Enhanced Scheme for Adaptive Multimedia Delivery over Wireless Video Sensor Networks

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***Abstract*— Lately Video Sensor Networks (VSN) are increasingly being used in the context of smart cities, smart homes, for environment monitoring, surveillance, etc. In such system, the trade-off between Quality of Service (QoS) and energy consumption is always a big issue. As the wireless transmission part plays the dominant role in power consumption, many researches propose energy saving schemes based on the adjustment of duty cycle by adaptively switching between wake-up/sleep state of nodes. However, the main drawback of this method is that it affects streaming quality in terms of throughput and delay. Therefore, one of the most important challenges when designing an energy-aware VSN is to keep the balance between energy consumption and video delivery quality.**

This paper proposes an Enhanced scheme for Adaptive Multimedia Delivery (eAMD) that dynamically adjusts the wake-up/sleep duration of video sensor nodes based on the node remaining battery levels and network performance. A Markov Decision Process (MDP)-based framework is used to formulate the problem and an innovative algorithm based on Q-Learning is proposed to find the optimal policy for video sensor nodes. Using both a systematic and algorithmic approach, our proposed system architecture and algorithms hold the potential to improve the trade-off between video streaming quality and energy efficiency in comparison with other state-of-the-art adaptive video based algorithms.

I. INTRODUCTION

Wireless Sensor Network (WSN) and in particular Wireless Video Sensor Network (WVSN) systems have been deployed in many aspects of our life, for instance, in smart cities for traffic monitoring [1],[2], in smart homes for environment monitoring and security [3], in entertainment for video summarization [4], and in diverse situations for surveillance [5]. Such systems use a video compression technique, such as: H.264/AVC [6] or H.265/HEVC [7] as the video coding standard. Multimedia content including video and audio at diverse quality levels is sensed and transmitted from multimedia sensor nodes to sink nodes or gateways, often via WVSNs. WVSNs play key roles, especially in many recent Internet of Things (IoT) deployments [8]. An analysis from Cisco estimates that in 2020, there will be around 50 billion devices connected to the Internet and about 75% of the total traffic will be video [9]. Although in recent years, there has been a huge increase in the hardware platform development for sensor devices, the improvement in battery capacity is still far behind. For example, lithium-ion is considered as the best battery technology, but its energy density is increasing only 5% per year [10]. In this context, it is clear that one of the most important aspects in any IoT system is battery life time and its optimization.

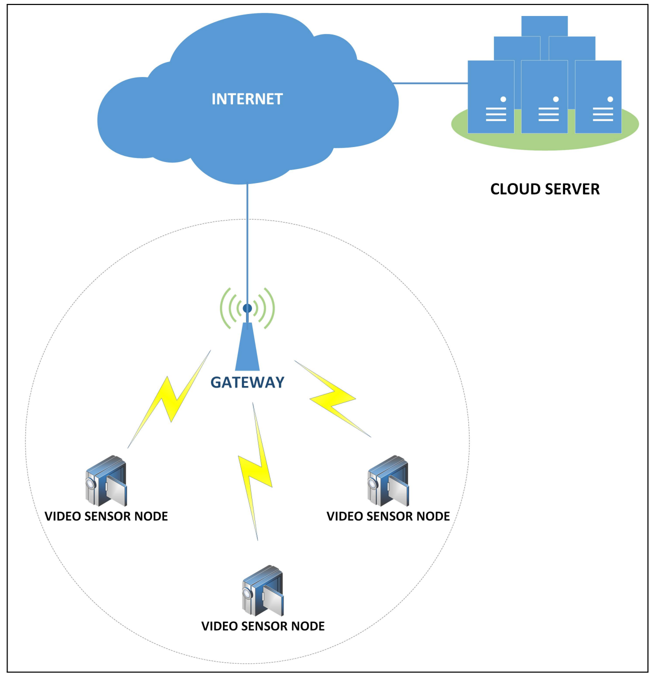

Fig. 1. A generic Video Sensor Network

A typical architecture of a video sensor network is illustrated in Fig. 1 [11]. This type of sensor network is equipped with tiny camera sensor nodes, embedded processors, and wireless transceivers. The video sensor nodes communicate with an aggregation node (or also called Gateway) or with each other via wireless links supported by wireless technologies from the IEEE 802.11 family (i.e. WiFi), cellular space (e.g. LTE) or IEEE 802.15 family (e.g. 6LowPan), etc.

