Optimization of an Adaptive Link Control Protocol for Multimedia Packet Radio Networks

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Abstract*-Packet radio technology is currently used in a wide range of tactical military communication systems, including SINCGARS, EPLARS, and NTDR, for the transfer of data based messages across the battlefield. The DARPA GloMo program is also investigating the use of this technology for the transfer of multimedia voice, data and video traffic among dismounted infantry users in *ad hoc* mobile radio networks. A key aspect of the GloMo program is the development of adaptive protocols that minimize energy consumption and maximize the battery life of a user's handheld terminal. Under sponsorship from DARPA and internal research and development funding from ITT Industries, we have developed a unique set of algorithms to minimize energy consumption by adaptation of physical and link layer protocol parameters within a packet radio network. This paper presents a brief overview of these algorithms and then presents a design and modeling approach, based upon Taguchi techniques, for the optimization of these algorithms. We present a metric that optimizes performance as a function of the number of successful information bits at the output of the decoder per unit of energy transmitted. When applied to hand-held or portable, packet radio communication equipment, this metric provides improved performance with respect to battery life and signal intercept performance. OPNET models are used to run a set of matrix experiments to arrive at an optimized set of design parameters for operation of theses adaptive transmission protocols in a tactical environment.

I. INTRODUCTION

Adaptation of parameters at the physical and link protocol layers has been considered [1] and analyzed [2] as a solution to increasing communication reliability within *ad hoc* packet radio networks. Such adaptation is particularly valuable in military applications, where the mobility of nodes relative to one another over irregular terrain result in rapidly varying path loss, multipath fading and variable radio connectivity. Physical and link layer parameters, such as transmit power, error control code rate and symbol transmission rate, can be adapted to improve communication reliability over these time varying radio channels. In order to control the adaptation process effectively, methods are required to detect changes in radio channel quality and then adapt these parameters to enhance reliability. While channel quality detection methods and adaptation algorithms have been widely studied and applied to cellular communication networks [3,4], the application of similar algorithm's within an *ad hoc* packet radio network is made difficult by the lack of a feedback channel for closed-loop control of parameters. As a result, the performance of an adaptive power and information rate algorithm in an *ad hoc* packet radio network is particularly sensitive to statistical variations in the radio's electrical performance. In particular the resolution, accuracy and range over which parameters can be adapted is limited as well as the accuracy with which channel quality can be measured.

This paper presents a heuristic design and modeling approach, that utilizes Taguchi techniques [5,6] to optimize performance under highly variable RF channel and radio performance conditions. Our goal is to identify a set of physical and link layer protocol parameters that increase performance and minimize variability due to statistical variations of the radio's electrical performance. A design metric, based upon the number of successful information bits at the output of the decoder per unit of energy transmitted, is used as the basis to compare relative performance. When applied to portable radio equipment, this metric provides an indication of performance with respect to battery life and signal intercept performance. OPNET models are used to run a set of matrix experiments and to arrive at an optimized set of parameters for radio operation in a tactical environment.

II. OPERATIONAL SCENARIO

The protocols described in this paper operate on the ITT Handheld Multimedia Terminal (HMT) hardware platform [7]. Fig. 1 illustrates how the HMT supports communications among users in a dismounted infantry company. The HMT supplants the Combat Net Radio and its voice command and control mission with a single radio solution that provides data and video communications in addition to highly reliable net voice operation. Currently, the warfighter commanders and/or leaders at company, platoon, and squad echelons carry two radios to simultaneously receive voice command and control messages from the next higher echelon while issuing voice commands within the commander's and/or leader's echelon. For this effort, it is intended to preserve this critical voice command and control function, but carry out the mission with a single versus multiple radios. This is illustrated in Fig. 1 by ovals that encircle users and designate the virtual voice nets formed within the HMT network

Within this operational scenario, the adaptive link control protocols select a set of physical and link communication parameters that minimize transmit energy while providing reliable point-to-point communications as a function of

