

# Combined Routing, Channel Scheduling, and Power Control in Packet Radio Ad Hoc Networks with Cellular Overlay

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**Abstract**— We present the development of a framework for a high capacity wireless network for Internet applications. By replacing some of the network nodes with wireless routers, we form a wireless multihop network overlaid on a cellular structure. This paper addresses the problem of jointly optimizing routing, channel scheduling, and power control to maximize the total system throughput under a transmit power constraint. We demonstrate that by considering the interrelationship among the network, data link, and physical layers, we increase the network throughput. The work is based on minimizing a defined objective function which includes the cost related to the transmit power for emptying the buffer with a certain amount of information and the selected route to the final destination.

## I. INTRODUCTION

In recent years, wireless communications, most notably wireless telephony, has experienced tremendous growth, and it is expected that wireless access to data services and the Internet will show similar expansion in the near future. A promising method for wireless access to both data and multimedia services is to integrate an ad hoc network with the expansive cellular infrastructure [1], [2]. This allows for any mobile station (MS) to act as a relay in routing/forwarding packets toward any base station (BS) in the upstream and toward other mobile stations in the downstream. For clarity and without loss of generality, we assume here that the terminal and router functions are assigned separately to individual entities in the radio network. Hence, a router will not be a source or destination for traffic and is likely located in the network randomly.

This multihop structure can result in higher data rate support by additional processing of the information on the network [3]. In [4], [5], the authors have derived algorithms for power control in a conventional cellular network in which an array of modes (transmit power level, modulation method) is selected based upon the current state of the system. The algorithm is based on minimizing the average cost until the buffer of the node empties. This approach, appropriately formulated to include relevant dynamic system variables, may load-balance an overlaid ad hoc network by minimizing the total path cost. This, in turn, yields higher throughput.

The optimum solution for the problem of maximizing throughput in multihop networks is a strategy which jointly designs techniques and algorithms for physical, data link, and network layers. More specifically, this strategy determines the following decision variables:

- the techniques and technologies to be used in receivers and transmitters,
- to whom the transmission should be addressed,
- which channels to use for transmissions and receptions,
- the amount of information to be transmitted on each channel, and
- the transmit power level.

The optimum solution for these decision variables depends on: 1) the available information on the network, 2) system constraints and 3) defined objective function. Available information to receivers and transmitters may include knowledge of traffic characteristics, statistics of the interference, propagation losses between different nodes, and so on. Constraints may include maximum transmit power of each node, maximum acceptable delay for different types of traffic, or maximum probability of error. The objective function could be defined in several ways in order to minimize network resources (e.g., total transmit power), maximize system throughput, minimize interference, or maximize total expected forward progress.

The optimum transmission strategy is defined as: *the strategy which satisfies all the constraints while utilizing all the nodes' knowledge of the network to optimize an objective function*. By describing the problem in this way, we can formulate it based on dynamic programming, a method which admits a distributed and potentially scalable implementation.

## II. SINGLE LINK CAPACITY

Consider a data block with duration  $T_s$  sec to be transmitted on a channel with bandwidth  $W_s$  Hz and coherence time  $T_{coh}$  sec =  $1/B_d$  with  $B_d$  as the Doppler frequency. When the fading process is ergodic in time, ergodic capacity is defined if the transmission time is long enough to reveal the long-term ergodic properties of the fading (i.e., if  $T_s \gg T_{coh}$ ) [6]. However, in packet cellular networks, where interference

is changing from slot to slot, the ergodic Shannon capacity can no longer be used for transmission of each packet. In this case, capacity can be defined for any instance of the channel state random variable, and to efficiently utilize the channel, use of variable-rate, variable-power transmission is a must.

#### A. Power-Constraint Capacity

In this section, we discuss the capacity of a general finite-state channel to provide insight into the methods for optimizing network capacity. We restrict our attention to flat fading and assume that perfect channel state information (CSI) is available to both transmitter and receiver. This is a practical assumption for slowly varying channels. In practice, for the transmission of each packet, path loss and shadowing loss are known to both the transmitter and the receiver; however, the fading information is only known to the receiver with some delay and noise, both of which depend on the channel estimation technique. The terms of the fading which vary too quickly and cannot be fed back to the transmitter are considered in the ergodic Shannon capacity formula.

