STELA: A Transceiver Duty Cycle Management Strategy for Energy Efficiency in Wireless Communications

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***Abstract*—This paper introduces the Slow sTart Exponential and Linear Algorithm (STELA), a novel transceiver duty cycle management strategy which intelligently adapts the sleeping schedule of mobile terminal radio interfaces during multimedia data transfer over wireless networks in order to reduce energy consumption while maintaining high delivery performance. The paper presents the algorithm, a simulation-based model and performance evaluation in terms of energy consumption and network Quality of Service (QoS) parameters. The proposed algorithm, STELA, is compared with similar algorithms used by IEEE 802.11 and IEEE 802.16 MAC standard protocols. Experimental testing results demonstrate that in the context of various Constant Bit-Rate (CBR) and Variable Bit-Rate (VBR) traffic patterns, typical for multimedia content delivery, STELA reduces the energy used by the mobile device for wireless communication with up to 55%, while maintaining good network QoS levels.**

I. INTRODUCTION

Currently wireless networks are widely deployed and mobile devices are increasingly popular due to the flexibility, convenience and relatively low costs associated with these devices and wireless communications. However, the limited battery life seriously restricts the usage of portable devices. Therefore, huge effort is invested into development of energy efficient solutions for wireless data communications [1] [2] [3] [4] [5].

The Medium Access Control (MAC) protocol has a critical impact on energy efficiency as it controls the behaviour of the wireless interface, regarding its access to the wireless medium, and consequently the duty cycle of the radio transceiver. Two major categories of MAC protocols can be distinguished based on the medium access strategy employed: contention-based and schedule-based. Contention-based solutions [6] [7] prevent collisions by employing a contention control scheme such as Carrier Sense Multiple Access (CSMA). OMC-MAC [8] provides higher priority to delay sensitive applications and achieves high throughput with low collision rates. Schedule-based mechanisms [9] [10] usually employ Time Division Multiple Access (TDMA) for medium access control. They are collision free in nature, but flexibility and scalability are sacrificed. Other than TDMA-based solutions, Frequency Division Multiple Access (FDMA) solutions, such as [11], are proposed for collision free frequency allocation. OFDMA-based solutions such as [12] achieves statistical multiplexing gain through the division of data channel and control channel.

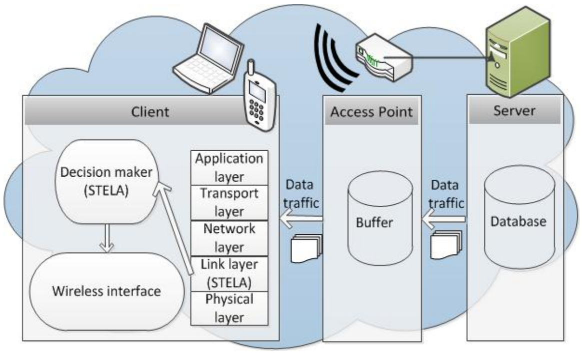

Fig. 1. STELA - Deployment Scenario

In this paper, a novel transceiver duty cycle management solution, *the Slow-sTart Exponential and Linear Algorithm (STELA)* is introduced. STELA relies on the fact that data traffic shows a significant amount of regularity; packets are sent in bursts, with relatively short inter-arrival duration during bursts, while long intervals are observed between bursts [13] [14]. STELA, to the best of the authors knowledge, is the first algorithm to consider the traffic pattern and its bursty nature at the MAC layer. Both energy efficiency and QoS are achieved through adaptive initiation of three phases: slow start, exponential increase and a novel linear increase stage which are efficiently combined by STELA.

II. SLOW START EXPONENTIAL AND LINEAR ALGORITHM (STELA)

STELA's deployment is illustrated in Fig. 1, as part of a client-server wireless communications architecture. STELA is implemented at the MAC sub-layer of the data link layer at the client-side. Following client request for data, STELA monitors the incoming traffic from the server and alters the energy footprint of the client wireless network interface by dynamically managing its sleep mode in an intelligent manner. The server-client communication is assumed to be performed in infrastructure mode via a wireless access point which receives and forwards packets both uplink and downlink. More importantly, the access point buffers the data packets addressed to the mobile client when the device's wireless interface is in sleep mode.

