A Context-aware Cross-layer Energy-efficient Adaptive Routing Algorithm for WLAN Communications

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***Abstract*—Smart phones have gained great popularity all around the world, supporting rich media applications with Internet connectivity. Since increasing number of people own powerful mobile devices, ad-hoc WLANs can be deployed in public areas part of heterogeneous networks environments, as flexible and inexpensive alternatives to infrastructure-based approaches. However, these mobile devices are powered by battery with limited energy budgets, which introduces big energy-related challenges in ad-hoc WLAN routing algorithm design. This paper proposes a context-aware cross-layer energy-efficient adaptive routing algorithm for WLAN communications (AWERA) that performs energy-efficient context differentiated routing in wireless communications. It introduces a cross layer self-learning solution that monitors the context of device usage, and takes routing decisions based on current energy-oriented context. Compared with other state-of-the-art wireless routing protocols, simulation results show both better performance and energy efficiency context-based differentiation.**

I. Introduction

Last decade has seen extreme developments in terms of mobile devices. Feature phones have been replaced by smartphones, which are powerful digital personal assistant devices that not only make phone calls, but also support rich media-based infotainment. According to IDC, the global smartphone market witnessed a growth of 61.3 percent in 2011 alone [1]. These devices used to rely on classic wireless communication via cellular networks or infrastructure based WLANs in fixed hot spots. Lately, the fast growing number of devices make also possible to form ad-hoc wireless networks for local networking services as an inexpensive alternative. Such ad-hoc WLANs can be deployed in schools, shopping centres, theme parks, etc [2], part of a more complex heterogeneous wireless network environment.

The latest developments of wireless communication technologies in terms of mobility and scalability enable mobile devices to connect people anywhere and any time. This requires smartphones to be complex, slim and light, but also powered by batteries with limited lifetime. Consequently, the energy-efficiency is a key issue in such scenarios [3][4]. When the battery runs out, devices become useless. In ad-hoc WLANs, load balance and even energy distribution are also very important, as a non-operational device cannot relay packets for other devices. Many research efforts have been put in devising energy aware routing algorithms for wireless communications. Minimum Total Transmission Power Routing (MTTR) [5] is one of the early attempts to the design an energy aware routing algorithm. Since energy is consumed to transmit packets through the link between a pair of nodes, MTTR calculates the energy cost of a route by accumulating the total energy cost of each link along the route. At last, the route with the least energy cost is considered the most energy-efficiency route. Compared with MTTR, Minimum Battery Cost Routing (MBCR) [6] chooses the total remaining battery capacity of every device, instead of the energy cost along each path as the metric. It sums up the total remaining energy levels for each possible route and then considers the one with the highest remaining energy as optimal. For infrastructure wireless networks, nodes need to communicate with base stations regardless of their distance to the base station. However, routing protocols could organize nodes into clusters and elect a head node in each cluster so that only the head has to communicate directly with the base station. In this manner, the rest of the nodes in the same cluster only need to communicate with the head node, which is closer and more energy efficient to be accessed. Low Energy Adaptive Clustering Hierarchy (LEACH) [7] is a cluster-based solution working like this.

Existing solutions consider devices operating in the same context, using energy level or battery capacity only to calculate routing costs. This does not suit current smart devices-dominated wireless communications scenarios, where different contexts (e.g. energy-oriented device characteristics [8], applications and network conditions, etc) put different loads on devices and result in different energy expected lifetimes. This paper proposes a *context-AWare cross-layer Energy-efficiency adaptive Routing Algorithm (AWERA) for WLAN communications*, which collects context information of device

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energy usage, differentiates devices with regard to the context-related characteristics and adjusts routing strategy adaptively, in order to optimize routing decisions with respect to the balance between performance and energy-efficiency. Simulation testing results demonstrate how AWERA saves energy with priority for the devices that need the most, when compared with other two state of the art solutions: AODV and MBCR.

II. AWERA

This section describes the algorithm for the Context-aware Cross-layer Energy-efficient Adaptive Routing Algorithm for WLAN Communications (AWERA). The two major contributions of AWERA are: *1) a context monitoring and a self-learning process of the context in wireless communication environments comprised of smart devices; 2) an adaptive energy-efficient wireless routing protocol based on context-based information.*

A. Context-aware self-learning process

The context of smart device usage in WLAN communications includes: application properties, device features (e.g. screen size, battery capacity), network conditions and user preferences. This context is often energy related. For example, different applications put different work load on the hardware and this results in different energy consumptions [9]. Compared with devices with smaller screens and larger battery size, those equipped with larger screens and smaller battery capacity suffer from shorter lifespan between recharges. Besides a wireless link with bad signal reception may need multiple retransmissions before successful communication, which is energy consuming.

All the above-mentioned context-related information can be accessed at the application layer via the operating system. Therefore, AWERA constructs *a Component Workload Profile Table*, a mapping between the workload on each major device hardware component and the corresponding energy depletion rate, and makes routing decisions according to the current operational point and this table. The context-related solution includes two phases: Initialization and Monitoring. Network conditions are evaluated by the link quality utility function which is described in the Routing Protocol subsection.

