

On the Use of Adaptive OFDM to Preserve Energy in Ad Hoc Wireless Networks

Kamol Kaemarungsi and Prashant Krishnamurthy
Telecommunications Program,
School of Information Science, University of Pittsburgh
135 North Bellefield Avenue, Pittsburgh, Pennsylvania 15260.
Tel. 412-624-4099, Fax. 412-624-2788
{kakst112, prashk}@pitt.edu

Abstract - Orthogonal frequency division multiplexing (OFDM) is the physical layer in emerging wireless local area networks that are also being targeted for ad hoc networking. Mobile devices in ad hoc networks need to conserve their energy because of the limited battery power. Adaptive OFDM is a technique that can improve the performance of OFDM in terms of increasing the capacity for a given transmit power by exploiting the channel condition over a link. We believe that adaptive OFDM can be also exploited in ad hoc networks to improve the energy performance of mobile devices. In this paper, we evaluate the improvement in performance of adaptive OFDM over non-adaptive OFDM in ad hoc networks using simulations.

1. INTRODUCTION

Orthogonal frequency division multiplexing (OFDM) is important in wireless networks because it can be used adaptively in a dynamically changing channel. OFDM has also been selected as the standard physical layer for IEEE 802.11a and IEEE 802.11g wireless local area networks (WLANs). At the same time, ad hoc networking using WLANs has received attention in recent years [1]. In ad hoc networks, energy efficiency,

throughput, and routing efficiency are important performance metrics. Energy efficiency is especially important for mobile devices with limited battery power. Cross-layer protocol design and optimization can prolong the battery life of mobile devices [1]. Researchers have investigated making OFDM or discrete multitone (DMT) adaptive to maximize channel capacity by using adaptive modulation and loading algorithms. Bits and power loading algorithms control how the number of bits and power are allocated across all subcarriers in OFDM such that the capacity over the link is maximized or the transmit power is minimized. Several loading algorithms have been proposed in the literature. For instance, the algorithm of Fischer and Huber [2] is well known for its simplicity and efficiency for discrete multitone loading. Campello in [3] also proved the near optimality of the discrete greedy loading algorithm and suggested algorithms for efficient loading with low complexity. However, it is not clear how the ad hoc network performance constraints can impact making OFDM adaptive. In ad hoc networking these measures may not be sufficient to extend the battery life. This paper is a preliminary effort to understand whether adaptive

OFDM can impact the energy consumption in ad hoc networks and how OFDM can be made adaptive. As a first step to understanding this problem, we compare the use of adaptive and non-adaptive OFDM in ad hoc networks in terms of energy consumption and bit error rates using simulations with QualNet. We only employ primitive cross-layering in that we preempt transmission if there are insufficient power resources at the transmitter based on channel knowledge. In section 2 of this paper, we discuss the notion of adaptive OFDM and bit loading algorithms for adaptive OFDM. In Section 3, we provide a brief review of energy conservation techniques in ad hoc networks. Section 4 discusses the details of the simulation, the set up, and the results. Section 5 considers approaches for future work.

2. ADAPTIVE OFDM

OFDM is a sub-class of multicarrier modulation (MCM) that combines parallel data transmission with frequency division multiplexing (FDM) technique and allows spectral overlap of subchannels. The idea is to transmit single high-rate data stream over multiple parallel low-rate data streams [4]. The low-rate data streams are modulated onto orthogonal subcarriers in order to avoid adjacent carrier interference and improve spectrum efficiency. Due to the longer symbol period on each subcarrier, the OFDM signal is more robust against large multipath delay spreads that are normally encountered in wireless environments. With a cyclic prefix or a repetition of part of OFDM symbol added at the beginning

of the symbol, the inter-symbol interference (ISI) caused by multipath fading can be further reduced. Digital modulation schemes such as phase shift keying (PSK) or quadrature amplitude modulation (QAM) are usually used on each subcarrier; however, the modulation technique does not have to be the same for all subcarriers.

