Energy-Adaptive Scheduling and Queue Management in Wireless LAN Mesh Networks

Johanna Nieminen
Nokia Research Center
P.O. Box 407
FIN-00045 Nokia Group
Email: Johanna.1.Nieminen@nokia.com

Harri Paloheimo
Nokia Research Center
P.O. Box 407
FIN-00045 Nokia Group
Email: Harri.Paloheimo@nokia.com

Riku Jäntti
Communications Laboratory
Helsinki University of Technology
PL 3000 02015 TKK
Email: riku.jantti@tkk.fi

***Abstract*—Energy efficiency is of critical importance in future wireless communication systems where networked low-power devices relying on batteries should be able to communicate transparently. We present a novel cross-layer energy-adaptive scheduling and queue management framework EAED (Energy Aware Early Detection) for minimizing energy consumption in WLAN mesh networks. EAED aims at saving energy by delaying and early dropping packets with respect to target delay and packet loss constraints. We argue that gracefully trading off energy against QoS is justified by future networking scenarios where high connectivity is more important than bandwidth. We show performance results of EAED with real-time traffic in realistic WLAN Mesh network simulation scenarios and discuss possible use-cases for EAED framework. We conclude that considerable energy savings can be obtained with our scheme under certain limitations and propose ideas for further improvement.**

I. Introduction

For decades, networking research has been driven by the increasing consumer demands for higher bitrates. Networks have been mainly designed for providing services and meeting the requirements of western consumers while certain parts of the world have remained completely disconnected. As the telecommunication markets are beginning to saturate new growth potential can be identified in the currently disconnected areas where basic connectivity with affordable price could make a difference. Designing a low price, low energy and low bit rate communication architecture would be an important step towards fully utilizing this emerging potential. Using this kind of architecture e.g VoIP calls or video conferencing could become a reality in developing countries or emergengy situations in rough environment.

Wireless mesh networks can be seen as a basis for creating the architecture due to their decentralized nature, easy and fast deployment, inexpensiveness and reliability. No centralized Access Point is required and alternative routes can be used if one Mesh Point (MP) in the network fails. Since Mesh Points are small battery powered devices with limited energy capacity, energy consumption is one of the most critical technical problems to be solved. In this paper, we will focus on energy awareness in IEEE802.11s Mesh networks. IEEE802.11s [1] is a draft IEEE802.11 amendment for mesh networking that defines a way for wireless devices to interconnect in an ad-hoc manner. Within this context we propose a new energy-adaptive cross-layer scheduling and queue management framework EAED (Energy Aware Early Detection) for real-time traffic in particular. EAED can be seen as a key enabler for creating a low energy, low bit rate mesh radio communication architecture.

EAED framework consists of packet scheduler and queue management parts. The scheduler part utilizes the theory of dynamic modulation scaling (dms) presented in [2] and aims at choosing the most energy efficient modulation and coding scheme under the constraints on packet delay. Required transmission power is computed based on modulation, coderate and feedback of channel conditions. Our algorithm applies both adaptive modulation and coding with variable bit error rate (BER). It does not make any assumptions of traffic arrival process and realistically considers the effects of 802.11s physical and MAC layer on total delay.

Queue management part applies a novel idea of randomized early packet dropping for saving energy and avoiding congestion. Packet dropping is feasible particularly for streaming traffic that can tolerate delay of 400 ms and packet drop of 15-20 % according to ITU-T G114. For this type of traffic performance deterioration due to occasional and random packet drops could be less severe than loss of many consecutive packets due to congestion.

In the rest of this article we first provide a review of energy energy saving mechanisms, present communications theory relevant to EAED and formulate the algorithms. Finally, we evaluate performance and energy saving potential of EAED and discuss future work.

II. Background

A. Energy saving mechanisms

In energy constraint mesh points, the utilized scheduling and transmission strategies should be selected to be as energy efficient as allowed by the quality of service constraints. Several different approaches have been suggested. Transmit power control combined with scheduling and selecting routes can be utilized to minimize the energy consumption caused by packet transmissions. There is significant amount of work on using transmit power control and jointly defining routing and power levels in ad hoc networks, see e.g. [3], [4]. The basic idea of transmit power control is to select the smallest

Digital Object Identifier: 10.4108/ICST.WICON2010.8521
http://dx.doi.org/10.4108/ICST.WICON2010.8521

possible transmit power such that the received power is just above the receiver sensitivity level. In multi-hop networks, also the utilized transmit power will have an impact on the network topology which then affects routing [5], [6], [7].

Most of transmit power literature assume that the data rate is fixed. Some methods have utilized multiple modulation and coding schemes supported e.g by IEEE 802.11g, a, h and n air interfaces. In [8] an energy-saving scheme MiSer was proposed that uses optimal, adaptive rate-power combination in terms of energy efficiency for each data transmission attempt. However, this scheme only considers BER as Quality of Service criteria. When considering real-time traffic such as VoIP or video streaming modulation scaling [2] or lazy scheduling [9], [10], [11], [12] can be used for selecting the modulation and coding method such that the energy consumption is minimized while enforcing the packet delay bounds. Typically, the lower order modulation is used, the less power is needed to transmit the packet with given packet error rate. Work done so far on modulation scaling and lazy scheduling has been theoretic. [9], [10] and [11] propose optimal packet transmission schedules for simplified channel models under strict assumptions on traffic arrival process. [2] and [12] do not make as strict assumptions on incoming traffic but they also fail to consider relevant MAC and physical layer effects of specific radio technology. We argue that these effects can considerably increase the total delay experienced by the packet and thus the scheduling decision must not be based on the expected transmission time only. Our scheduling scheme is based on real-time estimations so that it can dynamically adapt to the effects of radio technology as well as different traffic arrival patterns.

