Energy-Efficient Channel Access Scheduling For Power-Constrained Networks

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Abstract

In this paper we introduce the Distributed Energy-Aware Node Activation (DEANA) channel access protocol for power-constrained networks. Conventional channel access protocols waste energy during periods of idle listening and collisions. In DEANA, the radio is switched to a low power, stand-by mode when a node is not transmitting or receiving which makes DEANA very attractive for sensor networks. Using an analytical model, we show that the proposed approach can achieve significant energy savings (up to 95%).

Keywords

Power-constrained networks, energy-aware scheduling, channel access, node activation, MAC

INTRODUCTION

Nodes that take part in multihop wireless ad hoc networks are typically power constrained. Consider, for example, sensor networks in which nodes are typically deployed and left unattended for extended periods of time. Because sensor nodes are usually power anemic and their main source of energy consumption is the radio, an energy-efficient channel access scheme is critical to prolong the network's lifetime.

Most channel access protocols (either contention-based or scheduling-based) are not power-aware, i.e., they provide no explicit mechanisms to achieve energy efficiency. The main source of energy consumption is idle listening, in which a node is in receive mode[1] even though it is not scheduled to receive or transmit any data. In addition, at high offered load, contention-based channel access protocols spend energy unnecessarily when collisions occur. PAMAS [4] is an improvement over contention-based protocols by reducing idle listening. However, it does not avoid the problem of energy waste due to collisions, and it needs a separate signaling channel. S-MAC [7], a contention-based protocol focusing on sensor networks, tries to save energy by making nodes sleep periodically. However, for higher traffic load, energy consumption increases due to the overhead incurred by exchanging control messages that maintain sleep schedules. Sohrabi etal proposed a TDMA-based protocol for wireless sensor networks [5] that establishes individual slots for communication but does not solve the problem of collisions.

[1] It has been shown that the energy spent in receive mode is 50-100% of energy spent in transmit mode for standard IEEE802.11 radios [6]

We present and analyze DEANA (Distributed Energy-Aware Node Activation), a channel access protocol for power-constrained networks using node activation to schedule conflict-free transmissions. DEANA is a TDMA-based MAC protocol that adapts the Neighborhood-aware Contention Resolution (NCR), and node activation approach used in the Node Activation Multiple Access (NAMA) protocol [3]. The novel feature introduced by DEANA is that whenever a node is not scheduled for transmission or reception, the node's radio is switched to a low-power mode. It addresses the energy consumption caused by collisions and idle listening: (1) using the Neighborhood-aware Contention Resolution (NCR) mechanism [3] for collision-free channel access, and (2) selecting the state of the radio transceiver based on three different node states, namely transmitter, receiver, or idle in order to conserve energy. Since sensor networks are usually static, a simple neighbor discovery protocol could be used to distribute the two-hop neighbor information needed for the contention resolution protocol.

The remainder of this paper describes DEANA, our energy model and numerical results obtained by applying this model to DEANA followed by concluding remarks and directions for future work.

DYNAMIC ENERGY-AWARE NODE ACTIVATION

We assume there is only a single channel for communications (both data and signaling) and the channel is time-slotted. DEANA adopts the neighborhood-aware contention resolution (NCR) node activation scheme [3] used by NAMA. The time division structure shown in Figure 1 is the basic (energy-unaware) node activation scheme derived from NAMA. Data packet transmission happens during a *transmission slot*. Time slots are grouped into sections and sections are grouped into blocks. In each block, the last section is reserved for updating node neighborhood information. NAMA's distributed node selection scheme guarantees collision freedom based on two-hop neighborhood information at each node. When a node is activated for transmission in a particular time slot, it requires all its neighbors to be in receive mode and thus can communicate with any one of them during that slot without conflict. Note that only for broadcast communication, a transmitter needs all its neighbors to be in receiver mode. Thus, when multicasting or (especially) unicasting data, considerable energy is wasted due to idle listening.

