A High Capacity Multihop Packet CDMA Wireless Network

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ABSTRACT

Wireless multihop networks overlaid with cellular structure have the potential to support high data rate Internet traffic. In this paper, we consider techniques by which the system capacity of such networks can be increased. First, methods for increasing link capacity in single-user systems are explored. Subsequently, we consider a different set of techniques suitable for multiuser systems. We also investigate the effect of traffic dynamics on system capacity and ways to achieve the maximum throughput. Finally, we present capacity bounds which illustrate how these techniques help in trading off the conserved power for capacity advantage.

Keywords-Internet, multihop networks, ad hoc networks, wireless packet CDMA, network capacity, space-time processing, smart antennas, routing strategy.

1. INTRODUCTION

Considerable research and development has been underway to extend the wireless communications to encompass wireless Internet. Among these recent technologies, ad hoc networks and systems nearly alike (e.g., Metricom's Ricochet, Bluetooth-based piconets) are examples of the progress to provide a broad connectivity based on multihop technology. A wireless multihop network can be considered 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 life-time batteries and therefore, energy conservation is a critical design criterion.

The high propagation loss on radio links normally requires a high power at the transmitter and hence a high total consumed power. The transmit power may be reduced by breaking down the distance between two communicating points into smaller segments. Routers establish the path between mobile terminals and base stations subject to the constraints and requirements imposed by the network.

A straightforward method to improve capacity of wireless cellular networks is to increase the number of channels in the space by reducing the cell size. However, small cells are not often desirable, as base stations and their interconnections to the wired backbone are costly. Here, as depicted in Fig. 1, we consider adding inexpensive wireless routers to the conventional network structure to increase the system capacity. Simply adding the routers to the current cellular networks may not improve the throughput, since all packets are finally relayed towards the base stations and thus traffic is artificially increased. Additional processing of information on the network is required in order to treat the excess interference and trade off the conserved power for capacity advantage.

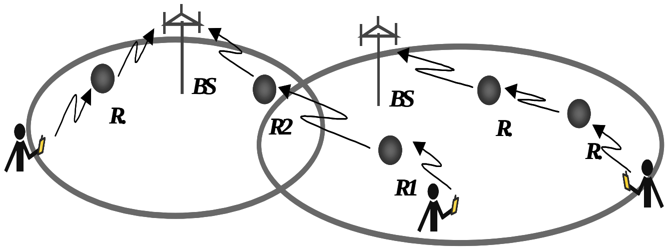

Figure 1: Network structure: base stations (BS), routers (R) and terminals are distributed uniformly in the network. Terminals in a cell might transmit to a base station in another cell based on the routing strategy.

For a multihop network, capacity can be defined as the total rate by which information originated by all sources reaches the final destinations. Therefore, the techniques and strategies for maximizing capacity must compromise between the total amount of information that can be carried through each link and the number of hops that the information must take to reach the destinations.

This paper examines some of the techniques by which we can augment the capacity or enhance the system performance in multihop networks. We focus on a simple architecture and address the connectivity scenarios. Inherent fading and interference averaging effect makes CDMA an attractive access scheme to achieve a high system capacity. Hence, we limit our attention to this scheme, although the work can be extended to include other access methods.

Two frequency bands are assumed to carry the information on the uplink and downlink independently. The uplink and downlink transmissions may involve multiple routers in which packets are relayed in the same frequency band us-

