Energy-Efficient Routing in Frequency-Hop Networks with Adaptive Transmission

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Abstract: We describe and evaluate an energy-efficient protocol for routing traffic in frequency-hop (FH) store-and-forward packet radio networks that employ an adaptive transmission protocol. The adaptive transmission protocol allows the radios to adjust the power in the transmitted signal and the rate of a Reed-Solomon code to respond to variations in partial-band interference and propagation loss. Routing is accomplished using least-resistance routing (LRR) with a new metric that provides a quantitative assessment of the ability of a radio to receive and forward packets and includes a measure of the energy that is expected to be required for successful transmission. The new energy metric and LRR are integrated with the adaptive transmission protocol, and the performance of the new protocol suite is evaluated for a distributed FH network. The performance results presented in this paper are obtained from a simulation of wireless FH radio networks in which the characteristics of the links vary with time. Our results demonstrate that in FH networks that employ an adaptive transmission protocol, the new method for routing can adapt quickly to changes in interference conditions. We find that LRR with the energy metric works with the adaptive transmission protocol to improve the information throughput and energy efficiency of the network.

I. INTRODUCTION

Packet radio networks can provide wireless communication capability for military tactical applications. In order to be able to maintain a reliable network, adaptive link and network layer protocols are required that can operate efficiently in a battlefield environment. The primary characteristics of mobile packet radio networks are the unreliability and unpredictability of the links due to the mobility of the radios and variability of the propagation conditions. Time-varying interference also contributes to the dynamic environment, and the sources of interference can be external to the network (e.g., jamming or other transmitters) or generated from within the network (e.g., multiple-access interference).

Adaptive transmission, including the adaptation of the transmitter power, code rate, and symbol rate, can be employed to improve both the reliability and energy efficiency of a link in a packet radio network. A method in which the radios can adjust the power in a transmitted signal and the rate of the Reed-Solomon code to respond to variations in the propagation loss and partial-band interference is described in [1] and [2]. The performance of an adaptive transmission protocol based on this method is evaluated in [3] for a network that employs errors-and-erasures decoding with erasure decisions that are determined by side information from the FH receiver. The adaptation is based on this side information and on information derived from the decoder. In this paper we use the protocol of [3] with a modification to the algorithm that adapts the transmitter power.

Use of adaptive transmission has been shown to improve the reliability and energy efficiency of a network [3]. To further improve the performance of the network, changes in the characteristics of the links that result from adapting the transmission parameters must be accounted for in the routing protocols. For example, the routing protocol should update its routing table if the transmitter power has been changed by the adaptive transmission protocol. More generally, the use of adaptive transmission may result in alternative routes with approximately the same probabilities of successful transmission. However, differences in code rates or power levels that are selected by the transmission protocol may result in differences among the energy requirements of the alternative routes. An energy-efficient routing protocol can reduce energy consumption while meeting a specified quality of service.

The focus of this paper is on an energy-efficient protocol for routing traffic in frequency-hop (FH) store-and-forward packet radio networks that employ an adaptive transmission protocol. Routing is accomplished using least-resistance routing (LRR) [4] with a new metric. One of the previous versions of LRR employs the EEA metric [4] to provide a measure of the ability of a radio to receive and forward packets. The EEA metric for a given link is determined by the numbers of errors and erasures reported by the receiving radio and the success of the previous transmission attempt on that link. If the EEA metric is employed, the resistance assigned to a given link is a measure of how much interference is experienced by the receiving radio on that link and how busy that radio is in receiving and transmitting packets. In the current investigation, LRR is used with a new energy metric, referred to as the EN metric, which is an extension of the EEA metric. The EN metric accounts for the energy requirements, errors and erasures counts, and the busyness of the receiving radios for each link in the possible route. The LRR protocol with the EN metric is integrated with the adaptive transmission protocol, and the performance of the new protocol suite is evaluated for a distributed FH network. The performance results presented in this paper are obtained from a simulation of wireless FH radio networks in which the characteristics of the links vary with time.