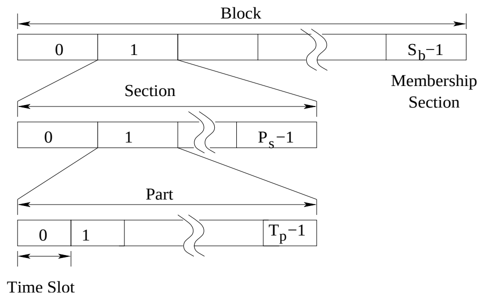


Figure 1. Time division structure for NAMA

DEANA aims at reducing energy consumption in nodes that are not the intended receivers in a particular time slot. We divide NAMA's transmission slot into a control and data portion. During the control slot, the node activated by NAMA transmits a control packet with the identity of the intended receiver(s) and the actual data is transmitted during the data slot. Hence, all the one-hop neighbors of the selected node must be in receive mode during the control slot. During the data slot, only the intended receiver(s) need to be in receive mode while all other neighbors could be switched to low-power, standby mode. The modified slot structure is shown in Figure 2. Time is divided into cycles of scheduled access and random access. The scheduled access period is used for data transmission using the scheme described above and the random access period is used for transmission of small packets of signaling information containing neighbor information. We also allow some guard period for switching the radio in between transmission slots. The length of the scheduled and random access periods depend on the mobility of the network and the size of the signaling frame. In the case of sensor networks, there is very little or no mobility depending on the type of application. Hence, the main function of the random access period is to permit node additions (deployment of new nodes) or deletions (failure of nodes). Time synchronization could be done during this period. For this paper, we assume that we have exact slot synchronization by GPS or other methods. During the random access period, all participating nodes in the sensor processing task must be in either transmit or receive mode. Hence, the duration of the random access also plays a significant role in energy consumption. Slot synchronization and energy efficiency during random access are directions for future work.

Our energy conservation heuristics consists of the following rules:

- If the winner of the current transmission slot is in a node A's one-hop neighborhood, then set node A to receive mode during the control slot. If node A is selected as a receiver during the control slot, then keep node A in receive mode during the data slot; else switch node A to standby mode.
- If the winner of the current transmission slot is in node A's two-hop neighborhood, then set node A to sleep mode for the entire transmission slot.
- If node A is the winner of the current transmission slot and has packets to send, then set node A to transmit mode, inform the intended receiver(s) during the control slot, and transmit the data packet(s) during the data slot.
- If node A is the winner of the current transmission slot and does not have a packet for transmission, set node A to standby mode for the entire transmission period.

ENERGY MODEL

In this section we present the mathematical model quantifying DEANA's energy consumption. As performance baseline, we also derive the expression for energy consumption of a protocol with no standby mode. We use *the expected energy consumption of a node during one transmission period* as performance metric.

The notation used in the remainder of the paper.

N_2	:	Node's number of two-hop neighbors
N_1	:	Node's number of one-hop neighbors
q	:	Channel access probability
p	:	Probability that the selected node has a packet to transmit
p_{me}	:	Probability that a node is selected as receiver by its one-hop neighbor
T_c	:	Length of the control slot in seconds
T_d	:	Length of the data slot in seconds
T_t	:	Length of the transition period between transmission slots
P_{tx}	:	Average power consumption in transmit mode
P_{rx}	:	Average power consumption in receive mode
P_{st}	:	Average power consumption in standby mode
$P_{x,y}$	:	Average power consumption in transition from mode x to mode y
E_c	:	Average power consumption during the control slot
E_d	:	Average power consumption during the data slot
E_t	:	Average power consumption during the transmission slot

The channel access probability q is the probability that a node is selected as a winner for a time slot. We assume that q is independent across nodes and is a function of the number of two-hop neighbors (N_2) of a node. We also assume that all the nodes have the same number of two-hop neighbors.

The power consumed when switching from a state to another is set to the higher value of power consumption when the transition is from the lower- to the higher power mode and is set to the average value when the transition is from the higher-

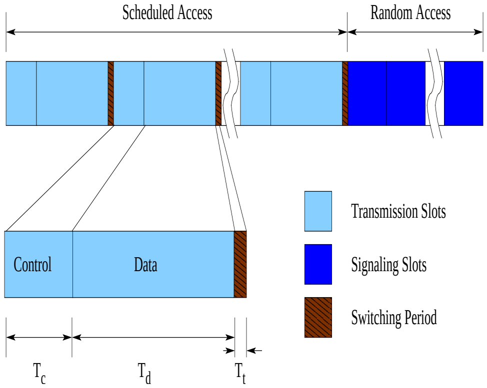


Figure 2. Time division structure for DEANA

to the lower power mode. Hence, the power consumption while in transition state is given by the following equations:

$$P_{tx,st} = (P_{tx} + P_{st})/2 \quad (1)$$
$$P_{st,tx} = P_{tx} \quad (2)$$
$$P_{rx,st} = (P_{rx} + P_{st})/2 \quad (3)$$
$$P_{st,rx} = P_{rx} \quad (4)$$
$$P_{tx,rx} = (P_{tx} + P_{rx})/2 \quad (5)$$
$$P_{rx,tx} = P_{tx} \quad (6)$$

