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A Novel Power Saving Strategy for Greening IEEE 802.11 based Wireless Networks

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Abstract—**We propose a novel power saving strategy called Sleep during Neighbor-Addressed Frame (SNAF) for improving energy efficiency of IEEE 802.11 based wireless networks. IEEE 802.11 (Wi-Fi) radios that employ SNAF mode can turn OFF their wireless transceivers (*i.e.,* put radios in sleep mode) within specific periods of neighbor-addressed frames while they are being received. The sleep duration of transceivers is easy to determine with no loss of packet's critical control information. The proposed SNAF mode operation does not have any negative effect on network throughput and even complements Power Saving Mode (PSM) available in 802.11 standard. We further propose GreenFrame format for next generation wireless networks. In experiments conducted in wireless LAN scenarios, we observed savings as much as 57.8% when we implement SNAF mode in 802.11 standard and up to 49.5% when we implement SNAF mode in 802.11 PSM.**

I. INTRODUCTION

Wireless systems based on IEEE 802.11 standards, that shipped more than 387 million radios in 2008, consume significant amount of energy. Originally, IEEE 802.11 was not designed for energy efficiency. Power Saving Mode (PSM) was retrofitted to the 802.11 standard. PSM saves energy by keeping the radio in sleep mode whenever it is not expected to transmit or receive packets. Though PSM saves energy (especially in low-traffic scenarios), it has been found that PSM can eventually result in higher consumption of energy [1], [2], [3] and poor throughput and delay performance. Further, in moderate-to-high traffic scenarios, PSM cannot be able to put radios in sleep mode and, therefore, fails to address energy efficiency issue completely for many real-world traffic scenarios. In [1], authors suggested the use of turn OFF for the entire NAV (Network Allocation Vector) period. However, their solution has many deficiencies including high collisions, low throughput, packet loss, and the inability to decrement the back-off counter during channel busy states – a very important MAC activity for CSMA/CA protocols– among other issues.

We now illustrate with an example the energy inefficiency problem present in 802.11 standard. Consider a WLAN system with one Access Point (AP) and n WLAN clients (nodes or users). When the AP transmits a packet to a node (node-addressed frame), say node 1, due to broadcast nature of wireless medium, the AP's transmission is typically received by all the nodes in the vicinity of the AP. All the nodes except node 1 find the packet was not addressed (neighbor-addressed frame) to them and they discard the packet (*i.e.,* they completely receive the whole packet thus spending energy just like the node 1 and then drop the packet). Typically, the energy spent for reception is a significant fraction of the energy spent for transmitting a frame (refer Table I). For a frame with transmission duration of 10 ms, energy consumed at the transmitter using Atheros card is about $13.5\ mW \times s$. However, with a dozen nodes in the network, the total energy spent for receiving the 10 ms transmission is $11 \times 1.02W \times 10ms = 112.2\ mW \times s$. *That is, excluding the energy required to be spent by the addressed receiver node, the collective energy wasted is about 750%.* Given the proliferation of WLAN systems, the collective energy wasted by the nodes in reception mode will be very significant. Figure 1 shows number of unicast frames received by different users during one hour trace interval in our campus WLAN environment. This trace was collected inside a library location by using a traffic sensor device which keeps Wi-Fi radio in *monitor* mode to overhear all frames in a selected Wi-Fi channel. Figure shows the frames that are actually destined for individual users after excluding all broadcast frames. It can be observed that 80% of users are almost idle, but they still need to spend energy just like active users (20%). In order to address this energy inefficiency present in 802.11, we propose a novel power saving strategy, Sleep during Neighbor-Addressed Frame (SNAF), in this work. The proposed SNAF strategy allows a node to go into sleep mode during reception of neighbor addressed frames, thereby, helping idle users to significantly save their energy.

TABLE I
POWER CONSUMPTION RATES OF 802.11 WI-FI CARDS.

Activity	WaveLAN [2]	Atheros [4]	Intel PRO
Transmission	1.65W	1.35W	1.914W
Reception	1.4W	1.02W	1.386W
Idle or Listen	1.15W	0.89W	0.294W
Sleep or Doze	0.045 W	0.16W	0.128W

The rest of the paper is organized as follows. Section II explains SNAF strategy and Section III discusses GreenFrame design format. In Section IV, we provide detailed performance results and finally, we conclude the paper in Section V.