II. SYSTEM AND CHANNEL MODELS

The FH radio network and channel models are similar to those described in [3]. Each data packet contains a fixed number of information bits, which are encoded with a Reed-Solomon (RS) code. For an \((n, k)\) RS code, a set of \(k\) information symbols is transmitted as a set of \(n\) code symbols, so the rate of the code is \(r = k/n\), and the block length is \(n\). The system employs binary transmission, and the nonbinary symbols for the RS code are formed from sequences of binary symbols. Each packet is divided into one or more error-control blocks of \(L\) code words each. Each error-control block is interleaved and transmitted in \(n\) consecutive dwell intervals [5]. The hopping patterns are modeled as sequences of independent, identically distributed random variables, each of which is uniformly distributed on the set of allowable frequencies. The receiver performs optimal bit-by-bit noncoherent demodulation of the

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received signal.

Partial-band interference is present at times on some of the links. It is modeled as band-limited white Gaussian noise that in a fraction \( \rho \) of the band has two-sided power spectral density of \( \rho^{-1}N_0/2 \). Thermal noise with power spectral density \( N_0/2 \) is present in each of the receivers. For those receivers experiencing partial-band interference, the total power spectral density is \( \rho^{-1}N_1/2 + N_0/2 \) in a fraction \( \rho \) of the band and \( N_0/2 \) in the remainder of the band. The partial-band interference can represent partial-band jamming or FH multiple-access interference or a combination of the two.

The test-symbol method [5] is used to provide side information. In this method, a number of binary test symbols are transmitted in each dwell interval in addition to the encoded data. These symbols are known to both the transmitter and receiver. The entire dwell interval is erased if the number of errors detected in the test symbols exceeds a given threshold.

The network uses the channel-access protocols described in [3]. With these protocols, when radio \( A \) has a packet to transmit to radio \( B \), \( A \) first transmits a request-to-send (RTS) packet to \( B \). In this a paper, a packet is understood to be an information packet unless it is specified otherwise (e.g., RTS packet). If the RTS packet is successfully received, radio \( B \) transmits a clear-to-send (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 \( B \). If the packet is decoded correctly, an acknowledgement is sent by \( B \) to \( A \). If \( B \) receives the packet but fails to decode it correctly, it transmits a negative acknowledgement to \( A \).

### III. Adaptive Transmission Algorithm

The adaptive transmission protocol used in this paper is a modification of the protocol in [3]. In the description that follows, we consider a scenario in which radio \( A \) wishes to transmit a packet to radio \( B \). We refer to radio \( A \) as the source radio and radio \( B \) as the destination radio in this description. Each source radio has two tables for each destination radio. The first table, the \( R \)-table, is used to store the power level and code rate the source radio will use for the next packet transmission to the destination radio. In the second table, the \( T \)-table, is used to store the power level and code rate information that the source radio stores the power level and code rate that it expects the destination radio to use on the next transmission from the destination radio to the source radio.

An exchange of RTS and CTS packets is made between the source and destination radio, during which the proper power level and code rate are determined for the source radio’s next packet transmission. The packet is then transmitted by the source radio to the destination radio at the newly determined power level and code rate.

The method of adapting the code rate is as described in [3]. Upon receipt of the packet, the destination radio determines the number \( Y \) of dwell intervals erased in the packet. This number is compared to \( \tau \) to determine the code rate for the next packet transmission. Once the new code rate is determined, the receiver calculates \( P_e(e,t,l) \), the conditional probability of packet error, which is defined as

\[
P_e(e, t, l) = 1 - (1 - P_{cw}(e, t, l))^L,
\]

where

\[
P_{cw}(e, t, l) = \sum_{i=\lceil \frac{e}{e+1} \rceil}^{\lfloor e \rfloor} \binom{n-e}{i} \hat{p}^i (1-\hat{p})^{n-e-i},
\]

and

\[
\hat{p} = \frac{t}{n-e}.
\]

The average number of errors in each code word of the received packet is \( t \), the average number of erasures in each code word of the received packet is \( e \), and \( I = n - k \). 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 number of symbol errors is not known, and the receiver estimates the number of symbol errors as in [4]. If more than \( n - k \) dwell intervals are erased, the receiver estimates the number of symbol errors to be 0.

