

ADAPTIVE TRANSMISSION PROTOCOLS FOR FREQUENCY-HOP RADIO NETWORKS

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ABSTRACT

The focus of this paper is on the performance of an adaptive transmission protocol for frequency-hop (FH) radio networks in which the radios can 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. The adaptation is based on side information from the FH receiver and on information derived from the decoder. The results presented in this paper are obtained from a simulation of a wireless FH radio network in which the characteristics of the links are time-varying. These results demonstrate that the adaptive transmission protocol can improve the quality of a link by adapting to variations in both path-loss and interference to take advantage of favorable channel conditions.

I. INTRODUCTION

A communication link in a mobile wireless communication network exhibits time variations in both the interference and the propagation loss, due in part to the network mobility and the dynamic environment. A common design approach is to choose transmission parameters so that adequate performance is achieved for the worst-case channel conditions. Such an approach achieves reliable communication but is inefficient. During periods in which channel conditions are favorable, energy is wasted and the information rate is less than can be achieved. Adaptive transmission, including adaptation of the transmitter power, code rate, and symbol rate, can improve both the reliability and

energy efficiency of such a link.

The interaction between the physical and network layers of the protocol suite has previously been exploited to use side information developed in a spread-spectrum communication receiver in adaptive forwarding and routing protocols. Specifically, side information from the demodulator and decoder in the frequency-hop (FH) receivers is employed in [1] to give a quantitative measure of the capabilities of the links, and this information is used in the adaptive routing algorithm known as least-resistance routing to select the best routes through the network. Further results on the metrics that are employed to characterize the links of the network are provided in [2].

Although the use of adaptive routing to avoid poor-quality links can improve the performance of a network, even better performance can be obtained by adapting the transmission parameters to improve the links. The ability of the adaptive transmission protocol to maintain the links in the network is of particular importance for voice traffic, because it is necessary in many situations to keep all of the links in a route functioning adequately in order to deliver an entire voice message over the route that has been set up for that message. Adaptive transmission methods can help maintain a route for a voice connection until a new connection can be set up.

The focus of the present paper is on the performance of adaptive link-level transmission protocols for FH radio networks in which the radios can adjust the power in the transmitted signal and the rate of the Reed-Solomon code to respond to variations in partial-band interference and propagation loss. A method has been proposed [3], [4] for adapting the power and code rate. The performance of a version of this method is evaluated in the present paper 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 infor-

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mation and on information derived from the decoder. The results presented in this paper are obtained from a simulation of a wireless FH radio network in which the characteristics of the links are time-varying.

II. SYSTEM AND CHANNEL MODELS

The FH radio network is similar to the one described in [2]. Each data packet contains a fixed number of information bits, which are encoded as Reed-Solomon (RS) code words. 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 received signal.

The channel model includes variable path loss and partial-band interference. Variable path loss illustrates the effects of occasional deep fades. The partial-band interference is modeled as band-limited white Gaussian noise that occupies a fraction ρ of the band. Its two-sided power spectral density is $\rho^{-1}N_I/2$. Thermal noise with power spectral density $N_0/2$ is also present, so the total power spectral density is $\rho^{-1}N_I/2 + N_0/2$ in a fraction ρ 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, each dwell interval contains a number of binary test symbols 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.

III. THE ADAPTIVE TRANSMISSION ALGORITHM

In the descriptions that follow it is convenient to envision a scenario in which radio 1 wishes to transmit a packet to radio 2. A *neighbor* of radio 1 is any other radio in the network that is within communication range of radio 1. We are interested in the scenario in which radio 2 is a neighbor of radio 1. In this paper we are not concerned with whether radio 1 originated the packet or is simply relaying it, nor are we concerned with whether

radio 2 wants to use the information in the packet or intends only to relay it to another radio. We are interested only in the transmission from radio 1 to radio 2. In this situation we refer to radio 1 as the *source* and radio 2 as the *destination*. By this we mean that radio 1 is the source for the transmission, not necessarily the original source for the packet. Similarly, radio 2 is the destination for the transmission, and not necessarily the packet's final destination in the network.

Each radio has two tables for each neighbor. In one table, the *T-table*, the radio stores the code and power information to be used for the transmission of data packets to that neighbor. In a second table, the *R-table*, the radio stores the code and power information to be used for the reception of data packets from that neighbor.

