A Novel Device and Application-Aware Energy Efficient Routing Algorithm for WLANs

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***Abstract*—The latest mobile devices such as smart phones and tablet PCs, equipped with high resolution interactive screens, highly advanced CPUs, wireless networking and multimedia processing capabilities have become very important in people's daily life. The growth of these devices' popularity has determined an increased interest from shopping malls, theme parks, institutions, convention centre, etc. to deploy wireless network infrastructure and offer diverse online services addressed to such device users. However infrastructure deployment is expensive and highly localized, so accessing content from mobile devices supported by ad-hoc wireless connectivity is considered a very good alternative solution. In such scenarios, energy efficiency has always been a key issue and highly important especially for wireless routing algorithm design as the mobile wireless devices are powered by batteries with limited power capacity. Moreover different applications, e.g. online games, online chat, video streaming, etc. put different loads on different hardware components (e.g. CPU, wireless card, screen) and result in different energy constraints. In this context, we propose a novel Application-aWare Energy efficient Routing Algorithm (AWERA) for heterogeneous wireless networks which performs energy-aware routing based on application-related characteristics and nodes' energy budget. AWERA predicts nodes' energy depletion according to the application type they run, network load and remaining battery energy level, in order to assist a novel cross layer energy efficient routing solution. Simulation results show how our solution has better performance and energy efficiency when compared with other wireless routing protocols.**

***Index Terms*—Energy, Application aware, Wireless Routing.**

I. Introduction

In recent years, the applications relying on wireless communications have extended their usage from narrow industrial or military areas to people's daily life. The latest innovative digital mobile devices, such as smart phones and tablet PCs, are witnesses of the extensive deployment of wireless communication technologies in the consumer device sector. A Microsoft blog [1] reports that of the world's 4 billion mobile phones in use, over 1.08 billion are smartphones, and half of the local searches are performed on mobile devices. According to IDC, the global smartphone market experienced a growth of 61.3 percent in 2011 alone [2].

The latest digital mobile devices support complex rich media applications which offer excellent user experience and vast range of services, including file sharing, online gaming, adaptive streaming [3], online finance services, GPS navigation, etc. For example, the number of applications on the Android App Market reached 500,000 by the end of 2011 and it is still growing [4]. This trend shows how people increasingly use mobile wireless-enabled services.

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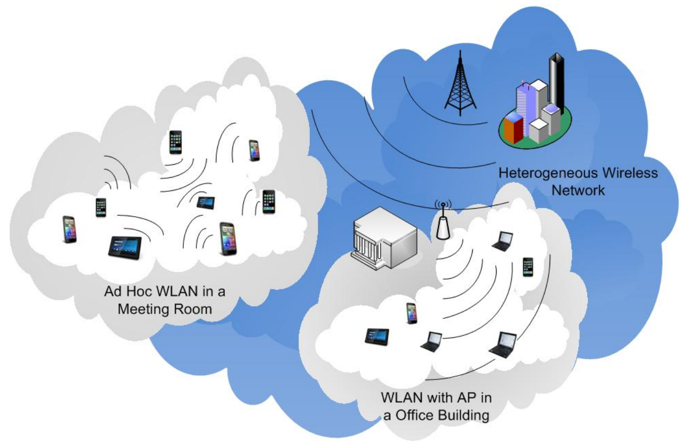

Fig. 1. Mobile users in a heterogeneous wireless network environment

In order to provide access to mobile users to information and complex applications, often WLAN infrastructure is deployed in family homes, shopping malls or theme parks [5]. This kind WLAN may work alone or act as part of a heterogeneous network environment connected to the Internet. However infrastructure deployment is expensive and highly localized, so in some situations, for example in convention centres, universities, etc, accessing content from mobile devices over ad-hoc wireless networks is considered a very good alternative solution. A hybrid ad-hoc and infrastructure network environment is illustrated in Fig. 1.

In the context of ad-hoc networking, the energy constraints of the latest mobile devices are important, as their owners are on the move and want to be able to use the devices anywhere and anytime. Unfortunately these devices tend to have relative short lifespan in-between battery recharges. Additionally, the increasingly complex applications and wireless communications already pose growing energy pressure on the devices.

