Application-aware Adaptive Duty Cycle-based Medium Access Control for Energy Efficient Wireless Data Transmissions

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***Abstract*—This paper introduces a novel Medium Access Control (MAC) strategy for energy efficient wireless data transmissions which reduces energy consumption while minimizing the negative impact on network Quality of Service (QoS). This strategy adaptively adjusts the sleeping window of the mobile devices' wireless transceiver. The proposed mechanism - the Slow sTart Exponential and Linear Algorithm (STELA) - consists of three sleeping window adaptation phases, each phase employing a different duty cycle management function. Based on analyzing historic data regarding traffic arrival patterns, traffic modeling is used to estimate future patterns. Consequently, the specific adaptation phases are scheduled and tuned to improve energy efficiency without compromising data delivery performance. Simulation-based testing results show significant energy savings with reduced impact on network QoS achieved when STELA is used, as opposed to other existing MAC layer protocols (IEEE 802.11 and IEEE 802.16) considered in this paper for performance comparisons.**

I. Introduction

Last decades have witnessed fast developments of wireless communications technologies, especially the IEEE 802.11 [1], which has become highly popular mostly due to its ease of deployment, low cost and widespread connectivity oportunities. However, using wireless technologies increases the energy consumption which presents many design challenges in the context of battery powered devices. As a consequence, power management has raised awareness in both research and industrial communities and huge efforts have been invested into energy conservation techniques and strategies deployed within different components of the mobile devices [2] [3].

Our research effort focuses on the Medium Access Control (MAC) layer of the networking protocol stack since this layer directly controls the Wireless Network Interface Card (WNIC) duty cycle, which has significant impact on the overall energy consumption, especially due to the fact that the WNIC is one of the main power consumers among the various components of mobile device architecture [4]. WNIC duty cycle is managed by the MAC protocol and involves sleep/wake state scheduling which dictates when and for how long the wireless radio transceiver stays in low power mode.

There are mainly two categories of MAC protocols based on whether a contention-based or schedule-based medium access strategy is employed. The contention-based solutions [1] [5] prevent collisions by employing a contention control scheme such as Carrier Sense Multiple Access (CSMA). The idea of multiple channels with different attributes is adopted in [6] and [7] to conserve energy. The schedule-based mechanisms [8] [9] usually employ Time Division Multiple Access (TDMA) for medium access control which divides time into slots and assign these slots to different terminals according to a predetermined schedule. They are collision free in nature, but flexibility and scalability are sacrificed. Hybrid MAC protocols [10] [11] combine the above mentioned categories with better results in terms of energy saving and network performance.

This paper introduces a novel traffic-aware MAC layer strategy which adapts the sleep/wake state schedule of the radio transceiver according to the bursty nature of data traffic and real time observation of data packets in terms of arrival time. The strategy involves three phases: slow start, exponential increase, and linear increase. A similar approach proposed by the authors in [12] reduces energy consumption by employing the three-phase sleeping window adjustment strategy. In this work, an additional traffic modeling algorithm is employed to analyze historical traffic data and estimate the arrival time of the next burst. STELA achieves energy saving through intelligent and adaptive increase of WNIC sleeping interval in the second and the third phase and at the same time guarantees delivery performance through optimal WNIC waking timing before the estimated arrival of new data burst.

II. STELA Design

STELA is deployed as part of the MAC protocol and is mainly in charge with the size of the sleeping window of WNIC. The principle of STELA is shown in Fig. 1. .

Several assumptions are made in the design of STELA:

- *Bursty nature of traffic*: Applications have been extensively studied with regard to data arrival patterns. It has been proved that the arrival pattern of real traffic exhibits bustiness instead of continuity [13] [14]. Large bursts of packets are transmitted with short inter-arrival delay while relatively long interval time is observed between consecutive bursts.
- *Regularity of data patterns*: Studies such as [15] have demonstrated that traffic flow shows a significant amount

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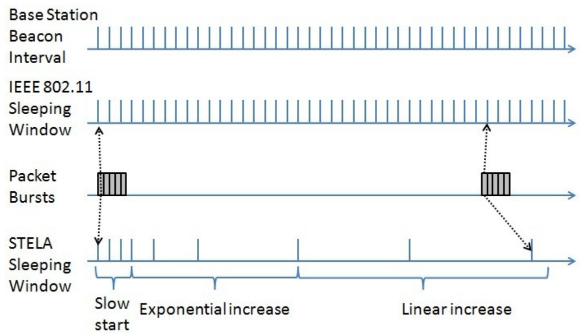

Fig. 1. Illustration of STELAs principle

of regularity which means historical traffic patterns can be utilized to predict future traffic arrival behaviors.

