Self-Organizing Packet Radio Ad Hoc Networks with Overlay (SOPRANO)

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ABSTRACT

The SOPRANO project involves a novel adaptive and scalable wireless network architecture utilizing a mixture of cellular and multihop packet radio system topologies with the potential to support a variety of applications including high-data-rate Internet and multimedia traffic at a reasonable degree of implementation complexity. This article discusses the potential benefits of this structure and addresses several relevant issues necessary to support such a network. More specifically, it focuses on connection establishment and self-organization, investigates the formulation of an optimum transmission strategy, and examines some of the techniques by which we can augment the capacity or enhance the system performance in this multihop network. We also present capacity bounds that illustrate how these techniques help in trading off conserved power for a multifold capacity advantage.

INTRODUCTION

Ad hoc wireless networking is expected to play a major role in nomadic computing and communications in the home, office, and many other venues. Such networks will not have the luxury of a centralized node for allocating channels, controlling usage, or provisioning of services. Rather, they will need to be adaptively self-organizing. The protocols for doing so are fundamentally complex. Moreover, the problems are compounded by a wireless medium rife with interference, multipath, fading, obstructions, and limited bandwidth, particularly when a wide area of coverage is considered.

A wireless multihop network can be defined as a collection of wireless nodes that are located dynamically and randomly and form the network routing infrastructure in an ad hoc fashion. Terminals in this type of network mainly rely on short-lifetime batteries; therefore, energy conservation is a critical design criterion. The high propagation loss on radio links normally requires high power at the transmitter and hence high total consumed power. Because of the power law path loss, the transmit power may be reduced by breaking down the distance between two communicating points into smaller segments.

Considerable research and development has been undertaken to provide wireless access capability for local data networks. Recent published standards for wireless local area networks, referred to as IEEE 802. 11, Bluetooth, and HiperLAN2, exemplify the progress made to date. Ad hoc networking has been considered in the systems above to provide rather simple connectivity. Furthermore, an extended-range mobile connectivity based on multihop technology has also been taken into account. However, these technologies, whether single or multihop, are designed with a limited range of operation. When extended in range and scaled for a large number of users, all of the issues stated above combine to produce a formidable task for the designers of such networks to provide for adequate capacity, quality of service (QoS), reliability, and implementation complexity to make them viable.

Aside from the original military application of multihop networks, which traces its roots to the packet radio network project [1], there has been great interest in several arenas: sensor networks, appliance networking, and wireless Internet. One of the recent attempts to deploy this technology for wide-area high-speed mobile wireless access to the Internet was the Ricochet system developed by Metricom [2]. This system provided its customers in major metropolitan areas with access to the Internet at data rates up to 128 kb/s. The predictions on the proliferation of handheld devices and notebook computers with wireless access needs were major drivers for early development of the network. Unfortunately, a number of factors, including the prevailing unfavorable economic conditions at the time of network expansion and other technical system design aspects, prevented the company from sustaining its business model and resulted in the shutdown of services. In

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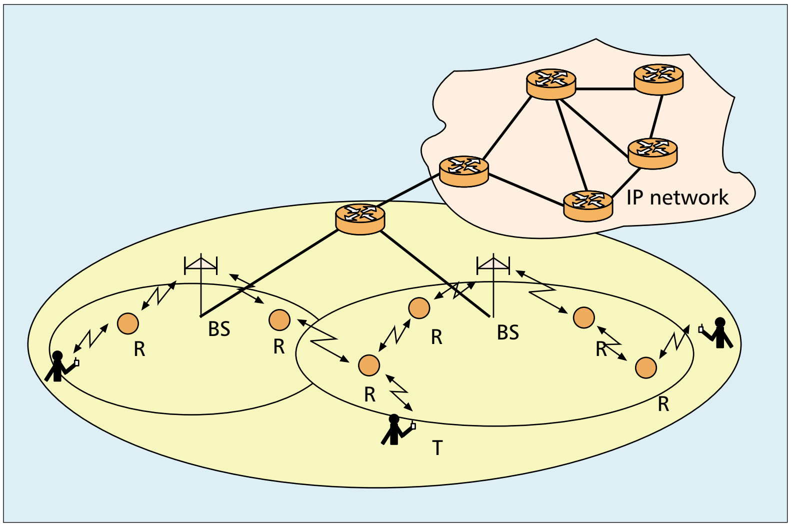

Figure 1. *Network structure: base stations (BS), routers (R), and terminals are distributed uniformly in the network. Terminals in a cell might transmit to a base station in another cell based on the routing strategy.*