In general, energy consumption in a sensor node is mostly due to the radio communications [12]. This is highly dependent on the MAC layer solution employed, so improvement of these solutions is considered fundamental in operational improvement of any energy-aware system such as a VSN. One avenue for such improvement is to adjust the sensor

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node duty cycle. In such a scheme, sensor node's transmission component dynamically switches between *on* and *off* states. The energy consumption of sensor nodes are high when they are in an *on* state. When nodes are switched *off*, they save energy. These solutions are especially important for video sensor nodes where the energy consumption is higher than in comparison with other scalar sensors. However, there is a trade-off when using duty-cycle based schemes. Throughput and delay are affected by the potential long sleep periods. In contrast, the energy consumption is high if VSN nodes stay in active state for long periods of time. So, it is necessary to propose schemes which consider both energy efficiency and delivery quality and employ a mechanism to balance them.

In this paper, the problem of energy-quality trade off for VSN at node level is addressed by:

- Formulating the problem in a Markov Decision Process (MDP) framework context.
- Using Q-Learning [13] to find an optimal policy for the node to dynamically adjust its active/sleep duty cycle periods by taking into account both energy and network performance parameters.
- Proposing the enhanced Adaptive Multimedia Delivery (eAMD) scheme to include the optimal duty cycle adjustment policy and best balance performance and energy.
- Validating the proposed approach and making comparisons with other state-of-the-art duty cycle-based algorithms for WSNs.

The rest of this paper is organized as follows: section II discusses related works from the literature on VSN including some adaptive duty-cycle adjustment and battery-aware schemes. In section III eAMD - the proposed solution is described in terms of its block-level architecture and proposed algorithm. The testing plans on both simulation environment and real hardware platform are described in Section IV. Section V presents the testing results and result-related discussions. Finally, conclusions are drawn and future work directions are indicated in section VI.

II. Related Works

In the context of the work presented in this paper, next some research solutions on the following topics are discussed: 1) adaptive video delivery over wireless networks, 2) adaptive adjustment of duty-cycle of sensor nodes, and 3) the use of MDP in WSN.

[18] proposes a solution for enabling multimedia content personalisation based on user device screen resolution, as well as multimedia content adaptation based on the available network bandwidth. In [15] and [16], the authors made use of utility functions in network selection or content adaptation during video delivery to mobile devices. The video configuration settings, i.e., bit rate, frame rate, are adapted based on the utility value achieved from the proposed the utility function. In another work, diverse solutions for the trade-off between the encoding complexity and communication power consumption in a VSN are investigated [17]. The same work also proposes several algorithms to reduce the power consumption in VSNs in different uses cases.

Duty cycle has received much attention in the research literature and its variation is considered an effective way to reduce energy consumption for wireless network nodes. The basic idea behind duty cycle adaptive operation is adjustment of the wake-up/sleep time of the radio transmission. One of the most cited work on duty cycle is SMAC [20]. SMAC aims to implement a fixed duty cycle value for all sensor nodes and proposes a mechanism to synchronize between neighbor nodes in a cluster. Enhancing the operation of SMAC, TMAC [22], XMAC [23] and LCMAC [24] have introduced adaptive schemes which change the duty cycle according to traffic load. However, most of these previous works are not suitable for multimedia delivery as they focus only on scalar sensor types and do not include mechanisms to support any Quality of Service (QoS) requirements.

To achieve trade-off between QoS requirements and energy consumption, various researchers have focused on the adjustment of duty cycle based on distance between sink and sensor nodes, packet delivery flow, and network traffic conditions. First of all, in [25], Xie *et. al.* have argued that the QoS requirement can be prioritized for sensor nodes that are close to the sink nodes, whereas nodes that are far from the sink can be deployed with a special duty cycle to reduce the energy consumption. The authors of [26] have proposed another method for duty cycle adjustment based on the comparison between the entire packet delivery flow and sensor node energy consumption. Another solution presented in [27] has focused on the management of the duty cycle by considering network traffic load conditions. Researchers have also proposed battery power-aware solutions for adaptive video delivery in [28] and [29].