2.1 The Channel State Information

Adaptive OFDM takes advantage of the independence of subcarriers by assigning higher energy and larger number of bits to subchannels that have better quality or higher SNR and assigning less energy and bits or none at all to the poor quality subchannels. This technique is a well-known result from information theory that states that the channel capacity can be maximized by a water-filling or water-pouring technique [3]. An important assumption is that the transmitter has the channel state information (CSI) in order to perform power or bit allocation to achieve the maximum channel capacity. This may be difficult to achieve in practice, but it is possible that the estimated channel information can be obtained at the transmitter using feedback from the receiver or in the case of reciprocal channels. Note that the CSI is only applicable between a given communication pair and different CSI are required for different pairs of communicating nodes. The channel state should also change slowly compared to the frame duration [5]. Otherwise, adaptive OFDM may perform worse than non-adaptive OFDM. In indoor wireless local area networks, it is likely that the channel changes very slowly because the mobility of the node is limited. Both

adaptive and non-adaptive OFDM require channel knowledge at the receiver in order to detect the correct transmit symbol on each subchannel. This can be achieved by using known training symbols or blind detection [6], [7]. All OFDM systems require channel coding (such as convolutional codes) to maintain low bit error rates [8].

2.2 Loading Algorithms

The water-filling power distribution is known to be the optimal solution for any spectrally shaped channel [3]. The resulting bits or power allocation maximizes the information capacity and it is called the *capacity-achieving distribution*. A greedy algorithm can be used to find the optimal solution for this problem. For a large number of bits and subchannels on the order of 1000s, the greedy algorithm is inefficient due to operations involving channel gain sorting and the number of iterations [3]. However, in the case of small number of bits and channels such as those in IEEE 802.11a, the number of bits is between 48 and 288 (to be loaded on 48 subchannels for data rates between 6 Mbps and 54 Mbps) [9]. For instance, 48 bits per one OFDM symbol with 4 μ sec symbol duration is needed to achieve a 6 Mbps data rate that includes a convolutional rate $\frac{1}{2}$ code.

A number of loading algorithms have been proposed in the literature such as the algorithms by Fischer and Huber [2], and Campello [3]. They propose different approaches to solve the loading problem such as minimizing the bit-error-rate (BER) (rather than maximizing the SNR or the capacity of the channel). Most algorithms try to avoid intense sorting and searching that causes

inefficiency in greedy-like algorithms. The result is a slightly suboptimal allocation, but with a dramatically reduced computational complexity [3]. The authors predict that with advances in digital signal processing, the loading algorithms will be able to perform in real time and be suitable for operations such as those envisaged in this paper.

An OFDM link can be modeled as a group of parallel AWGN channels. The wideband radio channel is partitioned into discrete narrowband subchannels with channel bandwidth of Δf Hz. Each channel is free of inter-symbol interference when Δf is small and the channel response appears to be flat for each channel. In the case of single carrier communications, the information capacity for an ideal channel with AWGN follows Shannon's information capacity theorem. In practical systems, a quantity called SNR gap is introduced and used to determine the efficiency of a modulation or encoding scheme compared to the ideal scheme [3]. For a practical modulation or encoding scheme, the system can transmit at most R bits/transmission with the lowest acceptable error rate. The SNR gap is defined as a ratio of ideal SNR at which the system can transmit at C bits/transmission over a practical SNR at which the system can transmit R bits/transmission. It is a measure of how well the practical system compares to an ideal modulation system. The channel capacity in bits per transmission can be calculated by [10].

$$C = \frac{\alpha}{2} \log_2(1 + SNR) \quad (1)$$

Note that α is the dimension of modulation scheme, i.e. $\alpha = 2$ for M -QAM modulation scheme. Rearranging Equation 1 enables us to express the SNR as $SNR = 2^{2C/\alpha} - 1$. Using a similar expression for the SNR of practical systems, the SNR gap, denoted by Γ , can be calculated as

$$\Gamma = \frac{2^{2C/\alpha} - 1}{2^{2R/\alpha} - 1} = \frac{SNR}{2^{2R/\alpha} - 1}. \quad (2)$$

The SNR for additive white Gaussian noise (AWGN) with noise variance of σ^2 per dimension can be defined as $SNR = \frac{|H|^2 \varepsilon}{\alpha \cdot \sigma^2}$, where H is channel gain and ε is the transmit power per symbol. Therefore, for a particular combination of encoding scheme and modulation with 2-dimensional symbol constellation, the SNR gap can be used to determine the data rate for subchannel n in multicarrier communications [3] as

$$R_n = \log_2 \left(1 + \frac{|H_n|^2 \varepsilon_n}{2\Gamma_n \sigma_n^2} \right) = \log_2 \left(1 + \frac{G_n \varepsilon_n}{\Gamma_n} \right), \quad (3)$$

where $G_n = \frac{|H_n|^2}{2\sigma_n^2}$. If T_{sym} is the OFDM symbol duration, the data rate of OFDM over all subchannels is $R = \frac{1}{T_{sym}} \sum_{n=1}^N R_n$. By rearranging Equation 3 the energy function can be written as a function of bits per subcarrier as

$$\varepsilon_n = \frac{2\Gamma_n \sigma_n^2}{|H_n|^2} (2^{R_n} - 1) = \frac{\Gamma_n}{G_n} (2^{R_n} - 1) \quad (4)$$

