Energy Savings by Intelligent Interface Idling in 802.11 based Wireless Networks

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Abstract

In this paper we propose and analyze a new interface idling mechanism for improving carrier-sense energy expenditure of IEEE 802.11 based wireless network interfaces. A novel protocol state analysis technique is developed for detecting time windows during which a node consumes energy due to erroneous carrier sensing. During this window, energy savings at the MAC layer is accomplished by forcing a wireless interface to a relatively low-energy idling state. At the end of this window, an interface is transitioned back to its regular receiving mode. Energy savings are realized by exploiting the difference in power consumption between the erroneous carrier sensing state and the idling state. We evaluate the proposed protocols using ns-2 simulator. Simulation experiments demonstrate that the proposed mechanisms are capable of significantly reducing erroneous carrier sensing expenditure for newer generation of 802.11 cards that support low-energy idling modes as described above. Our experimentation with Socket Communication Inc.'s low power 802.11 card demonstrate that the reduction in combined overhearing and erroneous carrier sensing expenditure can be up to 62% and can extend network life by up to 154%. Results also show that the proposed MAC layer idling is fairly insensitive to mobility.

1 Introduction

In MANET networks running IEEE 802.11 at MAC layer the expended *transmission energy* at a node is generally a tiny fraction of its total communication related energy expenditure. In addition to transmission and reception, there are three sources of non-essential energy expenditure [2] in an 802.11 network. The first one is due to *idling*, which corresponds to energy consumption when a wireless interface is neither transmitting nor receiving. In 802.11, even in idle state an interface must be up and ready to receive possible traffic. For older generation hardware, the consumption during this state is significant. Lucent's 915 MHz WaveLAN card, for instance, consumes 1.15W when idling, 1.2W while receiving and 1.6W while transmitting [3].

The second component is *overhearing*, during when an interface receives data and control packets that were transmitted to some other node. Overhearing is caused by the fact that when a unicast packet transaction is carried out in a node's immediate neighborhood, it does not have any mechanism for not receiving that packet. Energy expenditure during overhearing is same as that during reception.

The third and the component of interest in this paper is *Erroneous Carrier Sensing (ECS)*, which corresponds to reception of signal with unacceptable Signal to Interference Ratio (SIR) [10]. In order to reduce collisions, 802.11 MAC protocol employs an extended carrier sense range which relies on a higher carrier sense sensitivity compared to the receive sensitivity. Although a higher carrier sense range reduces the collision rate, for an interface it increases the duration of ECS. ECS consumes same amount of energy as reception. The goal of this work is to develop MAC layer syntaxes to minimize the ECS energy expenditure without significantly sacrificing system throughput and packet drop rates.

A number of researchers have investigated the issue of energy conservation both at the routing layer [4,6,8,15,16] as well as at the MAC layer [5,17,18,19,20,21]. Since this paper deals only with MAC layer syntaxes, we concentrate on the latter set. The papers in [5,18,20] work outside the 802.11 framework and they propose their own MAC architectures. Although the idea of reducing overhearing is a common feature in [5,17,20,21], none of these papers provide mechanisms for reducing the ECS energy. The paper in [19] refines the standard 802.11 power saving features in DCF mode by employing a long term *sleep* mechanism that works in the time constant of 802.11 beacon intervals. Our work, on the other hand, employs a short term *idling* mechanism that works at packet duration time constants. Shorter sleep/idling has the advantage of smaller delays and therefore, less impacts on upper layer protocols and applications. However, because of different operational time constants, our mechanism can coexist with that proposed in [19].

1.1 Non-essential Energy Expenditures

To investigate the energy breakdown we conducted simulation experiments with ns-2 [11] for a typical MANET running 802.11b at the MAC layer and routing protocol AODV [12] at the routing layer. For the energy model, we have used Socket Communication Inc.'s Low Power Wireless LAN Compact Flash Card that consumes 594mW while receiving and 924mW while transmitting at full power [2]. In addition, the card supports a low-power *idling* mode in which it listens for carrier and consumes only 66mW. As soon as carrier is detected in the channel, it transitions into the receiving mode. A number of next generation wireless chipsets support advanced power management modes. Another notable example is GlobespanVirata's PRISM GT (formerly from Intersil) 802.11 chipset [1] that supports four low-power modes with current consumption ranging from 30mA to 190mA. A summary of all its interface states and their energy expenditure is presented in Table 1.