Suppose the source radio has a packet to send. Using the multiple-access protocol in [2], it first sends to the destination a request-to-send (RTS) packet containing the code and power information from its T-table for that destination. Upon receipt of the RTS packet, the destination radio compares the code and power information in the RTS packet with the information contained in its R-table for the source. If a discrepancy exists, the destination radio chooses the code specified by the source, and it selects the higher of the two power levels. The destination radio updates its R-table with the new code and power information and sends the new power information to the source in a clear-to-send (CTS) packet. Upon receipt of the CTS packet, the source updates its T-table with the power information contained in the CTS packet, and it uses the code and power information from the T-table for the transmission of the data packet. Similarly, the destination uses the code information from its R-table to decode this data packet.

Upon receipt of the data packet, the destination radio determines the number Y of dwell intervals that are erased in a given packet and computes \hat{p} , the relative frequency of errors among unerased symbols, which is defined as

$$\hat{p} = \frac{1}{(n - Y)L} \sum_{i=1}^{n-Y} X_i,$$

where X_1, X_2, \dots, X_{n-Y} are the numbers of symbol errors in the $n - Y$ dwell intervals that are not erased, and L is the number of code words per packet. If the received word is successfully decoded, the number of symbol errors in each received word is determined from the decoder. If the decoder does not specify the error locations, they can be found by encoding the decoder

output and comparing to the received word. 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 so the receiver must estimate the number of symbol errors in its computation of \hat{p} . In the event of a decoder failure the number of errors is estimated as in [1]. If more than $n - k$ dwell intervals are erased, the receiver estimates the number of errors to be 0.

The destination radio uses Y and \hat{p} to determine the code rate and power level for the next transmission. The selection of the code rate is based on the value of Y , and the selection of the power level is based on the value of \hat{p} . The protocol specifies values for the adaptation parameters τ , τ_c , τ_1 , and τ_2 . The parameter τ_c is always less than τ , and τ_1 is always less than τ_2 . If $Y > \tau$, the highest power level and the lowest code rate are selected for the next packet transmission. If $\tau_c < Y \leq \tau$, the code rate is decreased if possible, but if $Y \leq \tau_c$, the code rate is increased if possible. If $\hat{p} \leq \tau_1$, the power is decreased if possible; if $\tau_1 < \hat{p} \leq \tau_2$, the power level is unchanged; otherwise, the power is increased if possible. Once the code rate and power level are selected, the destination radio updates the code and power information in its neighbor table.

If the data packet is decoded successfully, the destination radio sends the new code and power information to the source in an acknowledgment (ACK) packet. We have modified the channel-access protocol described in [2] so that the destination radio can send this information to the source radio in a negative acknowledgment (NACK) packet if the data packet is not decoded successfully. If a sufficiently long sequence of ACKs and NACKs fail to decode, the source radio decreases the code rate if possible; otherwise, the source increases the power level if possible. The source radio updates the code and power information in its T-table accordingly, and initiates the next transmission by sending the new code and power information to the destination radio in an RTS.

IV. RESULTS

The adaptive transmission system that we consider in this paper selects either a (32,24) RS code or a (32,12) RS code. The transmitter power has three possible values: P_1 , $P_2 = P_1 + 1.5$ dB, and $P_3 = P_1 + 3.0$ dB. The adaptation parameters are $\tau = 17$, $\tau_c = 6$, $\tau_1 = 0.004$, and $\tau_2 = 0.093$.

Simulation results are presented for the performance of a single communication link. Several different chan-

nel states are considered. Channel state A is an additive white Gaussian noise (AWGN) channel. For transmitter power P_1 , the signal-to-noise ratio \mathcal{E}_s/N_0 is 10 dB for state A, where \mathcal{E}_s is the received energy for each binary symbol. Channel state B contains partial-band interference with $\rho = 0.4$. For transmitter power P_1 , $\mathcal{E}_s/N_0 = 10$ dB and $\mathcal{E}_s/N_I = 1$ dB for state B. Channel C is an AWGN channel for which $\mathcal{E}_s/N_0 = 7$ dB for transmitter power P_1 . Channel state D has partial-band interference with $\rho = 0.4$. The path loss for state D is 3 dB greater than for state B, so that $\mathcal{E}_s/N_0 = 7$ dB and $\mathcal{E}_s/N_I = -2$ dB for transmitter power P_1 .

The *throughput rate* is defined as the average number of correct information bits at the decoder output per transmitted binary symbol. This measure, however, does not account for the extra energy required to transmit a packet at a lower code rate or higher power. Thus, we also consider the *throughput efficiency*, which we define as the average number of correct information bits at the decoder output per unit of energy expended by the transmitter.