II. SNAF: SLEEP DURING NEIGHBOR-ADDRESSED FRAME

Our objective here is to reduce the energy that a wireless client (node) needs to spend on processing 802.11 MAC frames that are not addressed to itself. The IEEE 802.11 has three kinds of MAC frames: Management, Control, and Data

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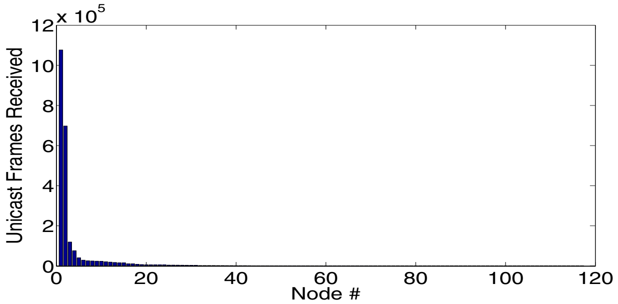

Fig. 1. Total unicast frames addressed to different users.

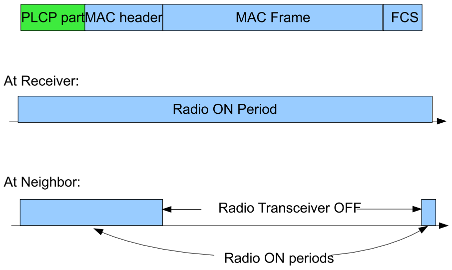

Fig. 2. An example of SNAF strategy.

frames. The management and control frames are typically short because they contain only MAC header and no payload. However, Data frames are typically long and carry data from higher layers. Data frames, therefore, occupy channel for a long duration and contribute to most of the energy consumption at nodes. Ideally, in order to save energy, a node must receive only the most important parts of frames (*header part*) and it can sleep during less important parts of frames (*payload part*). Therefore, in SNAF mode, for a neighbor-addressed frame (*i.e.,* a frame that is addressed to a neighbor of the node that receives or overhears the frame), only the header part of the MAC frame should be received by the node. By going to *sleep mode* when the data payload part of neighbor-addressed frame is being delivered over wireless medium, a node can save energy by avoiding unnecessary reception and processing of the rest of the frame. The operation of SNAF strategy is illustrated in Figure 2 where, for receiver nodes, the radio transceiver is ON for the entire duration of the frame, however, for neighbor node(s), the radio transceiver is ON only during the Physical Layer Convergence Protocol (PLCP) and MAC header parts of the frame. One challenge here is in determining the duration of the turn OFF (*i.e., sleep* period because the Duration field in the MAC header of a Data frame contains the duration for the complete frame exchange (*i.e.,* DATA-ACK), therefore, it cannot be used. We utilize the PLCP header fields, *SIGNAL Field* and *PSDU LENGTH Word*, that carry information about the transmission rate and length of the MAC frame, respectively, for determining the time duration at which the radio transceiver can be turned back ON. The time to sleep is obtained by subtracting MAC header size from *PSDU LENGTH Word* and dividing the remaining (*i.e.,* payload size) with *SIGNAL Field*. Once the transceiver is ON, the node can start contending for transmissions or ready to receive from others.

The above discussion also tells us that, when a node is receiving a frame, it just needs the destination address of that frame for taking a decision to sleep for a part of the frame. In 802.11 standard, bytes 6–10 contain address of intended receiver of the frame. Thus, if a node is receiving a neighbor-addressed frame it can potentially go into sleep mode as soon as it receives first 10 bytes of the MAC frame.

In Algorithm 1 (lines 11 to 15), the energy consumed for reception of 10 bytes of header and waking up from sleep mode (Wakeup) is compared with energy consumed for reception of the whole packet and idle time for SIFSTime. If the former is lesser, SNAF is activated and node's radio is put into sleep mode. We are assuming here that the time for Wakeup is exactly same as SIFSTime.