Besides transmit power control the best way to save energy is switching off the radio. There are several different sleeping options. In MAC layer, the state of art energy saving scheme is the X-MAC [13] in which the nodes are set to sleep in random fashion. A node wishing to transmit packet sends multiple RTS type of packets until the receiver wakes up and replies with CTS. Another approach is to control the sleeping based on the transmit buffer [14]. In [15] a theoretic framework for combining both dynamic modulation scaling and sleeping is provided. However, sleeping mechanisms might not be feasible for our application scenario since strict delay bounds for real-time traffic would require very frequent synchronization procedure for waking up the nodes and initiating communication.

Another method for saving energy is early dropping packets well before battery gets empty. As far as the authors are aware of, the idea of energy aware early dropping has not been proposed before. The only related solution can be found in queuing theory: a concept called "Impatient customers" that refers to the case, in which customers leave the system after their patience runs out even if they have not got any service. In wireless context, this is equivalent to mesh points dropping out any packet that cannot meet its deadline. The idea of early dropping is not just to drop those packets that cannot meet their deadline in the given link, but also drop packets to prevent congestion as in RED. The novelty of this paper is to show, that early dropping can also be utilized to save energy while still meeting the minimum QoS requirements of the flow.

B. Energy model used by EAED

In wireless device energy is consumed in Power Amplifier (transmitter side), radio electronics (ASIC), Host CPU, display etc. In order to fully analyze energy efficiency of protocols and algorithms all these components should be modeled. However, most of the existing work concerns measurement of total energy consumption in wireless network interface [16], [17] without considering the effect of components independently. Also the effect of different radio parameters such as modulation, coding and propagation models has not been analyzed accurately enough. Furthermore, these measurements have been performed with Laptops or PDAs, not with mobile devices or Internet tablets. As no feasible experimental energy model exists, we will use theory of dynamic modulation scaling (dms) [2] for modeling the energy consumption.

The scheduler part of our framework aims at saving energy by delaying packets so that transmission power consumption can be decreased correspondingly. Theoretically the operation of our algorithm is based on the principles of dynamic modulation scaling (dms). Denote by b the modulation level (number of bits per symbol). Average time to transmit one bit (T_{bit}) with a selected modulation level and symbol rate R_S can be expressed as

$$T_{bit} = \frac{1}{b \times R_S}. \tag{1}$$

Energy consumed for transmitting one bit (E_{bit}) is then given by [2]

$$E_{bit} = (P_{tx} + P_E) \times T_{bit}, \tag{2}$$

where P_{tx} denotes the power consumed by Power Amplifier (PA) for transmission and P_E denotes the power consumed in electronic circuitry.

From (2) it becomes obvious that transmitting at maximum modulation level is energy-wise optimal strategy if constant power is used. However, if P_{tx} can be controlled, delaying packets becomes more beneficial.

Let us first derive expressions for P_{tx} and P_E assuming for simplicity that QAM modulation method is used. BER, signal to noise ratio (SNR) and noise power P_N are given by [2].

$$BER = \frac{4}{b}\left(1 - \frac{1}{2^{\frac{b}{2}}}\right) \cdot Q\left(\sqrt{3 \cdot \frac{SNR}{2^b - 1}}\right) \tag{3}$$

$$SNR = \frac{P_{tx}}{P_N} \cdot A \tag{4}$$

$$P_N = N_0 \cdot \beta \cdot R_S, \tag{5}$$

where A symbolizes all transmission loss components, N_0 denotes noise power spectral density and β is a factor taking into account other elements such as filter non-idealities. Manipulating these equations yields

$$P_{tx} = C_S \cdot R_S \cdot (2^b - 1) \tag{6}$$

Digital Object Identifier: 10.4108/ICST.WICON2010.8521
http://dx.doi.org/10.4108/ICST.WICON2010.8521

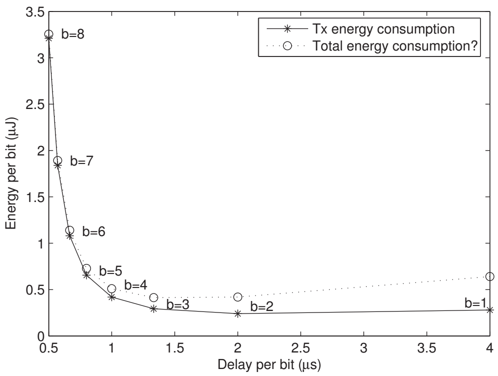


Fig. 1. Energy versus transmission time

$$C_S = \frac{N_0 \cdot \beta}{A} \cdot \Gamma \tag{7}$$

$$\Gamma = \frac{1}{3}\left[Q^{-1}\left(\frac{1}{4}\cdot\left(1-\frac{1}{2^{b/2}}\right)^{-1}\cdot b \cdot BER\right)\right]^2. \tag{8}$$

Assuming fixed symbol rate the expression for power consumed in electronic circuitry is given by

$$P_E = (C_E + C_R) \cdot R_S, \tag{9}$$

where factors (C_E,C_R) $\propto V^2$ (operation voltage). Combining the expressions derived above energy consumed for transmitting one bit is given by

$$E_{bit} = C_S \times \frac{2^b - 1}{b} + (C_E + C_R) \times \frac{1}{b}, \tag{10}$$

where the first part describes the energy required to generate electro-magnetic waves carrying information and the second part describes the rest of the radio energy consumption. The total transmission energy consumption as a function of transmission time is a monotonically decreasing and convex function, as depicted in Figure 1 (R_S = 250kHz, C_S = 100 nJ and $C_E + C_R$ = 180 nJ, corresponding to implementation of an adaptive QAM system). Thus, the more time is used for transmitting packets, the more energy can be saved assuming that transmission power is adapted according to (6). Figure 1 also shows total energy consumption (transmitter and receiver) with arbitrarily selected receiver parameters. Depending on receiver parameters, total energy consumption might not be monotonically decreasing for smallest values of b. However, in this paper the focus is on energy consumption in the transmitter side.