For comparison purposes, we define two nonadaptive transmission protocols with transmitter powers and code rates chosen from those used in the adaptive protocol. Transmission with power P_3 and a (32,12) RS code achieves the best possible performance for state D, the worst channel state. In subsequent discussion, we refer to this set of parameters as the *worst-case* transmission parameters. We also consider transmission with power P_2 and a (32,12) RS code. Among the possible combinations of code rate and power, this combination achieves the smallest maximum difference in throughput rate and efficiency over all four channel states, relative to the best achievable rate and efficiency for each state. We refer to this set of parameters as the *minimax* parameters.

The results presented below are for a system in which NACKs are transmitted. We have also considered a system in which NACKs are not transmitted. If NACKs are not transmitted, the performance of the adaptive protocol is slightly worse for the scenarios presented.

The performance of the adaptive protocol for each channel state is given in Figures 1 and 2. The adaptive protocol achieves large gains in performance relative to the worst-case and minimax parameters for states A and C by taking advantage of the lack of interference. For states B and D, the adaptive protocol achieves a moderate throughput rate and efficiency. The values of τ , τ_c , τ_1 , and τ_2 are chosen to maximize the throughput rate and efficiency for channel states in which in-

interference is not present. By choosing different values, the performance of the adaptive protocol in the face of interference can be improved at the expense of its resistance to increased path loss.

In Figures 3 and 4, we show the performance of the adaptive protocol for scenarios in which the channel is in one state for the first half of the duration of the simulation and a second state for the second half of the duration. For example, the channel denoted $A \rightarrow B$ begins in state A and ends in state B. The adaptive protocol clearly performs better than the minimax parameters for each channel. The worst-case parameters produce a slightly higher throughput efficiency for channel $B \rightarrow D$, for which partial-band interference is present for the entire duration of the simulation.

The performance of the adaptive protocol is shown in Figures 5 and 6 for several Markov channels. For Markov channel 1, the state of the channel is either A or B. For each transmission of a data packet, the channel changes state with probability 0.1. For Markov channel 2, the state of the channel is either A or C. The channel changes from state A to C with probability 0.01 and from state C to A with probability 0.02. For Markov channel 3, all four states are possible. The transition probabilities are similar to those of Markov channels 1 and 2. The results show that the adaptive protocol can provide large gains in throughput efficiency relative to the worst-case and minimax parameters. The adaptive protocol has a smaller throughput rate for Markov channel 3 relative to the nonadaptive protocols.

V. CONCLUSIONS

These results demonstrate that the adaptive transmission protocol can improve the quality of a link by adapting to variations in both path-loss and interference. Changes in the characteristics of a network's communication links must be accounted for in the network protocols, as well. Future investigations will incorporate this link-level adaptation into adaptive routing and forwarding protocols.

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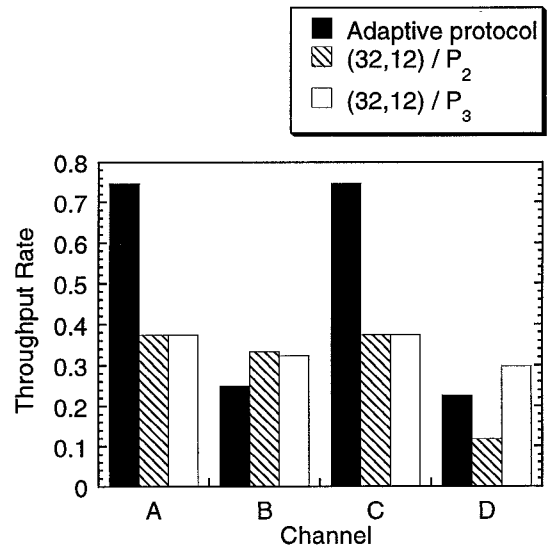


Figure 1. Throughput rate of transmission protocols for different channel states.

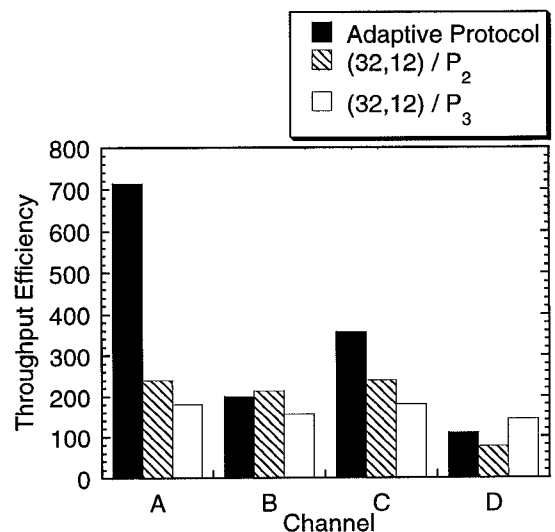


Figure 2. Throughput efficiency of transmission protocols for different channel states.