Now consider a fading channel and let the slowly varying part of the path loss level be denoted by  $\Gamma$ . For each value of  $\Gamma$ , the standard Shannon capacity, calculated based on the distribution of the quickly-varying component of the path loss, can be used. In this paper, we neglect this quickly-varying component and model the interference from other CDMA channels as AWGN. Let  $P_n$  denote the average power of AWGN at the receiver and  $P_{T,avg}$  the average transmit signal power. We define  $\gamma = \Gamma/P_n$  with a known distribution  $p(\gamma)$  and let  $P_T(\gamma)$  denote the instantaneous transmit power as a function of channel variation  $\gamma$ .

Capacity optimization is usually subject to an average power constraint  $P_{T,avg,max}$ :

$$\int_{\gamma} P_T(\gamma)p(\gamma)d\gamma \leq P_{T,avg,max}. \quad (1)$$

With this average power constraint, as shown in [7], the channel capacity, in terms of bits-per-second-per-Hertz, when CSI is available both to the transmitter and the receiver can be written as:

$$C(P_{T,avg}) = E[C(\gamma)] = \int_{\gamma} C(\gamma)p(\gamma)d\gamma$$

$$P_T(\gamma): \int_{\gamma} P_T(\gamma)p(\gamma)d\gamma = P_{T,avg} \int_{\gamma} \log_2(1 + P_T(\gamma)\gamma)p(\gamma)d\gamma \quad (2)$$

in which the maximization is over all the transmit strategies with the same average transmit power. Therefore, the optimum transmit power to achieve maximum capacity is [7]:

$$P_T(\gamma) = \begin{cases} \frac{1}{\gamma} - \frac{1}{\gamma_0}, & \gamma \geq \gamma_0 \\ 0, & \gamma < \gamma_0 \end{cases} \quad (3)$$

where  $\gamma_0$  is a function of the average transmit power and distribution of  $\gamma$  and must satisfy the power constraint.

The distribution of  $\gamma$  is independent of transmit power, and therefore, by knowing the required capacity,  $\gamma_0$  can easily be obtained. In the optimum power strategy when the fading coefficient is below a threshold, no power is transmitted. Thus, for the time that the signal is severely faded no power is wasted in transmitting data. Above the threshold, the transmission power is directly proportional to the fading coefficient. To achieve this capacity, a variable-rate, variable-power communication technique is needed. For each value of  $\gamma$ , a different codebook with rate  $\log_2(1 + P_T(\gamma)\gamma)$  and power  $P_T(\gamma)$  must be used.

#### B. Dynamic Programming-Based Formulation

In this section, we reformulate the problem of power-constraint capacity by employing dynamic programming (DP). This technique is general since it can consider different types of constraints and objective functions. As a DP problem, the capacity calculation based on Shannon's formula can be expressed in terms of the following constraints and objectives:

- Considering  $C$  bits/sec as the average required capacity, the constraint is to transmit  $CT$  bits of information in  $T$  sec when  $T$  goes to infinity.
- The only system resource is the total transmit power.
- The objective is to obtain the optimum power strategy which minimizes the total transmit power.

In other words, in the classical approach, we are maximizing the total information transfer with a fixed amount of power. However, in the present statement of the problem, we minimize the total transmit power for a fixed amount of information transfer. It is clear that if power and capacity have a one-to-one relationship, the solutions for the above two methods will be the same.

Since we typically have statistical information about the channel and the source, cost functions must be defined based on weighted sample averaging. The aim of this strategy is to find the optimum transmission rate and power to maximize the channel throughput based on the actual required traffic rate.