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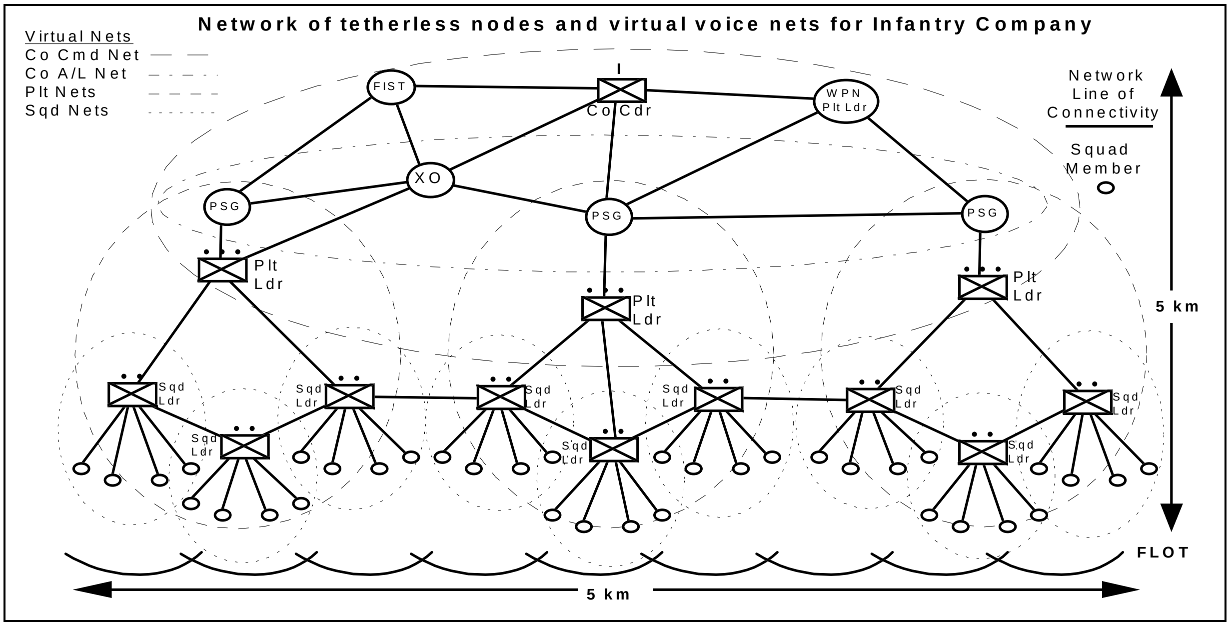

Fig. 1. HMT operational scenario for operation of adaptive link protocols.

packet destination, message type, message length and channel conditions. The traffic types, packet lengths, channel conditions and reliability that the physical and link layers must support on a point-to-point basis are summarized below:

- Message type: real-time voice, real-time video, interactive data, tactical data
- Packet Length: 128 to 2048 bytes
- Channel Characteristics:
  - specular multipath channel
  - Operating Frequency: 2.4 GHz ISM Band
  - Delay spread < 4 usec
  - Fade rate < 3 kHz
  - maximum path loss < 134 dB
- Packet Reliability: Pr(Packet decode without error) > 99%

III. Waveform Description

The HMT operates on four frequency channels in the ISM band from 2.4 to 2.48 GHz at carrier center frequencies of 2.41, 2.43, 2.45 and 2.47 GHz. The waveform employs Direct Sequence (DS) modulation at a chip rate of 32 Mchips/sec to support the transmission of data packets at variable channel information rates that range from 0.125 to 1.5 Mbps. The waveform structure, illustrated in Fig. 2, supports implementation of a CSMA/CA (Carrier Sense Multiple Access/Collision Avoidance) channel access protocol and Rake equalizer at the receiver.