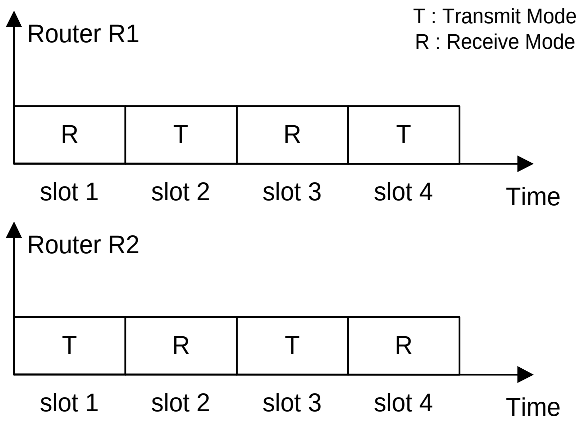

Figure 2: Routers time slot structure in uplink or downlink frequency for the sample path comprised of two hops as shown in Fig. 1. In each time slot, the two routers are in different modes and can exchange data.

ing time division duplex (TDD) scheme (see Fig. 2). Note that due to high power level difference between transmit and receive 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 collision. Practically, exact synchronization is only necessary within the range of a few hops.

Terminals and routers may send and receive on several spreading sequences, dynamically assigned by base stations. Base stations instruct the nodes which channels to listen to and on which channels to transmit their data. In each slot, almost half of all the routers are in transmit mode and the rest are in receive mode. The routers change their mode alternatively at the end of each slot, hence other nodes know when they can transmit packets to them. Efficient use of routers leads to a reduction in the required transmit power, thereby providing an opportunity to extend the cell size or to allow higher data rate. It further helps in a better scheduling of the traffic. For example, bursty traffic can be handled through a route without affecting the reception capability of the other parts of the network. In the following sections, we show how the network can take advantage of this power saving to support higher data rate traffic.

Realizing the full potential of the allocated bandwidth will require taking advantage of all of the new proposals for coding and space-time processing for radio links. In a multiuser system, link capacity can also be increased by techniques like 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.

2. LINK CAPACITY IN SINGLE USER SYSTEM

The maximum spectral efficiency in terms of bits-per-second-per-Hertz is obtained based on Shannon capacity theorem and it depends on channel statistical behavior as well as design aspects such as power control strategy and receiver technology. As more information on the channel becomes available to transmitter and receiver, a better strategy may be devised to achieve a higher throughput.

A simple case is when there are 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 both to transmitter and receiver. In the optimum power strategy when the fading coefficient is below a threshold, no power is transmitted. Above the threshold, the transmitted 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 [1]. 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 noise, both of which depend on the channel estimation technique.

We proceed to review some of the techniques that increase the link capacity when our knowledge on the rest of the network is limited to the average received interference. In direct sequence spread spectrum modulation, this interference is well modeled by a normal distribution and therefore channel capacity for AWGN can still describe the link. Note that connections among routers and base stations using highly efficient links have a direct effect on increasing the total capacity of cellular structure. As interference due to relaying packets is reduced, routers act like stand-alone base stations and system capacity is increased proportional to the ratio of routers to base stations.

2.1 Diversity Techniques

Although multipath fading severely attenuates the transmitted signal, it also provides several replicas of the signal at the receiver. These replications can be used at the receiver by optimally separating and combining the total received power. This so called diversity is the single most important contributor to reliable wireless communications. It is known that by increasing diversity order, distribution of fading tends to follow a Gaussian distribution with higher capacity limit [1].

Temporal diversity can be obtained through the use of error correcting codes in conjunction with time interleaving. First, by use of error correcting codes, information is spread over time and then by time interleaving the data sequence the possibility that correlated data are faded together is reduced. In CDMA systems, information is spread over frequency by increasing the bandwidth of the data signal. RAKE receivers in CDMA give a frequency diversity of the order equal to the number of receiver fingers. Space diversity is obtained when spatially separated or differently polarized antennas are used. More information on the transmitted signal is obtained by increasing the number of samples of its corresponding space-time process at independent points in space. The total diversity order achieved is the product of all diversity orders in independent domains [4].

In multihop networks, receiver can benefit from one other diversity domain which is obtained from receiving several replicas of the same packet in different time slots and transmitted from different nodes. Therefore, it gives rise to both diversity gain and coding gain. Later, we show how this diversity method can also highly reduce interference and increase system capacity.