In this context, there is a need for an efficient wireless routing protocol that observes the different energy constraints of the mobile devices and best balances the need for efficient routing with the energy savings. This paper proposes a *novel device and Application-aWare Energy efficient Routing Algorithm (AWERA) for wireless networks* that performs energy efficient routing based on application-related characteristics and device energy budgets. The algorithm differentiates between devices in terms of their energy levels and application-dependent depletion rates in order to select the best packet forwarding route in terms of the balance between both delivery efficiency and energy saving. Simulation testing results show how AWERA saves energy for all the devices as compared to two other solutions AODV and MBCR. Unlike these other schemes, AWERA also differentiates these savings based on the applications the devices are running and their battery energy levels.

The remainder of this paper is organized as follows. Related works are presented in Section II. In Section III, the architecture of proposed solution is introduced followed by the description of the algorithm in Section IV. Section V presents the proposed solution's performance evaluation in comparison with classic approaches and conclusions are in Section VI.

II. Related Works

Energy efficiency has always been a key issue for wireless routing algorithms design as many wireless devices are powered by batteries with limited capacity. A device running out of battery does not offer the service expected any more, and more importantly, this could lead to network partitioning, where a section of the network fails to inter-connect with other sections properly. Consequently, many energy efficient routing algorithms have been developed to reduce the overall energy consumption for the network during data transmissions and to balance load among nodes in the network in order to achieve even energy distribution.

It is natural to apply power related metrics for routing cost computation, for example, Flow Augmentation Routing (FAR) [6] considers the initial energy of the node, the residual energy at the transmitting node and the cost for a single transmission, in order to select the most efficient route. Minimum Battery Cost Routing [7] takes the total remaining battery capacity of each device along each path and this gives the total remaining battery capacity of each route. It compares the battery capacity of all possible routes and the one with devices containing the most remaining energy is considered as optimal. Because MBCR considers a path as one entity, it fails to notice that such paths could include devices with very little remaining energy acting as potential points of failure. Inspired by the energy model proposed by [8], Arezoomand et al. [9] improved MBCR by recording the hop count of each route as well as the total energy consumption to avoid devices with little energy which will bring down the average remaining energy per hop.

Hierarchical routing is another approach for better energy efficiency from the routing point of view, where nodes are organised into clusters and each cluster elects a head node to aggregate data from the rest of the nodes in the same cluster. In this manner, most nodes do not have to communicate directly with the base station/access point; instead they conserve energy by communicating with the cluster head node that is nearer to them. LEACH [10], [11] is such a cluster based routing solution.

Besides, location-based routing conserves energy by making use of location information. As an example, the Geographic Adaptive Fidelity Protocol (GAF) [12] constructs virtual grids from location information and assign nodes into different grids accordingly. It elects nodes with the highest residual energy to be master nodes of their grids, and the master node forwards packets to other grids for the slave nodes in its grid. In this manner, the majority nodes (slave nodes) conserve energy by not having to send packets far away. Recently, Zhang et al. [13] proposed an energy-efficient beacon-less geographic routing protocol (EBGR). Conventional Geographic Routing solutions use the beacon mechanism to maintain location information for routing decisions and this results in extra routing overhead. EBGR does not use such a beacon-based mechanism; instead a localized routing decision is made when a host has a packet to transmit. First, the host will have to define the ideal position for the next hop based on the direction of sink and energy efficiency distance, and then it chooses the host that is the closest to the ideal position with respect to the upper bound of distance and energy consumption. Recently, the networks transmit increasing amount of multimedia content and this requires quality awareness as a important challenge in the design of routing protocols for wireless networks. Reliable Energy Aware Routing Protocol (REAR) [14] compares the residual energy capacity of each node in routing paths and supports multi-path routing to enable energy efficient and reliable data transmission.

The above proposals are effective in reducing the energy cost for routing in wireless networks, where energy depletion is considered to be mainly affected by networking traffic load on the hardware. However these solutions do not address the features and energy constraints of the latest smart devices that comprise the latest wireless ad-hoc networks. Different applications such as online gaming, online chat, video streaming, etc. put different loads on different hardware components and result in different expected lifetimes of the smart devices. This paper proposes AWERA, a novel cross-layer energy efficient routing solution, which predicts nodes' energy depletion according to the application type they run, network load and remaining battery energy level.

III. Architecture

AWERA is a device and application-aware cross layer routing protocol that involves both network and application layers. Fig. 2 details the major components of AWERA and how they exchange information to perform application-aware energy efficient routing for wireless data transmissions. The highlighted components are the novel aspects of the proposed protocol and will be explained in details next.