A pseudo-noise (PN) sync sequence is transmitted at the start of every RTS, CTS, Packet and ACK transmission to provide for detection of a signal and acquisition of symbol timing. On the RTS, CTS and ACK transmission, the sync sequences are followed by a 32 bit control header that is DPSK modulated onto the carrier at 250 kbps. On the packet transmissions, data information is DPSK modulated onto the carrier at channel information rates of 0.125 to 1.5 Mbps as a function of selected code and data rate combinations. The information is then spread via direct-sequence signaling at 32 Mchips/sec.

The 32 bit control headers within the RTS, CTS and ACK are used to convey control and channel quality information with respect to the adaptation of physical and link layer parameters. The range of parameters that can be controlled at the physical and link layer are listed below:

- Transmit Power: 0, 6, 12, 18, 24, 30 dBm
- Information Rate/(Code Rate): 125/(1/2), 250/(1/2), 500/(1/2), 1000/(1/2), 1500/(3/4)
- Frequency Channels: 4

Provision is made in the RTS/CTS exchange for accepting a packet transmission on the basis of packet priority and estimated signal quality. The destination may reject an RTS if the quality of the received RTS is estimated to be too weak to to support the requested parameters for the subsequent packet transmission. Also, the destination node may reject the packet if the packet time-to-receive does not meet the destination nodes available capacity for the specified packet priority. The following measurements, taken in the receiver of the HMT, are used to estimate the quality of a receive RTS or Packet reception:

- IF Signal-to-Noise Ratio (SNR) for RTS, PKT and ACK
- Post Detection Signal Quality(PDSQ) in 250 kHz detection bandwidth
- Number of paths tracked by RAKE modem
- Receive packet channel bit error rate (BER)

The following sections describe in more detail how the contents of the RTS/CTS/ACK header fields are used in

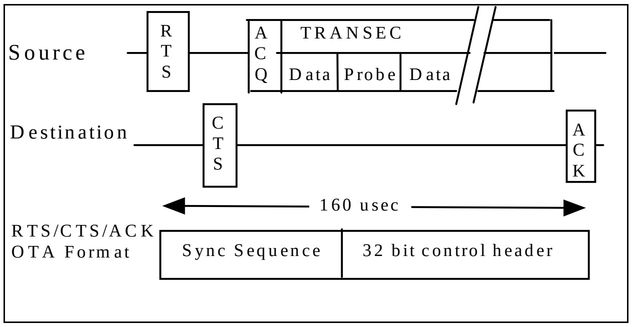

Fig. 2. Waveform diagram.

conjunction with these channel quality measurement methods and link layer algorithms to adapt physical and link parameters for the transmission of data packets.

IV. ADAPTATION ALGORITHM

Our interest is in a system which adapts the information rate, and transmitter power level. The adaptive transmission protocol utilizes the measurements made in the destination radio's receiver (IF SNR, PDSQ, number of tracked paths, and BER) to optimize the transmission parameters for subsequent packet transmissions. The protocol strives to maximize the information throughput per unit time and minimize the energy expended per correct information bit delivered. Fig. 3 illustrates a general overview of the adaptive transmission protocol.

In the discussion that follows, we are interested in a single communication link of a direct-sequence packet radio network. The *source radio* is defined to be the source of the transmission, not necessarily the source of the packet. Similarly, the *destination radio* is defined to be the destination for the transmission, not necessarily the final destination for the packet. The destination radio is assumed to be within range of the source radio.

If the source radio has a packet to send to a given destination radio, it proposes the symbol rate, code rate, and transmitter power level to be used for the packet transmission. The proposed values are based on channel quality measurements included in the ACKs and NACKs resulting from N_A previous packet transmission attempts to the given destination radio. If more than T_d seconds have elapsed since the last NACK was received, the available channel quality measurements from the previous transmission attempts are considered out-of-date and are discarded. The channel quality measurements included in the ACKs and NACKs are made at the destination receiver during the reception, demodulation, and decoding of the previous packet from the source radio of interest. If the source has no recent channel quality information for the link to the destination radio, default values are selected for the transmission parameters. The source radio informs the destination radio of the proposed symbol rate and code rate by including these values in the RTS. The source radio stores its proposed transmitter power level.