1) Initialization Phase: Due to the difference among devices of different specifications, the same application results in different loads on different components. More importantly, the same percentage of workload results in different battery depletion rates on different devices. To address this issue, the initialization phase is applied prior to the construction of such context-aware energy efficient ad-hoc WLAN.

The screen (SCR), graphics processor (GRA), WLAN interface card, such as WiFi for example (WLAN), cellular network interface module such as GSM for instance (CELL) and the processing chip set (CPU) are the major energy consumers among the hardware components of the latest mobile devices (i.e smart phones or tablet PCs) [9]. Therefore these five components are considered specifically. Energy consumption can vary a lot on these hardware modules for different applications.

TABLE I
APPLICATION PROFILE OF TYPICAL WORKLOAD ON EACH COMPONENT

	WL_{CPU}	WL_{GRA}	WL_{CELL}	WL_{WLAN}
App(j)	WL_{CPU}(j)	WL_{GRA}(j)	WL_{CELL}(j)	WL_{WLAN}(j)

During initialisation, AWERA runs a set of predefined tasks to put various loads (e.g. 5%, 25%, 50%, 75% and 100%) on the five different device components and monitors the power consumption on them. AWERA considers this reduced set of cases to reduce the overhead. The power consumption at any level between the values measured in the initialization phase is determined by linear interpolation, which has limited accuracy, but requires less resources. As an output from the Initialization Phase, a table establishes the relationship between the percentage of workload and the consumed energy for each major hardware component.

2) Monitoring Phase: In the Monitoring Phase, the *Application Profile Table* saving the energy constraint of each application is constructed. Once a new application is launched, AWERA starts to record the workload on the mentioned hardware components. Once the application shuts down, the average value is calculated and recorded as a new entry in the *Application Profile Table*.

Table I shows one simple implementation of the *Application Profile Table*. For application j, WL_{CPU}(j) gives the workload of CPU. WL_{GRA}(j), WL_{CELL}(j) and WL_{WLAN}(j) follow the same idea. Notably, the workload of the screen, recorded as the brightness, is highly dependent to the lumination of the environment and user preference.

All the context information is learned and maintained via this self-learning process. The workload of each hardware components is monitored and sampled by the process for each application on current device, so that the application-related energy constraint is recorded as application profile. By taking this approach, AWERA is able to deal with the large number of applications on the market.

B. Calculation of node cost based on application profile

The context aware node cost is calculated based on the current operation point and the application profile table obtained from the context-awae self-learning process. As long as the smart device is powered on, the current application type and the current screen brightness are accessible from the operating system. The node cost is calculated according to this information and the record in the application profile table is updated as indicated above. If the running application has no record in the application profile table, AWERA monitors all the relevant readings as described in the previous section and creates a new application profile entry. The following description explains how the node cost is calculated based on the application profile.

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, screen, graphics, WLAN card and cellular module, respectively. 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 components on the overall utility function. For example, WLAN interface card shows significantly higher energy consumption than the other hardware components in highly network-intensive applications [9]. Weight values W_{comp_i} are obtained by dividing the maximum energy consumption of each of the components to 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).

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

$$G_{comp_i} = \frac{E_{comp_i}}{MaxE_{comp_i}} \tag{2}$$

$$W_{comp_i} = \frac{MaxE_{comp_i}}{\sum_{i=1}^{n} MaxE_{comp_i}} \tag{3}$$

As to the hardware specifications, AWERA deals with the variation proposed by all the major hardware components in the above. However, the remaining energy level of the battery have to be considered. 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. The value of G_{eLevel} is normalized as a grade ranging from 0 to 1.

$$E_{frac} = \frac{E_{cons}}{E_{total}} \tag{4}$$

$$G_{eLevel} = \frac{E_{frac}}{e^{1-E_{frac}}} \tag{5}$$

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.

$$C_{node} = W_{app} \cdot G_{app} + W_{eLevel} \cdot G_{eLevel}$$
$$W_{app} + W_{eLevel} = 1 \tag{6}$$

C. Routing Protocol

In terms of the routing mechanism, AWERA enhances the AODV protocol [10] adding the context energy-awareness already described. The routing cost of one route is comprised of both node and link costs. The node cost reflects the context-based node characteristics as described in the previous sections. The link cost considers the received signal strength. In Equation (7), C_{link} is the value of signal strength threshold of successful packet receiving over the value of the received signal strength and it ranges from 0 to 1. It is assumed that devices transmit via the link with the strongest signal.

$$C_{link} = \frac{signal\_strength\_threshold}{received\_signal\_strength} \tag{7}$$

AWERA assumes each node within the wireless network deploys the proposed context-aware self-learning process and can compute the utility function as indicated by (6). Equation (8) presents how the cost of a route accumulates the utility cost of each node and each link 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*. Notably, the weight values in (6) and (8) are to be tuned in each specific networking environment for optimal results.