The Application Monitor (AM), Remaining Energy Monitor (REM) and Energy Constraint Computation Module (ECCM) sit in the application layer for application-related information collection. AM keeps record of current running application

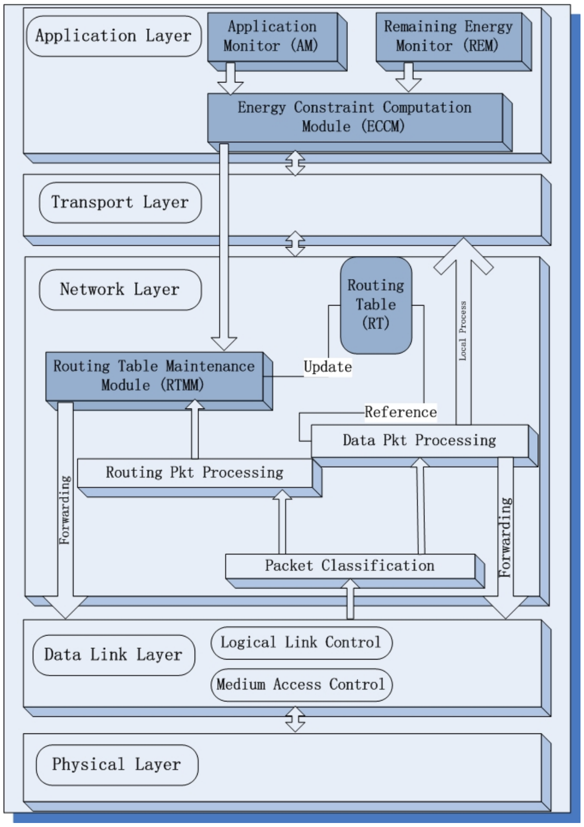

Fig. 2. Architecture of AWERA

type and network load. REM monitors the remaining energy level. ECCM includes an energy model which maintains the relationship between application-related information (i.e. type and networking traffic throughput) and typical energy consumption. From AM and REM, ECCM fetches application-related information and invokes the energy model to calculate a metric value reflecting the application layer energy-related information.

The application layer energy-aware information is passed on to the Routing Table Maintenance Module (RTMM) at network layer where routing decision is made. RTMM maintains a timer for information obtained from the application layer. It requires the cost of routing related to the current device from ECCM every time the timer times out, then the timer is restarted. RTMM updates the Routing Table periodically. The Routing Table is specifically designed to accommodate the routing cost of each path worked out by the RTMM. Every time this timer times out, RTMM checks the whole Routing Table and deletes outdated routes.

In order to differentiate data packets from routing control packets, any incoming packet will be filtered by the Packet Classification Module (PCM), which hands over data packets to the Data Packet Processing Module (DPM) and hands over routing control packet to the Routing Packet Processing Module (RPM). DPM inspects the destination of each packet and checks the Routing Table; if the data packet's destination is the current device, it passes the packet to upper layers for further local processing; otherwise, it forwards the data packet to the next hop if any route is available in the RT. RPM hands over routing control packets to RTMM. If the control packet contains fresher route information, RTMM adds the route to the RT. Then RTMM adds the energy constraint of the current device to the route cost contained in the control packet before sending out the control packet for further route construction.

IV. AWERA

This section presents the novel application-aware energy efficient routing protocol for wireless networks (AWERA) in details. The two major contributions of AWERA are:

- a novel application-aware energy model for smart devices.
- a novel energy efficient wireless routing protocol based on the application layer information.

A. Application-aware Energy Model

Current smart phones share a similar structure and run similar applications. However, different applications put different work load on the hardware and this results in different energy consumptions. Fortunately the energy consumption of each hardware component shows distinctive features, and each typical application scenario (e.g. making a phone call, audio play out, etc.) shows distinctive energy requirement as well [15] [16]. Additionally current mobile software distributors introduced built-in application categorization which gives opportunity for application layer scenario recognition. We propose an energy constraint recognition model for smart devices that models the typical energy requirement for each category of application.

From the point of view of the energy efficiency, the display sub-system (screen, graphics), WLAN interface card (e.g. WiFi), Cellular network interface module (e.g. GSM) and CPU (processing chip set) are the major energy consumers among the hardware components of the latest mobile devices (i.e smart phones or tablet PCs) [16]. Energy consumption can vary a lot on these hardware modules for different applications. Therefore we address these four components in our utility function.

$$G_{app} = \frac{\sum_{i=0}^{n}(W_{comp_i} \cdot G_{comp_i})}{\sum_{i=0}^{n} W_{comp_i}} \quad (1)$$

$$G_{comp_i} = \frac{E_{comp_i}}{MaxE_{comp_i}} \quad (2)$$

$$W_{comp_i} = \frac{MaxE_{comp_i}}{\sum_{i=0}^{n} MaxE_{comp_i}} \quad (3)$$

In equation (1), G_{app} represents the utility function corresponding to the energy constraints imposed by the application on all the major device hardware components considered: CPU, display, WLAN card and Cellular module, respectively.