2.2 Multiple-In Multiple-Out Radio Links

In bandwidth limited wireless channels, high data rate transmission requires a highly spectral efficient code with large constellation size. As a result, this cannot be a practical approach to achieve data rates higher than a certain limit on a link. Another solution is to increase the number of channels between the transmitter and receiver pair by using more antenna elements at each site. Note that this is the direct extension of the space diversity discussed earlier.

Performance analysis of this method has been investigated based on capacity-versus-outage. When there is no significant change in a channel during the transmission of a data block, the ergodic Shannon capacity cannot be used anymore. In this case, capacity can be defined for any instance of channel state random variable. This capacity is called capacity-versus-outage and its probability distribution gives a performance measure for the channel. Based on this definition for capacity, an outage probability relates to the rate that the channel cannot support.

When 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 ij^{th} element gives the propagation from the j^{th} transmit antenna to the i^{th} receive antenna. Let P_0 and P_n denote the transmit signal power and average power of AWGN, respectively. When perfect CSI is available at the receiver, Shannon capacity as a random variable can be obtained as [3]:

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

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 far as possible uncorrelated at antenna elements to give a channel matrix with full rank. The idea is that increasing power in a single channel is not as effective as sharing that power between separate channels. For large number of antenna elements, unlike 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, equation (1) is simplified as:

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

This capacity can be achieved by multiplying input SNR by antenna gain when array weight vector $\omega = (\omega_1, \omega_2, ..., \omega_{n_R})$ 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 multiple-in multiple-out 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% 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[2]. This rate is almost 40 times higher than the achievable rate in a single-element antenna link.

2.3 Space-Time Coding

Space-time coding is a recently developed technique which takes advantage of the available high capacity in multi-antenna radio links [7]. Although link capacity is maximized for completely uncorrelated fading coefficients at antenna elements and when perfect CSI is available at the receiver, recently published results [8] show that design criteria remains valid even in the absence of these constraints. These space-time codes introduce temporal and spatial correlation into signals transmitted from different antennas, so as to provide diversity at the receiver, and coding gain over an uncoded system. At the receiver, an individual space-time code can be decoded based on one dimensional decoder structure iteratively.

In practice, uncorrelated diversity branches can be obtained at the mobile by spacing the antenna elements about a half wavelength (λ_c) apart. For base stations, an antenna separation of about $20\lambda_c$ is required to obtain a correlation of about 0.7. Still, with this high value of correlation, a significant diversity improvement can be realized. 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 which are normally mounted on larger devices with better power supplies can afford highly efficient space time codes.

3. LINK CAPACITY IN MULTIPLE USER SYSTEM

When the receiver also has the knowledge of the signaling waveform and the channel from each interfering user, a high gain can be achieved by using more complex techniques for decoding. Without this knowledge, power scaling does not affect the performance of the network. As SNR increases, background noise becomes gradually insignificant compared to multi-user interference. Clearly, increasing the power of all nodes does not change the signal to interference ratio (SIR). In other words, the link capacity versus SNR is bounded.

In this section, we consider the case that more information on other users such as spreading codes and direction of arrivals (DOA) is available to the receiver.

3.1 Multiuser Detection

In a flat slowly fading environment when K users are simultaneously transmitting to a receiver, the channel can be described by K random variables ν_i modeling the propagation from the i^{th} 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 can be obtained as [1]:

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

Note that in this formula unlike multi-element receiver antenna, just powers are added together. For a large number of users, this formula is simplified to [1]:

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

where P_{av} denotes the average transmitted power per user. This capacity can be achieved in CDMA systems where the deleterious effect of fading is mitigated by averaging inter-user 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 as noise, resulting in a performance degradation as more users become active in the network. Multiuser detection is a method to obtain the achievable capacity as the cochannel interference increases by receiving more packets from other users. The preceding equation also shows that by increasing the number of transmitted packets, the maximum information that each packet can bear is reduced. One effective method to overcome this problem is to use methods like hybrid ARQ where packets are saved at the destination and more parity bits are requested by receiver until data is decoded. By this method, multirate traffic is generated with the rate changing adaptively based on channel state.