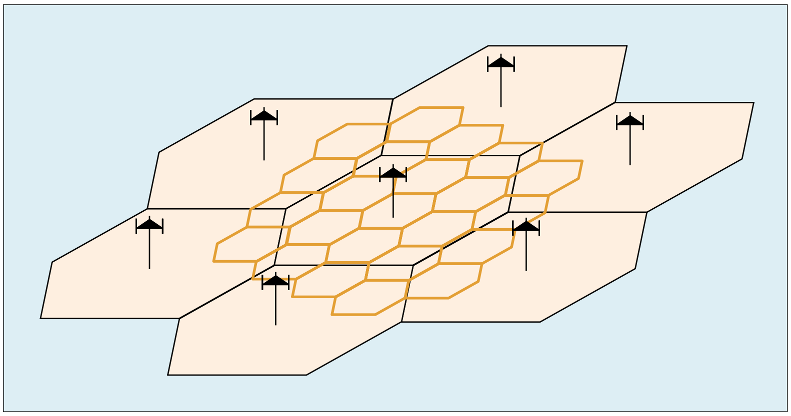

Figure 2. *By shortening the distances by cell splitting, more channels are available in the network and path losses are reduced.*

third-generation cellular networks, an example of multihop technology is given by "opportunity-driven multiple access (ODMA)"which is an option in 3GPP — time-division duplex wideband code-division multiple access (TDD WCDMA) — for extended coverage for high-data-rate services.

In this article, a wireless multihop network overlaid with a cellular structure is proposed to combine the advantages of both cellular and ad hoc networks [3] (Fig. 1). The advantages of using such a structure include:

- Increasing robustness and scalability of the system
- Supporting dynamic topology through packet radio
- Load balancing in the network due to routing opportunity
- Extending the cell coverage area
- Providing a broad connectivity based on multihop technology
- Exploiting spatial diversity through adaptive routing
- Reducing the total consumed power
- Increasing the network capacity

We discuss the potential benefits of this structure and the related issues necessary to support such a network. More specifically, the article focuses on connection establishment and self-organization, investigates formulation of optimum transmission strategy, and examines some of the techniques by which we can augment the capacity or enhance the system performance in multihop networks.

Realizing the full potential of the allocated bandwidth will require taking advantage of new proposals for coding and space-time processing for radio links. In a multi-user system, link capacity can also be increased by techniques such as interference cancellation and multiuser detection. As more information on the whole network is available, medium access techniques and routing strategies can highly increase the total capacity. We mention some of these techniques with an eye toward their possible deployment without attempting to be specific about their actual implementation at this early stage.

CAPACITY INCREASE BY THE CELL SPLITTING TECHNIQUE

Multihop cellular structure can be described well by analogy to the cell splitting technique. Cell splitting results in two benefits:

- Channel increase in space
- Power loss reduction

Figure 2 shows the case of splitting one cell into a number of smaller cells. Scaling down the cell area does not affect the number of channels per base station. Therefore, the total number of channels in space, and hence the network capacity, can be linearly increased proportional to the number of new base stations or the scaling factor. Shortening the links reduces the required transmit power per hop. However, in interference-limited systems this path loss reduction cannot increase the network capacity since power scaling does not increase the signal-to-interference ratio (SIR).

The problem with cell splitting is that small cells are not often desirable, since base stations and their interconnections to the wired backbone are costly. In multihop cellular, new base stations are replaced by wireless routers to establish a multihop wireless network. Routers establish the path between mobile terminals and base stations subject to the constraints and requirements imposed by the network. The routers are not considered part of the fixed network infrastructure, and thus, radio resources are needed to be used for their interconnections to the base stations.

In reality, one may consider selected mobile terminals to act also as routers, provided that they have within them the necessary routing and relaying functionalities. Here, for clarity and without loss of generality, we assume that the terminal and router functions are assigned separately to individual entities in the radio network. Hence, a router node will not be a source or destination for traffic, and it is likely located in the network randomly.

In this structure, in both the upstream and downstream, traffic concentration is higher toward the base stations due to packet relaying by routers. Since channel increase is per unit area and not per base station, the base stations are still bottlenecks for system throughput. Additional processing of the information on the network is required in order to benefit from the two properties of cell splitting to increase capacity.

NETWORK ARCHITECTURE AND SELF-ORGANIZATION

In this section we present a simple structure for the network and briefly explain self-organization issues. The upstream and downstream transmissions may involve multiple routers; thus, routers must be able to receive on all the channels on which they transmit. Also, note that due to the high power level difference between transmit and receive signals, simultaneous transmission and reception in the same frequency band is not practical. Thus, from an implementation point of view, the simplest practical way of creating transmit and receive channels is to use a TDD scheme (Fig. 3).

Although it is possible to employ the same frequency for upstream and downstream, here for clarity, we consider two frequencies to operate in the upstream and downstream directions independently, each in the TDD mode. In each frequency, time is divided into fixed slots, and in each time slot, CDMA is used as the access technique. Inherent fading and the interference averaging effect makes CDMA an attractive access scheme to achieve high system capacity and to implement simpler algorithms for dynamic channel assignment. Nodes may send and receive on several dynamically assigned spreading sequences. Nodes within the range of a few hops are required to be synchronized in order to reduce packet collision. The routers alternate their modes at the end of each slot; hence, other nodes know when they can transmit packets to them.