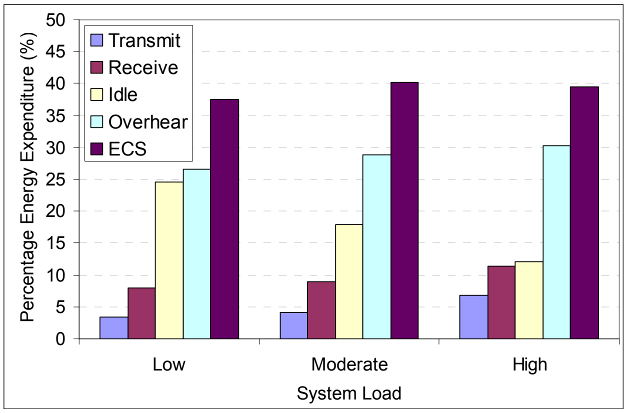

Figure 1: Breakdown of transmit, receive and non-essential energy expenditure in an 802.11 network

Experiments were performed with three traffic loading scenarios. For each scenario, the energy statistics was captured at the time of battery exhaustion for the node that was exhausted first. Percentage energy breakdown for transmission, reception and the non-essential expenditures are presented in Figure 1. Following observations are to be made: 1.Transmission accounts for only a tiny fraction (3.4% to 6.8%) of the total energy expenditure. 2. Non-essential expenditures (idling, overhearing and ECS) are responsible for the majority of consumption (88.7% for low load and 81.8% for high load) 3. All the energy components, except idling, increase with load; this is because with increasing traffic load part of the idling duration is converted to transmit, receive, overhearing and ECS.

1.2 Energy Savings by Interface Idling

Putting an interface to a low-power *sleep* mode [15,8] during transmission and reception inactivity is an obvious way to cut the non-essential expenditure. Problem with forcing a wireless interface to a complete sleep state is that most of today's wireless interfaces typically take 10s of milliseconds to transition from sleep to any other state. Lucent's WaveLan card, for instance, takes around 100ms [9] for this transition. When compared with typical packet duration of few milliseconds, this transition latency is way too high.

The key idea in this paper is to limit Erroneous Carrier Sensing (ECS) expenditure by leveraging advanced power management features offered by next generation wireless hardware such as Intersil's PRISM GT 802.11 chipset [1] and Wireless LAN Compact Flash card from Socket Communication Inc [2].

To avoid high wake-up latency from complete sleep, we propose forcing the interface to a low-energy *idling* state (e.g. the idle state as specified in [2]) during transmission and reception inactivity. In the *idling* state, instead of shutting the entire card off, certain parts of its electronics are kept powered so that the transition time to a non-idling state is only around 20μs. Unlike in complete sleep based mechanisms, in this approach we do not reduce the idling component of the non-essential energy. Instead, we convert much of the ECS components to forced-idling. Due to the low idle consumption numbers (66mW compared to 594mW for overhearing and ECS in [2]) we achieve overall reduction in non-essential expenditures. Similar technique, reported in [17,20,21], can be also used for reducing the energy consumption due to overhearing.

The main contribution of this paper is a MAC layer protocol extension for reducing consumption due to erroneous carrier sensing (ECS) in 802.11 interface cards. Upon detecting ECS, an interface forces itself to idle for a duration that is estimated based on dynamically measured MAC layer packet sizes. This mechanism reduces the time a node spends in ECS mode and increases duration of low energy idling, and in turn reduces the energy

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[1]

consumed due to ECS. We evaluate this mechanism through simulation and show that this forced state-switching can extend network life significantly by cutting on ECS energy expenditure.

2 E-Idling: Idling for ECS Reduction

We propose e-idling as a mechanism for reducing energy consumption due to erroneous carrier sensing (ECS). The idea behind e-idling is when a node starts receiving ECS signal, its wireless interface is forced to switch to the low-energy idling state till the transmission causing ECS is over. Consider the scenario in Figure 2, in which node A is outside node D's receive range but within its carrier sense range [14]. Node C, on the other hand, is within the receive range of D. After an RTS-CTS transaction, when D starts sending a data packet to node C, D's transmission appears as ECS signal to A, which cannot transmit or receive during this packet duration.