The probability that a node is selected as the receiver by its one-hop neighbor is given by:

$$\begin{aligned} p_{me} &= \sum_{n \in N_2} q.(1/N_1).(N_1/N_2) \\ &= q \end{aligned} \quad (7)$$

For simplicity, in the following analysis we consider only unicast communication. Though we switch a node to idle mode for the entire transmission slot if the selected transmitter for the slot is a two-hop neighbor, we assume that a node could be either transmitting or receiving during the control slot for our analysis. The probability of a node in transmit or receive mode during the control slot is given by q and $(1-q)$, respectively. Hence the energy consumption during the control slot is given by:

$$E_c = T_c.[(1-q).P_{rx} + q.P_{tx}] \quad (8)$$

During the data slot, a node could be in either transmit, receive, or standby mode. Nodes take a finite period of time to switch modes when switching from the control to the data slot. Therefore, the energy spent in switching should also be accounted. The energy consumption during the data slot is thus given by:

$$\begin{aligned} E_d = \; & (1-q).\{p.p_{me}.T_d.P_{rx} + \\ & (1-p_{me}+1-p).[P_{st}.(T_d-T_t) + P_{rx,st}.T_t]\} \\ & + \; q.\{p.T_d.P_{tx} + \\ & (1-p).[P_{st}.(T_d-T_t) + P_{tx,st}.T_t]\} \end{aligned} \quad (9)$$

The first term in Eq. 9 corresponds to the case where the node is not a winner of the current transmission slot. This occurs with probability $(1-q)$. The node can either switch to receive mode if it is the chosen receiver or to standby mode if it is not the intended receiver or if the transmitter does not have a packet to send. The second term in Eq. 9 corresponds to the case where the node is the winner of the transmission slot. Here the node can transmit or go to standby mode depending on whether it has a packet to send or not.

The energy consumption during the switching period T_t depends on the state of the node in the previous transmission slot and the state of the node in the next transmission slot. It is given by:

$$\begin{aligned} E_t = \; & T_t.\ \{q.[\ p.(q.P_{tx} + (1-q).P_{tx,rx}) \\ & +(1-p).(q.P_{st,tx} + (1-q).P_{st,rx})\ ] \\ & +(1-q).[p_{me}(p.(q.P_{rx,tx} + (1-q).P_{rx}) \\ & +(1-p).(q.P_{st,tx} + (1-q).P_{st,rx})) \\ & +(1-p_{me}).(q.P_{st,tx} + (1-q).P_{st,rx})]\} \end{aligned} \quad (10)$$

In the above equation all the possible state transitions are taken into account with the corresponding transition probabilities.

The average energy consumption during a transmission slot, E^{tot}_{std}, can be derived as:

$$E^{tot}_{std} = E_c + E_d + E_t \quad (11)$$

When using radios with no standby mode, a node could be either in transmit or receive mode. Therefore, the total energy consumption in this case is:

$$\begin{aligned} E^{tot}_{nostd} = \; & T_t.\{q.[q.P_{tx} + (1-q).P_{tx,rx}] \\ & +(1-q).[q.P_{rx,tx} + (1-q).P_{rx}]\} \\ & +(T_d + T_c).\{q.P_{tx} + (1-q).P_{rx}\} \end{aligned} \quad (12)$$

PERFORMANCE COMPARISON

In this section the performance of DEANA is compared with that of regular NAMA. The performance metric used is the percentage of savings in energy and is computed as:

$$savings = [E^{tot}_{nostd} - E^{tot}_{std}]/E^{tot}_{nostd} \quad (13)$$

Note that nodes have to be in either receive or transmit mode during the random access period. Thus, the energy savings achieved by switching radios to standby mode only happen during transmission slots.