One other benefit of multiuser detection is its capability for reducing sensitivity of decoding to near-far effect and power control. In the uplink, this results in lower bit error rate and in the downlink in high power conservation since we are not obliged to transmit the same power for close and far users. Multiuser detection is an effective technique that can remove the saturation region of capacity versus SNR and therefore it has the potential to take advantage of the conserved power in multihop networking to increase capacity.

3.2 Smart Antennas and Interference Cancellation

Even with multiuser detection, link capacity will not linearly increase by the number of transmitted packets. Specially for high SNR, spliting power on different channels results in a better performance. Cell sectorization using directional antennas at base stations can increase the system capacity in the uplink and downlink by a factor equal to the number of sectors. However, due to the imperfection in practical antennas, the reliability of reception from terminals located in the areas where adjacent sectors overlap is degraded significantly. Using directional antennas at terminals and routers is not effective, since due to wide angular spread of the signal, receive antennas cannot distinguish between direction of signal arrivals from different transmitters. An M-element smart antenna [9], however, can null $M-1$ interferers independent of the multipath environment. By adding routers to the cellular structure, as the number of nodes communicating to any node is reduced, smart antennas can be more effective. In this structure, even array antennas with fixed pattern are performing better since beam separation needed for transmission can be accomplished more easily.

Another problem arises when space-time coding and smart antenna technique are used together. In each symbol period, the set of symbols transmitted on different branches of antenna construct the array weight vector and define the radiation pattern. Therefore, the transmit antenna pattern steers in different directions from symbol to symbol creating interference for other parts of the network. For reception, this pattern change results in receiving interference from other sources. Therefore, array processing techniques must be combined by encoding and decoding techniques to compromise between interference reduction and link capacity increase.

4. NETWORK CAPACITY

In the previous sections, we have addressed the methods to increase the maximum information that can be transferred through the network links. We have been mostly concerned with the randomly varying nature of the transmission medium and how to achieve a reliable link when there is interference.

In a wireless network, space, time, and frequency are the three main domains that must be shared between different network nodes. In our multihop packet CDMA network, we only have to be concerned with time and space allocation. Time scheduling is usually referred to as medium access protocol and space sharing is referred to as routing strategy. Within the network, the packet end-to-end quality of service is an important parameter of concern. Information exchange between nodes is useful if only it directs the information toward the destinations.

Determination of an optimal transmission strategy including transmit power adjustment, time scheduling, and routing is not simple for radio networks. Different packet types bear different amounts of information and need different SNRs to be detected. Also, QoS requirements like minimum acceptable bandwidth and maximum delay add other constraints to the system that affect the capacity calculation. Just like 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.

In multihop wireless networks, unlike its wired counterpart, medium access technique and routing strategy cannot be considered separately. When transmission is destined to a very close neighbor, not very strict scheduling is needed. On the other hand, if transmission is directed toward a region with many receiving nodes, slot assignment can significantly reduce the interference level and result in a better performance.

Routing has a significant impact on the network capacity due to two functions. First, assigning the transmit power and next hop for each node in a way to increase the number of available channels in the space. Second, directing the traffic in a way to make information exchange more toward destination with fewer 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 a more extended cell coverage.