Algorithm 1 Transceiver turn-OFF decision algorithm

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 1: DA = Destination MAC Address present in receiving MAC frame
 2: NA = MAC Address of Node receiving MAC frame
 3: PL = Packet Length of MAC frame in bytes
 4: DR = PHY Data Rate in bytes/sec
 5: $P_{Sleep}$ = Power consumed in Sleep mode
 6: $P_{Receive}$ = Power consumed in Receive mode
 7: $P_{Idle}$ = Power consumed in Idle mode
 8: SD = Sleep Duration
 9: $E_{Wakeup}$ = Energy consumed in Wakeup
10: Receive the first 10 bytes of the MAC frame
11: if DA $\neq$ NA then
12:   if ((PL-10)$\times P_{Sleep}$/DR+10$\times P_{Receive}$/DR+$E_{WakeUp}$)
      $<$ (PL$\times P_{Receive}$/DR+SIFSTime$\times P_{Idle}$) then
13:     SD = (PL-10)/DR
14:     Turn OFF radio for SD time interval
15:   end if
16: end if
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A. Applying SNAF in Legacy 802.11 devices

The 802.11 standard does not contain a separate checksum field for MAC header part of frames and Frame Check Sequence (FCS) located at the end of MAC frames is for the entire frame. When a node is receiving the header part of the frame, a check is made if the frame is addressed to itself by directly comparing address field in the frame (*i.e.,* bytes 6–10) with its own MAC address, that is, without checking the header's accuracy using an additional checksum field. Node can put its radio in sleep mode immediately after completing reception of first 10 bytes of the frame if the checking process tells that frame is not destined for itself as explained in Algorithm 1. Will the protocol be correct and is data sanity maintained in the presence of potential bit errors that can creep into the header fields and go undetected? A detailed observation reveals that MAC operation does not face any problems and we brief our observations here.

Error(s) in the address fields of the frame: This kind of errors can turn a node-addressed frame as a neighbor-addressed frame and vice versa. In the first case, a receiver node treats frame as neighbor-addressed one and sleeps for the rest of the frame. This is, in fact, good for energy savings because the frame is anyway going to be dropped later due to FCS check failure. In the second case, node will receive the frame in its entirety just like in 802.11 standard (therefore no energy saving) and it will be dropped due to FCS check failure.

Error(s) in non-address fields of the frame: This kind of errors may not create any problems for the node that the frame is addressed to. Like the above case, the node will drop the frame due to FCS failure. However, this scenario can be troublesome for the neighbors who will receive only the frame header when they employ SNAF scheme. The trouble is mainly because some fields in the MAC frame header such as the Duration field will be used by neighbors for virtual carrier sensing thereby leading to erroneous estimates on the duration of the expected transmission. While such an erroneous Duration field may not create any errors, it can potentially prevent the neighbor nodes from using the channel for a much longer time than required. An error in the Duration field of a DATA frame header may result in an abnormally longer or shorter Network Allocation Vector (NAV) period for neighbors. In order to solve this problem, we suggest the use of NAV cancelation timer solution. Upon seeing a DATA frame, neighbor node sets NAV vector cancelation timer as (2 × SIFSTime) + (ACK Time), so that the impact of erroneous Duration field can be alleviated. When NAV cancelation timer expires before seeing any channel activity, node clears NAV and it can, therefore, start contending for channel.

One exception to the above discussed NAV cancelation timer is when the received packet is a fragmented DATA frame (not the last fragment, whose case is exactly equal to above case), where the Duration field of the fragment typically includes time needed for next fragment and its ACK. Hence, in this case, neighbor node needs to set its NAV cancelation timer as (2 × SIFSTime) + (ACK Time) + (2 × SIFSTime). All these changes require only software changes and, therefore, the proposed SNAF scheme can be applied to legacy 802.11 a/b/g/n clients efficiently.

III. GREENFRAME DESIGN

The motivation for GreenFrame design is to help the nodes apply energy saving strategies selectively at different parts of the frame and to ensure that data correctness is not violated due to potential error possibilities. The ideal GreenFrame design is when the MAC frame is split into two separate parts for checksum verification. The regular FCS field at the end of frame is used for protecting the MAC frame payload and a new two-byte Header Checksum (HCS) field is added for protecting the MAC header. The value addition by the HCS is that the MAC header is protected and the inefficiency, due to the wrong address fields or other control information, can be alleviated. That is, the simple addition of a HCS field for the frame header, at bytes 11–12 (immediately after the receiver address field) can help in verifying the correct address of receiver node. All broadcast packets are considered node-addressed packets in this case. Such an addition of the HCS field, exclusively for the MAC header, is in existence in many popular frame formats such as the PLCP part of the 802.11 MAC frame and cell frames of ATM networks, and found to be very useful. Through detailed experiments (presented in next section), we find that the performance remains largely unaffected by the additional overhead of GreenFrame design.