2.3 Campello's Algorithm

Campello suggests that the water-filling problem can be formulated in two ways from the

optimization perspective [3]. First, a bit rate maximization problem can be formulated by maximizing the total number bits across all OFDM subcarriers in Equation 3 subject to the constraint that a fixed amount of power is available to the transmitter. This is similar to the classical water-filling formulation in [10]. Second, an energy minimization problem can be formulated by minimizing the total amount of power on all OFDM subcarriers in Equation 4 subject to the constraint of a fixed amount of bits transmitted per OFDM symbol. Given an energy function $\varepsilon(R_n)$ for a particular modulation and coding technique where R_n is the number of bits on subcarrier n , R_{Total} is the total number of bits per OFDM symbol, E_{Total} is the fixed amount of power available, and B is the fixed number of bits per symbol per second, the formulation of these optimization problems are described below. Note that the resulting bit allocation should be a positive integer.

Bit Rate Maximization or Water-filling Problem

$$\text{Maximize } \sum_{n=1}^N R_n(\varepsilon_n) = R_{Total} \quad (5)$$

$$\text{Subject to } \sum_{n=1}^N \varepsilon_n \leq E_{Total} \text{ and } R_n \in \mathbb{Z}^+ \quad (6)$$

Energy Minimization Problem

$$\text{Minimize } \sum_{n=1}^N \varepsilon_n(R_n) = E_{Total} \quad (7)$$

$$\text{Subject to } \sum_{n=1}^N R_n = B \text{ and } R_n \in \mathbb{Z}^+ \quad (8)$$

The solution to either one of the above formulations can be found by forming a

Lagrangian equation and taking the partial derivative with respect to the multiple constraint variables, i.e. ε_n for bit rate maximization and R_n for energy minimization [3]. For instance, the Lagrangian equation for bit-rate maximization is

$$J = \sum_{n=1}^N \log_2 \left(1 + \frac{G_n \varepsilon_n}{\Gamma_n} \right) + \lambda \left(E_{Total} - \sum_{n=1}^N \varepsilon_n \right). \quad (9)$$

Assuming that the SNR gap is equal for every subchannel, the solution to the problem consists of a water-filling constant K . The subchannel energy allocation can be calculated using this constant and the SNR of the subchannel. The solution to the optimization in Equation 5 is

$$K = \frac{1}{N} \left(E_{Total} + \Gamma \sum_{n=1}^N \frac{1}{G_n} \right) \quad (10)$$

$$\varepsilon_n = \left(K - \frac{\Gamma}{G_n} \right)^+, \quad n = 1, 2, \dots, N \quad (11)$$

where $(x)^+ = x$ if $x > 0$, otherwise $(x)^+ = 0$. Any subchannel that has negative energy allocation will be turned off by the transmitter. Note that the amount of energy used is measured in joules = watts×seconds.

An example of the solution for energy minimization is shown in Figure 1 for OFDM with 64 subcarriers. Figure 1a represents the channel frequency response for a three equal-tap-gain channel model. Figure 1b represents the continuous bit loading result from the energy minimization algorithm in [3]. Figure 1c represents the discretized bit loading result and Figure 1d represents the corresponding power allocation. In this example, the noise variance is assumed to be 1 for all subchannels.