Two scenarios for traffic have been considered. First, all the communications between wireless terminals are routed through the base stations. Thus, whether a terminal is transmitting (receiving) to (from) a node in the backbone or another wireless terminal, the same connectivity scenario would apply. Therefore, unlike pure ad hoc networks, any of the base stations can be the final destination or the source of each packet for a specified terminal.

Second, communications between nodes within a certain range is considered local traffic and would not route through base stations. In this case, one of the routers in the path needs to switch to downstream frequency. The rest of the scenario is as before.

Self-organization encompasses architecture, algorithms, configurations, and all the means that allow mobile terminals to obtain interconnection to the network and adapt to the environment as changes occur. This includes access, control and service aspects, routing, traffic control, profile management, self-healing, and so on.

The steps in self-organization can briefly be described in the following order:

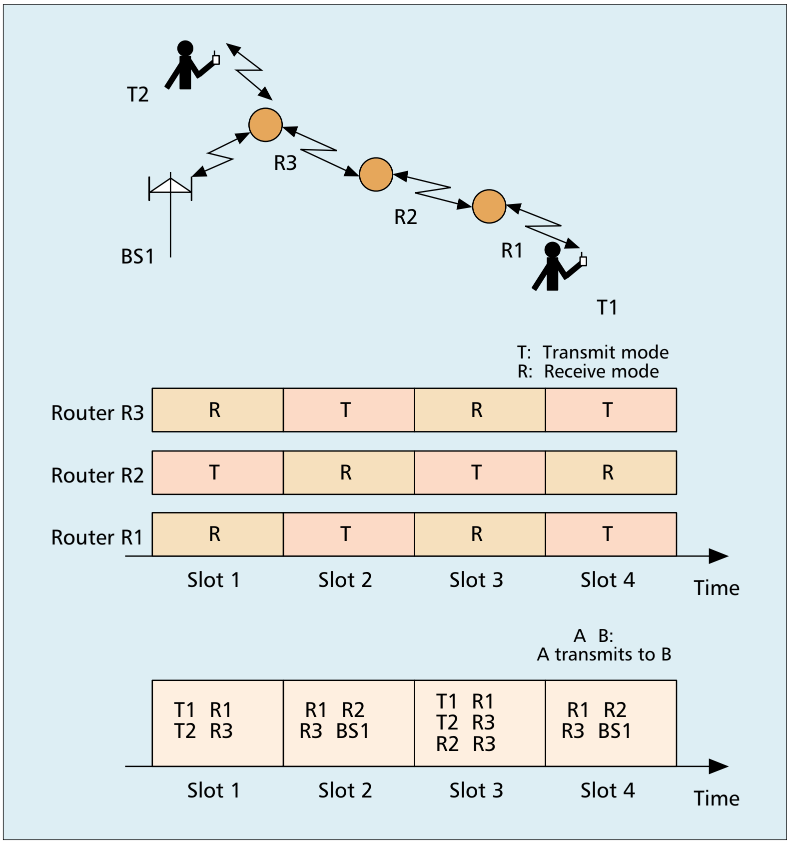

Figure 3. *Packet relaying upstream, assuming terminals T1 and T2 always have some packets to transmit. In each time slot, the neighboring routers are in different modes in order to be able to exchange data.*

Neighbor discovery: When a terminal powers up, it first looks for the neighbors, defined as routers or base stations from which the terminal can receive a carrier signal.

Connection setup: The node needs to register itself to the current network. Location updating for each node and how to find a node in the network will be covered under this item.

Channel assignment: Nodes need to have the information about to which channels to listen and on which channels to transmit their data. In asynchronous CDMA there are usually enough spreading sequences to be assigned for transmission of all packets.

Mode selection: A very important procedure in this structure is how routers plan their transmit/receive modes in different time slots.

Mobility management and topology updating: Since the locations of terminals and routers change over time, propagation losses for different links also change frequently as a result. Therefore, the routing strategy must be able to quickly and efficiently broadcast topology information, dynamically update the status of its links, and reconfigure the routing tables accordingly.

What and how control and routing information is changed: The complexity of the transmission strategy and the required control information that needs to be exchanged between nodes depends on the required performance. Therefore, this step must be optimized after determining the optimum transmission strategy.

The optimum transmission strategy is defined as the strategy that 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 develop a formulation based on dynamic programming.

OPTIMUM TRANSMISSION STRATEGY

"Information theory has not yet had a direct impact on networking" [4]. This assertion has remained true even as the pervasiveness of networks accelerates and research interest is at an all-time high. However, as further noted in [4], the catalyst behind many of the key advances within networking research have originated from information theoretical insights.

