Energy-Efficient Transmission and Routing Protocols for Wireless Multiple-Hop Networks and Spread-Spectrum Radios

Invited Paper

Michael B. Pursley, Harlan B. Russell, and Jeffrey S. Wysocarski
Department of Electrical and Computer Engineering, Clemson University, Clemson SC

Abstract — **We describe link and network layer protocols that can conserve energy in store-and-forward packet radio networks. At the link layer, an adaptive-transmission protocol allows the radios to adjust the power in the transmitted signal and the information rate to respond to variations in interference and propagation loss. The network-layer protocols are designed to account for the energy requirements of the alternative routes for each source-destination pair. Routing is accomplished using least-resistance routing (LRR) with a metric that includes a measure of the energy consumption.**

I. INTRODUCTION

Certain military and civilian applications require reliable wireless communications capability in a dynamic interference environment in which all elements of the network are mobile. To support such applications a distributed set of protocols is required that does not rely on a subset of designated radios to provide essential services or organization. The intranet protocols must provide solutions to the inherent problems of packet radio networks in a mobile environment, where conditions of link unreliability and unpredictability due to mobility and propagation conditions are further exacerbated by time-varying interference due to jamming and multiple-access interference. The quality of each link may vary due to movement of nodes, changes in the traffic patterns, and radio-frequency interference in the network. The dynamic link conditions result in a time-varying network topology.

We investigate a set of protocols that provide a fully distributed organization for delivering packets to any radio in the network. Because of the dynamics of the mobile environment, we believe that it is necessary for the adaptation that occurs in multiple layers of the protocol stack to be coordinated. Each of the layers in the stack responds in a different way and on a different time scale; however, we have found that even for protocols in different layers there is considerable benefit if they share information about the links in the network. This information allows the protocols to detect variations in link quality and respond quickly and efficiently to changes in the network topology. Furthermore, by keying the adaptation on the link-quality information, the different adaptive protocols cooperate in ensuring efficient utilization of radio links with varying quality and capacity. Through close coupling of the protocols the network can provide the quality of service required for mobile operations while conserving battery lifetime and reducing network congestion.

In this manuscript, we review recent advances in two of the protocols in the communication stack. The adaptive-transmission protocol utilizes link-quality information to adjust the transmission parameters to reduce energy and shorten the transmission time. When the channel conditions are favorable the improved efficiency of the transmission protocol permits increased network utilization and extends the time the network can operate. However, communication can still be achieved for the worst channel conditions that are expected. The adaptive-routing protocol responds to changes in link quality, transmission energy, and transmission time in selecting the links for a particular route. The goal is to maximize the network utilization, ensure reliable end-to-end connections, and minimize the energy required in delivering the application traffic.

Our investigations of adaptive communication protocols focus on spread-spectrum networks in which the radios can adapt many of the parameters of the transmitter and receiver for each transmission. For radios employing frequency-hop (FH) signaling, we assume the power of the transmitted signal and the code rate can be adapted. For radios employing direct-sequence (DS) signaling, we assume the data rate in addition to the power and code rate can be adapted. The details of the adaptive-transmission protocol depend on the type of spread-spectrum signaling that is employed, and we review recent results for FH and DS radios in the next two sections. While some of the features of the adaptive-routing protocol are insensitive to the particular type of spread-spectrum signaling, there are certain modifications required because of the details of the adaptive-transmission protocol and the way in which the interference environment affects the performance of the radios. Recent investigations that consider the interaction between the adaptive-transmission protocol and the routing protocol are also discussed below.

II. ADAPTIVE-TRANSMISSION PROTOCOL FOR NETWORKS WITH FH RADIOS

We have designed an adaptive-transmission algorithm for use with FH radios in a multiple-hop packet radio network. The protocol enables the transmitter to adjust the power and the rate of the Reed-Solomon code to respond to variations in the channel based on feedback obtained from the receiver. Evaluations of the adaptive transmission protocol for channels with varying path loss and partial-band interference are reported in [1], [5], and [6].