III. EAED FRAMEWORK FOR 802.11S

We use the energy models presented in section 2 as a basis for designing a new, distributed energy-adaptive cross-layer scheduling and queue management framework (EAED) for 802.11s mesh networks. EAED aims at saving energy by selecting appropriate modulation and coding scheme under the constraints on packet delay. Transmission power is chosen based on modulation scheme, coderate and channel conditions.

TABLE I
RESULTING DATA RATES WITH DIFFERENT MODULATION AND CODING SCHEMES

Modulation	Code-Rate	Data Rate (Mbps)	Coded bits/ symbol	Coded data bits/ symbol
BPSK	1/2	6	48	24
BPSK	3/4	9	48	36
QPSK	1/2	12	96	48
QPSK	3/4	18	96	72
16-QAM	1/2	24	192	96
16-QAM	3/4	36	192	144
64-QAM	2/3	48	288	192
64-QAM	3/4	54	288	216

In addition to adapting modulation, coderate and transmission power, EAED framework applies early packet dropping to ensure availability of energy resources in the future.

Physical and MAC layer features of 802.11s specification set boundary conditions for the operation of EAED. We have assumed physical layer corresponding to 802.11a/802.11g standards and MAC layer corresponding to 802.11e. Supported modulations and coderates are depicted in Table I. Modulation and code rate must be selected from these methods and MAC layer effects must be considered when determining how much extra delay can be allowed by EAED algorithm for energy saving purposes.

A. Description of packet scheduler

The EAED scheduler aims at finding optimal modulation and coding scheme (MCS) m. Denote by $\tilde{E}_{k,h}$ and $D_{k,h}$ energy consumption and total delay of packet k at hop h. Further denote by D_{max} the delay bound of a packet. Operation of EAED can be formalized as following optimization problem:

$$\min_m E\{\sum_{h=1}^{H} \tilde{E}_{k,h}\} \tag{11}$$

s.t.

$$\sum_{h=1}^{H} D_{k,h} \leq D_{max}. \tag{12}$$

We use a heuristic approach based on the theory presented in section 2 for solving this problem. We assume that whenever the MP is ready for transmitting a packet, energy-wise optimal solution is to select lowest possible modulation and coderate combination with respect to the constraint on packet delay.

It should be noted that all packets currently in node's buffers must be transmitted within delay bound. Let us denote by $D_{mac,h}$ the estimated waiting time of all data packets in the node's buffers due to MAC layer mechanisms and by $T_{m,h}$ the actual time for transmitting all the packets with certain MCS. Let us further denote by $Pdus_h$ the total number of data pdus in the node's buffers at hop h, by $SIFS_h$ short interframe space used before sending an ACK and by $D_{ack,h}$ the duration of ACK. It is assumed that constant modulation scheme and coderate is used for acknowledgements. D_h can

Digital Object Identifier: 10.4108/ICST.WICON2010.8521
http://dx.doi.org/10.4108/ICST.WICON2010.8521

be calculated as follows:

$$D_h = T_{m,h} + D_{mac,h} + Pdus_h * (SIFS_h + D_{ack,h}). \quad (13)$$

$D_{mac,h}$ is calculated by weighting for each access category i the estimated MAC delays $D_{mac(i),h}$ with the number of data pdus in the access category. Denote by AC the number of access categories.

$$D_{mac,h} = \sum_{i=0}^{i=AC} Pdus(i)_h * D_{mac(i),h}. \quad (14)$$

$D_{mac(i),h}$ is estimated in MAC layer with EWMA estimator. Denote by α the filtering coefficient of the estimator, by $IFS(i)_h$ the next inter frame space in access category i and by $B(i)_h$ the value for previous backoff timer.

$$D_{mac(i),h} = \alpha*(IFS(i)_h+B(i)_h)+(1-\alpha)*D_{mac(i),h}. \quad (15)$$

In heavy congestion delaying of packets might not be possible without violating delay bound. In this case the scheduler has to propose highest possible MCS even though it temporarily maximizes energy consumption. We also use MP's own estimate of medium utilization U (fraction of time when medium sensed virtually busy or ongoing transmission in the physical layer) as an indication of decreased ability to delay packets. If $U > U_{max}$, fixed MCS (16-QAM and 3 / 4) is used to avoid unnecessary collisions that might occur due to additional delaying.

In Physical layer the MCS m proposed by MAC layer must be checked against current channel conditions. The required transmit power for link h having pathloss L_h and using MCS m is $P_{tx,h,m} = \delta L_h P_{rx,m}$ where $\delta > 1$ is a power margin needed to compensate time varying fading, changes in the noise power, and inaccuracy of the pathloss measurement. The set $M_h = \{m : P_{tx,m} \leq P_{max}\}$ defines MCSs that can be utilized within the power budget P_{max} (20dBm).