Traditionally, the prospectives and aims of information theory and networking have been dissonant [5]. The information theoretic approach typically states the performance of the best possible scheme with simple assumptions for source traffic and a limited set of constraints. Specifically, it ignores the random arrival of messages, and the usual constraint is the average transmit power. In contrast, the networking approach considers more practical assumptions while mostly analyzing the performance of a particular scheme or algorithm. For example, most of the work in cellular networks is based on transmission of packets with fixed coding rate, and the question is how to minimize the interference or the outage probability for different base station selection criteria. In multihop, the main research thrust focuses on comparing different simple forwarding strategies but fails to clearly discuss the capacity of these networks.

For a multihop network, capacity can be defined as the total rate at which information data originated by all sources reaches the final destinations. Therefore, the general problem of maximizing capacity can be decomposed into two related subproblems: maximizing the total amount of information data that can be carried through all links for a given transmit power and minimizing the number of hops required for the data to reach the destinations.

The optimum solution for maximizing network capacity is a strategy that 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
- The transmit power level

The optimum solution for these decision variables depends on:

- The available information on the network
- System constraints
- A defined objective function

The information available to receivers and transmitters may include knowledge of traffic characteristics, statistics of the interference or the exact value of the interference, propagation losses between different nodes, number of packets in the buffers, and so on. Constraints may include maximum transmit power of each node, maximum acceptable delay for different types of traffic, complexity of algorithms, maximum probability of error, or minimum guaranteed information rate. 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.

A simple case is when there is a single transmit and a single receive antenna in a flat fading channel with an average power constraint and perfect channel state information (CSI) available to both the transmitter and receiver. In the optimum power strategy [6], when the fading coefficient is below a threshold, no power is transmitted. Above the threshold, the transmission power is inversely proportional to the fading coefficient. In fact, for the time that the signal is severely faded no power is wasted in transmitting data.

The optimum transmission strategy is defined as *the strategy that 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 develop a formulation based on dynamic programming (DP), a method that admits a distributed and potentially scalable implementation.

In [7], the authors have derived a DP algorithm for power control in a conventional cellular network in which an array of modes (transmit power level, modulation method) is selected based on the current state of the system. The algorithm is based on minimizing the average cost until the buffer of the node empties. This work has been extended in [8]. The strategy is based on minimizing the total transmit power for transmission of a packet from the source to its destination on a slot-by-slot basis and will provide the next hop, transmit power level, and the amount of information in bits to transmit.

CAPACITY AND THE PROTOCOL LAYERS

In this section we discuss the radio channel response for different link types in the system and investigate in more detail how applying different techniques and technologies in the physical, data link, and network layers affect the network capacity.

In a typical cellular radio system, base station antennas are usually elevated well above the local terrain, and there are few local scatterers in their vicinity. Mobile terminals and mobile routers, on the other hand, are surrounded by many different natural and manmade objects, which results in signal reception from many different directions with wide angular spread. Due to this multipath propagation, the transmitted signal from any of the network nodes experiences different delays and thus will spread in time before arriving at the receiver. The scattering environment is subject to constant change, giving rise to time variations in the channel impulse response and, equivalently, frequency spreading of transmitted signals. In general, the transmitted signal has a continuous distribution in space and must be modeled as a stochastic space-time process.

Replicas of a signal arriving from different paths can be considered uncorrelated, and based on the angular distribution of signal power, the space-time correlation function of the signal is obtained.

In a wireless network, the radio channel is typically modeled by the product of three independent components: fading, shadowing, and path loss. Fading describes the multipath effect of the channel and shows the variations of received signal over distances on the order of a wavelength. Shadowing models the slow variation in the mean envelope of the received signal over a distance corresponding to several tens of wavelengths and is well predicted by a lognormal distribution.

Path loss predicts how the mean signal power decays with distance from the transmitter. The simplest applicable path loss model is based on the propagation over a flat reflecting surface. For the case in which the distance between the transmit and receive antennas is much larger than the product of the height of the antennas divided by the carrier wavelength, signal power decays approximately as the fourth power of the distance. As this distance becomes smaller, the path loss tends to be proportional to the second power of the distance. This is a feature that multihop transmission can exploit to reduce power consumption.

In practice, path loss and shadowing loss are known to both transmitter and receiver; however, the fading information is only known to the receiver with some delay and inaccuracy, both of which depend on the channel estimation technique.

With the power control algorithm implemented in existing cellular networks, the effect of shadowing and path loss can be effectively neutralized even with open loop power control. Closed loop power control can be effective against slow to moderate multipath fading; with rapidity of fading there is an increase in residual power control error.

Figure 4 shows typical power conservation for different densities of routers, λ_R, in this type of network. Throughout this article, all the results are based on the transmission strategy introduced in [8] and described earlier. Also, for the configuration of the network and source traffic we assume that terminals generate Bernoulli traffic with probability of transmission .3 and average data rate of 1.5 b/s/Hz. The area is partitioned into regular hexagons with base stations located at their center. Terminals and routers are distributed uniformly in the plane with different per-cell-area densities. It is readily seen from Fig. 4 that increase from 0 to 10 in the density of routers per cell results in a 100 dB decrease in average transmit power. In the following sections, we show how the network can take advantage of this power saving to support higher-data-rate traffic.