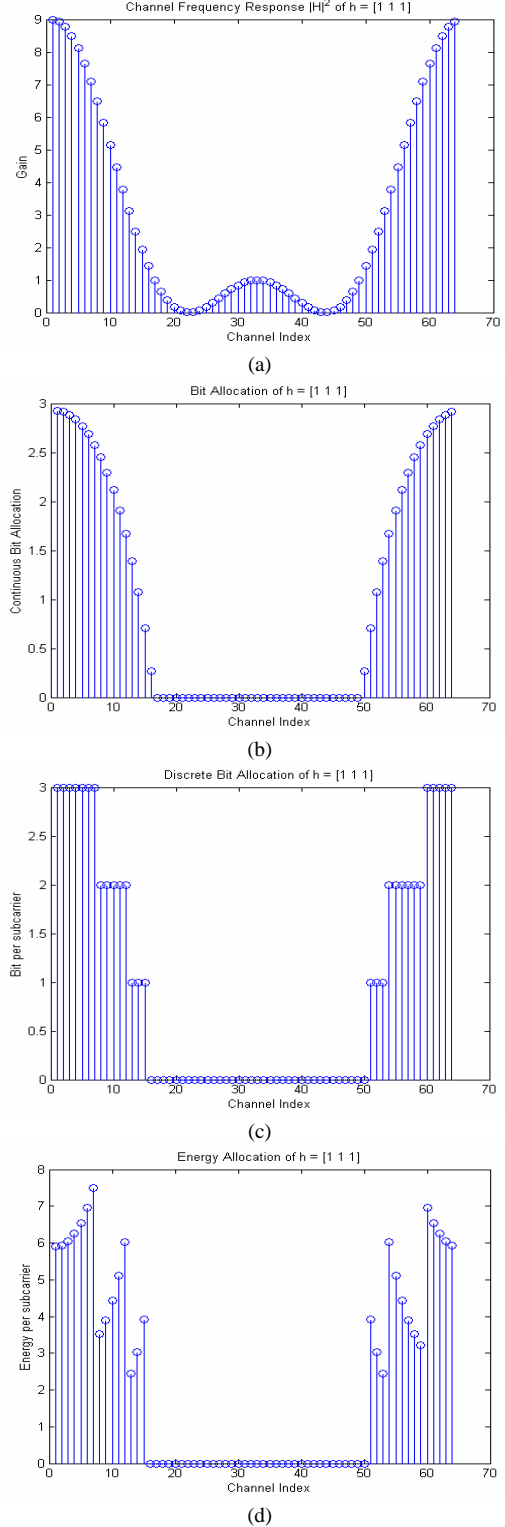


Figure 1. Example of Energy Minimization Loading, (a) Channel Response, (b) Continuous Bit Allocation, (c) Discrete Bit Allocation, (d) Power Allocation of Discrete Bit Allocation.

The dual formulations of water-filling solution can be applied at the physical layer to either maximize the data rate or minimize the energy on each frame transmission. These two alternatives are investigated in the next section for their impact on the energy consumption of an ad hoc wireless node. The question that this paper would like to answer is how much of energy can be preserved by employing adaptive OFDM on the physical layer. Another question regarding the cross-layer protocol design is how the channel information gain from the loading algorithm will help improve the energy preservation of ad hoc wireless network.

3. TECHNIQUES FOR REDUCING ENERGY IN AD HOC NETWORKS

Due to the emergence of small mobile devices with limited battery capacity, energy-aware protocols are key to the success of this technology. It is suggested that the energy optimization should be done across all protocol layers in a cross-layer approach [1]. Each cross-layer protocol stack should adapt its operations to the network load, the energy budget, and link characteristics. The cooperation and exchange of necessary information between layers must be allowed for any cross-layer protocol to adapt to global system constraints and characteristics. Energy on ad hoc wireless devices is consumed differently during the transmitting state, the receiving state, and the idle state. It has been shown from early measurement results that the power used during the idle state of a mobile node dominates the overall (total) energy consumption, while the

output power during the transmitting and receiving state add additional energy consumption to that of the idle state [11]. In the literature three separately energy preservation approaches are suggested at different layers for ad hoc wireless networks [12]. For instance, power saving protocols and power control protocols are suggested at the MAC layer and a maximum lifetime routing protocol is suggested at the network layer. These approaches only focus on the protocols at the medium access control layer and above. They try to minimize the energy consumption in different parts of ad hoc systems by maximizing the idle state, minimizing the transmit power, and using routing knowledge to extend the network lifetime.

3.1 Energy preservation at the MAC layer

Power saving protocols and power control protocols are categorized as energy efficient techniques *at the MAC layer*. The power saving protocol puts most of the ad hoc nodes into sleep mode as often as possible. It is more suitable for networks with a centralized control that is needed to maintain the connectivity of all adjacent nodes that go into sleep mode. To implement this approach in a peer-to-peer ad hoc network will be quite complex due to the scheduling of the sleep time. It also limits the capacity of ad hoc networks because these nodes cannot forward frames during their sleeping period. It is a tradeoff between network capacity and energy preservation [13]. There is also significant cost of changing the node state from sleep to idle and vice versa that may outweigh the power saving technique [14]. On the other hand, power control protocols reduce the

transmit power to levels that can just maintain the connectivity between adjacent ad hoc nodes. This approach can minimize the energy consumption due to transmission and additionally improve the network capacity by minimizing the interference between transmissions [13].