- *Infrastructure-based wireless network*: STELA is designed for infrastructure-based networks with the AP buffering packets addressed to sleeping hosts and all communications are relayed through the AP.

A. Slow Start Phase

The Slow start phase is the first stage of sleeping window adaptation during which the radio transceiver wakes up regularly to listen to every AP beacon. It is initiated either when a packet has been received, or when the mobile device has packets to send. On the one hand, it is highly possible that a successfully received packet is followed by continuous data within a burst according to the bursty nature of application traffic, therefore short duty cycle of one beacon interval guarantees short delay and low jitter. On the other hand, packets sent by the mobile host may involve a series of data response packets transmitted back to the host. Moreover, the Round Trip Time (RTT) may have been reduced significantly due to deployment of local proxies and caches, for example only a few milliseconds may be needed for data transmission between a client and the local server, indicating a quick response from the server could arrive at the receiver after the request is sent. In this case, frequent waking up the WNIC to sample the channel after requesting data from server provides fast response at the client side and reduces packet delay.

The slow start phase terminates when no packets are detected during channel sampling. Due to the burstiness of data traffic, the absence of data packets most likely indicates the completion of a data burst or empty buffer at the AP, and the WNIC should be switched off and put in sleeping mode to reduce energy consumption.

B. Exponential Increase Phase

The exponential increase phase starts as soon as the slow start phase terminates. At this stage, the sleeping window is doubled every time no data packet is detected during radio channel sampling. As stated earlier, empty buffer at the AP implies no data burst being transmitted and therefore it is a waste of energy to switch on the radio transceiver frequently without any benefits on delivery performance. Binary increasing the sleeping window improves energy efficiency through fast growth of sleeping interval.

The second phase is terminated when the size of sleeping window reaches a threshold value W_{thre}. Inappropriate W_{thre} values lead to unbalanced tradeoff between energy efficiency and delivery performance. Large W_{thre} values could lead to aggressive increase of sleeping window causing unacceptable QoS degradations. Small W_{thre} values guarantee better performance in terms of network QoS but at the expense of frequent switching the WNIC between states thus reducing battery lifetime. The binary exponential increase phase is also replaced by the slow start phase when any packet is received at the client side.

C. Linear Increase Phase

Once the threshold value W_{thre} is reached, the linear increase phase is triggered to perform moderate increase of sleeping interval. During this period, the size of the sleeping window keeps increasing with only one beacon interval for each step. The novelty of this phase lies in the adaptive threshold setting. It is not appropriate to configure the maximum sleeping window beforehand rather than adaptively based on traffic conditions and patterns. For example, a small threshold value is sometimes inappropriate as the WNIC wakes up frequently and battery power is wasted without any performance benefit. On the other hand, the linear increase phase allows the sleeping window grow at a moderate pace with one beacon interval at each step, which benefits energy efficiency without significant growth in delay and jitter. Therefore, the growth of sleeping window is self-adjusted based on real time traffic.

This stage is terminated and the slow start phase is re-initiated when a packet is received at the client side signaling a potential new data burst.

D. Threshold Adjusting

Due to the huge impact the threshold value W_{thre} has on the performance of STELA, a threshold adjusting phase is adopted at the beginning when a new application is running and a data flow is established between a client and the server. The goal of this phase is to configure the optimal W_{thre} value by monitoring the first two rounds of data transmission and modeling data arrival pattern so that the sleeping interval could be maximized without compromising QoS.

After the first round of data arrivals at the mobile host, W_{thre} is set to one beacon interval by default, and the sleeping window W_s follows the three phases of STELA which will double the sleeping window if it is smaller than W_{thre} or will increase it in increments of one beacon otherwise, as long as no packet arrival is detected during channel sampling. However, after each increase of W_s when no packet is detected, the new value of W_s is compared with W_{thre}. If W_s is at least twice greater than W_{thre}, then the threshold value W_{thre} gets doubled. This phase continues and the threshold value keeps increasing until the first packet of a next burst arrives at the client, at which point the inter-arrival interval between the two bursts is recorded as I_{ob}. W_{thre} is then set for the following data transmission within the same data flow.