THE PHYSICAL LAYER

The main goal here is to reduce the excessive interference due to packet relaying by using more efficient links. As interference due to relaying packets is reduced, routers act like standalone base stations and system capacity is increased proportional to the ratio of routers to base stations the same way as in the cell splitting method.

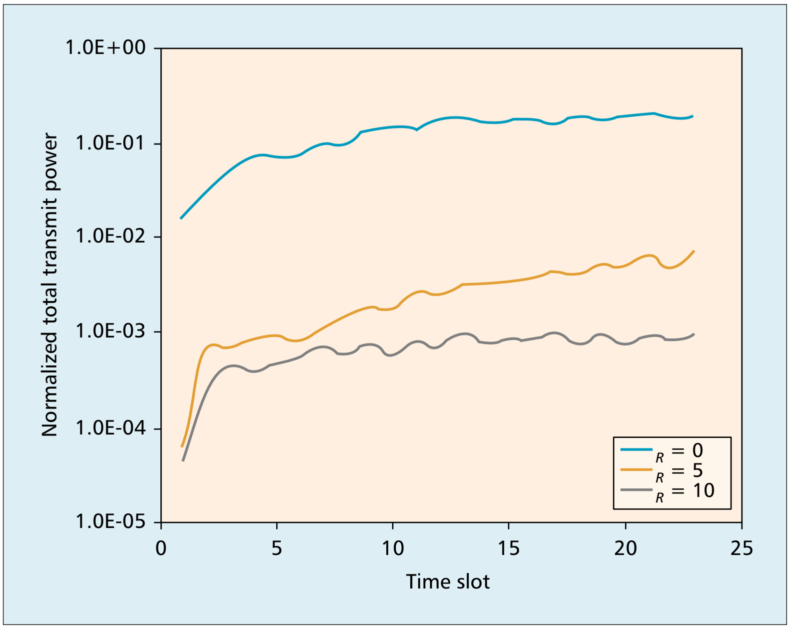

Figure 4. *Normalized total transmitted power as a function of time and for different router densities. Density of routers per cell* λ_R *= 0, 5, 10 and density of terminals per cell* λ_T *= 50.*

Multiple-In Multiple-Out (MIMO) Radio Channels — In bandwidth-limited wireless channels, high-data-rate transmission requires a highly spectral efficient code with large constellation size. As a result, employing this approach to achieve data rates higher than a certain limit on a link is impractical. Another solution is to increase the number of channels between the transmitter and receiver pair by using more antenna elements at each site.

Performance analysis of this method has been investigated based on capacity vs. outage [9]. To better explain this measure, first consider the case in which channel state can be modeled as a stationary ergodic process. This assumption requires the length of the data block to be much longer than the channel coherence time and results in the definition of ergodic Shannon capacity. However, when the channel is time varying but there is no significant change in the channel during the transmission of a data block, the ergodic Shannon capacity can no longer be used. In this case, capacity can be defined for any instance of the channel state random variable. This distribution of capacity gives rise to the notion of capacity vs. outage. Based on this definition, for any given rate there is an associated outage probability that the channel cannot support this rate.

If there are n_R receive and n_T transmit antennas in a flat slowly fading environment, the channel can be described by a (n_R, n_T) matrix H whose ijth element gives the signal amplitude loss from the jth transmit antenna to the ith receive antenna. Let P_0 and P_n denote the transmit signal power and average power of additive white Gaussian noise (AWGN), respectively. When perfect CSI is available at the receiver, Shannon capacity as a random variable can be expressed as [9]

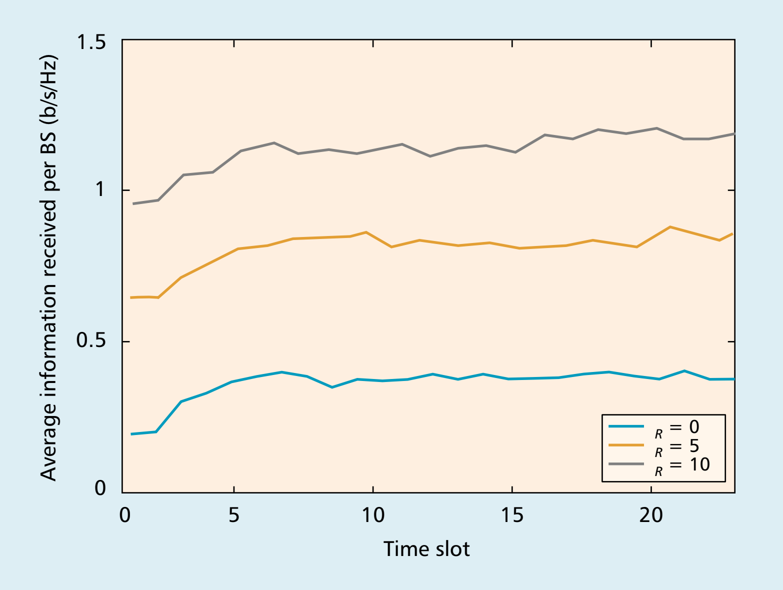

Figure 5. *Time evolution of average BS throughput for optimal transmission strategy for various density of routers, λ_R. Link efficiency for connections among routers and base stations is equal to 10.*