An open loop transmit power control scheme is utilized by our scheduler. The required transmission power $P_{tx,m,h}$ is computed iteratively in set M_h as follows:

$$P_{tx,m,h} = \left(\frac{1.0}{L_h}\right) * \delta, \quad (16)$$

where

$$\delta = RS_h * RSCoefficient(m,h) * RbFactor_h. \quad (17)$$

Modulation and/or coderate are decreased until power constraint is met or lowest m has been reached. The MP estimates the pathloss L_h from the received frame. Other values required for computing δ are directly related to the 802.11 a/g radio: ReceiverSensitivity (RS_h) and shadow facing margin $RbFactor_h$ are set when the MP is configured. Value used for $RSCoefficient(m,h)$ is selected by table lookup based on modulation and coding scheme proposed by the scheduler, as indicated in Table II. Minimum transmission power was set to 2 dBm due to possible inaccuracies in power adaptation algorithm. The energy model used by our scheduler assumed power adaptation logic corresponding to (6) in section 2. Our

TABLE II
RSCOEFFICIENTS FOR DIFFERENT MCS FOR 802.11A/G RADIO

Modulation	CodeRate	RSCoefficient
BPSK	1/2	10.0
BPSK	3/4	10.0
QPSK	1/2	25.12
QPSK	3/4	100.0
16-QAM	1/2	158.49
16-QAM	3/4	300.0
64-QAM	2/3	795.0
64-QAM	3/4	800.0

power control strategy is similar but we measure only the value for pathloss and use coefficients and factors derived from commercial WLAN cards for other parameters.

Transmitting with different power levels could possibly aggravate the well-known hidden-node problem in wireless networks. If our scheme was used in large mesh networks it should be combined with the mechanism of sending RTS/CTS packets with constant, sufficient power as proposed by authors in [8]. The authors throughly analyzed this kind of scheme and verified that adaptive transmission power does not excarberate hidden-node problem if combined with intelligent RTS/CTS transmission.

In the experimental part of this paper, operation without EAED scheduler is equivalent to water-filling approach. In water-filling, energy consumption is minimized by transmitting packets as fast as possible while keeping transmission power constant (20dBm). In practice, highest possible MCS that can be supported with this power in current channel conditions is chosen.

B. Description of packet dropper

Several active queue management mechanisms have been deviced for congestion avoidance in wireline networks. RED [18] and WRED drop packets proactively based on filtered queue length to prevent congestion in the first place. Our EAED dropper follows general RED paradigm but aims at avoiding both congestion and exhaustion of energy resources. The dropper uses EWMA filtered modulation and code rate combination proposed by the EAED scheduler in the MAC layer as a measure of energy consumption: the higher the modulation and coderate, the higher the energy consumption. Denote the EWMA filtered MCS m by $\tilde{m}$ s.t. $(m, \tilde{m}) \in (0,7)$. Value for $\tilde{m}$ is updated in the MAC layer as follows

$$\tilde{m} = \gamma * m + (1-\gamma) * \tilde{m}, \quad (18)$$

where γ is a filtering coefficient. Early dropping propability $p(i)$ in access category i is an increasing function of $\tilde{m}$. Assume two access categories, one for streaming type of traffic and other for VoIP type of traffic. If $\tilde{m} < 2$, early packet dropping is not necessary since low modulation and coderate level alone guarantee small energy consumption. Otherwise $p(i)$ for streaming type traffic is given by

$$p(i) = 1.5 * (\tilde{m} - 1), \quad (19)$$

Digital Object Identifier: 10.4108/ICST.WICON2010.8521
http://dx.doi.org/10.4108/ICST.WICON2010.8521

and for VoIP type of traffic

$$p(i) = 0.5 * (\tilde{m} - 1). \quad (20)$$

In order to prevent MAC layer retransmissions of early dropped packets, an ACK is sent back although the packet has not actually been received.

EAED dropper has been designed particularly for real-time traffic. It is especially feasible for streaming type media since the most advanced audio/video codecs can tolerate packet loss as high as 15-20% depending on what frame types are dropped. The dropping process is even more important than the loss rate: randomized packet drops have less severe effect on quality than consecutive drops due to deadline violation.

IV. Description of simulation environment

Simulation analysis was performed in order to evaluate energy saving potential and application performance with EAED algorithm. Used simulation tool was WLANSim, a dedicated WISE library based WLAN simulator developed in Nokia Research Center. Compared with other available WLAN simulation tools such as ns2, WLANSim provides support for more realistic physical layer models. For the purposes of this research work, WLANSim was extended with mesh networking capabilities and EAED functionality.

A. Simulation scenarios

Energy saving potential of our algorithm was tested in several scenarios in order to evaluate the effect of important parameters such as distance between nodes, pathloss exponent and traffic load on algorithm operation. In all scenarios, three alternative packet handling principles were compared:

- No EAED, packets sent with maximum power limited water-filling approach
- EAED without Early Dropping (TailDrop)
- EAED with Early Dropping

Due to the lack of similar enough schemes we did not compare EAED with other energy saving methods. Other methods were either based on sleeping not suitable for real-time traffic or lazy scheduling type of approaches where dynamics of traffic arrival processes as well as WLAN MAC and PHY layer were not considered.

A network consisting of three MPs was used in simulations. Small number of nodes can be justified by the fact that packet level scheduling and queue management mechanisms should be evaluated at first in a setup that allows detailed analysis of different parameters. Small number of hops is also motivated by the quality of service constraints. See e.g. [19]. All MPs were assumed to utilize same frequency (802.11g radio with 2.4GHz) and compete for the same channel. Modulation and coderate adaptation logic of EAED algorithm was used in all MPs while dropper was implemented only in the intermediate MP acting as a router.