The adaptive transmission protocol allows the destination radio to make a correction to the transmitter power level if there has been a significant change in the path loss or the interference conditions since the last packet transmission occurred. If the destination radio accepts the RTS packet, it employs the RTS channel quality measurements, the RTS transmission power level, and the source's requested symbol and code rates to propose a power level to be used in the transmission of the packet on the communication channel. In determining it's proposed power level, the destination also accounts for possible differences in fading and interference between the reservation channel and the communication channel. The destination radio informs the source radio of any proposed changes in transmitter power level by including it's suggested power level in the CTS.

Upon receiving the CTS, the source radio compares the destination suggested power level to its proposed power level that has been stored in a neighbor table. Although it is possible that the destination radio propose a lower power level than the source radio, our adaptive transmission protocol will only allow the destination to increase the transmitter power level. The decision to decrease the power level will only be made based on the more reliable statistics measured on the communication channel. Thus, the message packet is transmitted at the higher of the source-suggested power and the destination-suggested power.

Upon receiving the message packet, the destination radio estimates the channel quality of the communication link. The channel quality measurements are transmitted to the source radio in the ACK or NACK. Upon receiving the ACK or NACK, the source radio learns the value of the channel quality information. Each channel quality measure, combined with the available channel quality history, is compared against a set of thresholds. Based on these thresholds and on the previous transmission parameters, the source radio will propose a power level and information rate for the next transmission to the given destination. The channel quality information for the current transmission and the transmission parameters for the next transmission are stored for use in transmitting the next packet addressed to that destination radio.

V. OPTIMIZATION PROCESS

The performance of the adaptive protocol is significantly influenced by the choices in the design parameters, or *control factors*. These design parameters, listed in Fig. 4., include the time period T_d during which channel quality information is considered valid and the number of previous attempts N_A from which the channel quality measurements should be used to estimate the channel quality of a given link. The control factors also include the various threshold levels against which the channel quality information (SNR, BER, number of tracked paths, and PDSQ) is compared. The performance of the adaptive transmission protocol also depends on uncontrollable factors such as interference on the channel, communication range, traffic load variance, and statistical