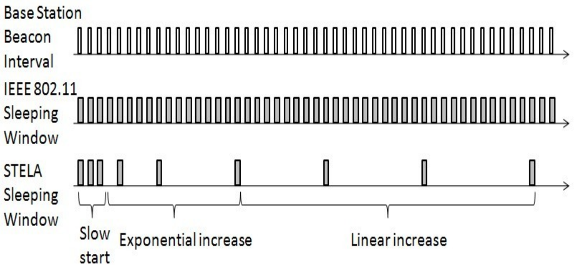

Fig. 2. Illustration of STELA's Energy Saving Approach

The power saving scheme employed by the IEEE 802.11 requires the wireless interface of mobile stations to wake up regularly, after fixed sleeping intervals. The binary exponential increase scheme used by the IEEE 802.16 [15] doubles the sleeping window duration each time the interface wakes up and no traffic is detected. Both mechanisms do not adjust the sleeping schedule according to real time traffic, resulting in wasted energy on idle listening.

The main operational principle of STELA is depicted in Fig. 2. As noted in the 802.11 and 802.16 standards, the access point beacons regularly. STELA adjusts the sleeping window of the client's wireless network (radio) interface based on the following algorithm. Initially, a slow start phase is activated in which packets are expected to arrive as a burst, followed by a binary exponential increase phase in which the sleeping window duration is doubled every time no packet is detected when the channel is sampled following interface waking up. Finally, STELA initiates a novel linear sleeping window increase stage in which a balance between energy conservation and QoS level preservation is achieved.

During *the slow start phase*, the first packet of each data burst is detected and the radio interface will wake up regularly for each beacon if packets continue to arrive. This assumes that the packets are delivered continuously (as part of a burst). This phase starts immediately when a packet is detected during channel sampling. Additionally, the slow start phase is also initiated once new content is expected following a request sent from the client to the server. The reason behind this is that the response from the server, which normally consists of series of packets, is transmitted to the client immediately after the client request is accepted by the server. This considers the fact that waking up the client's radio interface takes long amount of time, while the server response time is relatively short and in general high speed data transmission is involved. This behaviour reduces data packet delay.

The binary exponential increase phase is triggered if no packets are detected during the slow start phase. It is assumed that the last packet of a data burst has been received and a new burst transmission has not yet started. During this stage, the sleeping window is doubled each time the channel is sampled and no incoming packets are detected. This strategy is also used by the IEEE 802.16 standard. The exponential increase of the sleeping window ends when the window reaches a predefined maximum size (threshold). This threshold is used to fine tune the behaviour of the algorithm (conservative or aggressive) and has a great impact on both energy saving and network QoS parameters. It can be noted that the smaller the threshold is, the earlier the sleeping window stops growing exponentially, and therefore the more energy will be consumed by the wireless network interface.

STELA introduces an innovative *linear increase phase* after the exponential phase, during which the sleeping window is increased in steps of one beacon intervals. By using this approach instead of continuing to use the binary exponential increase phase, the sleeping window will not grow aggressively with negative effects in terms of increasing packet delay, while still reducing energy consumption.

The slow start phase will be re-initiated whenever a packet is received by the mobile terminal, signaling the beginning of a potential data burst.

