routers are randomly moving compared against when the mesh routers are static. When S-MAC is used, the MOS of the received video has a 13.51% decrease when the mesh routers are randomly moving compared against when the mesh routers are static. When AOC-MAC is used, the MOS of the received video experiences a 11.43% decrease when the mesh routers are randomly moving compared against when the mesh routers are static. In general, AOC-MAC has approximately 7.89% and 5.41% lower average MOS in comparison with IEEE 802.11s MAC and S-MAC when the mesh routers are static, respectively. When the mesh routers are moving, AOC-MAC has approximately 6.06% and 3.13% lower average PSNR in comparison with the IEEE 802.11s MAC protocol and S-MAC, respectively.

The measured MOS values of the received videos for AOC-MAC test cases are concluded in Table 8. Although the received video quality is slightly lower on comparison with IEEE 802.11s MAC and S-MAC, AOC-MAC achieves significant energy savings on the mesh routers according to the simulation test results presented in section VI A.

VII. Conclusions

This article presents AOC-MAC, an energy-aware MAC-layer solution for balancing energy saving and good service quality levels for devices in wireless mesh networks. Testing of AOC-MAC was performed via both simulations and a real-life experimental test-bed and its performance was assessed using objective and subjective quality methods.

AOC-MAC was analyzed in terms of the trade-off between energy consumption and traffic delivery performance on wireless mesh routers. It was compared against the duty cycle management scheme in the existing IEEE 802.11s MAC mechanism and an existing duty cycle management scheme S-MAC, with the same parameter settings of a multi-router mesh network. Performance analysis was investigated with the impact of various traffic data rates, number of mesh routers and mesh router mobility.

Simulation-based test results show that AOC-MAC sacrifices little QoS in terms of approximately up to 5% higher frame loss, 6%-12% higher delay and 8% lower video quality, for a significant 21.56% and a 11.18% energy saving in comparison with the IEEE 802.11s MAC protocol and S-MAC, respectively, with various settings of traffic data rates, number of mesh routers and mesh router mobility. Also, the energy saving and quality drop of AOC-MAC increase along with the increase of traffic data rate and decrease along with the increase of the number of mesh routers in the mesh network, while the energy saving and quality drop of AOC-MAC is roughly 8.95% and 1.87% lower when the mesh routers are static than when the mesh routers are moving. Experimental test results show that AOC-MAC achieves approximately the same video transmission quality level in comparison with the IEEE 802.11s MAC protocol and S-MAC.

Several future research directions can be identified for further progress of this work. One of the most important future research aspects is the optimization of AOC-MAC, including solving the ping-pong effect with either a delay decision on changing the parameters related to mesh router sleep-periods or employing hysteresis in its decision making process. Additional network-related data apart from the binary disconnect information AOC-MAC uses in this paper can be considered when performing future work in order to increase the energy-efficiency performance of the proposed solution.

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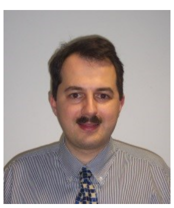
Dr. Shengyang Chen (S’11-S’15) was researcher with the Performance Engineering Laboratory, School of Electronic Engineering, Dublin City University, Ireland, which has also awarded him the Ph.D degree for research in energy and performance-aware multimedia delivery over heterogeneous wireless network environments in 2015, co-funded by the Irish Research Council and Everseen Ltd.. He received his Bachelor's Degree in Software Engineering at International School of Software, Wuhan University, China in 2009, and Master's Degree in Telecommunications Engineering at Dublin City University in 2010. His research interests include balancing performance and energy consumption when delivering multimedia content in heterogeneous wireless network environments.

Dr. Zhenhui Yuan (S'09-M'12) received his B.degree at Wuhan University in 2008 and PhD degree at Dublin City University in 2012. His research projects focused on wireless networking and QoS-based multimedia transmission. He was the postdoc researcher funded by Ericsson and Enterprise Ireland on project developing next generation telecommunication management system. He was the visiting scholar at Network Research Lab, UCLA, U.S. in 2014. He was 3GPP researcher at Huawei (Shanghai) Technologies.Co.Ltd during 2014-2015. Currently, he is the lecturer at School of Electronics and Information, Hangzhou Dianzi University. Based on the Ministry of Education Key Lab of Radio Frequency and Circuit, Dr. Yuan's research includes architecture/application of IoT and 5G. He has published over 20 papers at international journals and conferences. Dr. Yuan acts as the TPC member at international conferences such as IEEE Globecom, ICC, WCNC, etc. He is a member of IEEE.



Dr. Gabriel-Miro Muntean (S'99-M'04) is Senior Lecturer with the School of Electronic Engineering, co-Director of the Performance Engineering Laboratory at Dublin City University, Ireland and Consultant Professor with Beijing University of Posts and Telecommunications, China. He obtained his Ph.D. degree from Dublin City University, Ireland for research in quality-oriented adaptive multimedia streaming over wired networks in 2003. Dr. Muntean's research interests include quality and performance-related issues of adaptive multimedia streaming, performance of content delivery over wired and wireless networks and with various devices, and energy-aware networking. Dr. Muntean has published over 250 papers in top-level international conferences and journals and has authored three books and sixteen book chapters and edited six other books. Dr. Muntean is Associate Editor with the IEEE Transactions on Broadcasting, Associate Editor with the IEEE Communications Survey and Tutorials and reviewer for important international journals, conferences and funding agencies. He is a member of IEEE and IEEE Broadcast Technology Society