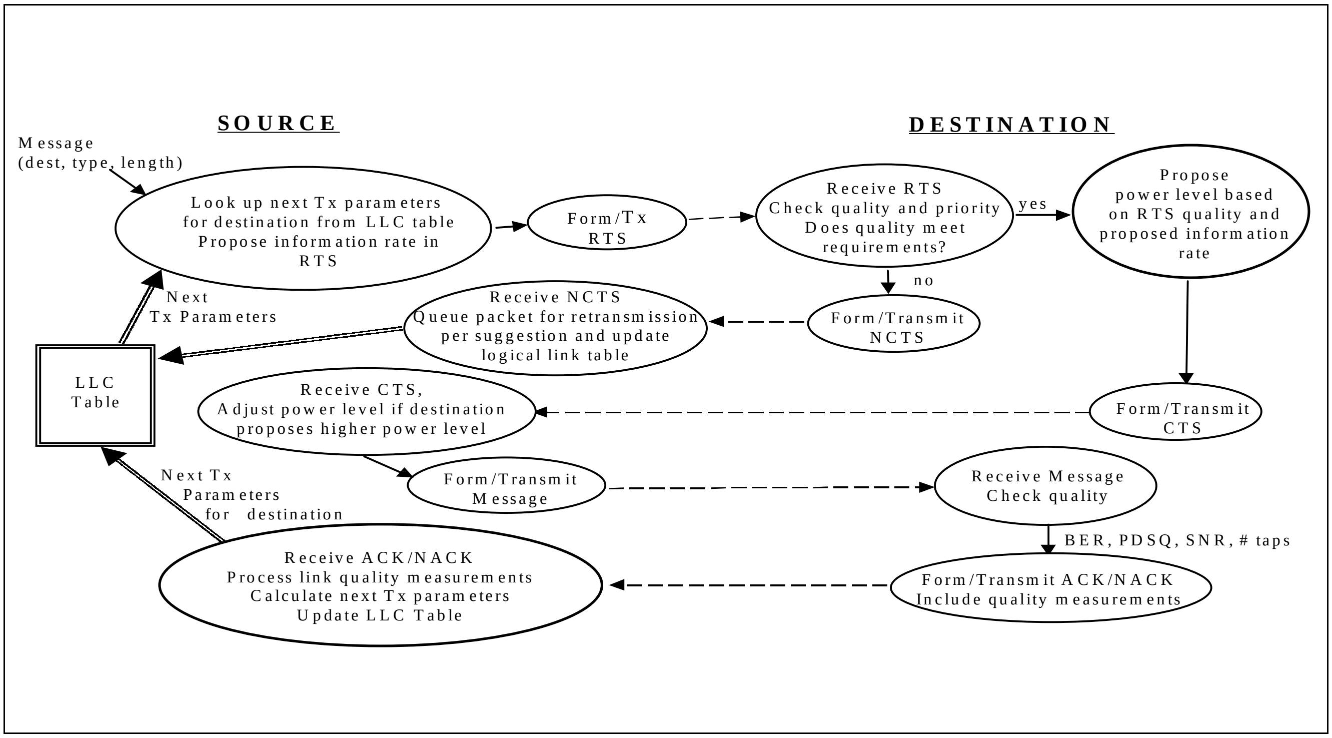

Fig. 3. Overview of adaptive transmission protocol.

variations of the radio's electrical performance. In the discussion that follows these uncontrollable factors are referred to as *noise factors*. The parameters used by the adaptive transmission protocol to choose the optimum power level and information rate are referred to as the *signal factors*.

We will utilize the Taguchi methods to efficiently optimize the performance of the adaptive transmission protocol. The Taguchi methods are designed to minimize the number of necessary experiments in the optimization process, as well as, the sensitivity of the protocol to variations in the noise factors. A parameter diagram, or *P-Diagram*, is used to represent, in an input/output format, the system's function and all of the influential factors on performance. The P-Diagram for the adaptive transmission protocol is illustrated in Fig. 4. The *system response function* is the metric used to measure the performance of the adaptive transmission protocol. The goal of our protocol is to maximize the number of successful information bits at the output of the decoder per unit energy; we will refer to this metric as the *throughput efficiency* [2]. Another measure of interest is the *throughput rate* [2], defined as the average number of successful information bits received at the decoder output per unit time

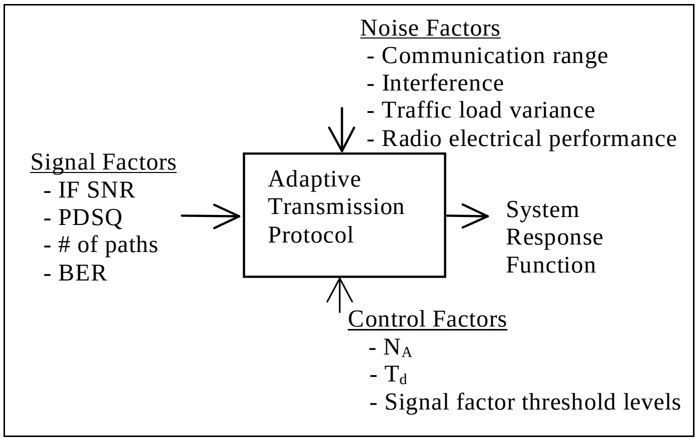

Fig. 4. P-Diagram for adaptive transmission protocol.