Two distance scenarios were defined, as depicted in Figure 2. In first distance scenario propagation was supposed to be line-of-sight while in the second scenario some obstacles were assumed to exist in the transmission path. Propagation model used took into account the effects of pathloss as well as fast and slow fading. Propagation conditions were modified simply by varying MaxLOSRange and PathlossExponent parameters. PathLoss was either 2.0 or 2.4. When pathLoss was 2.4, MaxLOSRange value was set to 15.0 in distance scenario 1 and to 40.0 in scenario2. ReceiverSensitivity was -73dBm and RbFactor was set to 2.0 or 4.0 depending on scenario.

Since EAED is primarily designed for real-time traffic, VoIP and Video were used as traffic types in the simulations. Random number generators were used for producing traffic patterns resembling the behavior of these applications. Packet interarrival time and packet size for VoIP were constant with means 20 ms and 178 bytes while Video used Normal distribution with parameters (20 ms, 6.7 ms) and (750, 250) bytes.

Simulation time was 37.5 million OFDM symbols for guaranteeing reliability of results. It was verified that longer simulation time would not have increased accuracy of results significantly. MAC layer parameters (AIFS, minCW, maxCW) for both access categories were set to reasonably small values in order to guarantee delay bounds without EAED. Traffic load was varied by changing the number of connections so that in first load scenario there were eight VoIP and Video connections, while in the second scenario there were eight VoIPs and ten videos. Half of VoIP and Videos transmitted in upstream direction, other half transmitted downstream.

V. Performance results

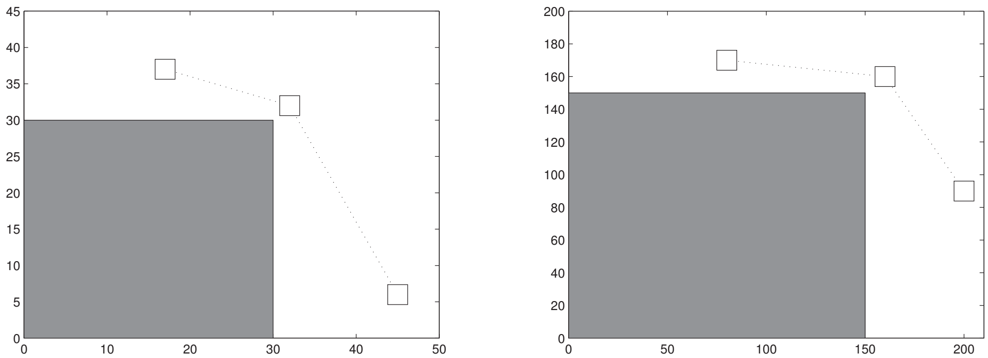
We performed extensive simulations for analyzing operation of EAED framework in terms of end-to-end application performance and energy consumption. Conventionally energy consumption has been modeled in a single node as a function of a selected modulation scheme, see e.g. [2]. We used a more holistic approach and studied energy consumption at the level of the network and individual MPs. Our choice is justified by the fact that in real networking scenarios traffic processes and channel quality are highly variable in time. Thus, modulation, coderate and transmission power are interrelated and have to be adapted frequently depending on traffic characteristics and channel conditions.

First, we examined energy saving potential of EAED algorithm with and without early dropping. Table III shows the total energy saving in the whole network for both access categories (AC2=Video and AC3=VoIP). Scenarios in Table III are defined as follows:

- Scenario1: Distance scenario 1, load scenario 1, pathloss exponent 2.0
- Scenario2: Distance scenario 1, load scenario 2, pathloss exponent 2.0
- Scenario3: Distance scenario 1, load scenario 1, pathloss exponent 2.4
- Scenario4: Distance scenario 2, load scenario 1, pathloss exponent 2.0

Energy saving percentages in Table III have been obtained by weighting the energy consumptions of individual MPs with relative amount of traffic transmitted by these MPs. As an

Digital Object Identifier: 10.4108/ICST.WICON2010.8521
http://dx.doi.org/10.4108/ICST.WICON2010.8521



(a) Distance scenario 1

(b) Distance scenario 2

Fig. 2. Distance scenarios

TABLE III
ENERGY SAVING POTENTIAL

	Energy Saving			
	EAED NoDrop AC2	**EAED Drop AC2**	**EAED NoDrop AC3**	**EAED Drop AC3**
Scen1	50.38 %	52.47 %	59.26 %	57.99 %
Scen2	49.86 %	51.86 %	59.77 %	58.65 %
Scen3	43.72 %	45.87 %	49.80 %	50.37 %
Scen4	3.43 %	2.89 %	1.82 %	3.1 %

TABLE IV
ENERGY CONSUMPTION IN SCENARIO1 FOR AC2

	NoEAED	**EAED NoDrop**	**EAED Drop**
Energy, MP 3	0.86 J	0.46 J	0.46 J
Energy, MP 2	2.29 J	1.18 J	1.12 J
Energy, MP 1	1.53 J	0.64 J	0.64 J
Weighted energy	1.74 J	0.87 J	0.89 J
Energy saving		50.38 %	52.47 %

example, Table IV shows detailed energy consumption results for each MP in scenario1 for Video traffic. It should be noted that energy consumption for EAED algorithm with dropper is different from pure EAED algorithm only in MP2 acting as a router since dropper has not been implemented in source and destination MPs.