The estimated W_{thre} is set to a smaller value than the sleeping window W_s when the first packet of the second data bursts arrives. The reason behind this is that a relatively conservative W_{thre} guarantees short delay and better QoS. Ideally, no extra delay is incurred in th1e best condition when the traffic pattern follows the exact same rule and the WNIC is switched on immediately after the data burst arrives at the AP and is ready for transmission. However, fluctuations exist in real traffic and it is highly likely that the inter-burst interval is a little bit longer or shorter than the monitored I_{ob}. In this case, a conservative value of W_{thre} guarantees earlier termination of binary exponential increase of the sleeping window size and therefore the next data burst could be received in time.

III. Testing

In this section, simulation-based testing results are presented to compare STELA's performance with other two schemes, namely the ones adopted by IEEE 802.11 and IEEE 802.16 [16] respectively. The performance of the three mechanisms is evaluated based on simulated models using Network Simulator version 3 (NS3) [17].

The simulation topology consists of two mobile stations wirelessly connected to the AP. The source pushes data periodically via the network to the sink. It can be seen as a server-client pair or two wireless hosts communicating with each other. At the source side, we set the traffic pattern with different intervals between bursts. This is a typical scenario for most applications including multimedia streaming with on/off traffic patterns. The AP beacons periodically to mobile stations every 102.4 milliseconds. At the client side, the three algorithms are individually deployed for each traffic pattern. IEEE 802.11 refers to the fixed sleeping interval scheme where the radio transceiver is powered on for each beacon interval. IEEE 802.16 refers to the binary exponential increase algorithm where the size of the sleeping window is doubled if no packets are detected during radio channel sampling until it reaches the maximum value of W_{max}.

Energy and quality of service including packet delay and delay jitter are analyzed based on the trace files generated by the simulator. Energy consumption is estimated based on the study presented in [18], which shows that for each second, 1.5 W of energy is spent in transmitting mode, 0.75 W - in receiving mode, and 0.01 W - in sleeping mode. State switching lasts for an average of 2 ms with an energy consumption of 0.75 W [19].

STELA is tested with various intervals between data bursts and different data rates generated from the source for 200 s. The test case parameters are listed in Table I. Each test case is comprised of three variables. Data is transmitted from server to client with different on/off patterns. Different data rates are also tested respectively to validate the performance of STELA. IEEE 802.16 is configured with maximum sleeping window W_{max} of 2 and 16 respectively for performance comparison.

TABLE I
TEST CASES PARAMETERS

Parameters	Value
On/Off interval	2s on/ 2s off
	2s on/1s off
	1s on/2s off
Data rate	0.5 Mbps
	1.5 Mbps
W_{max}	2
	16

Energy consumption is monitored, average end-to-end delay and average jitter is analyzed in order to estimate delivery performance. Simulation results are shown in Fig. 6 to Fig. 11. STELA saves similar amount of energy with IEEE 802.16 with maximum sleeping window set to 16, but significantly reduces the delay. When the sleeping window is set to 2, IEEE 802.16 generates similar or small amount of delay but with much higher energy consumption. IEEE 802.11 has the shortest delay due to frequent waking up, but at the same time wastes the most energy. For example, when generating traffic with a rate of 0.5 Mbps and 2s/1s on/off pattern, STELA saves with 36% more energy and with 2% increase in delay only compared with IEEE 802.11. STELA is also more energy efficient and provides better QoS than IEEE 802.16. Average jitter does not vary significantly in all three schemes.

IV. Conclusion

In this paper, we present STELA as a novel energy efficient scheme deployed at the MAC level. STELA is a three phase algorithm which saves energy consumed by the wireless network interface through adaptive control of transceiver duty cycle according to real time traffic patterns. Besides that, it uses data traffic modeling during the first round of data transmissions after the data flow is being established in order to optimally set the thresholds for the second and third phase in order to minimize QoS degradations. Performance evaluation based on simulations demonstrates that when using STELA, energy efficiency is achieved without compromising QoS as opposed to other two similar solutions.