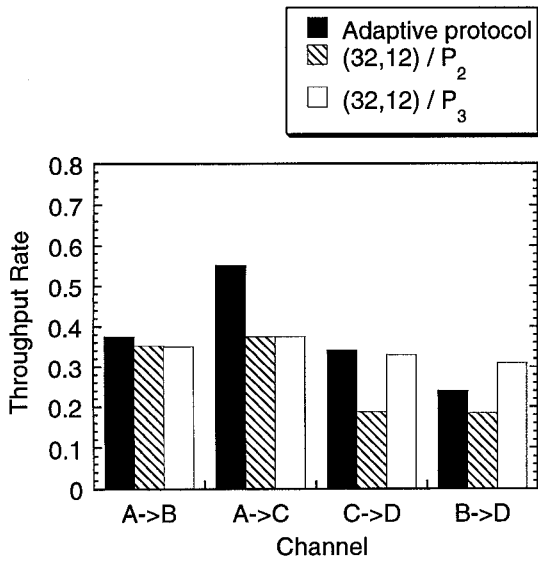


Figure 3. Throughput rate of transmission protocols for channels with one state transition.

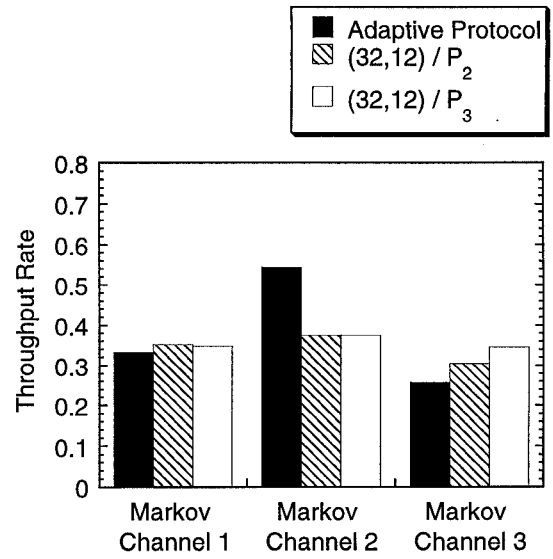


Figure 5. Throughput rate of transmission protocols for Markov channels.

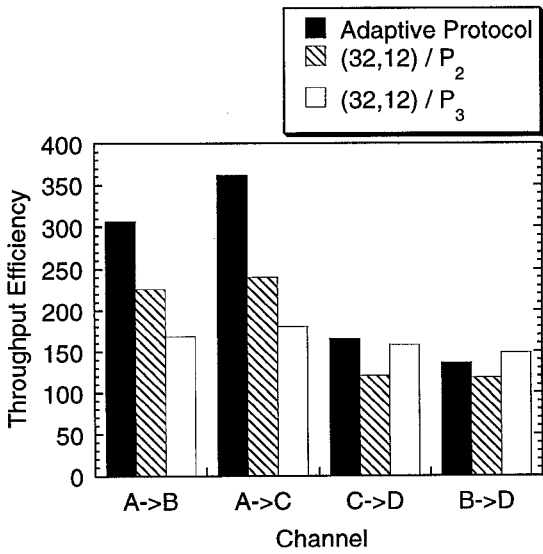


Figure 4. Throughput efficiency of transmission protocols for channels with one state transition.

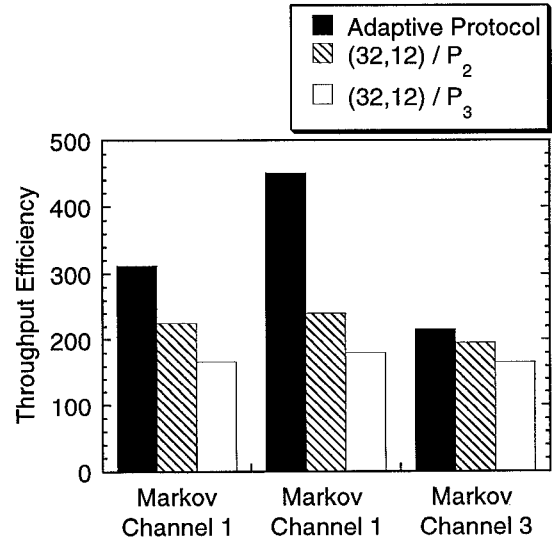


Figure 6. Throughput efficiency of transmission protocols for Markov channels.