In the research literature, MDP has been studied and applied for WSN when proposing innovative adaptive algorithms and protocols. In [32], Ye et al. have focused on the trade-off between energy efficiency and packet delivery over a WSN. The main purpose of this scheme is to maximize a reward function with the consideration of waiting time of packets in the buffer before being transmitted. Other works focusing on using MDP to adjust the duty cycle for WSN were also described in [33] and [34]. In [30], Brahmi et al. adopted MDP and a utility reward function when proposing an optimal decision policy for scheduling the transmission of the aggregated data for a sensor node. However, most of these works focus on scalar sensor types for WSN, and cannot be applied for VSNs which have higher requirements in terms of throughput, energy consumption, and delay.

Our previous work on the Uplink Adaptive Multimedia Delivery (UAMD) scheme [31] has proposed the use of an utility function with battery power level and throughput as variables. The UAMD scheme outperformed AWP [27] and S-MAC [20] in terms of both throughput and battery power consumption. However, UAMD did not consider the dynamic state of incoming packets and delay, but these are major issues in any multimedia delivery system.

This paper aims to bridge the gap between battery power level awareness and quality in the context of adaptive multimedia delivery in a VSN. Different from previous works, it proposes the eAMD solution which is built based on of a Markov Decision Process (MDP) framework. We find the optimal policy for VSN by applying Q-Learning [13], a model-free reinforcement learning technique, which is widely applied in fields that need to determine automatically the ideal behavior for agents within a specific context, in order to maximize its performance. With eAMD, VSN nodes make decisions by adjusting their radio transmission active/sleep time to save energy while also monitoring QoS in order to maintain good QoS levels.

III. The Enhanced Scheme for Adaptive Multimedia Delivery (eAMD)

A. Problem Formulation

In this subsection, we describe how the problem is formulated in a MDP framework. MDP is an optimization model for decision making under certainty. Generally, at each decision time (or also called `episode`), an agent (located at the level of a VSN node) stays in a certain state and it chooses an available action at that time. A reward for these $State$ and $Action$ pair is assigned and VSN node transits to next state. In WSN, MDP is usually used to leverage the interaction between a wireless sensor node and its surrounding environment to achieve some objectives [14].

1) ***State Space:*** At each episode, any node evaluates its current state S_k. A state is modeled as a tuple containing information that is used to make decision as follows:

$$S_k = (E_k, Th_k, D_k) \tag{1}$$

where:

- E_k denotes node energy consumption, including remaining battery level (%) and depletion rate (J/s)
- Th_k is defined as average throughput after each episode ($Mbps$)
- D_k represents waiting time since the last transmission (s)

2) ***Action Space:*** In our proposed solution, the duty cycle (denoted as δ) is chosen as the video sensor node action in each episode. We use the following definition for duty cycle:

$$\delta = \frac{T_A}{T_A + T_S} \tag{2}$$

In equation (2):

- T_A refers to the time duration the radio transmission of a video sensor node is in one of the Active states. These states are *Transmit (Tx)*, *Receive (Rx)* and *Idle (Idle)*.
- T_S refers to the time duration that the radio transmission of a video sensor node is in the *Sleep (S)* state. In this state other node components related to processing and sensing are still on.

Denote k as the number of available actions, we have a k-dimensional vector for action $\delta = \{\delta_0, \delta_1, \cdots, \delta_{k-1}\}$

The ultimate goal is to find the action (or duty cycle value) so that an expected reward function is maximized.

3) ***Reward Function:*** Our reward function is built based on a combination of energy, throughput, delay, and action utility value. The reward value is calculated in each episode k, given state S_k and action δ_k as follows:

$$R_k(S_k, \delta_k) = \omega_E \times U_E + \omega_{Th} \times U_{Th} + \omega_D \times U_D \tag{3}$$

In equation (3):

- U_E, U_{Th}, and U_D refer to utility functions for energy, throughput, and delay, respectively.
- ω_E, ω_{Th}, and ω_D are weighting factors for energy, throughput, and delay, respectively. It is assumed that: $\omega_E + \omega_{Th} + \omega_D = 1$.