$$C_{route} = \sum_{i=1}^{n}\left(W_{node} \cdot C_{node}^{i} + W_{link} \cdot C_{link}^{i}\right)$$
$$W_{node} + W_{link} = 1 \tag{8}$$

III. Performance Evaluation

This section evaluates the energy efficiency and the performance of AWERA in Network Simulator 2 [11]. An ad-hoc topology with 112 nodes was deployed in a 220m by 400m square grid. For simplicity, the 112 nodes were classified into three types, which differ in the application type they are running: 38 idle nodes (class A), 37 gaming nodes (class B) and 37 3G video streaming nodes (class C). Four pairs of randomly selected source-destination nodes transmitted video streaming-like traffic at three different qualities, at constant bit rates of 150 Kbps, 250 Kbps and 350 Kbps for three sets of tests. Each set was run for 30 rounds. The duration of each of the simulations was 135 seconds.

The wireless network deployed the IEEE 802.11b standard. Transmission range for each node was set to 45 m. Idle nodes' power was set to 250 mW, gaming nodes' power was set to 450 mW and the power of the 3G video streaming nodes was set to 650 mW. Additionally 400 mW was associated to the WiFi/WLAN transmissions. The initial energy for each node was 10 J, a reduced value in comparison with real life scenarios in order to reduce the simulation time.

We defined G_{app} according to the typical power of each application scenario as indicated before. 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, 0.45 for the class B nodes, and 0.65 for the class C nodes. When evaluating equation (6) W_{app} and W_{eLevel} are set to 0.4 and 0.6 respectively for maximum

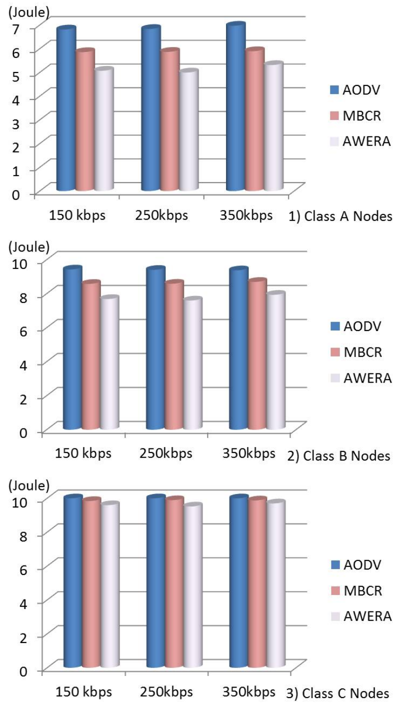

Fig. 1. Average Energy Consumption of Nodes from Class A, B, C

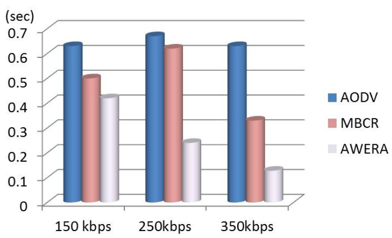

Fig. 2. Average End-to-end Delay

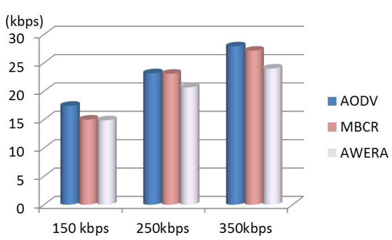

Fig. 3. Average Throughput of Receiver Nodes

energy efficiency. Since this is an evenly distributed topology, W_{link} and W_{node} in (8) are set to 0.1 and 0.9 in order to address the importance of the cost of the nodes.

Fig.1 illustrates how AWERA managed to conserve energy for each class of nodes when compared with both MBCR and AODV. Regardless of the traffic rates, AWERA saved approximately 22 percent energy for the class A nodes and between 11 and 15 percent energy for the class B nodes. AWERA conserved roughly 5 percent of the energy for class C nodes, which spent much more energy in local applications, and therefore a better routing strategy cannot make much energy saving. These results show how AWERA considers the context of applications and devices in the routing process and differentiates the energy savings based on it. In contrast, MBCR achieved only half the benefit offered by AWERA. In terms of performance, AWERA is also positively compared with both AODV and MBCR, mostly due to the periodical updates and adaptive features of the energy aware routing. As illustrated in Fig. 2, AWERA experiences reduced end-to-end delay from 30 percent to 80 percent, depending on the case, whereas MBCR achieved up to 33 percent lower delay than AODV, but its performance was not stable when traffic rates increased. In return for the energy saving, the throughput of AWERA was up to 15 percent lower than that of AODV, while MBCR suffered less throughput degradation with the increase in the traffic rate, as it is shown in Fig.3.

IV. Conclusion

This paper proposes a *Context-aware Cross-layer Energy-efficient Adaptive Routing Algorithm for WLAN communications (AWERA)*. AWERA introduces the concept of context-awareness during routing in ad-hoc WLAN communications, along with the idea of an adaptive learning process of context information in wireless network environment. Simulation-based testing demonstrates how AWERA outperforms other two state-of-the-art wireless routing protocols in terms of differentiated performance and energy savings.

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