Table 1. Average power consumption in different modes

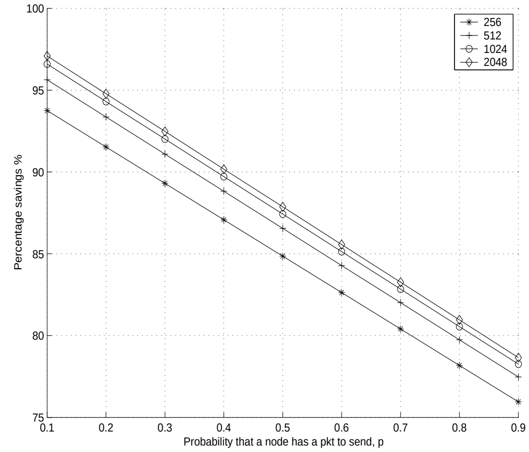
Mode	Power consumption in mW
Transmit	24.75
Receive	13.5
Standby	15×10^{-3}

Table 2. Transition times in μs

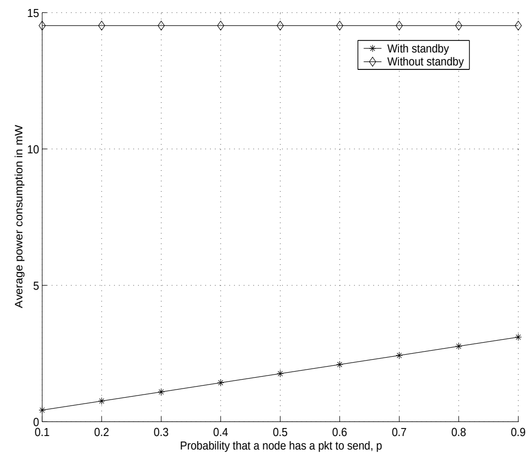
From/To	Transmit	Receive	Standby
Transmit	0	20	10
Receive	12	0	10
Standby	16	20	0

The radio we consider in our analysis, RFM TR1000 [1], has three modes of operation. Transmit-, receive-, and standby mode. The average power consumption and the latency involved in switching from one mode to another are given in Table 1 and Table 2 respectively. The data rate is $19.2KBPS$ and the length of the control and data slots depend on the size of the control and data packets and the channel propagation delay.

Figure 3(a) shows how energy savings is affected by p. For this analysis, The size of the control packet is fixed to 10 bytes and q is fixed at 0.1. We observe that energy savings are higher for lower values of p. For instance, for data packet size of 1024 bytes, energy savings is around 78% for $p = 0.9$ and the savings are 85% for $p = 0.5$. This is due to the fact that if the selected node does not have any packets to send, then DEANA switches the node to standby mode for the entire transmission period. This improves the savings as the transmit mode power consumption is much higher than the standby mode power consumption. We also show the effect of control slot overhead in savings. Because nodes are either transmitting or receiving during control slots, the savings depends on the percentage of data slot during a transmission slot. For a fixed control slot size of 10 bytes, we vary the data packet size. As the size of the data packet increases, we observe increased savings. In other words, energy saved is mainly dependent on the percentage of data in the transmission slot.
The average power consumption for different values of p is plotted in Figure 3(b). In schemes without standby mode, power consumption is constant, whereas power consumption increases with p when standby mode is available since nodes switch to standby state if it does not have a packet to send.



(a) Energy savings: different curves correspond to different sizes of the data packet (in bytes).

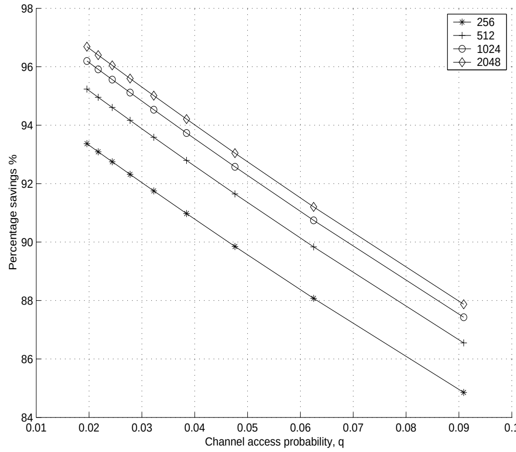


(b) Average power consumption

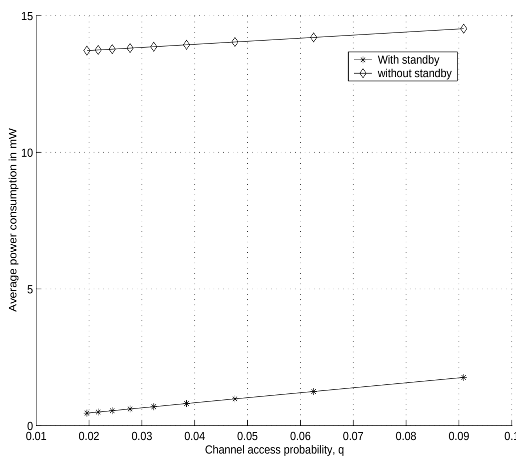
Figure 3. How p affects energy efficiency.