The utility function for energy introduced in our previous paper [31] is employed:

$$U_E(\delta) = 1 - \frac{[\delta \times P_A + (1-\delta) \times P_S] \times \Gamma}{E_{max}} \tag{4}$$

In equation (4):

- E_{max} (Joules): is the maximum energy of a battery pack.
- Γ (seconds): is the time period for utility function computation.
- P_S and P_A (Joules/second): are power consumption values when VSN nodes are in *Sleep* and *Active* states, respectively.

Denote R as the data rate at sender; provided there is no loss, the throughput is estimated as: $Th = R \times \delta$. The utility function for throughput [15] has the following formula:

$$U_{Th}(\delta) = \begin{cases} 0 & \text{if } Th < Th_{Min} \\ 1 - e^{\frac{-\alpha \times Th^2}{\beta + Th}} & \text{if } Th_{Min} \le Th < Th_{Max} \\ 1 & otherwise \end{cases} \tag{5}$$

In equation (5):

- Th_{Min} and Th_{Max} are minimum and maximum throughput (dependent on application).
- $\alpha = 5.72$ and $\beta = 2.66$ are two positive function parameters introduced in [15].

Finally, we explain how the utility function for delay is built. Denote T_{k-1} and T_k the times of two consecutive cycles; $\tau = T_k - T_{k-1}$ is equal to the duration of a cycle. Denote T_o the time at which a packet arrives; if $T_o > T_k + \tau \times \delta$ (i.e. the packet arrives when VSN node is in *Sleep* state), it must wait until the next cycle. So the delay (denoted D) is equal to $D = T_k - T_o$. The utility function for delay, as cited in [35], is shown in equation (6).

$$U_D(\delta) = \begin{cases} 1 & \text{if } 0 < D \le D_{min} \\ \frac{D_{max} - D}{D_{max} - D_{min}} & \text{if } D_{min} < D < D_{max} \\ 0 & \text{if } D_{max} \le D \end{cases} \tag{6}$$

In equation (6):

- D_{min} and D_{max} are two constants representing lower and upper acceptable limits for delay. They can be set based on application requirements.

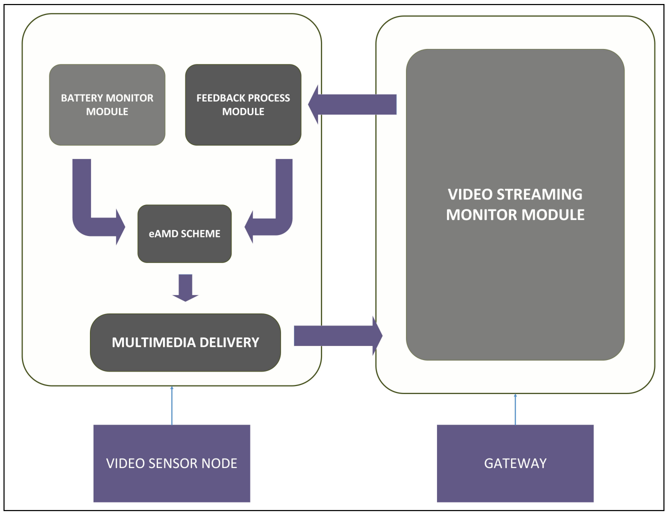

Fig. 2. eAMD-based system block-level diagram

B. Block-level Architecture

The block diagram of our proposed scheme is illustrated in Fig. 2. eAMD's main functional modules are described as follows in the context of its main two components: Gateway and video sensor nodes. We extended the architecture proposed in the context of our previous work UAMD [31] by applying the MDP framework at the core of the eAMD architecture.