3.2 Energy preservation at the routing layer

Instead of focusing on power consumption at each mobile node, an energy conserving routing approach tries to create energy aware routing mechanisms for ad hoc wireless networks. For example, in the maximum lifetime routing protocol, a selection is made from different routing metrics such as minimum energy routing, max-min routing, and minimum cost routing to preserve the energy in forwarding packets [12]. The ad hoc network routing protocol should consider both the cost of transmitting each packet and the residual energy of nodes that will be used to further forward packets. All three approaches discussed so far focus mainly on specific layer of the protocol stack and do not consider any cooperation between the techniques [12].

3.3 Adaptive vs. Non-adaptive OFDM

This paper suggests an adaptive protocol layer that fits into cross-layer design criteria at the physical layer with a primitive cooperation between the physical layer and MAC layer. A potential stronger cooperation is possible with the bit rate and power budget parameters as the information exchanged between the physical and MAC layer. Given that the radio channel characteristics can be estimated at the receiver, an adaptive OFDM physical layer can exploit the

temporal fluctuations of the channel in frequency selective fading media. The service requested by the MAC layer can be supported by this smarter physical layer equipped with a bit loading algorithm.

In our work, using adaptive OFDM, an extra channel capacity is gained during a short period when the channel is considered good for transmission. During this time, the physical layer can transmit a MAC frame faster using the same transmit power level as it could without adaptive OFDM. This benefit can be converted into the saving of energy consumed for transmission. The loading algorithm based on bit rate maximization [3] is selected as our choice of study. The idea here is to push as many bits across the channel as possible while the transmitter has the opportunity to do so thereby reducing the channel holding time on average. We assume that advances in digital signal processing techniques allow the radio channel to be estimated fast enough in a slowly changing wireless environment.

To solve the problem of channel state information at the transmitter, we add extra information in the MAC header of the IEEE 802.11 protocol within the request-to-send (RTS) and clear-to-send (CTS) packets and the details are discussed in the next section. Since the maximum allowable data rate in fading channels can be higher or lower than the MAC layer's minimum request rate, the MAC protocol in this paper decides on allowing the communication over the link by choosing to reply or not reply with a CTS frame. By this, the MAC layer avoids a longer

transmit time with smaller data rate that could consume more energy.

4. SIMULATION AND RESULTS

The performance of an ad hoc wireless network using adaptive OFDM is evaluated with the QualNet packet level simulator. Below we describe the parameters and scenario used in our simulations at various layers of the protocol stack.

4.1 Radio channel model

A two-ray path loss model is assumed with a shadow fading sigma of 12 dB which is suitable for indoor environments [16]. The thermal noise floor is calculated from the Boltzmann constant $k = 1.379 \times 10^{-23}$ W/(Hz·K°) at $T = 290$ K°, noise factor $F = 10$, and an effective noise bandwidth in BW Hz using the following equation $W = F \cdot k \cdot T \cdot BW = BW \cdot 3.9991 \times 10^{-20}$ Watt.

The simulator has a radio model with capture capability that can receive the strong radio signal among interfering signals [17]. Packet error is based on the SNR threshold – i.e., a packet is assumed to be in error if the SNR is below a threshold of 10 dB above the noise level. The physical and MAC parameters follow the IEEE 802.11a specifications [9] and are summarized in Table 1. However, the rate fall back feature is not used.

Table 1. IEEE 802.11a Specifications

Physical Layer	
Center Frequency	5.2 GHz
Channel Bandwidth	20 MHz
Minimum Data Rate	6 Mbps
Receiver Threshold	-82 dBm
Antenna height	1.5 m

The Rayleigh multipath fading is modeled with three tap gains according to the JTC indoor office areas Channel A, although this not strictly for a 5 GHz frequency band [18]. The tap parameters are shown in Table 2. Each tap is a random process generated before the actual simulation using Jakes' method [19]. During the simulation, a set of tap gains is randomly selected from a pool to simulate the Rayleigh fading between each pair of nodes.