$$C = \log_2 \det \left[I_{n_R} + HH^H \frac{P_0}{n_T P_n} \right], \tag{1}$$

where I_{n_R} is the $n_R \times n_R$ Identity matrix. This method can create up to $n = \min(n_T, n_R)$ parallel channels on which independent data may be transmitted. To maximize this capacity, fading should be as uncorrelated as possible at antenna elements to give a channel matrix with full rank. The principle is that increasing power in a single channel is not as effective as sharing that power between separate channels. For a large number of antenna elements, unlike a single-element antenna, capacity increases linearly rather than logarithmically with increasing signal-to-noise ratio (SNR). As an example, consider the familiar case of one transmit and multiple receive antennas. For this case, Eq. 1 simplifies to

$$C = \log_2 \left[1 + \frac{P_0}{P_n} \sum_{i=0}^{n_R} \left| H_i \right|^2 \right]. \tag{2}$$

This capacity can be achieved by multiplying the input SNR by the antenna gain when array weight vector $\omega = (\omega_1, \omega_2, \ldots, \omega_{n_R})$ is defined as $\omega_1 H_i = \omega_i H_1$ for all i. In the general case, to achieve the capacity limit a nonlinear beamformer is required.

The increased capacity in MIMO radio links is due to two effects. First, by increasing the number of channels, mean capacity is increased almost linearly with the number of antenna elements. Second, by providing temporal, transmit, and receive diversity, channel reliability is highly improved for higher data rates. Consequently, the outage capacity for high availability will increase with a rate higher than the number of created channels. Outage capacity for 95 percent availability at SNR of 10 dB has been reported to reach an order of 40 b/s/Hz with eight element antennas at both transmitter and receiver. This rate is almost 40 times higher than the achievable rate in a single-element antenna link.

Space-time coding is a recently developed technique that takes advantage of the available high capacity in multi-antenna radio links [10]. Because of electromagnetic interaction of antenna elements on small platforms, and the expense and power consumption of the receiver electronics for each antenna, it may not be practical to have multiple antennas on small devices. However, routers that are normally mounted on larger devices with better power supplies can afford highly efficient space-time codes.

Figure 5 shows the effect of increasing the density of routers on network capacity when highly efficient links are established among routers and base stations [11]. For a fixed received power, the ratio of the capacity of the links among the routers and base stations to the capacity of the links with terminals connected at one end is defined as the efficiency factor, η. We have assumed that η is a constant for all values of power. Due to randomness in the locations of routers and also the variance in the number of packets which routers relay, when $\eta = 1$, increasing the density of routers, λ_R, increases the interference variance and thus decreases the system throughput. In other words, when all the network links have the same capacity, power conservation does not result in better performance. As η increases, the higher density of routers improves the throughput. It is seen from Fig. 5 that for an efficiency factor of $\eta = 10$, increasing the density of routers from 0 to 10 will result in 300 percent network capacity increase.

Multi-User Detection (MUD) — In a flat slowly fading environment in which K users are simultaneously transmitting to a receiver, the channel can be described by K random variables ν_i modeling the power loss from the ith user to the receiver. For the case when the receiver has perfect CSI and the transmit power of each user is P_i, the maximum achievable capacity for all users is found to be [6]

$$C = \log_2 \left[1 + \frac{\sum_{i=0}^{K} P_i \nu_i}{P_n} \right]. \tag{3}$$

For a large number of users, this formula is simplified to

$$C = \log_2 \left[1 + \frac{P_{av}}{P_n} \right], \tag{4}$$

where P_{av} denotes the average received power per user. This capacity can be achieved in CDMA systems where the deleterious effect of fading is mitigated by averaging interuser effect.

Orthogonal synchronous CDMA transmissions lose their orthogonality once they go through a multipath, time-varying channel. In asynchronous CDMA, each user transmits on all available dimensions, creating interference for other users. In second-generation CDMA systems this interference is considered noise, resulting in a performance degradation as more users become active in the network. Multi-user detection is a method to obtain the achievable capacity as the co-channel interference increases by receiving more packets from other users. Equation 3 also shows that by increasing the number of transmitted packets, the maximum information each packet can bear is reduced. One effective method to overcome this problem is to use methods like hybrid automatic repeat request (ARQ) where packets are saved at the destination and more parity bits are requested by the receiver until data is decoded. By this method, multirate traffic is generated with the rate changing adaptively based on channel state.

Multi-user detection is an effective technique that can remove the saturation region of capacity vs. SNR, present in conventional detection; therefore, it has the potential to take advantage of the conserved power in multihop networking to increase capacity.