Two issues of concern in the routing strategies are: i) the optimum transmission power and ii) to whom the transmission should be addressed. Although transmission on short hops reduces the interference, at the same time the network traffic is artificially increased due to several transmissions of the same packet by intermediate hops. 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 has been introduced in [5] and can be extended

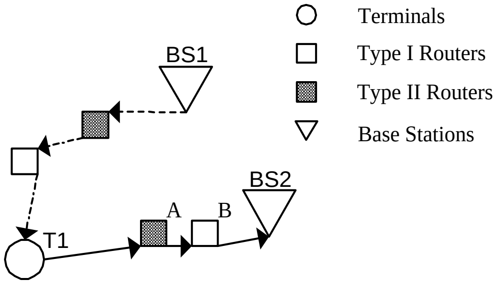

Figure 3: Transmission in the downlink from BS2 to T1 is not a good choice since transmitting packets from A to T1, creates high interference for the very close router B.

to cover our structure as well.

Still the strategy of minimum energy is far from optimum for maximizing capacity. Fig. 3 shows a structure with unilateral links and loop-free connections. In each slot, we have categorized all the routers which are in the same mode as routers of type I and routers of type II. Since transmission in the forward and backward direction in the link might create different interference levels on the neighboring receivers, some of the links are used as they are unilateral. Nodes A and B are the nearest neighbor to each other. However, in the downlink 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 a 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 multiuser projection receivers [6] are used in the physical layers, receivers can remove the high interference from the close neighbors and therefore the same path can still be used for the downlink transmission. In summary, to optimize the network for maximizing capacity routing strategy must be specifically designed for this purpose and it must be a function of the techniques used in the physical layer.

5. SYSTEM PERFORMANCE

In this section, we illustrate via some examples, the possible performance improvement to be achieved when previously stated techniques are deployed. We assume a simple scenario for routing. A transmitter sends data to a receiver for which the link propagation loss is minimum as compared to other links. We also assume that ideal power control is employed and the required received power levels at all receivers are the same. Terminals transmit data with probability p_t independently from slot to slot. Different types of network nodes are distributed uniformly in the plane with different per-unit-area densities.

We begin with the base formula, namely, the probability density function (pdf) of the received power per packet at each node, H_i. Let λ_{Rx} be the density of receivers, including routers in receive mode, and m be the propagation exponent. The pdf of the received power for a node in the center of a circular region, R_a, with radius a due to transmission of one packet within this region has been derived in [10] as:

$$f_{H_i}(h) \approx \frac{2}{mNh^{(1+\frac{2}{m})}} + \frac{1}{N}\delta(h-1) \tag{5}$$

in which $N = \lambda_{Rx}\pi a^2$, $\delta(.)$ is the Dirac delta function, and we have removed the terms that do not affect the calculations of moments. Using the terms intercell and intracell interference for each receiver, based on whether a transmission is destined to that receiver or not, the first term in above formula contributes to the total intercell interference and the second term to intracell interference. The moments of H_i in the limit as $N \to \infty$ are obtained as:

$$\lim_{N\to\infty} N \int_0^1 h^k f_{H_i}(h)dh = \tag{6}$$

$$1 + \frac{1}{mk/2 - 1} \text{ for } k \geq 1 \text{ and } m > 2.$$

Our simulation results have shown that the received power for different packets are nearly independent of each other. Therefore, the characteristic function of the total received power can be obtained from the characteristic function of the received power due to individual packets when a goes to infinity.

For example, for the case that all the transceivers are of the same type and links efficiencies are equal, the pdf of the total received power at each receiver, H_T, can be obtained as:

$$\begin{aligned} M(\omega) &= E(e^{-i\omega H_T}) \\ &= \exp\left(-\frac{\lambda_{Tx}}{\lambda_{Rx}} \sum_{k=1}^{\infty} \frac{(i\omega)^k}{k!}(1 + \frac{1}{(mk/2-1)})\right) \end{aligned} \tag{7}$$

in which λ_{Tx} is the density of packets in the network. The pdf function can easily be obtained by calculating inverse fast Fourier transform of this characteristic function. It is interesting to note that for $m = 4$, this function can be expressed based on error function, where fast numerical algorithms for its calculation exist:

$$M(\omega) = \exp\left(-\frac{\lambda_{Tx}}{\lambda_{Rx}}\sqrt{i\pi\omega}\,\mathrm{erf}\left(\sqrt{i\omega}\right)\right) \tag{8}$$