Table 2. JTC Indoor Office Areas Channel A

Tap No.	Relative Delay (nsec)	Average Power (dB)
1	0	0
2	50	-3.6
3	100	-7.2

The maximum Doppler shift frequency of the model is set to $f_d = 30$ Hz for slow time-varying channels which corresponds to the maximum mobile speed of $v = 1.73$ m/s at $f_c = 5.2$ GHz. Each OFDM symbol has symbol duration $T_{sym} = 4$ μsec. Assuming a maximum data frame length of 4096 bytes and each OFDM symbol can support 24 uncoded bits, the frame duration is approximately $T_{frame} = (4096 \times 8 \times 4 \mu\text{sec}) / (24) \approx 5.461$ msec. The normalized maximum Doppler rate is $f_d \times T_{frame} \approx 0.1638$ which is close to the reasonable values for the rate adaptive physical layer system in [20].

4.2 Physical layer model

A continuous bit loading algorithm based on Campello's bit rate maximization algorithm [3] is implemented in the simulation for both transmitter and receiver. It is possible to find the maximum number of bits per OFDM symbol. The digital

modulation scheme on each subchannel is assumed to scale the constellation from 1 bit to higher bits per symbol using BPSK and M -QAM modulations. The SNR gap is assumed to be 8.8 dB for un-coded QAM bits with error rate P_e of 10^{-6} as given in [7]. The resulting bit rate is based on a continuous bit distribution and needs to be discretized by rounding down to the nearest integer. Campello [3] suggests an *Energy Tighten Algorithm* to reallocate the left-over energy from the rounding bit to guarantee an optimal solution. Assuming the loading calculation can be done in real time due to the small number of bits and subcarriers (as discussed previously) we ignore the energy spent on this calculation as not significant. The bit loading can only be done on a data frame since the transmitter can gain the channel information only after the CTS frame has arrived. Therefore, all signaling (control) frames – the RTS and CTS are not adaptive. Due to the multiple receiver possibility, the MAC broadcast frames are also non-adaptive. Both control and broadcast frames are sent at a rate of 6 Mbps.

The power consumption is based on the estimated values given in Agere’s product specification 2003 [21]. The estimated active receive and transmit power consumption of an 802.11a standard device is given as 951 mW and 1412 mW respectively. The idle state power consumption is assumed to be equal to power consumption in receive mode although this is an over-estimate. We use per packet energy consumption in this paper. The energy consumed by each frame is linearly dependent on its

transmission duration, which depends on the instantaneous data rate and frame size for a given transmit power. The transmit energy is calculated by multiplying the transmit power consumption of 1412 mW by the duration of the frame. The energy consumption rates for both transmit, receive, and idle states are assumed to be constant over time.

4.3 MAC layer model

The IEEE 802.11 MAC layer is based on Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). The simulation operates only in the distributed coordination function (DCF) mode. It also has the request-to-send (RTS) and clear-to-send (CTS) control signaling to avoid the hidden terminal problem and to carry extra information for channel estimation procedures as in [20]. The overhead information is the SNR level and channel impulse response estimated at the receiver. Figure 2 illustrates an adaptive OFDM transmission procedure.

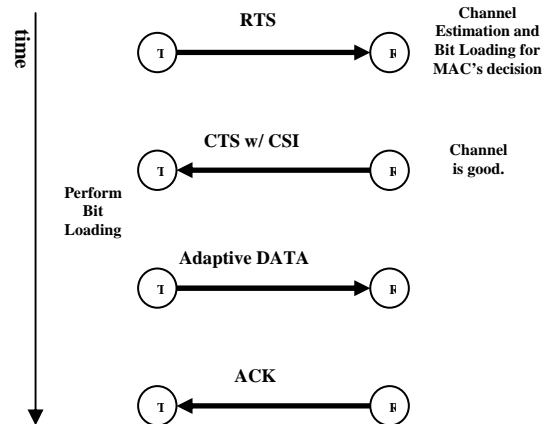


Figure 2: Procedure of DATA frame transmission

The network allocation vector (NAV) duration for each data frame is calculated from the smallest data rate of 6 Mbps. We do not vary it according

to the variable duration of the adaptive OFDM frame. This causes a longer waiting time due to the NAV in neighboring nodes, but it does not cause any problems to the transmission. The data frame duration will be guaranteed to have at least 6 Mbps of bandwidth in our modification to the MAC protocol in the case of adaptive OFDM. We note that this study does not attempt to maximize capacity, but only evaluate the energy savings from adaptive OFDM.

4.4 Network layer model

The network layer is the internet protocol (IP) and the transport layer is UDP. The routing protocol is ad hoc on demand distance vector (AODV) in unicast mode [22]. This protocol discovers a route whenever there is a request by issuing a Route Request (RREQ) message. The routing table on each node is filled by both RREQ message and the reply information on the unicast Route Reply (RREP) message from the neighboring nodes. The old route in the table is eliminated based on the sequence number and its activity. In this study, we do not modify this protocol to learn of the change from the physical layer. The routing protocol parameters are set according to the values in [22].