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The design of the adaptive protocol accounts for the characteristics of FH signaling, and the channel model is based on a standard model for slow FH communications [3]. Each information packet contains a fixed number of information bits. Depending on the (n, k) Reed-Solomon (RS) code that is selected for a particular transmission each packet is divided into one or more *error-control blocks* of L code words each. All of the error-control blocks for a particular information packet are included in a single transmission. In this paper, a *packet* is understood to be an information packet unless it is specified otherwise.

A simple request-to-send (RTS) and clear-to-send (CTS) channel-access protocol is employed. When radio A has a packet to transmit to radio B, A first transmits a RTS packet to B. If the RTS packet is successfully received, radio B transmits a CTS to A and will then expect to receive a packet from A. Once the CTS is successfully received by A, it transmits the packet to B. During the exchange of the RTS and CTS packets, the power level and code rate are selected for packet transmission. If the packet is decoded correctly, B sends an acknowledgement to A. If B receives the packet but fails to decode it correctly, it transmits a negative acknowledgement to A.

Upon receipt of the packet, the destination radio determines the fraction Y of dwell intervals erased in the packet. The rate of the code for the next packet is determined by the value of Y. Once the new code rate is determined, the receiver calculates the statistic P_p which is defined as $P_p = 1 - (1 - P_w)^L$, where

$$P_w = \sum_{i=\left\lceil \frac{l-e}{2} \right\rceil}^{\lfloor n-e \rfloor} \binom{\lfloor n-e \rfloor}{i} \tilde{p}^{\,i} (1-\tilde{p})^{\lfloor n-e \rfloor - i}, \qquad (1)$$

and $\tilde{p} = t/(n-e)$. The parameter t is the average number of errors per received word, e is the average number of erasures, and $l = n - k$. If the received word is successfully decoded, the number of symbol errors in each received word is determined from the decoder. If a decoder failure occurs, or if there are too many erasures to attempt to decode a particular received word, the receiver estimates the number of symbol errors as in [4]. The transmission power for the next packet is determined by the value of P_p for the most recent packet. The complete specification of the transmission protocol is given in [5].

We have evaluated the performance of the adaptive-transmission protocol by simulating a link in a FH spread-spectrum wireless communication network. As in [5], the codes available to the adaptive transmission system for these results are the (32,24) and (32,12) RS codes, and the possible transmitter power levels are P_1, $P_2 = P_1 + 1.5$ dB, and $P_3 = P_1 + 3.0$ dB. The adaptation parameters are defined in [5]; the values used for the results reported in this paper are $\tau = 4$, $\tau_1 = 10^{-5}$, and $\tau_2 = 0.2$.

The receiver in the simulation has thermal noise with two-sided spectral density $N_0/2$. The communication link provides a received energy-to-noise ratio E_s/N_0 of 8 dB for a transmission at power level P_1, where E_s is the energy in each binary symbol in the received packet. There is partial-band interference with one-sided power spectral density $\rho^{-1} N_I$ in a fraction ρ of the band. The values of ρ vary over the range from 0 to 0.4, and $\rho = 0$ means there is no partial-band interference. If $\rho > 0$, then $E_s/N_0 = 8$ dB and $E_s/N_I = -5$ dB on the link.

A valid information bit is an information bit that is part of a packet that is decoded correctly. The throughput efficiency is defined as the average number of valid information bits at the decoder output of the destination radio per unit of energy expended by the transmitters of all radios in the network. The energy used to send an acknowledgement packet or a reservation packet is not included in this performance measure.

We compare the performance of the adaptive-transmission protocol with a protocol that is constrained to use the same transmission parameters for each packet; specifically, it must use rate 3/8 and power level P_3. For the channel considered, these choices of code rate and transmitter power provide the best throughput efficiency among the power levels and code rates available. We refer to the resulting transmission system as the *fixed transmission system.* It represents a typical design philosophy for a transmission system that does not adapt to the channel state.

We consider a single link whose channel state is fixed but unknown to the radios. Partial-band interference is present in a fraction ρ of the band. The throughput efficiencies obtained by the adaptive and fixed transmission systems are compared in Figure 1.