IV. PERFORMANCE RESULTS

We studied the benefits of SNAF and GreenFrame by simulating it using QualNet simulator and developing a prototype device. The simulations are performed in a WLAN with 50 nodes (one Access Point and 49 clients) placed in a terrain area of 100m×100m. Transmission range is kept quite higher (284 m) to ensure that each node overhears other nodes. Channel frequency is 2.4 GHz and two-ray path loss propagation model is employed. In our QualNet's energy model, transmission, reception, idle (overhear or listen), and sleep activities consume 840 mW, 612 mW, 534 mW, and 42 mW power, respectively. MAC PHY data rate is 11 Mbps with ARF (auto rate fallback) enabled. RTS/CTS handshake mechanism is enabled, however, the SNAF scheme is limited to only MAC DATA frames.

We compare performances of the following schemes: 802.11 standard (802.11), 802.11 with SNAF enabled (802.11+SNAF), GreenFrame with SNAF enabled (GreenFrame+SNAF), 802.11 with PSM enabled (802.11+PSM), 802.11 with PSM and SNAF enabled (802.11+PSM+SNAF), and GreenFrame with SNAF and PSM enabled (GreenFrame+SNAF+PSM). In all experiments, we use Constant Bit Rate (CBR) flows and 50% of flows start from a randomly selected client and terminate at AP and vice versa. We used a packet length of 1250 bytes. All the simulations are executed for 100s. We measured performance in terms of aggregate energy consumption (mAHr) and aggregate network throughput (Kbps). The aggregate energy consumed is the sum of total energy consumed at all nodes in the network. The aggregate throughput is the sum of throughputs of all CBR flows in the network. Each experiment is repeated for 20 seeds and the results are averaged.

A. Simulation Results

1) Effect of Traffic Load: In this experiment, we have 25 CBR flows starting at random times during the simulation and staying till the end of simulation experiment. Traffic load is varied from 200 Kbps to 11 Mbps by varying CBR flows' Inter Arrival Times (IATs). Figure 3 shows variation of aggregate energy consumption in the network with offered traffic load for all schemes. As shown in the figure, significant savings (up to 56%) in terms of reduction in energy consumption are achieved with SNAF and GreenFrame modes compared to 802.11 standard. As traffic load increases, the number of neighbor packets present in wireless medium increases. In 802.11+SNAF and GreenFrame+SNAF, nodes will go to sleep mode in more occasions, and hence energy consumption decreases with increase in traffic load. However, nodes that do not employ SNAF design need to receive and then drop most of the packets in wireless medium (*i.e.,* neighbors packets), therefore, energy consumption increases with increase in traffic

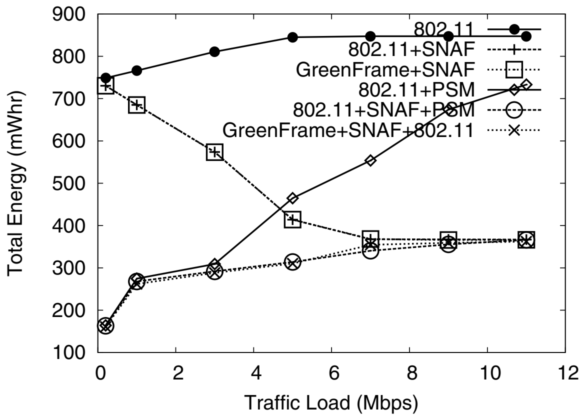

Fig. 3. Energy vs Traffic load in different schemes.

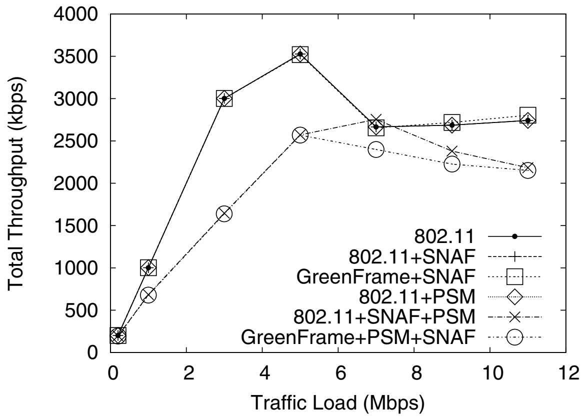

Fig. 4. Throughput vs Traffic load in different schemes.

load. Hence, high traffic situations are ideal scenarios in the case of SNAF design for observing higher benefits in terms of energy savings. Traffic helps to save energy! It is to be noticed that when offered load reaches 7 Mbps, network reaches its saturation point because we used 802.11b PHY with 11 Mbps.