DATA LINK LAYER

In a wireless network, space, time, and frequency are the three main domains that must be shared between different network nodes. Medium access control (MAC) is a set of rules that attempts to efficiently share a communication channel among independent competing users. Its main task is to guarantee data traffic quite close to the capacity limit but not more than that to reduce the probability of outage and increase system throughput. In a multihop wireless network, unlike its wired counterpart, channel scheduling and routing strategy can no longer be considered separately. When transmission is destined to a very close neighbor, only very loose scheduling is needed. On the other hand, if transmission is directed toward a region with many receiving nodes, clever slot assignments can significantly reduce the interference level and result in better performance.

The statistical properties of today's network traffic show a long-range dependency in time and self-similarity characteristics. Thus, traffic measurements at the receiver bear significant information on the traffic dynamics of the network. Different packet types bear different amounts of information and need different SNRs to be detected. Also, QoS requirements, like minimum acceptable rate and maximum delay, add additional constraints to the system that affect the capacity calculation. Just as in the single channel case where capacity is a function of CSI, feeding back system state information (SSI) to the transmitting nodes has a direct effect on the choice of adjustable parameters such as transmission power and data rate to achieve the capacity limits.

Consider a variable-rate, variable-power transmission link in a flat slowly fading channel and assume that perfect CSI is available to both transmitter and receiver. γ is defined as the fading coefficient normalized by average power of AWGN at the receiver. Figure 6 shows the effect of delay-constraint bursty traffic on the optimum transmit power strategy. For each value of γ, the standard Shannon capacity can be used for relating transmit power and the achievable data rate. The power strategy is obtained for a maximum tolerable delay of 7 time slots, a uniform distribution of γ in the range of [.5, 1], with a Bernoulli traffic source with probability of packet arrival equal to 1/8 and an average information rate of .25 b/s/Hz. As seen in Fig. 6, a constraint on the delay makes the transmitter more aggressive as it tries to transmit more data with higher power when there are enough data in the buffer.

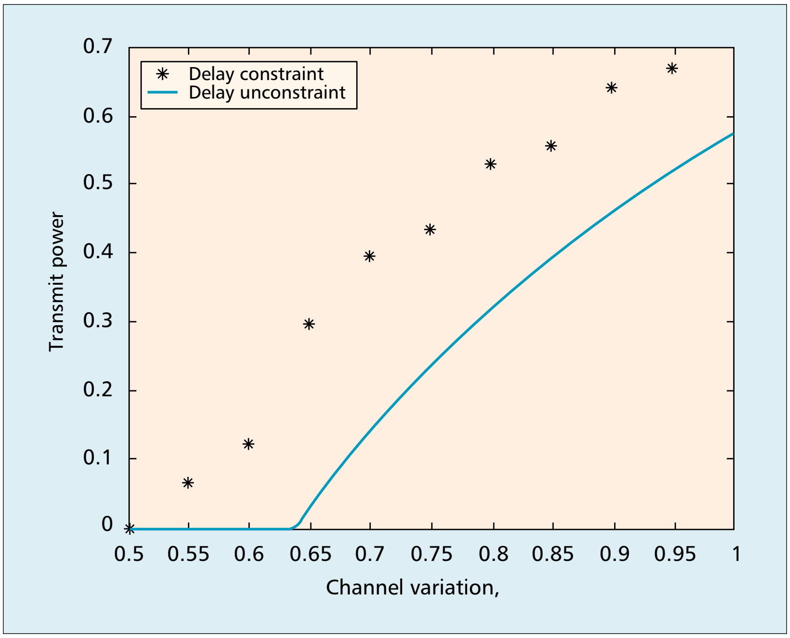

Figure 6. *The effect of a bursty traffic model on the optimum transmit power strategy. With bursty traffic, for all values of γ, the transmitter sends data through the channel more aggressively.*

THE NETWORK LAYER

Routing has a significant impact on the network capacity based on two functions:

- Assigning the transmit power and next hop for each node in a way to increase the number of available channels in the space

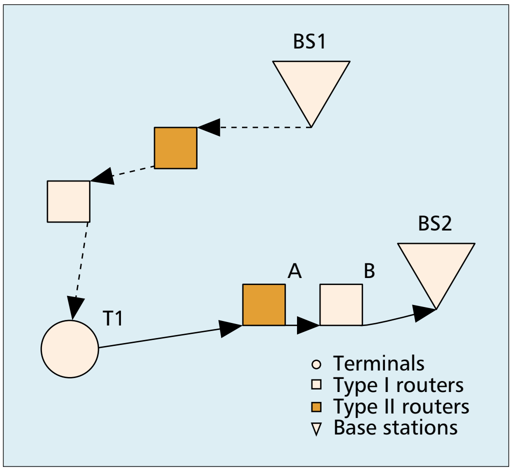

Figure 7. *Transmission in the downlink from BS2 to T1 is not a good choice since transmitting packets from A to T1 creates high interference for the very close router B.*