VI. MODELING RESULTS

The performance of the adaptive transmission protocol is evaluated for a simple, two-node network, where only one of the radios is transmitting information packets. We refer to the transmitting radio as the *source radio* and the receiving radio as the *destination radio*. The communication link between the source and destination radios is characterized as an AWGN channel with moderate path loss. No other types of interference are present. The path loss model, derived from the Longley-Rice program [8], represents smooth terrain at an operating frequency of 2.4 GHz. The distance between the source and destination radio is varied in discrete steps of 50 meters, for a total range of 50 to 3400 meters. Approximately 300 packets are sent at each distance. The destination radio may be receiving a packet while moving. Fig. 5 and Fig. 6 illustrate the throughput efficiency and throughput rate as a function of distance, respectively. The sharp increase in throughput efficiency from 50 to 100 meters is due to routing initialization and stabilization of the adaptive transmission protocol. By default, the transmit power level is initialized to the maximum power level and the information rate is initialized to the maximum information rate at the beginning of the simulation. Fig. 5 illustrates that the throughput efficiency decreases as distance increases due to increases in transmit power. Similarly, Fig. 6 illustrates that the throughput rate decreases as distance increases due to decreases in the information rate.

VII. CONCLUSIONS

In this paper, we have defined a set of adaptive protocols for controlling the symbol transmission rate, error control code rate, and transmit power within in a packet radio network. We have conducted a set of experiments to illustrate the performance of the adaptive transmission protocol in the presence of AWGN and path loss that increases as a function of distance. The focus of this optimization process is to maximize the information throughput per unit of energy expended under statistically varying link conditions. The performance of the protocols is shown to be highly dependent on the accuracy with which link conditions can be estimated and radio parameters can be controlled. We will investigate the performance of this protocol in different interference environments and apply the Taguchi methods to optimize the performance of our protocol over a variety of channel conditions. Detailed results illustrating the performance of the protocol in different interference environments will be presented at the conference. It is our intent to expand this investigation, as part of the GloMo contract, by applying the same Taguchi techniques to the optimization of adaptive routing protocols which will be necessary to respond to the adaptive link layer protocols. The performance of the adaptive routing protocols will be measured on the basis of energy expended for successful packets, on an end-to-end basis, within a network of HMT terminals.

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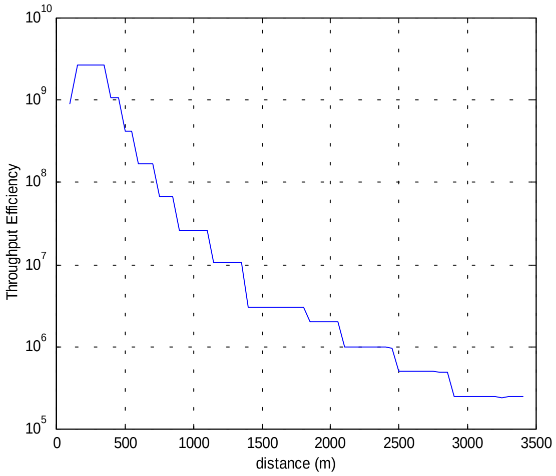

Fig.5. Throughput efficiency of adaptive transmission protocol as a function of distance for an AWGN channel.

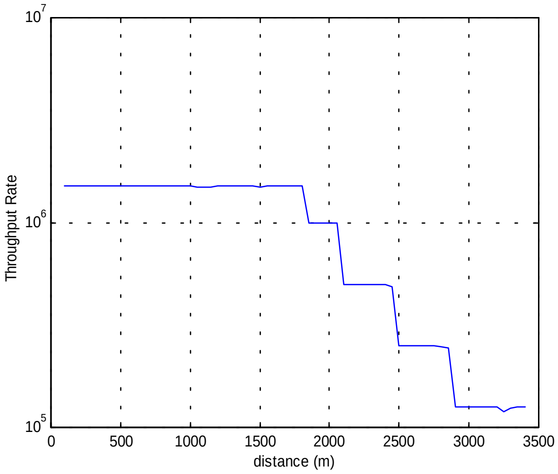

Fig. 6. Throughput rate of adaptive transmission protocol as a function of distance for an AWGN channel.