III. SIMULATION-BASED TESTING AND RESULTS

The performance of STELA is evaluated based on simulations, using Network Simulator 2 (NS-2) [18]. The simulation scenarios involve a server connected to an access point over a wired link and a mobile host attached to the access point receiving data over the wireless link. The simulation consists of a total of 240 sets of test cases under different networking conditions: **Traffic** refers to types of data traffic used at the application layer including both CBR and VBR traffic shapes which are widely used by applications involving multimedia content delivery. **Type** refers to traffic patterns. For both CBR and VBR traffic, three different traffic patterns are compared respectively. These patterns have different on/off intervals and traffic rates to validate the performance of STELA under different application configurations. Type 1, 2, 3 represent on/off CBR traffic, (20s on, 20s off), (10s on, 20s off) and (20s on, 10s off) respectively, and Type 7 is staircase type CBR traffic with 200s duration and a rate variation of 0.5Mb for each stair. Type 4, 5, 6 represent on/off VBR traffic, (0.01s on, 0.01s off), (0.02s on, 0.01s off) and (0.01s on, 0.02s off) respectively, and Type 8 is a staircase type VBR traffic with 200s duration and a rate variation of 0.5Mb for each stair. **Rate** refers to the data rate which is set to 0.5 Mbps, 1.0 Mbps and 1.5 Mbps respectively in distinct test cases. Two staircase patterns are additionally considered for both CBR and VBR traffic with a step rate of 0.5 Mbps and 200s duration for each step. **Threshold** refers to the threshold values used by STELA. The threshold values assigned for each of the test cases are 2, 4, 8, and 16, respectively. These values represent multiples of beacon time intervals.

These four test scenario parameters form a vector <traffic, type, rate, threshold>, and only one value is changed in every individual test case. STELA is compared with the Power Saving Mechanism (PSM) scheme used by the IEEE 802.11 and the binary exponential increase function employed by the IEEE 802.16. Unlike STELA, the sleeping strategies used by the IEEE 802.11 and IEEE 802.16 standards do not consider the type and particularities of data traffic.

TABLE I
TESTING RESULTS FOR CBR AND VBR TRAFFIC WITH STELA THRESHOLD VALUE SET TO 2 BEACON INTERVALS

Traffic CBR	**Scheme**	**Energy (Joule)**	**Delay (ms)**	**Jitter (ms)**	**Traffic VBR**	**Scheme**	**Energy (Joule)**	**Delay (ms)**	**Jitter (ms)**
0.5Mb Type 1	Fixed	51.38	18.02	5.76	0.5Mb Type 4	Fixed	75.76	16.97	5.76
	Exponential	40.13	18.03	5.76		Exponential	58.97	21.68	12.55
	STELA	29.14	19.96	6.17		STELA	50.00	21.89	12.55
0.5Mb Type 2	Fixed	49.41	18.02	5.76	0.5Mb Type 5	Fixed	76.82	16.72	5.85
	Exponential	36.28	18.03	5.77		Exponential	61.13	20.60	10.81
	STELA	23.44	21.18	6.48		STELA	51.94	20.97	11.03
0.5Mb Type 3	Fixed	52.35	18.02	5.76	0.5Mb Type 6	Fixed	73.20	17.18	6.23
	Exponential	42.98	18.03	5.77		Exponential	53.72	23.32	14.28
	STELA	33.83	19.50	6.11		STELA	43.82	24.94	15.81
1.0Mb Type 1	Fixed	56.98	14.98	7.68	1.0Mb Type 4	Fixed	82.08	16.36	7.24
	Exponential	45.73	15.0	7.68		Exponential	68.25	19.19	9.21
	STELA	34.56	15.98	7.87		STELA	58.80	19.52	9.29
1.0Mb Type 2	Fixed	53.61	14.98	7.68	1.0Mb Type 5	Fixed	85.94	16.04	7.40
	Exponential	40.48	15.01	7.68		Exponential	72.49	18.17	8.49
	STELA	27.43	16.61	8.0		STELA	63.28	18.44	8.59
1.0Mb Type 3	Fixed	59.35	14.98	7.68	1.0Mb Type 6	Fixed	77.33	16.62	7.21
	Exponential	56.98	15.0	7.68		Exponential	59.09	21.24	10.64
	STELA	37.54	15.89	7.86		STELA	49.11	22.51	11.39
1.5Mb Type 1	Fixed	62.58	14.61	5.47	1.5Mb Type 4	Fixed	88.87	15.83	6.06
	Exponential	51.33	14.61	5.48		Exponential	74.09	18.52	7.34
	STELA	40.00	15.27	5.60		STELA	64.80	18.70	7.30
1.5Mb Type 2	Fixed	57.81	14.61	5.47	1.5Mb Type 5	Fixed	95.03	15.36	5.71
	Exponential	44.68	14.61	5.47		Exponential	81.39	17.09	6.34
	STELA	31.43	15.69	5.69		STELA	72.18	17.23	6.38
1.5Mb Type 3	Fixed	66.35	14.61	5.47	1.5Mb Type 6	Fixed	81.73	16.20	6.03
	Exponential	56.97	14.62	5.48		Exponential	63.35	20.66	8.38
	STELA	47.50	15.12	5.58		STELA	53.30	21.64	8.69
0.5Mb Type 7	Fixed	452.00	15.53	6.52	0.5Mb Type 8	Fixed	387.06	15.37	6.55
	Exponential	414.50	15.53	6.52		Exponential	300.81	15.72	6.61
	STELA	378.01	15.54	6.52		STELA	222.89	19.55	7.70