Figure 4(a) shows the effect of the channel access probability q with p fixed at 0.5. The energy savings decrease for higher q because nodes spend more time transmitting and receiving. Figure 4(b) shows the average power consumption for different values of q. As expected, the average power consumption increases for both schemes. As previously pointed out, this is due to the fact that as q increases the proportion of time spent by a node in transmit mode increases. Because power consumed in transmit mode is higher than in receive mode, the average energy consumption is higher when standby mode is not available.

Finally, we study the energy savings for different network densities and for different traffic conditions. The channel access probability q is dependent on the network density and p is dependent on the traffic conditions. For this experiment, we fix the data and control packet size at 512 and 10 bytes, respectively. Figure 5 shows the variation of energy savings with different traffic loads for different network densities. As we can observe, for a given network density the savings increases with a decrease in load. Also for the same traffic load, the savings increases with an increase in network density. As the network density is increased, the channel access probability decreases which leads to increased savings. For a moderately loaded system, the number of two-hop neighbors $N2$ ranges from 10 to 20. This gives a channel access probability of 0.091 and 0.047, respectively, assuming uniform distribution for channel access. The corresponding energy savings ranges from 77 to 88 % for $p = 0.9$.



(a) Energy savings: Different curves correspond to different sizes of the data packet (in bytes).



(b) Average power consumption

Figure 4. How q affects energy efficiency.

CONCLUSION AND FUTURE WORK

In this paper, we introduced the Distributed Energy-Aware Node Activation (DEANA) channel access protocol which uses a set of heuristics to select nodes to be switched to low-power, standby mode. Using an analytical model, we show that DEANA can achieve significant energy savings (up to 95%).

One of the main disadvantages of the proposed protocol is that, in practice, frequent switching between radio modes can lead to unnecessary power consumption and cancel out the benefits of switching nodes to standby mode. To address this problem, a link activation scheme could be used instead. We are currently investigating energy efficiency heuristics for link activation schemes. We are also implementing DEANA on a network simulation platform (namely Qualnet [2]) to study its performance under a wider range of network conditions.

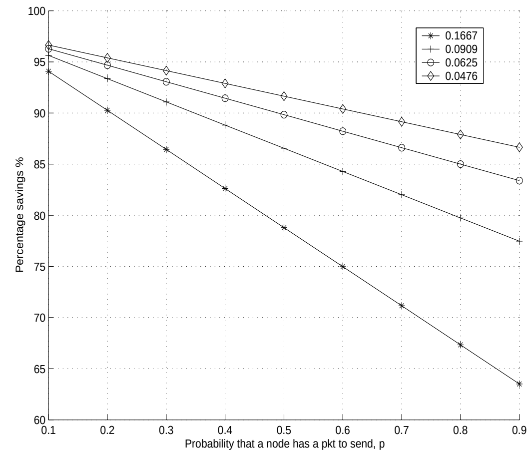


Figure 5. Effect of network density and traffic characteristics

REFERENCES

[1] "Product specification, http://www.rfm.com/products/data/tr1000.pdf."

[2] "Scalable networks, http://www.scalble-solutions.com."

[3] L. Bao and J. J. Garcia-Luna-Aceves, "A new approach to channel access scheduling for ad hoc networks," in *The seventh annual international conference on Mobile computing and networking 2001*, pp. 210–221, 2001.

[4] S. Singh and C. Raghavendra, "PAMAS: Power aware multi-access protocol with signalling for ad hoc networks," 1999.

[5] K. Sohrabi, J. Gao, V. Ailawadhi, and G. J. Pottie, "Protocols for self-organization of a wireless sensor network," *IEEE Personal Communications*, October 2000.

[6] M. Stemm and R. Katz, "Measuring and reducing energy consumption of network interfaces in hand-held devices," in *Proceedings of 3rd International Workshop on Mobile Multimedia Communications*, september 1996.

[7] W. Ye, J. Heidemann, and D. Estrin, "An energy-efficient MAC protocol for wireless sensor networks," in *INFOCOM 2002*, june 2002.