TABLE I
CALCULATION OF INDIVIDUAL COMPONENTS' UTILITY FUNCTIONS

	G_{CPU}	G_{DISP}	G_{CELL}	G_{WLAN}
App_j	$\frac{E_{CPU}(j)}{MaxE_{CPU}}$	$\frac{E_{DISP}(j)}{MaxE_{DISP}}$	$\frac{E_{CELL}(j)}{MaxE_{CELL}}$	$\frac{E_{WLAN}(j)}{MaxE_{WLAN}}$

TABLE II
REAL READINGS IN IDLE STATE WHEN GSM AND WIFI ARE USED [15]

	G_{CPU}	G_{DISP}	G_{CELL}	G_{WLAN}
Idle State	7%	80%	9%	1%

G_{comp_i} represents the utility grade corresponding to the energy constraint imposed by the applications on the i-th device component. Normalized weights are used to balance the contribution of different hardware component on the overall utility function. For example, WLAN interface card shows significantly higher energy consumption of up to 7 times the sum of the other hardware components energy consumptions in highly network-intensive applications [16]. Weight values W_{comp_i} are obtained according to the maximum energy consumption of each components over the maximum system energy consumption as indicated by equation (3), where $MaxE_{comp_i}$ represents the maximum energy consumption of the hardware component *i*. For each application scenario, G_{comp_i} of each individual component is obtained according to the ratio of typical energy consumption (E_{comp_i}) over the maximum energy consumption of that component ($MaxE_{comp_i}$), as described by equation (2). In Table I, G_{CPU}, G_{DISP}, G_{CELL} and G_{WLAN} are the utility grades of actual components of G_{app} and the table demonstrates how equation (1) can be applied for different applications. For application j, $E_{CPU}(j)/MaxE_{CPU}$ gives G_{CPU} which is given by the value of the typical CPU energy consumption in normal situations when the current application is running over the maximum CPU energy consumption. $E_{DISP}(j)/MaxE_{DISP}$, $E_{CELL}(j)/MaxE_{CELL}$ and $E_{WLAN}(j)/MaxE_{WLAN}$ follow the same principle.

When it comes to the deployment, it is feasible to record each reading of Table I for typical application scenarios following detailed testing phase as shown in Table II which uses the results published in [15], so that deployed devices will be able to recognize the scenario and make use of the results to calculate the utility of the current application energy constraint.

$$E_{frac} = \frac{E_{cons}}{E_{total}} \quad (4)$$

$$G_{eLevel} = F_b \cdot \frac{E_{frac}}{e^{1-E_{frac}}} \quad (5)$$

The remaining energy level of the device is another factor contributing to the device's energy constraint. In (4), E_{cons} is the amount of consumed energy at the time of measurement and E_{total} is the total capacity of the battery. E_{frac} is used to denote the ratio of E_{cons} over E_{total}. Equation (5) presents the utility function associated with the energy level at the device. The equation uses an exponential formula to address the fact that the less energy amount is at the device, the more critical the situation is. This is because the less energy residual is, the less time is left for the user to react. The value of G_{eLevel} is normalized as a grade ranging from 0 to 1. In addition, the energy depletion is not the same for all battery systems. A factor reflecting individual battery features (F_b) is also introduced to compensate for this effect. This factor varies from one manufacturer to another, but remains constant for the same battery.