Once calculated, \( P_e \) is compared to the thresholds \( \tau_1 \) and \( \tau_2 \). If \( P_e \leq \tau_1 \), the power level is decreased if possible; if \( \tau_1 \leq P_e \leq \tau_2 \), the power level is unchanged; otherwise, the power is increased if possible. To avoid problems that might occur as a result of several consecutive packets failing to decode, we include the following backup mechanism. If two successive packets fail to decode, the code rate is decreased, if possible, for the next transmission; otherwise, the transmitter power is increased if possible. The destination radio updates its \( R \)-table with the new code rate and power level. If the data packet is decoded successfully, an acknowledgement packet that contains the new code and power information is transmitted by the destination radio to the source radio. If the packet is not decoded correctly, a negative acknowledgement that contains the new code and power information is transmitted by destination radio to the source radio. If a sufficiently long sequence of packets is transmitted without the source radio successfully decoding a positive or negative acknowledgement, the source radio decreases the code rate if possible; otherwise the source radio increases the power level if possible. The source radio updates its \( T \)-table with the new power and code information accordingly.

### IV. Routing Protocol

Knowledge of the link qualities in a radio network is essential for the operation of the network protocols, and the key feature of LRR is that link-quality information is used to aid the network protocols in selecting routes. 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. In this paper the resistance of a route is the sum of the resistances of the links that make up the route. A distance-vector routing algorithm is used to find the routes of least resistance through the network. For our present application, the link resistance is designed to characterize the channel as seen by a FH receiver.

The probability that a packet that is sent from radio \( A \) to radio \( B \) reaches its ultimate destination is a function of the error probability for transmissions on the link from \( A \) to \( B \) and the probability of radio \( B \) to forward the packet. A term \( I(A,B) \) is included in each metric to characterize the reliability of the link from \( A \) to \( B \). \( I(A,B) \) accounts for fading, propagation loss, and other features of an individual link. One metric we have investigated previously is the EE metric, for which \( I(A,B) = 2t + e \), and the link resistance is given by

\[
LR(A,B) = \alpha_1(2t + e).
\]
The values for \( t \) and \( e \) are determined from the most recent packet reception on the link from \( A \) to \( B \). The value for \( t \) is the average number of symbol errors per code word in that packet, and \( e \) is the number of dwell intervals that are erased in that packet.

In addition to accounting for link reliability, LRR has been enhanced [4] to include a measure of the receiving radio’s ability to forward a packet in a timely fashion once it demodulates and decodes that packet successfully. The EE metric with this enhancement is referred to in [4] as the EEA metric. However, this enhancement is employed for each of the two metrics examined in this paper, we refer to the metric as the EE metric with the understanding that LRR includes the enhancement regardless of the metric that is employed. The enhancement is applied to LRR in this paper as follows. Each time an RTS or information packet is transmitted on the link from \( A \) to \( B \) and no CTS or acknowledgment is received by \( A \), radio \( A \) increases by one the resistance it has stored for that link. This feature is included to account for radio \( B \) being busy or the RTS not being received and decoded correctly.

In this paper the network routing is based on the EN metric, for which the general form of the resistance for the link from radio \( A \) to radio \( B \) is

\[
LR(A, B) = \alpha_1 I(A, B) + \alpha_2 U(A, B),
\]

where \( \alpha_1 \) and \( \alpha_2 \) are coefficients that are selected to give the desired emphasis to the individual components.