Unlike the method in [5], we assume that all packets have the same time duration. However, they may use different modulation/coding schemes to carry different number of information bits. In each time slot, a transmitter/receiver pair must first negotiate on the communication mode prior to packet transmission. A communication mode is defined as a transmission scheme which can carry a certain amount of information successfully. To obtain a network capacity formula independent of the actual implementation of the modulation/coding schemes, for each value of SNR, we use the Shannon capacity formula for the achievable data rate which can be successfully transmitted through the channel.

Each packet is transmitted in one slot duration and time slots are indexed by  $n \in \{1, 2, \dots\}$ . The transmit power in each time slot is considered as the cost function. Let  $J(b, \gamma)$  be the minimal average cost until the queue is empty, given that currently there are  $b$  bits in the buffer and the channel variation is  $\gamma$ . We assume that interference level  $I$  takes independent values in different time slots with the identical distribution  $f_I(i)$ . Therefore, assuming a data block with duration  $T_s$  sec to be transmitted on a channel with bandwidth  $W_s$  Hz, the cost function can be written as:

$$J_n(b_n, \gamma_n) = \min_{P_T(b_n, \gamma_n)} \{P_T(b_n, \gamma_n) + \int_0^\infty J_{n+1}(\max(0, b_{n+1}), \alpha(i)) f_I(i) di\} \quad (4)$$

$$b_{n+1} = b_n - W_s T_s \log_2(1 + P_T(b_n, \gamma_n) \gamma_n)$$

In a CDMA system with processing gain  $L$ , and background noise with one sided power density  $N_0$  J/s/Hz,  $\gamma$  can be written as:

$$\gamma = \frac{\Gamma}{W_s N_0 + i/L} \quad (5)$$

The use of the max function in (4) will ensure that we exclude the transmit power values which could transmit more than the amount of information in the buffer. Note that if the transmit power results in negative values of  $b_{n+1}$ , the associated cost will be zero, and the optimization will produce the minimum power required to make  $b_{n+1}$  equal to zero.

The terminal cost  $J_N$  is the required transmit power to empty the buffer at slot  $N$ . This also guarantees the exclusion of the all zero trivial answer for  $P_T$ :

$$J_N(b, \gamma) = \frac{2^b - 1}{\gamma} \quad (6)$$

Fig. 1 shows the convergence of the DP problem for different values of  $N$  to the calculation as in (3). The power strategy is obtained for a uniform distribution of  $\gamma$  in the range of  $[.5, 1]$  and capacity is set to  $C = .25$  b/s/Hz.

### C. Power-Constraint Capacity: Known Input Traffic

Unconsidered in the algorithm thus far is input traffic. The goal of the routing strategy is thus adjusted to emptying, within  $N$  time slots, the current buffer size  $b$  as well as the average amount of information that will arrive between slots 1 and  $N - 1$ . Note that the location of the router or MS will be a factor, as the input traffic process will undoubtedly be a function of BS proximity. (Even if the distribution of the traffic were assumed constant, the rate of traffic arrival would be greater for a router near a BS.) Assuming input traffic distribution  $f_\Lambda(\lambda)$  and that the input rate  $\lambda$  (in bits/slot) could

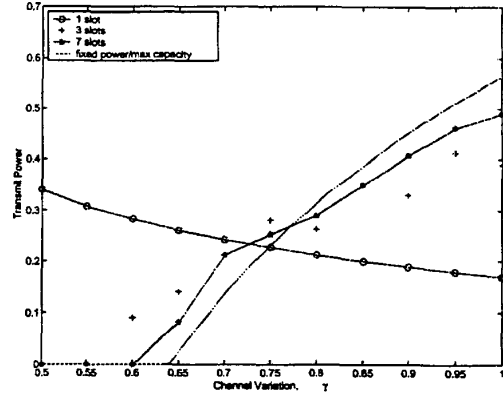


Fig. 1. Optimum transmit power, when system is trying to empty the queue of size  $.25 * N$  in  $N$  slots.