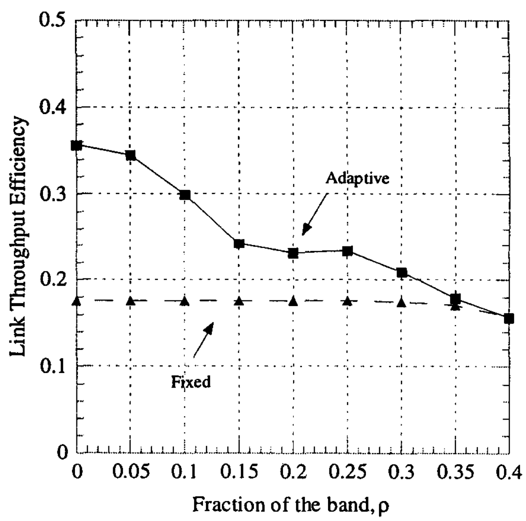

Figure 1. Link throughput for adaptive-transmission algorithm.

As shown in Figure 1, the adaptive-transmission system provides a much larger throughput efficiency than the fixed-transmission system for $\rho \leq 0.3$; both systems provide approximately the same throughput efficiency for $\rho \geq 0.35$. The higher throughput efficiency for adaptive transmission is a consequence of the ability to adapt to the channel by using the high-rate code if ρ is small. The adaptive-transmission protocol is able to take advantage of favorable channel conditions when they exist. Since fixed transmission cannot adapt to differences in ρ, it is forced to use the low-rate code so that it can provide acceptable throughput rates on channels for which ρ is large.

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III. ADAPTIVE ROUTING FOR WIRELESS NETWORKS

In least-resistance routing (LRR) the link-quality information is employed to select the routes through the network. We have shown that LRR gives significant improvement in network performance over conventional minimum-distance routing algorithms [4]. Recently, we have extended LRR to operate in cooperation with the adaptive-transmission protocol. The goal of the adaptive-transmission protocol is to adjust the information rate and power level to maintain an acceptable packet success probability while also minimizing the energy that is required in utilizing the link. The routing protocol is extended to not only utilize a measure of the quality of the links in selecting reliable routes, but also to account for the energy required to utilize the links.

The metrics in LRR specify how a radio is to calculate a resistance value for each link. The resistance of a given link is a quantitative measure of the ability of a link to deliver packets in an energy-efficient manner and the ability of the receiving radio to receive and forward packets that are transmitted to it on that link. The metrics must be consistent with the characteristics of the despreading, demodulation, processing, and decoding subsystems in the radio receiver. We define the resistance for the link from radio A to radio B as

$$LR(A,B) = \alpha_1\, I(A,B) + \alpha_2\, U(A,B), \tag{2}$$

where α_1 and α_2 are coefficients that are selected to give the desired emphasis to the individual components. The probability that a transmission from radio A to radio B is successful depends on both the quality of the link from A to B as well as the ability of B to store and forward the packet. The term $I(A,B)$ is the link-dependent resistance, which characterizes the quality of the link from A to B. It accounts for the fading, propagation loss, SNR, and other features of that particular link. The component of $LR(A,B)$ that provides a measure of the energy requirement is $U(A,B)$.

Because adaptive transmission is employed, the transmitter power and information rate may vary from one transmission to the next. In our adaptive transmission protocols, a set of information rates is available, and let r_1 denote the maximum of these rates. Let $r(A,B)$ denote the information rate that is selected by the adaptive transmission protocol for the next transmission from A to B. Similarly, a set of power levels is available to the adaptive transmission protocol, and P_1 denotes the minimum of these power levels. The power level selected for the next transmission from A to B is denoted by $P(A,B)$.

To account for the relative energy required to transmit on the link from A to B we define $U(A,B) = r_1 P(A,B)/r(A,B)P_1$. For this metric $U(A, B)$ is equal to 1 if the lowest power and highest information rate are employed on the link from A to B. If the adaptive-transmission algorithm increases the power or decreases the information rate, U equals the ratio of energy required to utilize the link compared to the minimum possible energy. Although this routing metric can be employed in a wide range of routing protocols, our performance evaluation is for a distance-vector routing algorithm [8].