TABLE III
EXAMPLE OF THE APPLICATION-AWARE ENERGY MODEL

Traffic Category	G_{CPU}	G_{DISP}	G_{CELL}	G_{WLAN}
Idle	L	L	M	L
Call	M	L	H	L
Email	M	M	M	M
Web	M	M	L	M
Video Playout	H	H	M	L
Video Streaming	H	H	M	H
Local Gaming	H	H	M	L
Network Gaming	H	H	M	H
Audio Playout	M	L	M	L

Equation (6) puts together the utility functions proposed for the application-related energy drain and battery energy level. The utility cost of any individual device C_{node} is a normalized value in the [0 , 1] range influenced by two factors: G_{app} - the utility grade of the device according to the energy-related application layer information, and G_{eLevel} - the utility grade dependent on the remaining energy level. Normalized weights W_{app} and W_{eLevel} tune the contribution of each factor in the overall utility cost.

$$C_{node} = W_{app} \cdot G_{app} + W_{eLevel} \cdot G_{eLevel}$$

$$W_{app} + W_{eLevel} = 1 \quad (6)$$

Table III illustrates a sample implementation of such an energy model, where the grade of four hardware components is assigned according to the typical energy consumption obtained from testing before the deployment. For each category of applications, the value of G_{comp} is classified as high (H) to represent utility grade values over 0.66, medium (M) to represent grade values between 0.33 and 0.66, and low (L) to represent grade values below 0.33. When deployed in the actual devices, each device will be able to calculate its current energy constraint based on the application scenario with respect to this model. By using discrete values as in this example instead of real values as result of monitoring, AWERA's accuracy is lower, but also less system resources are required. However, classification with finer granularity and tests of more applications can also be adopted for higher accuracy. The proposed energy model allows flexibility in implementation.

B. Routing Protocol

$$C_{route} = \sum_{i=0}^{n} C_{node}^{i}$$

$$= \sum_{i=0}^{n} (W_{app} \cdot G_{app} + W_{eLevel} \cdot G_{eLevel}) \quad (7)$$

AWERA assumes each node within the wireless network deploys the proposed application-aware energy model and can compute the utility function as indicated by equation (6). Equation (7) presents how the cost of a route accumulates the utility cost of each node along the path to give a total cost of the path C_{route}. AWERA selects the path with the least cost and stores it in the Routing Table. The calculation is performed locally so that only the final routing cost is transmitted, which minimises the overhead of networking traffic.

In terms of the routing mechanism, AWERA enhances the AODV protocol [17] adding the application energy-aware features already described and making use of its on-demand features and its distance vector mechanism. AWERA enhancements are as follows.

- AODV uses sub-optimal routes even when there is low mobility because as long as it has established a route, it does not allow node to further request different paths from the same source. Unlike AODV, AWERA involves multiple requests and considers paths changes as long as the new routes have lower costs.
- AWERA reacts to the change of the energy-related utility value gathered from the application layer instead of only to topology changes. In this way it includes a proactive periodical request-based update scheme allowing source node to send periodically requests to the destination.
- AWERA employs a cross-layer approach allowing the network layer to use application layer information for application scenario recognition, as shown in Fig.2 and enabling routing strategy adjustments to be performed accordingly.

V. Performance Evaluation

In this section, the performance of AWERA is evaluated by using NS2[18] and a 200m by 200m square ad-hoc topology with 150 randomly distributed nodes. For simplicity, three types of nodes were considered, which differ in the application type they are running: idle nodes (class A), video playout nodes (class B) and 3G video streaming nodes (class C) as shown in Table IV, with 50 nodes of each kind. Three pairs of source nodes and destination nodes were randomly selected. They transmitted video streaming-like traffic with the packets size of 210 bytes at constant bit rate (CBR) (bit rate: 1 Mbps). Random movement was applied to all the nodes.

The duration of simulation was 420 seconds and the simulation was conducted for 10 rounds. The average energy consumption per node for each group of nodes, average end-to-end delay among the three traffic flows and the average throughput in the three traffic flows were recorded. The simulation is conducted with AODV, MBCR and AWERA, respectively and the results are compared.

IEEE 802.11b was deployed to the whole network. Transmission range for each node was set to 35 m. Idle nodes power was set to 250 mW, video play back nodes' power was set to 400 mW and the power of the 3G video streaming nodes was set to 950 mW. Additionally 600 mW was associated to the WiFi/WLAN transmission. The initial energy for each node was 30 J, a reduced value in comparison with real life scenarios in order to reduce the simulation duration.