range over all positive values, the algorithm would be modified as follows:

$$J_n(b_n, \gamma_n) = \min_{P_T(b_n, \gamma_n)} \{P_T(b_n, \gamma_n) + \int_0^\infty \int_0^\infty J_{n+1}(\max(\lambda, b_{n+1}), \alpha) f_I(\alpha) f_\Lambda(\lambda) d\alpha d\lambda\} \quad (7)$$

$$b_{n+1} = b_n + \lambda - W_s T_s \log_2(1 + P_T(b_n, \gamma_n) \gamma_n)$$

### III. OPTIMUM TRANSMISSION STRATEGY

In this section, we present a routing strategy for the multi-hop cellular network based on the above results. We consider only the case that interference is unresponsive to the transmitter actions and assume that each node measures the distribution of the interference at its neighboring receivers based on the samples of the previous slots.

#### A. System Model

Two frequency bands are assumed to carry the information on the upstream and downstream independently using code division multiple access (CDMA). The upstream and downstream transmissions may involve multiple routers in which packets are relayed in the same frequency band using a time division duplex (TDD) scheme. Note that due to the high power level difference between transmitted and received signals, simultaneous transmission and reception in the same frequency band is not practical. All nodes are required to be synchronized in order to reduce packet collisions, but practically, exact synchronization is only necessary within the range of a few hops.

Terminals and routers may send and receive on several dynamically assigned spreading sequences. We assume that the terminals and routers have the information on which channels to listen to and on which channels to transmit their data. We assume that each node can transmit variable bit rate packets, and for simplicity, packets can bear any continuous amount of information. Furthermore, each node has access to the following information: queue size; transmit power; list of possible next hops with their link propagation losses, induced interference, and cost (defined below); incoming traffic rate; and total induced interference. We also assume that routers select their transmit or receive mode randomly and nodes exchange this information as well.

### B. Formulation

The optimization strategy is based on minimizing an objective function on a slot by slot basis. Minimizing this function will give us the next hop, transmit power level, and the amount of information in bits to transmit. In each time slot, we define a cumulative cost for each node with the following components:

- overhead cost, a function of the Shannon capacity with arguments of transmit power and aggregate interference at the receiver,
- transmit power cost, and
- next hop cost, the cost associated with the neighboring node with minimum cumulative cost.

Based on the previous formulation and for the simple case that interference level is independent from slot to slot, the cost associated with a node  $i$  at time slot  $n$  can be written as:

$$J_n^{(j)}(b_n, \gamma_n^{(j)}) = \min_{P_T(b_n, \gamma_n)} \left\{ J^{(j)} + P_T(b_n, \gamma_n^{(j)}) + \int_0^\infty J_{n+1}^{(j)}(\max(0, b_{n+1}), \alpha^{(j)}(i)) f_I^{(j)}(i) di \right\}. \quad (8)$$

$$b_{n+1} = b_n - W_s T_s \log_2 \left( 1 + P_T(b_n, \gamma_n^{(j)}) \gamma_n^{(j)} \right)$$

where  $\gamma_n^{(j)}$  is the fading coefficient over the noise power at neighbor node  $j$ ,  $J^{(j)}$  is the current cost at this neighbor based on its current queue size and selected next hop, and  $\Gamma^{(j)}$  is the fading coefficient to node  $j$ . The next hop for node  $i$  at time slot  $n$  is then given by:

$$Next\ Hop_n^{(i)} = \arg \min_j J_n^{(j)}(b_n, \gamma_n^{(j)}) \quad (9)$$

This algorithm is clearly dynamic and is expected to converge to an optimal solution after a small number of time slots.

For the general case, the statistics of the arrival process for each node needs to be carefully considered. Depending on

the type of traffic, source traffic at a terminal may or may not be independent from its link capacity. Even if we assume that source traffic and link capacity are independent for terminals, the statement is not true for routers. Based on our strategy, as the cost from a router increases, the number of packets forwarded to it are reduced.

### C. Algorithm Implementation

The algorithm presented above was implemented in a three-step process: periodic updating of cost and interference values of one-hop neighbors, calculation of optimal routes for each nodes, and forwarding of packets to the specified next hop.