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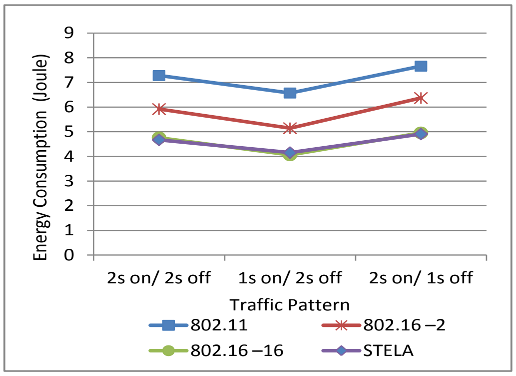

Figure 6. Energy consumption with 0.5 Mbps data rate.

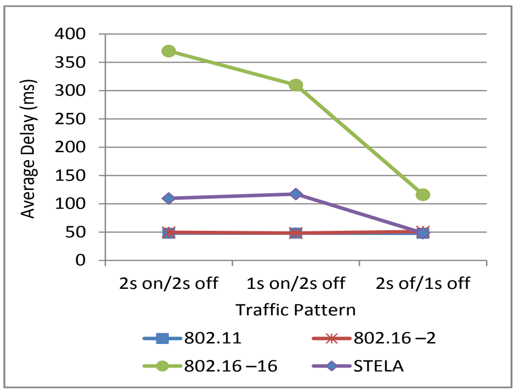

Figure 7. Average delay with 0.5 Mbps data rate.

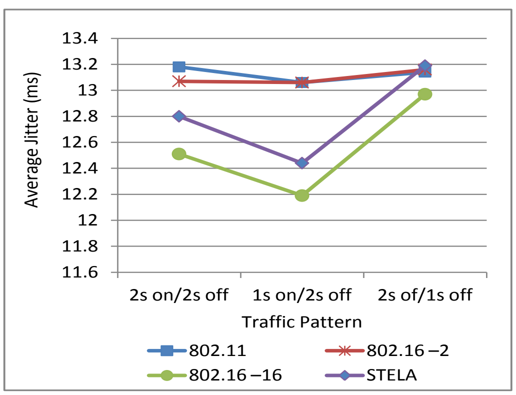

Figure 8. Average jitter with 0.5 Mbps data rate.

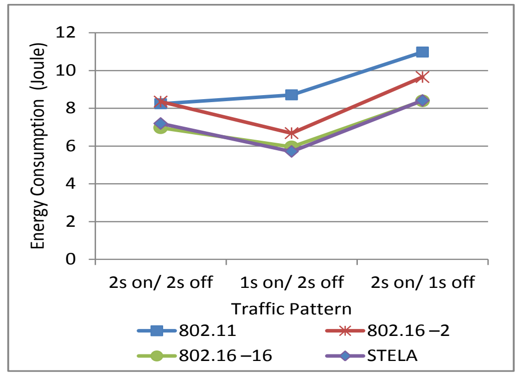

Figure 9. Energy consumption with 1.5 Mbps data rate.

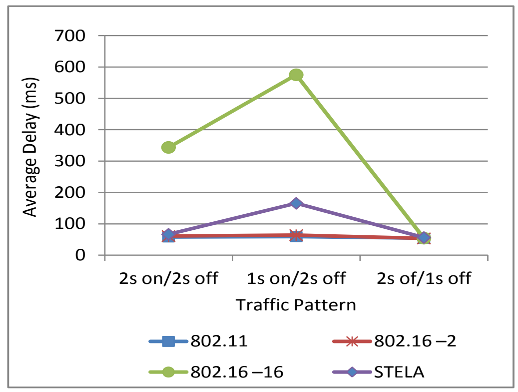

Figure 10. Average delay with 1.5 Mbps data rate.

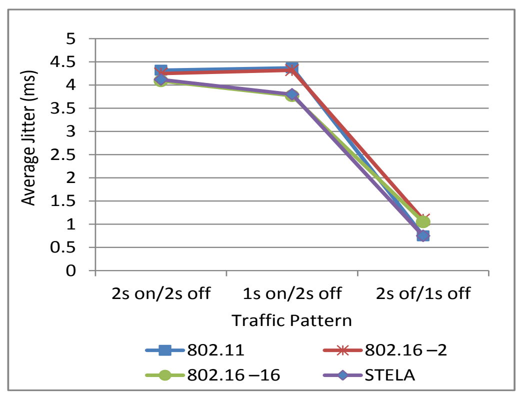

Figure 11. Average jitter with 1.5 Mbps data rate.

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