According to e-idling, upon reception of the ECS signal the interface at node A goes to a forced idling state and eventually transitions back after an anticipated data duration T_{Data}^{Max}. In between, the interface wakes up twice; first time after an anticipated MAC layer control packet duration $T_{MAC\_Ctrl}^{Max}$ and for a second time which is after an anticipated AODV control packet duration $T_{AODV\_Ctrl}^{Max}$. The rationale behind first intermediate wakeup is to respond to the scenario where the received ECS signal corresponds to a MAC layer RTS or CTS. If after waking up the node finds that the ECS signal still persists then it goes back to the forced idling state. The second wakeup is to address the situation where the received ECS signal corresponds to an AODV RREQ, RREP or RERR message. If the ECS signal still persists then the node assumes that the ECS signal is data and it goes back to forced-idling till T_{Data}^{Max} duration since start of the idling expires. The quantities $T_{MAC\_Ctrl}^{Max}$, $T_{AODV\_Ctrl}^{Max}$ and T_{Data}^{Max} are determined based on past measurements and they accurately reflect maximum durations of different packet types in the system.

It should be noted that the performance of e-idling is sensitive to the accuracy of duration estimation of different packet sizes in the system. Our proposed design assumes three sizes, namely, MAC control, AODV control and fixed size data packets. In applications where there are many more packet sizes, the approach outlined in Figure 2 will require modifications. Instead of having only two intermediate wakeup events, a polling based wakeup mechanism needs to be in place. In this context, the advantage of polling is that the performance of e-idling will no longer depend on the number of packet sizes in the system. The flip-side is that frequent polling may pose additional processing burden, which in turn will consume energy from the system.

Interface State	Description	Consumption
Idling	Interface is ready to receive but no carrier is present	66mW
Receiving	Receiving packets destined to itself	594mW
Overhearing	Receiving packets not destined to itself	594mW
Erroneous Carrier Sensing (ECS)	Receiving signal with unacceptable SIR	594mW
Transmitting	Transmitting packets	924mW max

Table 1: Energy consumption of Socket Communication Inc.'s Low Power Wireless LAN Compact Flash card

3 Performance

Performance of the proposed E-idling mechanism has been evaluated in conjunction with a similar technique O-idling, which has been used for reducing overhearing energy as reported in [21]. O-idling is a MAC layer protocol extension for limiting overhearing energy by forcing an interface to idle based on the following approach. While in overhearing state, if an interface detects a packet transaction in its neighborhood, it transitions to a lower energy idle state till the packet transaction is over. This way, it can reduce the energy consumed due to overhearing. After the surrounding transaction is over, the interface transitions back to the overhearing state. The concept of O-idling is very similar to the interface-sleep technique described in [17,20]. The wake-up latency issue [9] for interface-sleep has been addressed in O-idling [21] by leveraging the low-energy idle state [2] from which an interface can transition to receive state within only few microseconds.

Performance of O-idling and E-idling has been evaluated using ns-2 simulation package. A 60-node network has been simulated within a

550mx120m rectangular area. AODV and 802.11 have been used as the base routing and MAC layer protocols. For mobility pattern, we assume that each node pauses for a fixed duration between movements and after each pause it moves towards a random direction with an average speed of 6.4m/s. Traffic is generated as 512 byte long CBR packets. Various inter-packet spacing, ranging from 0.3s to 1.2s, are used for varying the loading conditions. CBR sessions are generated between randomly chosen source-destination pairs with each session lasting for 500s. For energy model, we use the power consumption figures for Socket Communication's low power wireless LAN card as summarized in Table 1.

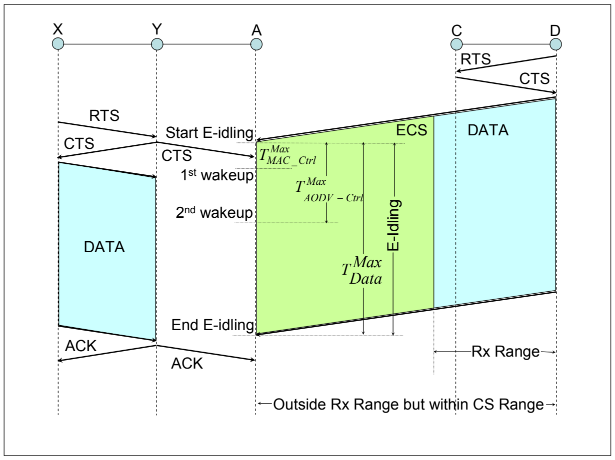

Figure 2: Mechanism and timing for e-idling

All our experiments were run in the presence of Transmission Power Control (TPC) [7]. We implement an open-loop TCP. Each node maintains a neighbor table that is built using AODV hello mechanism. For each neighbor, its geographical coordinate is stored for computing the physical distance. A node sends RTS, CTS and the broadcast packets with maximum available transmission power. However, for the data packets, a sender evaluates the physical distance to the receiver [7] and computes the necessary transmission power based on the propagation model and antenna properties. A two-ray-ground model has been used for our implementation.