To simulate the power consumption of a wireless interface, the energy measurement-based model presented in [16] is utilized. The experimental model indicates 750 mW as the power consumption of a wireless interface card in active mode including idle mode, receiving mode and transmitting mode, and 50 mW in sleeping mode. The energy consumed during state transition which involves the wireless interface waking up and listening to a beacon is modelled as 1.5 mJ based on a measurement of 750mW being consumed over a 2 ms period, which is observed through prototype testing.

The experiments show the significant impact of the threshold values on the performance of STELA. Threshold value of 2 presents the best performance in terms of energy saving and reduced negative impact on QoS, while a value of 16 reduces the benefit of STELA in comparison with the IEEE 802.16 only. Due to the limited space, only the testing results for these two extreme threshold values are presented in Table I and Table II, respectively.

The energy consumption of the three schemes are evaluated in all test cases, and the results with threshold value of 2 and 16 beacon intervals are presented in Table I and Table II (test cases with threshold value of 4 and 8 beacon intervals are proved to show similar results). It can be observed that STELA saves up to 55% energy for CBR traffic when compared with IEEE 802.11 (fixed window) and up to 36% when compared to IEEE 802.16 (exponentially increasing window). In the context of VBR traffic, it can be observed that STELA consumes less energy than the constant window algorithm (IEEE 802.11), up to 50% and up to 18% when compared with the exponential increasing window scheme (IEEE 802.16).

Testing results have shown the effect of each variable from the test vector on the performance of the three algorithms. When the traffic pattern varies, energy consumption and performance fluctuates. It can be seen that the longer the burst period and the shorter the idle period for both CBR and VBR traffic, the more energy is consumed. The same result is observed when the traffic rate increases. Besides that, threshold value is another determinant parameter influencing the performance of STELA. The smaller the threshold value the more power is conserved when compared with IEEE 802.16, due to the early initiation of the linear increase phase. The increase in packet delay and jitter is acceptable due to STELA's fast response to packet bursts. On the other hand, the larger the threshold value, i.e. 16, the more likely is STELA and IEEE 802.16 to perform similarly, as chances for a packet to arrive before the binary exponential increase phase terminates are higher. Even under the worst case scenario (i.e. threshold value set to 16), STELA performs similarly with the mechanism utilized in IEEE 802.16, while still outperforming IEEE 802.11 in terms of energy efficiency.

Although both average packet delay and jitter slightly increase when using STELA, their values are less than 25 ms, which is considered acceptable for multimedia content delivery [19], thus not compromising the delivery performance from the user perspective.