In order to minimize the energy expended in delivering a packet to its destination, the routing protocol must account for the transmitter power and the code rate that are used on each link of the alternative routes from the source to the destination. Because adaptive transmission is employed, the transmitter power and code rate may vary from one transmission to the next. In our adaptive transmission protocol, a set of RS codes of block length \( n \) is available, and the selection of the code rate for the next transmission on a link is based on the results obtained from the last transmission on that link. Let \( r_1 \) denote the maximum of the rates of the codes in this set. Let \( r(A, B) \) denote the rate of the code 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 \( P(A, B) \). The power levels are expressed in decibels (dB) relative to some reference power. For example, it is common to use a reference power of 1 mW, in which case the power levels are in decibels relative to 1 mW (dBm).

The EN metric is an extension of the EE metric in which we account for the energy that will be used for the next transmission from \( A \) to \( B \). The component of \( LR(A, B) \) that provides a measure of the energy requirement is \( U(A, B) \). For the results given in this paper, \( U(A, B) \) is defined by

\[
U(A, B) = \frac{r_1 \exp_{10}([P(A, B) - P_1]/10)}{r(A, B)},
\]

where \( \exp_{10}(x) = 10^x \).

Two features of LRR with the EE metric are preserved in LRR with the EN metric. First, the term \( I(A, B) \) in the EN metric is the same as in the EE metric. Second, LRR with the EN metric also increments by one the stored resistance value of the link to radio \( B \) when an RTS or information packet is transmitted on the link from \( A \) to \( B \) and a CTS or acknowledgement is not received by \( A \).

V. RESULTS

A simulation model similar to the one used in [3] is utilized to examine the performance of the new metric. Each error-control block has \( L = 30 \) fully interleaved codewords. The codes available to the adaptive transmission system are the (32,24) RS code and the (32,12) RS code, so \( r_1 = 3/4 \). Each transmitter can transmit at one of three power levels to transmit: \( P_1, P_2 = P_1 + 1.5 \), and \( P_3 = P_1 + 3.0 \). The values employed for the adaptation parameters are \( r_1 = 4 \), \( r_2 = 10^{-7} \), and \( r_2 = 0.05 \). The performance results presented in this section are for the EE metric with \( \alpha_1 = 1 \) and the EN metric with \( \alpha_1 = 0.5 \) and \( \alpha_2 = 2.75 \). Thus, for the EE metric the resistance for the link from \( A \) to \( B \) is \( LR(A, B) = 2t + e \), and for the EN metric it is \( LR(A, B) = 0.5(2t + e) + 2.75U(A, B) \).

Simulation results are presented for the network illustrated in Fig. 1. The upper links for the network of Fig. 1 are the link from radio 1 to radio 2 and the link from radio 2 to radio 4. The lower links are the link from radio 1 to radio 3 and the link from radio 3 to radio 4. All packets are generated at radio 1 and their common destination is radio 4. Transmissions are not allowed between radios 2 and 3, so there are only two routes available from radio 1 to radio 4.

Each receiver has thermal noise with two-sided spectral density \( N_0/2 \). The energy per binary symbol in the received signal on a given link is denoted by \( E_s \). The receiver for radio 3 may be subjected to partial-band interference. This partial-band interference has spectral density \( \rho^{-1}N_f/2 \) in a fraction \( \rho \) of the band, and it affects receptions at radio 3 only. If \( N_f > 0 \) we say that partial-band interference is present in the network; if \( N_f = 0 \) there is no partial-band interference.

One of the parameters required to specify the quality of a link is \( E_s/N_0 \), but the received energy depends on the transmitter power. For example, if the power for the transmission...
on the link from radio 1 to radio 2 is increased by 3 dB, the value for $E_s/N_0$ at the receiver of radio 2 is increased by 3 dB. If partial-band interference is present and the power for the transmission on the link from radio 1 to radio 3 is increased by 1.5 dB, for example, then $E_s/N_0$ and $E_s/N_1$ are increased by 1.5 dB. In this paper, all values given for $E_s/N_0$ are for transmission power level $P_1$. Similarly, the values given for $E_s/N_0$ correspond to transmission power level $P_1$ on the link from radio 1 to radio 3. The values of $E_s/N_0$ and $E_s/N_1$ for other power levels can be determined easily from the values specified for transmission power level $P_1$.