In the context of eAMD architecture, at the level of the video sensor nodes there exist:

- Battery Monitor Module: periodically collects the information about the video sensor node's battery level and depletion rate.
- Feedback Process Module: collects feedback from Gateway on the quality of video streaming.
- Enhanced Adaptive Multimedia Delivery: employs the proposed eAMD scheme which makes use of a reward utility function to make decisions regarding adjusting the wake-up/sleep time of radio transmission based on energy, video streaming throughput, and delay conditions of VSN nodes.
- Multimedia Delivery: delivers the multimedia content via the wireless interface.

At the level of the Gateway:

- Multimedia streaming monitoring module: receives the multimedia stream, makes an estimation on the quality of the delivery and sends feedback to video sensor node.

C. eAMD Algorithm

The proposed eAMD algorithm is presented in Algorithm I. The following parameters are used in this algorithm:

- Episode (or cycle) is the time duration between which VSN nodes can switch between *Sleep* and *Active* state.
- Q-Value table: In each episode, the Q-value for each pair $< State, Action >$ is calculated and stored in VSN nodes' memory in form of a table.
- Learning rate α (or step size) refers to how fast the algorithm converges. We use a constant value for α in this scheme.
- Discount factor γ is used to set the importance of the reward.

First of all, we initialize the state and action space, and the Q-Value table. Then the algorithm runs episodes iteratively. In each episode, each VSN node reads its current state parameters including: remaining energy, battery depletion rate, throughput, and delay. It then looks up in the Q-Value table to find the optimal action (duty cycle value) so that a maximum value of Q-Value can be achieved.

Next, based on the environment parameters, including next state and reward value, a new Q value for the $< State, Action >$ pair is updated for the current state and executed action.

Algorithm 1 Q Learning-based duty cycle adjustment

α: Learning rate
Initialize battery level E_0 to E_{Max} (Joules)
γ: Discount factor
ω_E, ω_{Th}, ω_D: Weighting factors for energy, throughput, and delay, respectively
$Q(s_0, \delta_0) \leftarrow 0.5$
for <each τ seconds> **do**
<Estimate value of Th_i>
<Estimate value of D_i>
<Estimate E_τ> as energy consumption in τ seconds
<Estimate remaining battery level $E_i = E_{i-1} - E_\tau$>
Choose duty cycle action δ_i
Assess $R(s_i, \delta_i)$
Wait τ seconds and observe next state s_{i+i}
Choose action δ_{i+1} in 2 steps:
Search in Q-Value table to find $max[Q(s_{i+1}, \delta_{i+1})]$ value
Update Q-Value for current <State, Action> pair following the equation:

$$Q(s_i, \delta_i) \leftarrow Q(s_i, \delta_i) + \alpha \times (R(s_i, \delta_i) + \gamma \times max[Q(s_{i+1}, \delta_{i+1})] - Q(s_i, \delta_i))$$

$s_i \leftarrow s_{i+1}$

IV. Performance Evaluation

A. Simulation based testing

Network Simulator (NS-3) [36] is employed as the modeling and simulation tool for testing the proposed eAMD scheme. Network topology (as illustrated in figure1) consists of one Gateway and a number of video sensor nodes. Each of node falls into one of the following four

TABLE I
SIMULATION SETUP

Parameter	Value
Simulation Length	40,000 seconds
Number of Gateways	1
Number of Video sensor nodes	6
Cell layout	Single cell; Radius - 100 meters
WiFi Mode	IEEE 802.11n 2.4 GHz
Antenna Model	Isotropic Antenna Model
Initial Energy	20,000 (Joules)
T_A + T_S	1 second
Data rate (Mbps)	2.0
P_{Tx} (Watts)	1.14
P_S (Watts)	0.10
P_{Idle} (Watts)	0.82
P_{Rx} (Watts)	0.94
Learning Rate	α = 0.5
Discount Factor	γ = 0.5
Delay bound	U_D = 1.0 & L_D = 0.1

categories: *Throughput-oriented*, *Balanced-oriented*, *Delay-oriented*, and *Energy-oriented*. The parameters for the simulations are included in Table I.

We assume that the video sensor nodes use the H264/MPEG-4 AVC video compression for their content delivery to the Gateway. Different video quality levels are considered and their associated characteristics including bit-rates, resolutions and frame rates are presented in Table II [15].