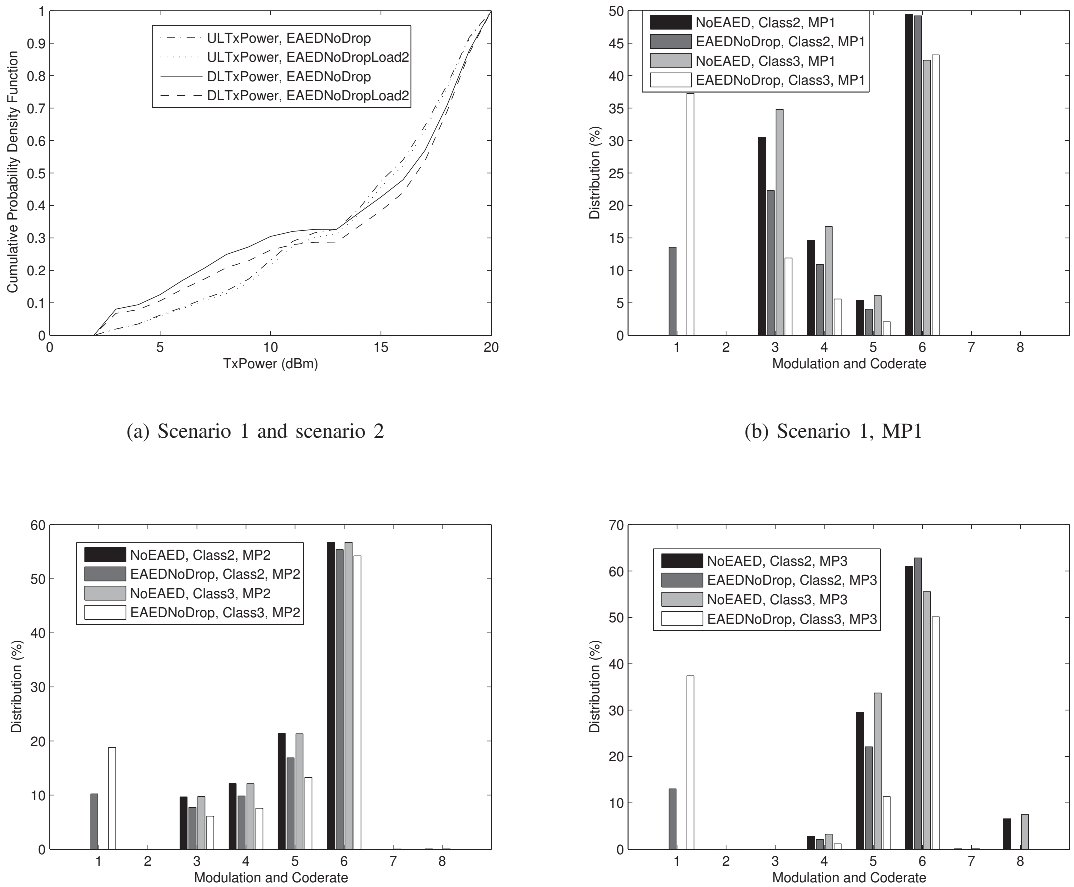
It can be concluded that considerable energy savings up to 40-60$\%$ can be obtained when load level and distance is low or moderate. By extrapolating the results it becomes evident that smaller loads and distances would allow even more energy to be saved. On the other hand, energy saving potential is only a few percentages with growing distances as can be observed from the results of scenario4. This is due to the fact that high enough transmission power must be used for guaranteeing the delay bound of real-time applications when attenuation increases. Same effect was observed when testing the algorithm with increasing load levels.

Energy saving obtained by early dropping is a few percentages compared to operation with pure EAED scheduling. Only in scenario1 and scenario2 energy saving for VoIP traffic is slightly smaller when dropper is used. It should be noted, however that if EAED was also implemented in the source and destination MP energy saving would most likely be larger. Furthermore, in a larger network topology early dropping could result in more considerable energy savings since a packet that might be dropped after having consumed resources in many hops could be early dropped by the first router along the path of the connection. Contrary to delaying, early dropping is feasible even with higher loads, if packet loss caused by congestion is below maximum packet loss requirement.

Energy saving depicted in Table III is possible due to adaptive transmission power, modulation and coding. Figure 3 (a) depicts uplink and downlink transmission power distributions for EAED algorithm without early dropping in scenario1 and scenario2. Power distribution with early dropper is almost the same as with pure EAED while transmission power distribution without EAED algorithm is constant 20 dBm. Transmission power distribution for EAED reveals that varying modulation and coderate levels have been used by the algorithm depending on MAC layer delays and channel quality. As an example, Figure 3 (b), (c) and (d) depict modulation and coderate distributions in each MP for both access categories with and without EAED (1=BPSK 1/2, 8=64-QAM 3/4) in scenario1. Corresponding transmission rate distribution could be derived from the values given in Table I. It is evident that EAED uses smaller modulation and coderate whenever possible. Lower modulation and coderate consume more time for the actual transmission but energy can be saved due to smaller required transmit power.

Figure 4 depicts end-to-end delay distributions for both access categories with and without EAED algorithm in all scenarios. EAED algorithm increases end-to-end delays but in scenario 1 and scenario 2 delays remain small enough for guaranteeing acceptable QoS for applications. On the contrary,

Digital Object Identifier: 10.4108/ICST.WICON2010.8521
http://dx.doi.org/10.4108/ICST.WICON2010.8521



(a) Scenario 1 and scenario 2

(b) Scenario 1, MP1

(c) Scenario 1, MP2

(d) Scenario 1, MP3

Fig. 3. Powers, modulations and coderates

in scenario 4 with longer distances end-to-end delay becomes almost unacceptable especially for VoIP traffic.

Table V, Table VI and Table VII depict link statistics as well as average packet losses and goodputs of connections in scenario1, 2 and 3. It can be observed that in all scenarios EAED algorithm spends more time in a state where there is one ongoing transmission in the network. Correspondingly, more time is also spent in collision state. Early drop probabilities and total packet losses (including early dropped packets) remained reasonable especially for Video traffic that could have allowed even more dropping assuming advanced codecs. Goodput was slightly better without EAED algorithm.