4.5 Network topology

Four ad hoc nodes are placed in a simple rectangular topology. The nodes are assumed to be stationary which is the case for most indoor operations of today. The distance between two closest nodes is varied from 25 meters to 200 meters. The simulation study compares the energy reduction achieved by adaptive OFDM over non-

adaptive OFDM when the received SNR is changed due to the distance. The simulation duration is 120 sec. Each experiment has 10 repetitions and we calculate the 95% confidence interval of the mean value of the energy consumed. We assume that nodes in the network always have packets for transmission. Each node has a constant bit rate (CBR) packet generator which generates a 2020-byte packet every 90 msec or a data rate of 179.556 kbps. The traffic is only one hop from the origin node and only 4 CBR streams from node 1 to node 2, node 2 to node 3, node 3 to node 4, and node 4 to node 1 are present. Each node cannot transmit and receive at the same time.

4.6 Results

The simulation results of the average transmit energy consumed per node is shown in Figure 3.

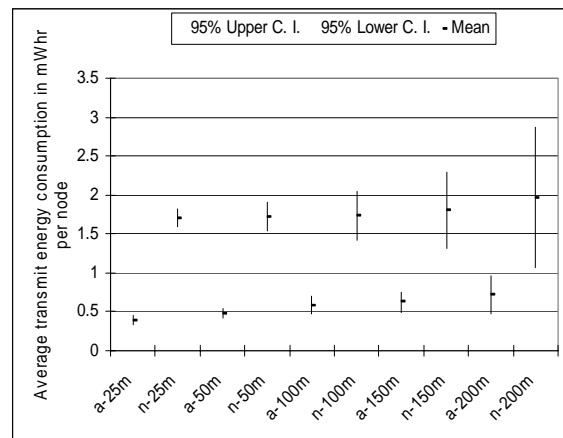


Figure 3. Comparison of transmit energy consumption

Here adaptive and non-adaptive nodes in each experiment are denoted with letter a and n following by the distance, respectively. At each distance point, the adaptive OFDM physical layer consumes less energy. This is because on average

a shorter DATA frame is transmitted by adaptive OFDM. It can exploit the temporal fading diversity in radio channel. Significant reductions in energy ranging from 76.94% down to 63.67% are possible depending on the distance between nodes and the received SNR.

Figure 4 shows the average number of RTS frames that are retransmitted due to timeout. This is compared because the MAC layer using adaptive OFDM has an option not to reply with a CTS message when the channel cannot support the minimum data rate. The result reports that on average the number of RTS timeouts is higher only in the mean for adaptive OFDM, but there is no statistical difference. That is, the energy consumption for RTS frame transmission is higher, but not significant and does not dominate the overall transmit power consumption.

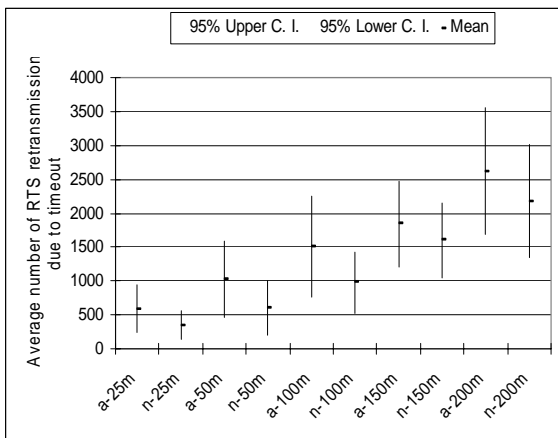


Figure 5. Comparison of RTS retransmissions

5. DISCUSSION AND FUTURE WORK

Taking the advantage of radio channel in addition to mitigating its harshness can provide benefits for ad hoc wireless networks. However,

adaptive OFDM mechanism is not sufficient to minimize the energy consumption in an ad hoc wireless network. The first step toward information exchange and Physical and MAC layer cooperation is suggested in this work by controlling the RTS/CTS signaling based on the knowledge of the physical layer. Based on our simulation with IEEE 802.11 MAC, the network throughput is expected to increase if we reduce the NAV time according to the shorter DATA frame duration. The neighboring nodes no longer have to wait for a longer NAV as in non-adaptive OFDM. Power control mechanisms as in [13] could be used with adaptive OFDM to decide a suitable transmission power depending on the range of communication between mobile nodes. Network layer cooperation can improve the energy conservation further. The impact of adaptive OFDM with such cross-layering approaches is part of our ongoing work.