The tests involving eAMD were performed with different values for the weighting factors as follows:

- Balance-oriented case: $\omega_E = \omega_{Th} = \omega_D = 0.33$
- Energy-oriented case: $\omega_E = 0.8$; $\omega_{Th} = \omega_D = 0.1$
- Throughput-oriented case: $\omega_E = \omega_D = 0.1$; $\omega_{Th} = 0.8$
- Delay-oriented case: $\omega_E = \omega_{Th} = 0.1$; $\omega_D = 0.8$

B. Test Results and Discussions

Figures 3, 4, and 5 illustrate the performance of different flavours of eAMD in comparison with S-MAC (SMAC) and UAMD schemes. The graphs plot the variations of throughput, battery level and delay with increasing number of episodes (and as time progresses), employing the different solutions, respectively. The results are averaged across the nodes.

- First of all, note that due to the learning process, each VSN node spends some time (i.e. several episodes) to collect data from environment before achieving an equilibrium state. From Table III, we can see that eAMD results in terms of throughput outperform those for SMAC, and UAMD. When using different eAMD flavours (i.e. Balanced, Throughput, and Delay-oriented, respectively) throughputs of 1.074, 1.292, and 1.260 $Mpbs$ are achieved in comparison with approximately 1.00 Mbps of both UAMD and SMAC.
- In terms of remaining battery level, after the simulation, as expected, the Energy-oriented eAMD shows the best result with 32.67% in comparison with 29.72% and 29.90% of UAMD and SMAC, respectively.

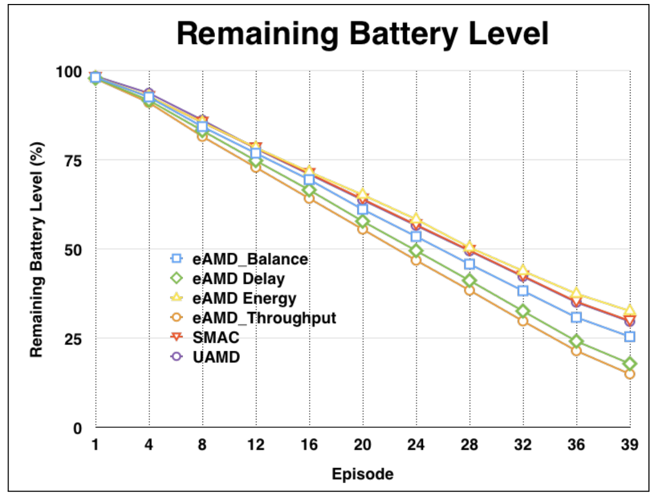

Fig. 3. Remaining Battery Level

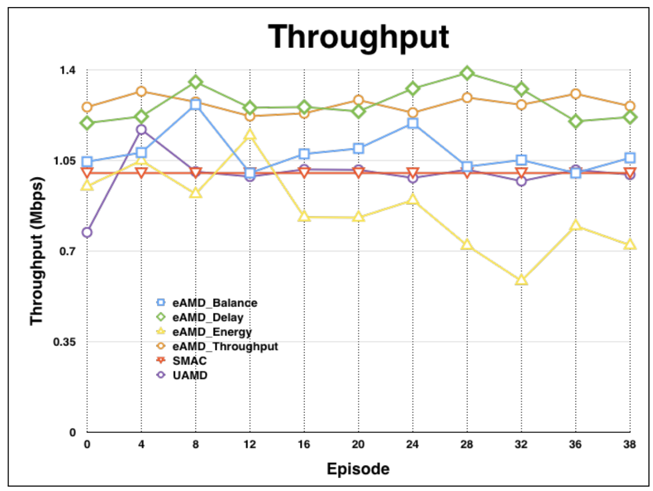

Fig. 4. Throughput

- The last set of results presented in Figure5 illustrate the delay of different schemes. eAMD outperforms SMAC and UAMD as the average delay for eAMD-Delay and eAMD-Throughput are 0.042 and 0.047 seconds, in comparison with 0.106 and 0.096 seconds recorded for UAMD and SMAC, respectively.