Now we compare power savings of our solution combined with PSM (802.11+SNAF+PSM) with 802.11, 802.11+PSM, and 802.11+SNAF. At low traffic, as PSM puts idle nodes in sleep mode for most of the time, it leads to significant energy savings compared to 802.11 schemes. However, with increase in traffic load, energy consumed by active nodes (transmitters and receivers of CBR flows) increases and hence energy consumed steadily increases with traffic load in 802.11+PSM scheme. When we compare 802.11+PSM with 802.11+SNAF scheme, for low traffic loads 802.11+PSM outperforms 802.11+SNAF scheme. This is because 802.11+SNAF savings are due to its sleep during reception of neighbor-addressed frames and there are less chances for it to go sleep mode when there is low traffic load in the network. On the other hand, 802.11+PSM exploits idle time (lack of frames destined for a node) and converts that efficiently into sleep time. 802.11+SNAF does not exploit idle time, instead it exploits reception time on neighbors packets and hence it saves a lot of energy when there is high traffic load and out-performs 802.11+PSM in high traffic conditions. Thus, these schemes are complementary as each one exploits different phases of the node state. This can be seen from the plot that 802.11+SNAF+PSM scheme saves more compared to 802.11+PSM and 802.11+SNAF schemes, and the savings increase with offered traffic loads.

When we look at the curves for GreenFrame design, the energy saved is almost the same as SNAF. Thus, in the energy plots the SNAF and GreenFrame curves are overlapping.

To prove that our 802.11+SNAF design will not affect network throughput, we plotted aggregate network throughput versus offered traffic in Figure 4. Both the 802.11 and 802.11+SNAF schemes have exactly same throughput because SNAF neither changes frame formats nor exchanges additional frames. The throughput increases initially, then saturates at 7 Mbps offered traffic load. PSM achieved lower throughput compared to 802.11 scheme because it increases delays in the delivery of frames. Depending on beacon interval length, transmitters may have to buffer frames for a while in order to inform receivers about their packets in the upcoming Announcement Traffic Indication Message (ATIM) window. PSM also incurs additional control overhead as it involves exchanging additional control frames like ATIM frames and PS-Poll frames between AP and WLAN clients. However, our solution (802.11+SNAF) does not suffer from any side effects as it puts a node in sleep mode only for a fraction of frame duration for packets that are meant for neighbors. Throughputs for 802.11+SNAF+PSM and 802.11+PSM schemes overlap and decrease with increase in number of flows due to increased delay in delivery of packets due to collisions. When the load is 7 Mbps, throughputs of 802.11 and 802.11+PSM overlap because 802.11 scheme experienced more collisions compared to 802.11+PSM. We observed on average 333 and 284 retransmissions per node at 7 Mbps in 802.11 and 802.11+PSM, respectively. With GreenFrame, there is a decrease in throughput at high traffic loads (>5Mbps). This is due to the 2 bytes of HCS added to the header.

2) Effect of Number of Nodes: In this experiment, we studied the effect of number of nodes by keeping the number of active flows and the traffic load kept constant. The total traffic load in the network is 5 Mbps, 3 nodes are transmitting to the AP and 2 nodes are receiving from the AP. The total number of nodes in the network is varied from 5 to 50. As shown in Figure 5, in 802.11 the total energy consumed in the network increases as the number of receiver nodes increases. From the difference between the curves of SNAF and 802.11 we can see that the energy savings due to application of SNAF strategy increase with increase in the number of nodes. The energy savings in the 50 node network is as high as 57.8% when we compare 802.11 with 802.11+SNAF. In PSM enabled schemes, the total energy consumed is less compared to other schemes as the number of idle nodes has increased. The PSM+SNAF enabled schemes show a further decrease in energy consumption as expected. Here also the energy savings

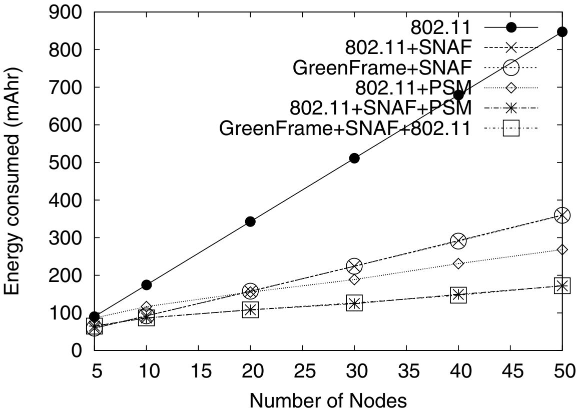

Fig. 5. Energy vs Number of Nodes in different schemes.