IV. METRICS FOR FH WIRELESS NETWORKS

As in previous investigations of LRR for FH networks [4], we adopt a count of errors and erasures to account for the link quality. Let $I(A,B) = 2t + e$, where t is the average number of symbol errors per code word, and e is the number of dwell intervals that are erased. The values for t and e are determined from the most recent packet reception on the link from A to B.

To provide an illustration of the improvement in energy efficiency that is possible by accounting for energy in the routing protocol, two metrics that are based on (2) are considered and their performance is evaluated for the network illustrated in Figure 2. The EN metric accounts for both the link quality and the energy requirements, and for this metric $\alpha_1 = 0.5$ and $\alpha_2 = 2.75$. The EE metric simply accounts for the link quality and does not differentiate between the energy requirements for various links, and for this metric $\alpha_1 = 1.0$ and $\alpha_2 = 0.0$.

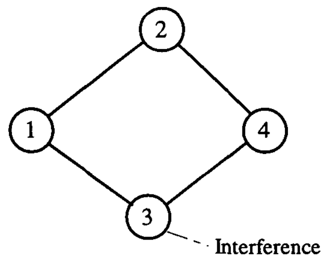

Figure 2. Network Topology.

The network simulation utilizes the same model for the links as described in Section II, and packets are generated at radio 1 for radio 4. Only radio 3 experiences partial-band inference. In the determination of throughput efficiency for the network shown in Figure 2 note that the energy being expended by the transmitters of radios 1, 2, and 3 is included in the performance measure. At power level P_1, E_s/N_0 is 8 dB for the each of the upper two links and 11 dB for each of the lower two links, and the value of E_s/N_I is –5 dB.

The simulation results obtained for the throughput efficiency for the two metrics are presented in Figure 3. For $\rho \leq 0.1$ we see from Figure 3 that the LRR protocol with the EN metric provides much larger throughput efficiency than the LRR protocol with the EE metric. The EN metric maintains the same level of throughput rate achieved by the EE metric, while greatly reducing the energy expended in the network. The EN metric provides an improvement over the EE metric for $\rho = 0.1$, but for $\rho \geq 0.15$ the throughput efficiency is approximately the same for the two metrics. The primary benefit displayed by the EN metric is that it takes advantage of more favorable conditions (i.e., values of ρ less than 0.1) when they exist in the network. Under such favorable conditions, the LRR protocol that uses the EN metric is able to conserve energy in the network by routing packets over the links that have smaller propagation losses.

V. METRICS FOR DS WIRELESS NETWORKS

Investigations into the performance of the energy metric have also been performed in a simulation of a DS wireless network. The model for the DS radio is based on the ITT Handheld Multimedia Terminal (HMT), and details about the radio and the simulation are found in [2]. The simulation includes an adaptive-transmission protocol that can adjust both the transmission power and the information rate.

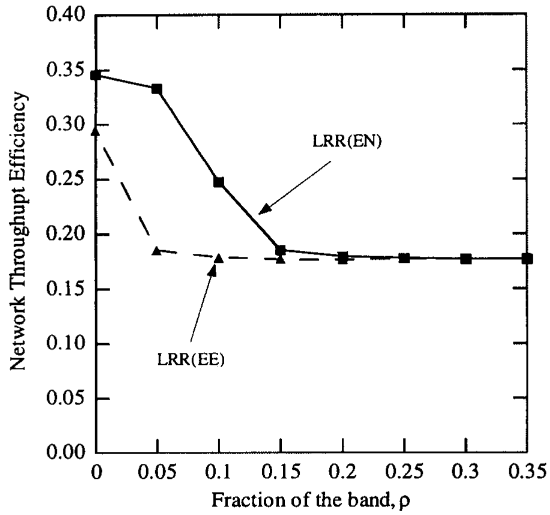

Figure 3 Throughput efficiency for fixed link parameters.