Our first experiment is to characterize the energy impacts of O-idling, E-idling and transmission power control, and to compare them with the base case of unmodified 802.11 with AODV routing. The base case is marked as "Plain 802.11" in Figure 3. As a first step we apply transmission power control which reduces the transmission expenditure somewhat (from 4.8% to 3.5%) but as expected, it does not have any appreciable impact on the non-essential expenditures. However, applying O-idling with power control reduces the overhearing energy substantially by converting most of the overhearing duration to low-energy idling. Applying E-idling cuts the non-essential consumption further by almost eliminating the erroneous carrier sensing (ECS) energy. Combined overhearing and ECS expenditure is reduced from 69% to 6.7%. Note that while reducing overhearing and ECS, these mechanisms contribute to a significant increase in idling (from 18% to 64%). However, due to almost an order of magnitude consumption difference (66mW during idling as opposed to 594mW during overhearing/ECS) the overall consumption is reduced. The final observation in Figure 3 is that application of these MAC and PHY layer mechanisms increase the consumption due to transmission as a percentage (4% to 12%) of the total consumption. This creates room for potential routing layer mechanisms [4,5,6] to extend node battery life by implementing energy-constrained routing.

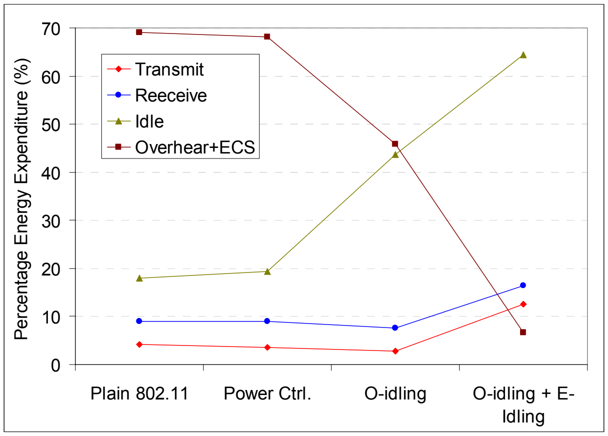

Figure 3: Impacts of power control, O-idling and E-idling on non-essential energy consumption

The effects of energy savings on overall network life are shown in Figure 4. The graphs show number of surviving nodes as the time progresses. For a given scenario, the measure of goodness for a energy-saving protocol is indicated by how far right the graph is pushed from the base case (marked as "plain 802.11") scenario. For all experiments, out of 60 nodes 30 are given an initial energy of 500Joule and the rest 30 are given 1000Joule. The low and high energy nodes are chosen completely randomly for energy heterogeneity. It is due to this differential energy distribution, we see that each graph in Figure 4 has an upper half that corresponds to the battery exhaustion of 30 low-energy nodes and then the lower half that corresponds to high-energy nodes.

We define the lifetime gain as the percentage increase of the life of the first battery-exhausted node. While transmission power control provides a gain of modest 4.5%, both O-idling and E-idling can offer significant extension in network lifetime. O-idling and E-idling, combined with power control, offer a 154% gain over the base case.

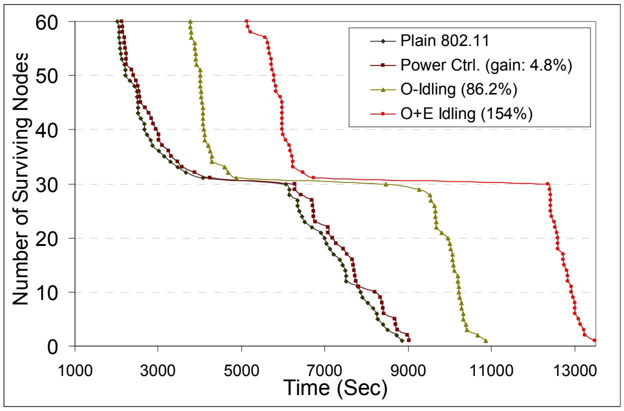

Figure 4: Impacts of forced idling on network life

Change of mobility is accomplished by adjusting pause times between node movements. The effects of different pause time are less pronounced. This is because we do not have any routing layer mechanisms that are more affected by mobility. Minor errors in idling-duration estimations, due to mobility, account for the slight gain losses with higher mobility.