For the first example, we consider the case where the system is using interference-limited receivers with multiuser detection capability of $K_c = 50$. Throughput is defined as the average number of packets generated by terminals. Fig. 4 shows the effect of increasing the density of routers when highly efficient links are established among routers and base stations. η is the efficiency factor and is defined as the efficiency ratio of links among the routers and base stations to links with terminals connected at one end. All the curves corresponding to different density of routers, λ_R, are the same when $\eta = 1$. In other words, when all the network links have the same capacity, in our simple routing scenario, power conservation does not result in better performance. As η increases, higher density of routers results in better performance. It is seen from the figure that for outage probability of 10^{-2} and efficiency factor of $\eta = 10$, increasing the density of routers from 0 to 10 will result in 300% throughput increase.

The next example illustrates the effect of diversity techniques and multiuser detection on performance. Each base station receives several times the information of a packet before it reaches the destination. Specially for nodes located at

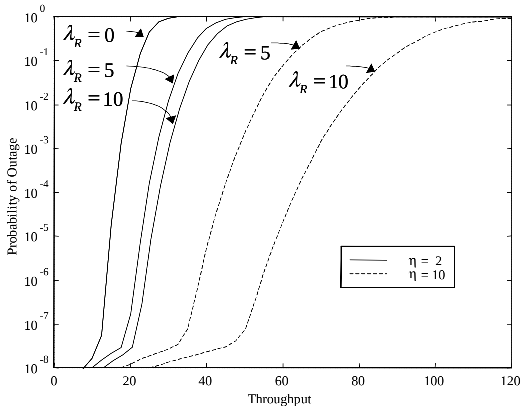

Figure 4: Probability of outage versus throughput for different density of routers $\lambda_R = 0, 5, 10$ and different link efficiencies, η, for connections among routers and base stations. Density of base stations is $\lambda_{BS} = 1$ and receivers are interference limited with multiuser detection capability $K_c = 50$.

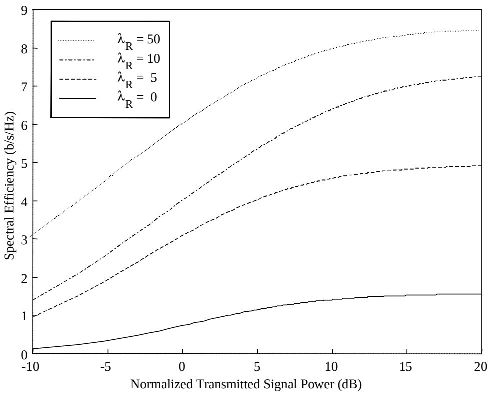

Figure 5: Spectral efficiency as a function of transmitted power for density of routers $\lambda_R = 0, 5, 10, 50$, density of terminals $\lambda_T = 50$, density of base stations $\lambda_{BS} = 1$.

the border of selection regions, originated packets and their replicas, relayed by routers, are both received at the base station with high power. When the packet is finally destined to the base station, it uses all the previously received replicas to decode the data. Decoding the packet, this information can now be used for removing the corresponding interference from the received signal in previous slots. As it is seen from Fig. 5, the effect of using these techniques is a multifold increase in system capacity as we are optimally making use of the conserved power.

6. CONCLUSION

The architecture considered in this paper 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 transmitted power of all nodes. Diversity, multi-element arrays, and space-time coding were discussed as some of the techniques that could reduce the interference due to packet relaying. We also discussed multiuser detection and smart antenna techniques to further reduce the interference by better channelization of space and benefitting of information available on interference. Some of the techniques reviewed here have already been implemented in enhancements to existing cellular networks and are of practical interest. We further addressed some of the many new challenges which were 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 widely-spread network with high data rate support.

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