Mechanisms for measuring the quality of a link are important elements of an adaptive-transmission protocol, and such mechanisms are described in [7]. Link quality is estimated by a combination of pre- and post-detection information from the receiver, and this estimate is used to select the transmission parameters. In general the quality of a link is a function of the propagation loss, interference from within the network (including multiple-access interference), radio-frequency emissions from outside the network (including intentional jamming), multipath interference, etc. For the results reported in this paper, the quality of a link is taken to be its propagation loss. It is assumed that the receiver has a perfect estimate of this loss, which it can send to the transmitter in an acknowledgment or control packet.

The channel model employed in this paper is the additive white Gaussian noise channel. Multiple-access interference is neglected, which is appropriate for the channel-access protocol that is employed. The reservation feature of the channel-access protocol results in no multiple-access interference for the vast majority of transmissions. It is assumed that there is no jamming and no multipath propagation. Although all of these modeling assumptions are slightly optimistic, their adoption for this paper permits us to concentrate on the tradeoffs that are involved in the design of routing metrics for a network that employs adaptive transmission.

While the primary purpose of LRR in most networks is to enable link-quality information to be utilized effectively by the route selection protocol, the focus of this paper is on the simpler problem of accounting for the propagation loss (and hence the communication range) in the selection of routes. In effect, what is being adapted in the adaptive-transmission protocol is the communication range of the transmission. Future investigations will account for other aspects of link quality in addition to the propagation loss.

We consider two metrics that enable that routing protocol to account for the transmission range. The EN metric is based on the expression in (2) with $\alpha_1 = 0.0$ and $\alpha_2 = 0.06$, and this metric accounts for the energy required to utilize a link. The ENC metric is the EN metric plus a constant. The ENC metric favors routes with fewer hops and longer transmission ranges over routes with more hops and shorter ranges. In effect, it sacrifices energy to reduce delay and congestion. A third metric is also considered and it does not account for the transmission energy. The C metric simply assigns the link resistance to a constant for a link in which at least one control packet has been exchanged between both radios forming the link.

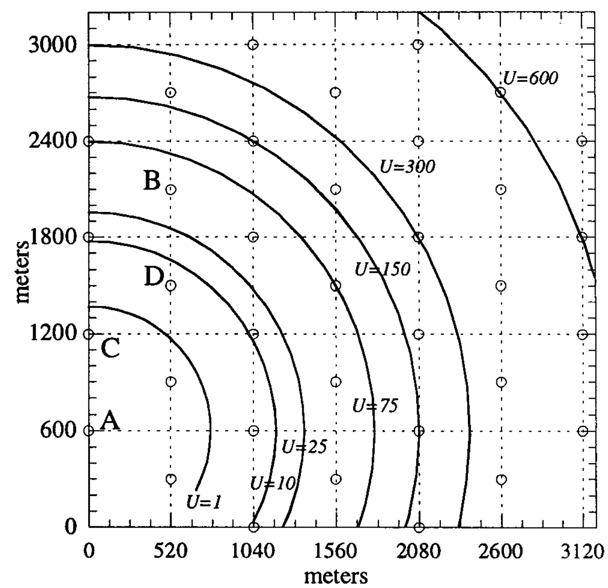

Figure 4. 35-radio network topology.

To examine the performance of the metrics, a simple topology is selected in which there are 35 radios with the fixed positions shown in Figure 4. The minimum distance between two radios is 600 meters. Based on the radio described in [2], the maximum range for a transmission is 3500 meters, and this is achieved with a transmission power of 27 dBm and an information rate of 125 Kb/s. Although the simulation supports a number of different energy levels, the possible values selected by the adaptive-transmission protocol are limited to those listed in Table 1 for the topology considered here. For radio A, the range that is achieved at each of the energy levels is illustrated in Figure 4.

Table 1. Possible energy levels for 35 radio scenario.

Trans. power (dBm)	Info. rate (Mb/s)	Energy metric, U	$\alpha_2 U$
10	1.5	1	0.06
20	1.5	10	0.6
24	1.5	25	1.5
27	1.0	75	4.5
27	0.512	150	9.0
27	0.256	300	18.0
27	0.125	600	36.0

A radio generates one packet at a time and an exponential distribution is utilized to determine the time between packet generations. The destination for a packet generated at a given radio is selected randomly with a uniform distribution over all other radios. Each radio's buffer can hold up to 60 packets, and for the parameters and network topology considered in this manuscript nearly all of the dropped packets are the result of one or more full buffers. That is, a packet is rarely dropped because it has had too many re-transmission attempts or has timed out.