IV. CONCLUSION

This paper introduces STELA, a novel energy-efficient MAC layer algorithm for wireless data communications, which adjusts the radio transceiver's sleeping window size according

TABLE II

TESTING RESULTS FOR CBR AND VBR TRAFFIC WITH STELA THRESHOLD VALUE SET TO 16 BEACON INTERVALS

Traffic CBR	**Scheme**	**Energy (Joule)**	**Delay (ms)**	**Jitter (ms)**	**Traffic VBR**	**Scheme**	**Energy (Joule)**	**Delay (ms)**	**Jitter (ms)**
0.5Mb Type 1	Fixed	51.38	18.02	5.76	0.5Mb Type 4	Fixed	75.76	16.97	5.76
	Exponential	30.22	18.37	5.87		Exponential	50.45	22.43	13.02
	STELA	28.48	21.18	6.39		STELA	49.71	22.07	12.84
0.5Mb Type 2	Fixed	49.41	18.02	5.76	0.5Mb Type 5	Fixed	76.82	16.72	5.85
	Exponential	24.69	18.72	5.99		Exponential	52.78	20.92	11.06
	STELA	22.62	23.38	6.90		STELA	52.11	20.70	10.89
0.5Mb Type 3	Fixed	52.35	18.02	5.76	0.5Mb Type 6	Fixed	73.20	17.18	6.23
	Exponential	34.58	18.64	5.93		Exponential	43.84	26.72	16.85
	STELA	33.01	20.87	6.9		STELA	43.69	24.59	15.72
1.0Mb Type 1	Fixed	56.98	14.98	7.68	1.0Mb Type 4	Fixed	82.08	16.36	7.24
	Exponential	35.78	15.9	7.72		Exponential	59.49	19.57	9.29
	STELA	33.80	16.61	7.98		STELA	58.67	19.57	9.31
1.0Mb Type 2	Fixed	53.61	14.98	7.68	1.0Mb Type 5	Fixed	85.94	16.04	7.40
	Exponential	28.84	15.38	7.76		Exponential	63.82	18.45	8.63
	STELA	26.48	17.73	8.22		STELA	63.20	18.33	8.51
1.0Mb Type 3	Fixed	59.35	14.98	7.68	1.0Mb Type 6	Fixed	77.33	16.62	7.21
	Exponential	41.50	15.32	7.75		Exponential	49.48	23.62	11.91
	STELA	39.70	16.43	7.97		STELA	49.48	22.16	11.21
1.5Mb Type 1	Fixed	62.58	14.61	5.47	1.5Mb Type 4	Fixed	88.87	15.83	6.06
	Exponential	41.34	14.74	5.50		Exponential	65.90	18.71	7.34
	STELA	39.12	15.68	5.68		STELA	64.53	18.81	7.41
1.5Mb Type 2	Fixed	57.81	14.61	5.47	1.5Mb Type 5	Fixed	95.03	15.36	5.71
	Exponential	32.98	14.87	5.53		Exponential	72.58	17.39	6.44
	STELA	30.35	16.43	5.84		STELA	71.75	17.31	6.45
1.5Mb Type 3	Fixed	66.35	14.61	5.47	1.5Mb Type 6	Fixed	81.73	16.20	6.03
	Exponential	48.43	14.83	5.52		Exponential	53.42	22.88	9.21
	STELA	46.40	15.57	5.67		STELA	52.97	21.73	8.79
0.5Mb Type 7	Fixed	452.00	15.53	6.52	0.5Mb Type 8	Fixed	387.06	15.37	6.55
	Exponential	381.63	15.54	6.52		Exponential	209.28	23.02	8.52
	STELA	377.39	15.59	6.52		STELA	197.88	28.07	9.72

to traffic patterns. STELA employs a novel sleeping window adjustment phase which results in reduction of energy consumption with minimum negative impact on network QoS parameters. The proposed solution has been modeled and simulated using NS-2 and its performance has been compared with that of similar solutions employed by the IEEE 802.11 and IEEE 802.16 MAC protocols. Simulation results show that STELA outperfoms these solutions in terms of energy saving without significantly degrading the delivery performance.

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