V. Conclusions and Future Works

This paper proposes eAMD, a battery-aware adaptive multimedia delivery scheme for a video sensor network nodes. The scheme is built based on a MDP framework and uses Q-Learning to find the optimal policy for VSN in the adjustment of duty cycle. eAMD was validated in a simulation environment in four different test cases: Throughput-oriented, Quality-oriented, Balance-oriented, and Energy-oriented. The simulation results showed how eAMD scheme outperforms other duty-cycle-based adjustment algorithms.

Future work will involve improvements of the performance of eAMD by enhancing the intelligence of the video sensor nodes. One possible way to do that is to collaborate with neighbor nodes in order to form a Machine-to-Machine

TABLE II
ENCODING SETTINGS FOR THE MULTIMEDIA STREAMING

Quality Level	Video Codec	Overall Bit-rate [Kbps]	Resolution[pixels]	Frame Rate[fps]
QL1		1920	800× 448	30
QL2		960	512× 288	25
QL3	H.264/MPEG-4	480	320× 176	20
QL4		240	320× 176	15
QL5		120	320× 176	10

TABLE III
SIMULATION RESULTS

REMAINING BATTERY LEVEL (in %)				
eAMD Balance-Oriented	25.48			
eAMD Delay-Oriented	17.9			
eAMD Energy-Oriented	32.67			
eAMD Throughput-Oriented	15.00			
UAMD	29.72			
SMAC	29.90			
THROUGHPUT (Mbps)				
	Mean	**95% Confidence Interval**	**Variance**	**Std. Deviation**
eAMD Balance-Oriented	1.074	[1.047; 1.102]	0.007	0.086
eAMD Delay-Oriented	1.260	[1.239; 1.280]	0.004	0.064
eAMD Energy-Oriented	0.870	[0.829; 0.909]	0.015	0.124
eAMD Throughput-Oriented	1.292	[1.270; 1.316]	0.006	0.074
UAMD	1.002	[0.983; 1.022]	0.04	0.060
SMAC	1.000		0.00	
DELAY (Seconds)				
eAMD Balance-Oriented	0.0844	[0.0779; 0.091]	0.0001	0.020
eAMD Delay-Oriented	0.0422	[0.0379; 0.0465]	0.001	0.0132
eAMD Energy-Oriented	0.217	[0.205; 0.229]	0.001	0.0374
eAMD Throughput-Oriented	0.0476	[0.0436; 0.0415]	0.0001	0.0121
UAMD	0.106	[0.1003; 0.111]	0.0001	0.0165
SMAC	0.096	[0.0903; 0.1013]	0.0001	0.0169

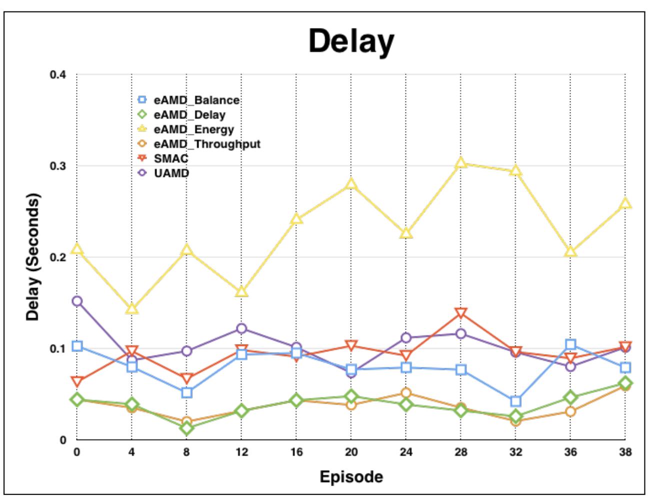

Fig. 5. Delay

(M2M) communications system or with other scalar sensor types (for example, motion detection sensors) and adapt the operation based on past experience. Validation of the eAMD work in a real life physical hardware platform (e.g. Raspberry Pi) is also envisaged. This will enable to collect real data and make comparisons with the simulation results.

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