TABLE IV
Simplified model used for testing

Traffic Category	Idle	Video Playout	Video Streaming
G_{app}	0.25	0.4	0.95

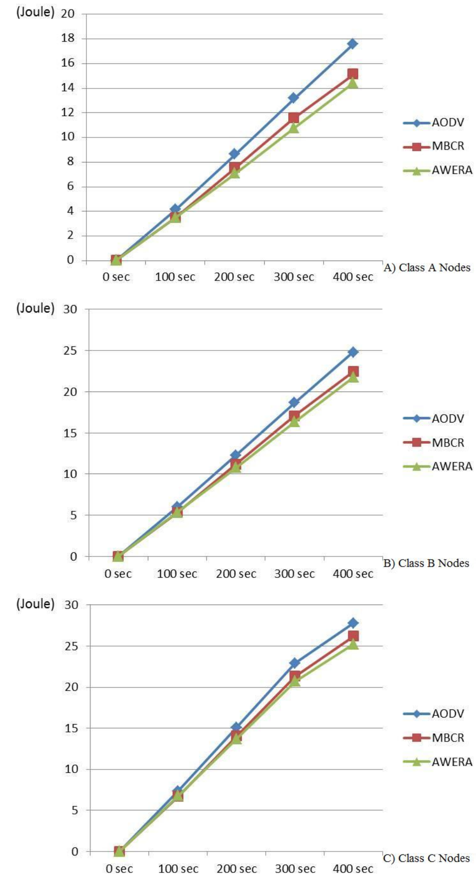

Fig. 3. Average Energy Consumption of Nodes from Class A, B, C

In this simplified scenario, we considered only two stages of energy consumption for each hardware components: full load (1) and minimum load (0). We defined G_{app} according to the typical power of each application scenario as above. For the calculation of the energy model as in equation (1), the grade of G_{app} was set to 0.25 for the class A nodes, 0.4 for the class B nodes, and 0.95 for the class C nodes. F_b in equation (5) was assigned a value of 1 in order to reflect the nature of the energy model in NS2 . From extensive tests, when evaluating equation (6), W_{app} and W_{eLevel} are set to 0.4 and 0.6 respectively for optimal trade-off between energy efficiency and performance.

At simulation time t=420 seconds, the energy of the class C nodes was completely used when employing AODV. Consequently we recorded the average energy consumption per node every 100 seconds and calculated end-to-end delay and

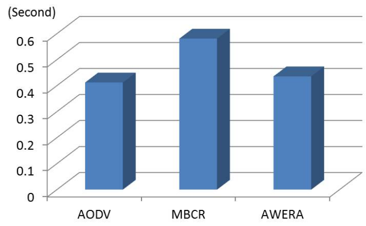

Fig. 4. Average End-to-end Delay

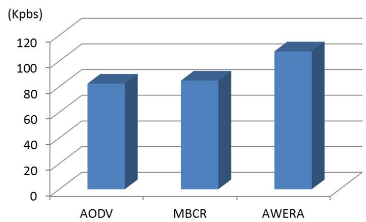

Fig. 5. Average Throughput of Receiver Nodes

average throughput for 420 second simulation time, in order to be able to fairly compare the three solutions. The lifespan of all nodes were extended as illustrated in Fig.3.

Fig. 3 clearly shows how AWERA outperformed both AODV in conserving energy for each group of nodes with improvements of 10 percent to 20 percent. During the whole course of battery depletion, AWERA demonstrated increased benefit in terms of energy in comparison with AODV and MBCR. As AWERA makes use of adaptive application-aware information and differentiates its treatment of the nodes accordingly, it manages to conserve more energy when nodes suffer from more critical energy constraint. AWERA outperformed MBCR considerably in terms of performance and conserved 5 percent more energy than MBCR.

With respect to the performance evaluation, MCBR suffered 40.9 percent end-to-end delay than AODV, in contrast AWERA increased the end-to-end by only 5 percent. Compared with AODV, AWERA increased the throughput by 30.5 percent while MCBR has nearly the same throughput. This shows that AWERA is more competent in delivering multimedia content on time than MBCR, and AWERA offers improvement in throughput when compared with the other two solutions.

In conclusion, AWERA achieved better energy efficiency than two other state-of-the-art schemes with much shorter delay and very little degradation in throughput.

VI. Conclusion

This paper proposes a *Novel Device and Application-Aware Energy Efficient Routing Algorithm for Wireless Networks (AWERA)*. AWERA introduces an application aware energy model which energy-related application information, including application type, network load and remaining energy level, in order to assist a novel cross layer energy efficient routing solution. AWERA then performs energy-aware routing based on application-related characteristics and nodes' energy budgets. The simulation results show that AWERA achieves better performance and energy efficiency compared with two other state-of-the-art wireless routing protocols.

Future works include further refining of the application and device based information collection. It is envisaged that a cross layer loop to be deployed between network and application layers. Extensive real life testing will be conducted on various mobile devices (e.g. Smart phones and tablet PCs) and on different platforms, involving multiple application types.

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