The link to radio 2 and the two links to radio 4 are characterized by the values for $E_s/N_0$ on those links. If there is no partial-band interference, the link to radio 3 is characterized by the value for $E_s/N_0$ on that link; if partial-band interference is present, this link is characterized by $\rho$, $E_s/N_1$, and the value for $E_s/N_0$ on that link. For convenience we use the term link parameters to refer to $\rho$, $E_s/N_1$, and the values for $E_s/N_0$ on each of the four links in the network. We let $\rho = 0$ designate that there is no partial-band interference.

The two performance measures that are evaluated for each scenario and each of the two metrics are the throughput rate and the throughput efficiency. A valid information bit is an information bit that is part of a packet that is decoded correctly. An information bit that is correct at the decoder output but is part of a packet that is not decoded correctly (i.e., is not error-free at the decoder output) is not a valid information bit. The throughput rate is defined as the average number of valid information bits at the decoder output of the destination radio (radio 4) per binary symbol transmitted by all of the radios in the network. In the simulation the throughput rate is determined by dividing the total number of information bits in packets that are decoded correctly by the total number of binary symbols that are transmitted in information packets by all radios in the network. Acknowledgment packets and control packets are not included in this performance measure. 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. Again, acknowledgment and control packets are not included.

In the first set of performance results the link parameters are fixed, but they are unknown to the radios. For this set of results $E_s/N_0$ is 8 dB for the each of the upper two links and 11 dB for each of the lower two links. Since these values of $E_s/N_0$ correspond to the same transmission power, it is clear that the propagation loss is larger for the upper two links than for the lower links. We examine the performance when there is no partial-band interference ($\rho = 0$) and when partial-band interference is present for several different values of $\rho$. When partial-band interference is present $E_s/N_1$ is -5 dB.

The results obtained for the throughput efficiency for the two metrics are presented in Fig. 2. There is no significant difference in throughput rate for the two metrics, and the results are not included here. For $\rho = 0$ we see from Fig. 2 that the LRR protocol with the EN metric provides much larger throughput efficiency than the LRR protocol with the EE metric. Similarly, for $\rho = 0.05$ a significant advantage in throughput efficiency is demonstrated for the EN metric. Notice 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 larger values of $\rho$ 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 $\rho$ 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.

The second set of performance results is for time-varying partial-band interference. The interference is modeled as a two-state Markov model. In the first state there is no partial-band interference the network, but in the second state partial-band interference is present. The two states are just the two scenarios considered above. That is, for either state the value of $E_s/N_0$ is 8 dB for the each of the upper two links and 11 dB for each of the lower two links. In the second state the value of $E_s/N_1$ is -5 dB.

The network is permitted to change states from one transmission to the next, but it is in a fixed state for the duration of a transmission. When in a state corresponding to no partial-band interference, the network changes states with probability 0.05 between two consecutive transmissions, and it remains in the same state with probability 0.95. When in a state in which partial-band interference is present, the network changes states with probability 0.15 between two consecutive transmissions, and it remains in the same state with probability 0.85. The results illustrated in Fig. 3 demonstrate that for small values of $\rho$ the use of the EN metric in the LRR protocol gives a higher throughput efficiency than is obtained from the use of the EE metric. This is consistent with the results of Fig. 2.

VI. CONCLUSIONS

We have examined the performance of the LRR protocol with the EN metric, a new metric that accounts for the energy consumed by the transmissions that are required for packets to reach their destinations in a FH packet radio network. The LRR protocol is combined with an adaptive transmission protocol to provide energy efficiency in both static and time-varying interference environments. The results presented in this paper demonstrate that the use of the EN metric permits the LRR protocol to select routes that conserve energy without decreasing the throughput rate.

REFERENCES


Fig. 2. Throughput efficiency for fixed link parameters.

Fig. 3. Throughput efficiency for time-varying partial-band interference.