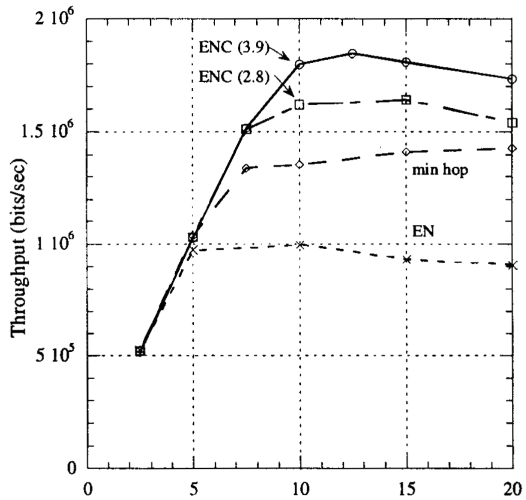

Figure 5. Throughput for the 35-radio network.

Two performance measures are evaluated. The *throughput* is defined as the average number of valid information bits that reach their destinations per second. The *throughput efficiency* is defined as the average number of valid information bits that reach their destination per Joule of energy expended in the transmission of all data packets and network-layer control packets by all radios in the network. The energy used in the transmission of RTS, CTS, or ACK packets is not included in the determination of throughput efficiency.

Simulation results are illustrated in Figure 5 and Figure 6. The ENC (3.9) label denotes the results obtained for the ENC metric if the constant is 3.9. The constant value enables the routing protocol to utilize links in this topology for which $U \leq 75$. That is, radio A can transmit a packet directly to B rather than relaying it through either C or D (see Figure 4). We also examined the ENC metric with the constant equal to 2.8, which restricts the routing protocol to utilizing links for which $U \leq 25$. This results in a slight increase in throughput efficiency but also a reduction in throughput. Setting the constant greater than 3.9 allows the routing protocol to use higher energy links (and increase the transmission range), but this results in both a reduction in throughput and throughput efficiency.

The EN metric considers the transmission energy only, and the routing protocol can select only those links in this topology for which $U = 1$. This metric choice results in poor throughput in this scenario because of the large number of relays that are required to reach many of the destinations. Note that at the low generation rates, the throughput efficiency is greater for the EN metric than the other metrics. However, larger gains in throughput efficiency are not realized at lower generation rates due in part to the fixed overhead from routing-control packets. For the simulation model employed in this investigation, routing-control packets are broadcast at the highest energy level to ensure network connectivity in arbitrary topologies.

The results labeled with *min hop* utilize the C metric with the constant equal to 6. In this situation, a route with the least resistance also has the fewest possible number of relays. For the topology in Figure 4, nearly all the radios are within communication range of each other, and a radio rarely is required to relay a packet. However, the increased congestion caused by transmissions at low information rates reduces both the throughput and the throughput efficiency.

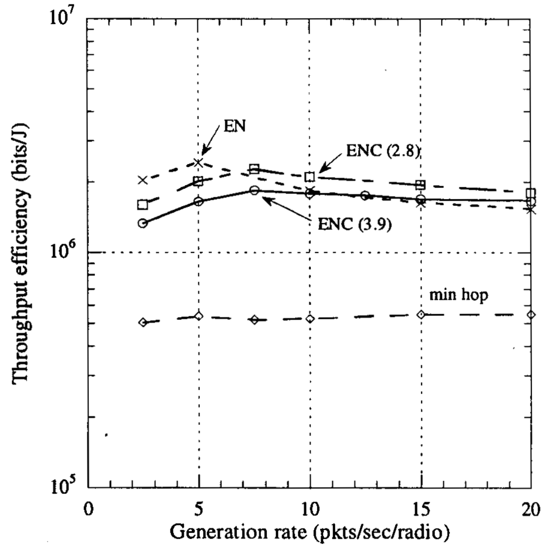

Figure 6. Throughput efficiency for the 35-radio network.

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