First, a table of routing cost and induced interference values of neighboring nodes is updated every  $m$  time slots. In this context, a neighbor is defined as any router or BS that is within one hop from the given transmitting node. For simplicity, the one-hop transmission range has been set to be a factor  $\kappa$  times the cell radius, defined as the maximum distance between a BS and cell edge, for both routers ( $\kappa_R$ ) and mobile stations ( $\kappa_{MS}$ ). As base stations are the terminal point of packets, base stations report to all neighbors a cost of zero. An example cost/interference (C/I) table for a transmitting station is shown in Table I.

Neighbor	Cost	Interference	Time Slot
ROUTER #3	10.57	0.23	2
BSTATION #11	0	0.56	2
...	...	...	...
ROUTER #23	25.56	1.23	2

TABLE I  
EXAMPLE COST/INTERFERENCE TABLE

Next, the optimal routes are determined according to the optimization in (8) and (9). The optimization itself is performed at the onset of the algorithm for values of  $b$  and  $\gamma$  within expected ranges. A look-up table is thus produced which specifies the optimal transmit power, amount of information to transmit, and the minimum cost as a function of  $b$  and  $\gamma$ . Each transmitter consults the table using its current value of  $b$  and the values of interference recorded in the C/I table. (The interference values are converted to  $\gamma$  values using (5).) The sums of these look-up costs and the costs recorded in the C/I table represent the total costs of transmission to the one-hop neighbors; the neighbor that produces the minimum total cost is identified, yielding the next hop, power, and amount of information. An example routing table is presented in Table II.

Finally, packets are forwarded to the determined next hop for the current time slot. As usual, for any hop in the network,

Next Hop	$P_T$	Information	Cost	Slot
ROUTER #5	0.78	0.68	12.25	1
BSTATION #11	0.55	0.20	5.64	2
ROUTER #2	0	0	20.5	3
...	...	...	...	...

TABLE II  
EXAMPLE ROUTING TABLE

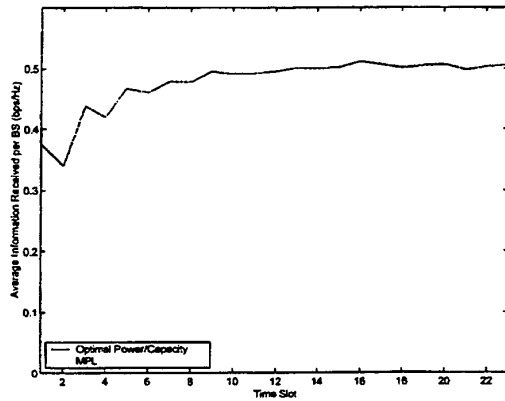


Fig. 2. Time evolution of average BS throughput for optimal power/capacity routing and MPL routing with transmission directly to the BS. (See text for parameters.)

the capacity of each channel limits the actual amount of information which may be transmitted reliably regardless of the amount of information optimally determined to be sent.

#### IV. RESULTS

Preliminary simulation results are presented in this section. Fig. 2 illustrates the performance of the algorithm in the case for which transmissions only to base stations are allowed (i.e., No routers are included.). In Fig. 2, the average BS throughput versus time is depicted for the optimal power/capacity routing scheme. The relative density of mobile stations to base stations was set to 10, and in each time slot, the probability of a packet arriving at an MS was 0.3. The optimization was performed over 8 time slots, and 10 Monte Carlo samples were averaged. For comparison, the minimum path loss (MPL) case is presented as well. In this scheme, which is representative of traditional cellular system operation, packets are forwarded to the BS for which the path loss observed is lowest. As can be seen from Fig. 2, the average throughput of the optimal routing strategy exceeds that of the MPL case by approximately 33% in steady state.

#### V. CONCLUSIONS

We have presented a multi-layer framework for an ad hoc wireless network with cellular overlay. Although the precise performance improvements will depend on density of routers, definition of cost functions, and other system parameters, this structure has the potential of increasing the throughput and highly reducing the total transmit power.

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