TABLE V
PHYSICAL LAYER, PACKET LOSS AND GOODPUT STATISTICS IN SCENARIO1

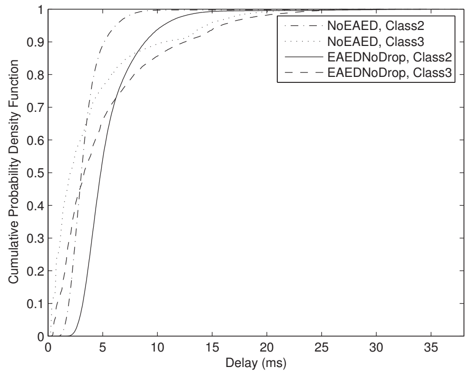
	NoEAED	**EAED NoDrop**	**EAED Drop**
T_{idle}	54.97 %	33.0 %	33.79 %
$T_{transmission}$	44.3 %	64.74 %	63.92
$T_{collision}$	0.73 %	2.26 %	2.29 %
AC2, $L_{EarlyDrop}$			4 %
AC2, L_{Drop}	2 %	2 %	7 %
AC3, $L_{EarlyDrop}$			1.13 %
AC3, L_{Drop}	3 %	3 %	5 %
AC2, goodput (Mbps)	2.36	2.35	2.24
AC3, goodput (Mbps)	0.55	0.55	0.54

VI. CONCLUSIONS

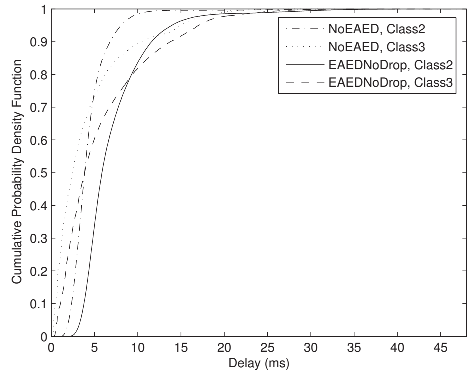
Providing connectivity at global level can be considered as one of the key trends in telecommunications. In this article we proposed a low price, low energy and low bitrate mesh network architecture for enabling basic connectivity in currently disconnected areas. We identified energy awareness as a critical research question and presented a new energy-adaptive scheduling and queue management framework EAED (Energy Aware Early Detection) for minimizing energy consumption in 802.11s mesh networks.

According to simulation results our scheme can save considerable amounts of transmission energy without violating application level QoS requirements when traffic load and distances are reasonable. Even with higher loads and larger

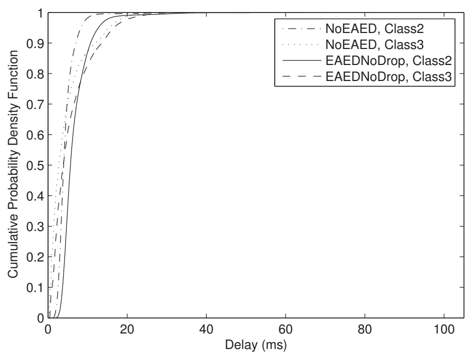
Digital Object Identifier: 10.4108/ICST.WICON2010.8521
http://dx.doi.org/10.4108/ICST.WICON2010.8521



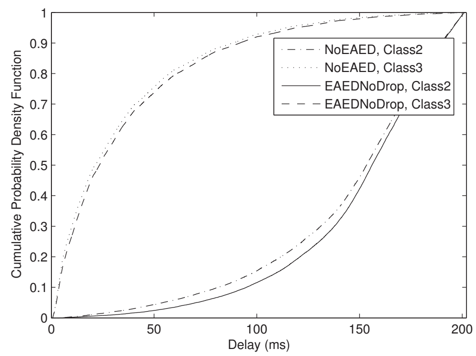
(a) Scenario 1



(b) Scenario 2



(c) Scenario 3



(d) Scenario 4

Fig. 4. Delay distributions in all scenarios

TABLE VI
PHYSICAL LAYER, PACKET LOSS AND GOODPUT STATISTICS IN SCENARIO2

	NoEAED	**EAED NoDrop**	**EAED Drop**
T_{idle}	47.06 %	22.99 %	24.24 %
$T_{transmission}$	52.22 %	74.54 %	73.30
$T_{collision}$	0.73 %	2.47 %	2.46 %
AC2, $L_{EarlyDrop}$			4.3 %
AC2, L_{Drop}	2 %	3 %	7 %
AC3, $L_{EarlyDrop}$			1 %
AC3, L_{Drop}	3 %	3 %	5 %
AC2, goodput (Mbps)	2.95	2.93	2.79
AC3, goodput (Mbps)	0.55	0.55	0.55

TABLE VII
PHYSICAL LAYER, PACKET LOSS AND GOODPUT STATISTICS IN SCENARIO3

	NoEAED	**EAED NoDrop**	**EAED Drop**
T_{idle}	43.71 %	24.62 %	25.68 %
$T_{transmission}$	55.33 %	73.02 %	71.94
$T_{collision}$	0.95 %	2.37 %	2.38 %
AC2, $L_{EarlyDrop}$			4 %
AC2, L_{Drop}	3 %	3 %	7 %
AC3, $L_{EarlyDrop}$			1 %
AC3, L_{Drop}	3 %	3 %	5 %
AC2, goodput (Mbps)	2.35	2.34	2.24
AC3, goodput (Mbps)	0.55	0.55	0.54

distances moderate savings can be obtained. Energy saving is possible due to joint adaptation of transmission power, modulation and coderate as well as early dropping of packets. Since transmission rate is determined through modulation and coding scheme and both are adapted frequently, no absolute throughput guarantees can be provided making our scheme suboptimal for very bandwidth intensive applications. However, using 802.11 as basic radio technology EAED would be beneficial in any use case where distances are expected to stay within the limits given by our simulation scenarios and connectivity is preferred over high bitrate. Public Safety Communications and basic connectivity in energy scarce locations

Digital Object Identifier: 10.4108/ICST.WICON2010.8521
http://dx.doi.org/10.4108/ICST.WICON2010.8521

are most evident examples of such cases. Delay and disruption tolerant networks (DTNs) would also appear to be a prominent application area. An example DTN type of application could be walkie-talkie like devices for providing voice messaging when hiking outdoors or coping with emergency.