Packet drop rate in Figure 6 is defined as the number of packets dropped for each successfully delivered packet. Packet drops are contributed by MAC layer buffer overflow and drops after pre-defined number of MAC retransmissions, which happens during local congestions. In this experiment we study overall packet drop rates for the base case as well after applying power control, O-idling and E-idling. As evident from the diagram, application of the MAC layer idling mechanisms raises the drop rate from around 0.6% to 4.4%. Note that the idling durations in both O-idling and E-idling (see Figure 3) are estimation-only and there are estimation errors, which can cause over-idling. In the events of over-idling a node may potentially lose packets that are transmitted towards it. These losses account for the drop rate increase.

Note that increased drop rate is the price being paid for improved energy efficiency. With proposed MAC layer idling mechanisms we observe a lifetime extension of 154% over the base case. This gain is traded for an increased packet drop rate from 0.6% to 4.4%. This would impact data oriented applications such as TCP more than the stream oriented applications that can tolerate higher packet drop rates. We did not observe any noticeable impact of the proposed energy saving mechanisms on packet delivery hop count and its associated delays.

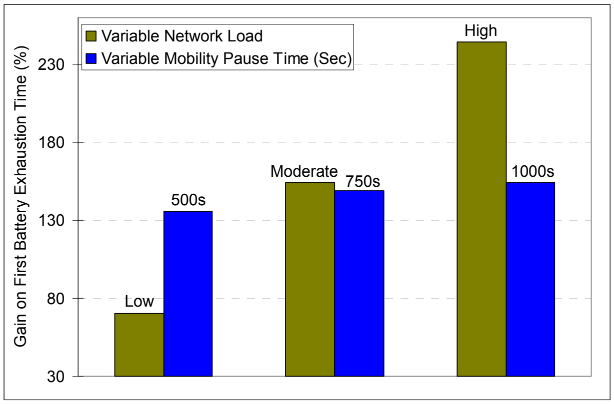

Figure 5: Effects of traffic load and mobility on network life

4 Summary and Conclusions

In this paper we have proposed and analyzed a forced interface idling mechanism for reducing energy expenditure due to erroneous carrier sensing in IEEE 802.11 based wireless interfaces. A novel protocol state analysis technique is developed for detecting time windows during which a node consumes non-essential energy by erroneous carrier sensing. During this window, energy savings at the MAC layer is accomplished by forcing a wireless interface to a relatively low-energy idling state. Experimental results demonstrate that in moderate loading conditions the proposed mechanisms are capable of reducing combined overhearing and ECS expenditure by up to 62% and can extend network life by up to 154%. This huge gain in network lifetime is traded for increased packet drop rates. The maximum packet drop rate that we observed was 4.4% with an overall network life extension of 154%. Results also show that the proposed MAC layer idling is fairly insensitive to mobility. To summarize, our proposed MAC idling mechanisms offer an efficient means for cutting on non-essential energy expenditures. This is accomplished by leveraging the low-power idling modes that are supported by next generation wireless interface cards.

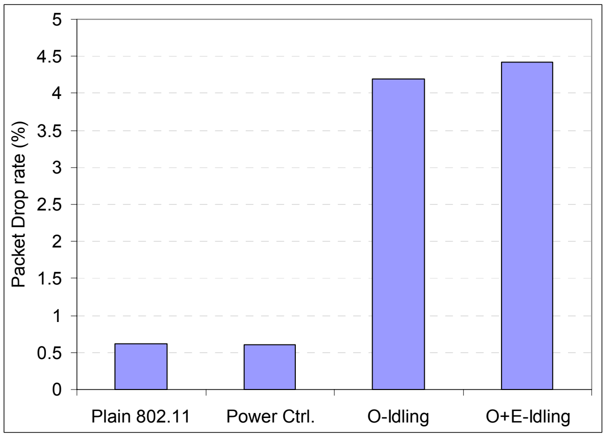

Figure 6: Impacts of forced idling on packet drop rate

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