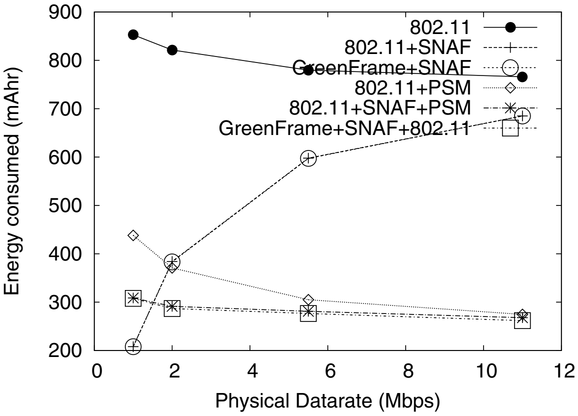

Fig. 6. Energy vs PHY Data Rate in different schemes.

increase with the number of idle nodes.

The throughput is not affected by SNAF on both 802.11 and 802.11+PSM. The graphs on the plot of throughput are exactly overlapping. Therefore, we omit it from the rest of this paper.

3) Effect of PHY Data Rate: In this experiment, we studied the effect of PHY data rates of energy savings by keeping the traffic kept constant at 1Mbps. IEEE 802.11b PHY data rates of 1 Mbps, 2 Mbps, 5.5 Mbps, and 11 Mbps are considered in this study. From Figure 6 we can see that with lower data rates, the nodes will take longer time to transmit a packet. So, in SNAF and GreenFrame modes, the idle nodes will get more time to sleep on neighbor packets. Thus, we see maximum savings at 1 Mbps and the least at 11 Mbps.

B. Results from the Prototype:

We prototyped SNAF solution using a programmable 802.11b platform, CalRadio [5]. The RF chip's transmission, reception, standby, and sleep modes consume currents at the rate of 15mA, 50mA, 1.5mA, and 1mA, respectively. We configured four CalRadio devices as a single-hop ad hoc network testbed and used the external clamp-on current meter (accuracy of 1mA) for measuring current consumption of the device under test. With 8 background traffic flows, generated by *Ping* utility using 1400 byte packets, we found that the CalRadio device under test resulted in 2 mA Root Mean Square (RMS) current saving with 802.11+SNAF scheme which makes a 24mW (RMS) saving with 12 V power supply. This result is confirmed by our other measurement on CalRadio which is given in Figure 7. In this figure, we can see the energy savings that our 802.11+SNAF scheme accrues compared to 802.11 and the energy savings (in time window of neighbor-addressed frames) increases rapidly with background traffic flows. This experimental validation stands as a proof-of-concept of energy savings as well as simplicity of SNAF implementation in prototype systems.

V. CONCLUSIONS

In this paper, we proposed a novel power saving strategy for WLANs which deals with turning the radio transceiver OFF during the reception of neighbor-addressed frames. We observed significant energy savings with proposed scheme, to the tune of 57.8% and 49.5%, compared to regular 802.11 and PSM of 802.11, respectively. Additional benefits of SNAF include: simplicity to implement, inter-operability with legacy devices, and absolutely no impact on throughput performance. We confirmed the benefits by implementing SNAF scheme in a real prototype device. We also proposed GreenFrame format, a modification to 802.11 frame, that also resulted in significant energy savings with minimal impact on network throughput.

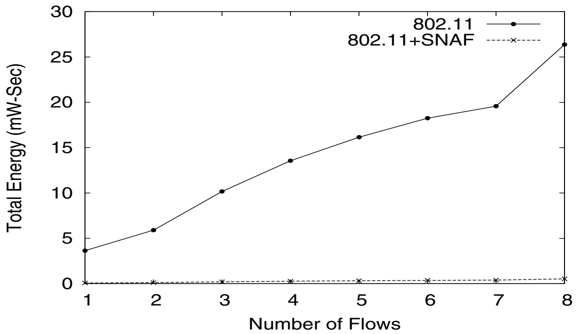

Fig. 7. An Idle User's Total Energy consumption due to reception of neighbor-addressed frames.

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