Regarding the simulations covered in this article, parallel measurements with real wireless devices are under way. The aim is to accurately model energy consumption of a WLAN enabled mobile phone and optimize the algorithm according to the model. Another important area of future work is development and comparison of different types of power saving schemes, including sleeping based mechanisms, for identifying optimal strategies for varying applications and scenarios. For TCP-like non-real-time traffic early dropping could be replaced with Explicit Energy Notification (EEN) where the endpoints and intermediate routers indicate by marking packets that congestion window of the source should be decreased due to increasing energy consumption.

References

[1] "Lan/man specific requirements - part 11: Wireless medium access control (mac) and physical layer (phy) specifications," in *Amendment: ESS Mesh Networking, IEEE Unapproved draft P802.11s/D1.02*, March 2007.

[2] V. Raghunathan, S. Ganeriwal, M. Srivastava, and C. Schurgers, "Energy efficient wireless packet scheduling and fair queuing," *ACM Transactions on Embedded Computing Systems*, vol. 3, no. 1, pp. 3–23, February 2004.

[3] S.-J. Park and R. Sivakumar, "Load sensitive transmission power control in wireless ad-hoc networks," in *IEEE Global Communications Conference (GLOBECOM)*, November 2002.

[4] P. Edmond and B. Li, "Smartnode: Achieving 802.11 mac interoperability in power-efficient ad hoc networks with dynamic range adjustments," in *23rd International Conference on Distributed Computing Systems*, 2003, pp. 650–657.

[5] S. Doshi, S. Bhandare, and T. X. Brown, "An on-demand minimum energy routing protocol for a wireless ad hoc network," *Mobile Computing and Communications Review*, vol. 6, no. 2, July 2002.

[6] R. Jantti and S.-L. Kim, "Joint data rate and power allocation for lifetime maximization in interference limited ad hoc networks," *IEEE Transactions on Wireless Communications*, vol. 5, no. 4, April 2006.

[7] P. P. Floreen, P. Kaski, J. Kohonen, and P. Orponen, "Lifetime maximization for multicasting in energy-constrained wireless networks," *IEEE J. Select. Areas Commun.*, vol. 23, no. 1, pp. 117–126, January 2005.

[8] D. Qiao, S. Choi, A. Jain, and K. Shin, "Miser: an optimal low-energy transmission strategy for ieee 802.11a/h," in *International Conference on Mobile Computing and Networking (Mobicom)*, 2003, pp. 161–175.

[9] A. E. Gamal, C. Nair, B. Prabhakar, E. Biyikoglu, and S. Zahedi, "Energy-efficient scheduling of packet transmissions over wireless networks," in *IEEE Infocom*, 2002.

[10] A. Tarello, J. Sun, and M. Zafer, "Minimum energy transmission scheduling subject to deadline constraints," *Wireless Networks*, vol. 14, pp. 633–645, 2008.

[11] M. A. Khojastepour and A. Sabharwal, "Delay-constrained scheduling: Power efficiency, filter design, and bounds," in *IEEE Infocom*, 2004.

[12] X. Zhong and C.-Z. Xu, "Delay-constrained energy-efficient wireless packet scheduling with qos guarantees," in *IEEE Globecomm*, 2005.

[13] M. Buettner, G. V. Yee, E. Anderson, and R. Han, "X-mac: a short preamble mac protocol for duty-cycled wireless sensor networks," in *4th international Conference on Embedded Networked Sensor Systems, Sensys'06*, October 2006.

[14] A. Fallahi, E. Hossain, and A. S. Alfa, "Qos and energy tradeoff in distributed energy-limited mesh/relay/networks: A queuing analysis," *IEEE Transactions on Parallel and Distributed Systems*, vol. 17, no. 6, June 2005.

[15] P. Nuggehalli, V. Srinivasan, and R. Rao, "Energy efficient transmission scheduling for delay constrained wireless networks," *IEEE Transactions on Wireless Communications*, vol. 5, no. 3, March 2006.

[16] M. Stemm and R. H. Katz, "Measuring and reducing energy consumption of network interfaces in hand-held devices," *IEICE Transactions on Communications*, vol. E80-, no. B(8), pp. 1125–1131, 1997.

[17] J.-P. Ebert, S. Aier, G. Kofahl, A. Becker, B. Burns, and A. Wolisz, "Measurement and simulation of the energy consumption of an wlan interface," in *Networking*, 2002.

[18] S. Floyd and V. Jacobson, "Random early detection gateways for congestion avoidance," *IEEE/ACM Transactions on Networking*, vol. 1, no. 4, pp. 397–413, August 1993.

[19] H.-P. Shiang and M. van der Schaar, "Informationally decentralized video streaming over multihop wireless networks," *Multimedia, IEEE Transactions*, vol. 9, no. 6, pp. 1299–1313, October 2007.

Digital Object Identifier: 10.4108/ICST.WICON2010.8521
http://dx.doi.org/10.4108/ICST.WICON2010.8521