ACKNOWLEDGMENTS

The authors would like to thank Scalable Network Technology for the QualNet simulator, Dr. Mark Wickert at UCCS, for the channel fading simulator toolbox, and Dr. Hueng-no Lee for his valuable comments and suggestions.

REFERENCES

- [1] A. J. Goldsmith and S. B. Wicker, "Design Challenges for Energy-Constrained Ad Hoc Wireless Networks," *IEEE Wireless Communications*, vol. 9, pp. 8-27, Aug. 2002.
- [2] R. F. H. Fisher and J. B. Huber, "A New Loading Algorithm for Discrete Multitone

- Transmission,” in *Proc. GLOBECOM*, 1996, pp. 724-728.
- [3] J. Campello de Souza, *Discrete Bit Loading for Multicarrier Modulation Systems*, PhD. Dissertation, Stanford University, 1999.
- [4] A. F. Molisch, Editor, *Wideband Wireless Digital Communications*, New Jersey: Prentice Hall, 2001.
- [5] S. Ye, R. S. Blum, and L. J. Cimini, Jr., “Adaptive Modulation for Variable-Rate OFDM Systems with Imperfect Channel Information,” in *Proc. IEEE Vehicular Technology Conference*, 2002, pp. 767-771.
- [6] T. Keller and L. Hanzo, “Adaptive Multicarrier Modulation: A Convenient Framework for Time-Frequency Processing in Wireless Communications,” *Proc. IEEE Wireless Communications*, vol. 88, pp. 611-640, 2000.
- [7] A. Leke, *Dynamic Bandwidth Optimization for Multicarrier Systems*, PhD. Dissertation, Stanford University, 1999.
- [8] W. Zou and Y. Wu, “COFDM: An overview,” *IEEE Trans. Broadcasting*, vol. 41, pp.1-7, Mar. 1995.
- [9] IEEE Std 802.11a/D7.0-1999, *Part11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications: High Speed Physical Layer in the 5GHz Band*.
- [10] T. A. Cover and J. A. Thomas, *Elements of Information Theory*, New York: Wiley, 1999.
- [11] L. M. Feeney, “An energy-consumption model for performance analysis of routing protocols for mobile ad hoc networks,” *Journal of Mobile Networks and Applications MONET*, vol. 3, pp. 239-250, Jun. 2001.
- [12] L. M. Feeney, (2002) Energy Efficient Communication in Ad Hoc Networks. [Online] Available: <http://www.sics.se/~lmfeeney/chapter.pdf>.
- [13] H. Woesner et al, “Power Saving Mechanisms in Emerging Standards for Wireless LANs: The MAC level perspective,” *IEEE Personal Communications*, vol. 3, pp. 44—48, Jun. 1998.
- [14] S. Singh and C.S. Raghavendra, “PAMAS – power aware multi-access protocol with signaling for ad hoc networks,” *ACM Computer Communication Review*, Jul. 1998.
- [15] S. Agarwal et al, “Distributed Power Control in Ad-hoc Wireless Networks,” in *Proc. PIMRC*, 2000, pp F-59—F-66.
- [16] M. Goldhammer, “System & proposal evaluation requirements: IEEE 802.16 Broadband Wireless Access Working Group”, IEEE C802.16e-03/10, Jan. 2003.
- [17] Scalable Network Technologies, Inc., QualNet: Network Simulation and Parallel Performance, [Online] Available: <http://www.scalable-networks.com/products/developer/index.php>, 2003.
- [18] K. Pahlavan and A. H. Levesque, *Wireless Information Networks*, New York: John Wiley & Sons Inc, 1995.
- [19] W. C. Jakes, *Microwave Mobile Communications*, New York: Wiley, 1974.
- [20] W. H. Yuen, H.-no Lee, and T. D. Andersen, “A Simple and Effective Cross Layer Networking System for Mobile Ad Hoc Networks,” in *Proc. PIMRC*, 2002.
- [21] Agere System Inc. (2003, Feb.) Agere Product Brief: WaveLAN 802.11a/b/g chip set. [Online] Available: <http://www.agere.com/client/docs/PB03044.pdf>.
- [22] C. E. Perkins, Editor, *Ad Hoc Networking*, Upper Saddle River: Addison-Wesley, 2001, pp. 173-219.