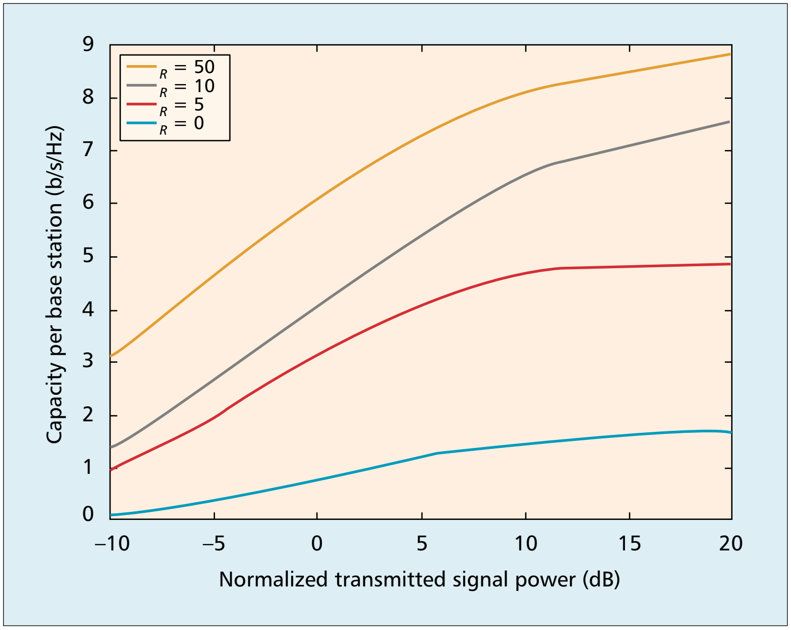

Figure 8. *Capacity per base station as a function of transmitted power for density of routers λ_R = 0, 5, 10, 50 and density of terminals λ_T = 50.*

- Directing the traffic in a way to make information exchange more toward the destination with a smaller number of hops

For any system structure based on transmit power constraint and propagation loss, not all nodes can be connected to each other. Routing helps establish a multihop link between any two nodes of the network, which results in more extended cell coverage.

Although transmission on short hops reduces the interference, simultaneously the network traffic is artificially increased due to so many retransmissions of the same data. Consequently, the optimum strategy must take into account the excess power consumption due to relaying of packets. A complete discussion of an optimum strategy for minimizing the total consumed power was introduced in [12].

When the routing calculation is distributed and information about more than one hop is not available (e.g., each node just listens to pilot signals of all its neighbors to find out each link path loss) transmission to the node that requires minimum power is optimum. If packets keep track of the routers they have visited, each relaying node can avoid creation of loops by deleting the old routers from its possible next hop list.

Note that in a minimum energy protocol we select the node that results in minimum energy for the total path. However, the strategy of minimizing energy is far from optimum for maximizing capacity. Figure 7 shows a structure with asymmetric links and loop-free connections. In each slot, we have categorized all the routers that are in the same mode as routers of types I and II. Since transmission in the forward and backward directions in the link might create different interference levels on the neighboring receivers, some of the links are used as if they are asymmetric. Nodes A and B are the nearest neighbors to each other. However, in the downstream, packets received from B to A cannot be relayed to the terminal, since due to high distance ratio from router A to terminal and router A to router B, this transmission creates very high interference at node B. In this case, a better choice is to transmit the terminal 's packets from a different base station and through a different path. However, if multi-user projection receivers [13] are used in the physical layer, receivers can remove the high interference from the close neighbors; therefore, the same path can still be used for the downstream transmission. In summary, to maximize network capacity, the routing strategy must be specifically designed for this purpose, and it must be a function of the techniques used in the physical layer.

Figure 8 illustrates the effect of using multiuser detection and optimum mode selection and routing on network capacity [8]. When using MUD receivers, by optimally scheduling the routers' transmit and receive modes, we can create opportunities to have slots with very low levels and therefore benefit from conserved power and highly increase capacity. As seen from Fig. 8, the effect of using these techniques is a multifold increase in system capacity since we are optimally making use of the conserved power.

CONCLUSION

The architecture considered in this article benefits from inexpensive routers in the cellular structure to achieve the target capacity obtained by the cell splitting technique. By a suitable routing strategy, total transmitted power is highly decreased in multihop transmission. However, power conservation may not necessarily result in higher capacity since SIR is not affected by scaling the transmitted power of all nodes. Multielement arrays and multi-user detection are discussed as some of the techniques that could reduce the interference due to packet relaying. These techniques have already been implemented as enhancements to existing cellular networks and are of practical interest. We further address some of the many new challenges encountered in optimizing the capacity of this structure. We have seen several illustrations of how different combinations of such techniques yield a multifold increase in system capacity. With the feasibility of increasingly sophisticated wireless devices, multihop networking promises a widespread network with high data rate support.

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ADDITIONAL READING

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To maximize network capacity, the routing strategy must be specifically designed for this purpose, and it must be a function of the techniques used in the physical layer.