Multihop Relaying for Broadband Wireless Mesh Networks: From Theory to Practice *

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Abstract

We summarize capacity results to show merits of multihop relaying in broadband cellular mesh networks. Under the guidance of these results, we provide design perspectives on relay deployment, spectrum allocation and end-to-end optimization of certain QoS measures such as throughput, coverage, reliability and robustness. We conclude with an overview of recent standardization activities and remarks on remaining open problems and design challenges.

I. Introduction

There is no doubt that the world is going wireless - faster and more broadly than anyone may have expected. Future wireless systems are expected to meet higher demands of enhanced quality of service (QoS) in terms of data rate, latency, reliability and robustness. In the meantime, the novel system architectures deployed to achieve these objectives should meet certain economic feasibility criteria in order to ensure attractive business opportunities for service providers and equipment manufacturers.

Currently deployed cellular communication architectures rely upon wireless links between wired infrastructure devices (base stations and access points) and end user devices (mobile

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stations) for voice and data transmission. Although research and development in the fields of multiple antenna techniques and advanced coding and signal processing techniques (such as low-density parity-check codes, interference cancellation algorithms, and so forth) have enabled ground breaking enhancements in system performance in terms of capacity, coverage and reliability and have become part of the latest wireless standards such as 3G, 802.16 and 802.11, these technologies on their own cannot satisfy future demands of wireless systems without further deployment of infrastructure devices, especially in reasonably large or densely populated areas [1]. In the meantime, cost-effective deployment of infrastructure-based solutions is desired in order to meet economic feasibility criteria; in this respect, it could be appealing for the additional infrastructure devices to not require any physical wired connection (e.g., electrical or fiber optic connection) to the core network, such as the telephone network or an Internet protocol (IP) network, but rather to transmit and receive in a completely wireless fashion.

The demands and constraints on future wireless networks outlined above lead to a *multihop cellular* or *mesh* architecture, an example of which is depicted in Fig. 1. The role of the additional infrastructure deployment points is to serve as *relay* terminals for the data to be *routed* between the wired infrastructure devices (labeled as BS, i.e. base station) and end users (labeled as MS, i.e. mobile station) and thereby to enhance the quality of end-to-end communication. Depending on the size of their coverage area, these fixed radio relay nodes are referred to as “micro” or “pico” base stations (e.g., nodes 102-110 in Fig. 1 each cover their respective shaded hexagonal micro cells) and are generally smaller in size and less expensive than the wired infrastructure devices. These relay deployments will serve toward various objectives, such as enhancing data rate coverage and enabling range extension over cellular networks. With this motivation, there has recently been growing interest from both academia and industry in the concept of relaying in infrastructure-based wireless networks such as next generation cellular networks (B3G, 4G), wireless local area networks (WLANs) (802.11, WiFi, HyperLAN) and broadband fixed wireless networks (802.16, WiMax, HyperMAN).

Although the literature contains significant research in the field of multihop wireless networking in the context of ad hoc networks and peer-to-peer networks [2], multihop in infrastructure-based networks has been less extensively studied. There are many challenges to be tackled, both on the theoretical and practical sides, for understanding performance limits and devising design principles for infrastructure-based multihop mesh networks, for both narrowband and wideband

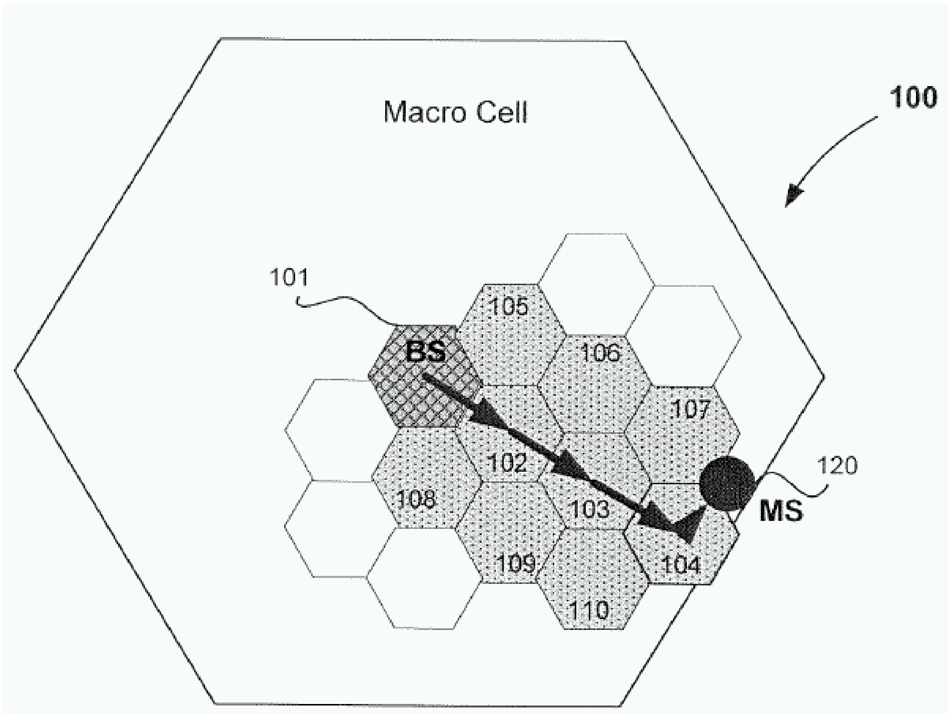

Fig. 1. Wide area multihop cellular network architecture.

applications. In this article, we review some of the recent research on theoretical performance limits over multihop/mesh networks, and discuss under the guidance of these results certain design perspectives on relay deployment, spectrum allocation and end-to-end optimization of QoS measures such as throughput, coverage and reliability. We emphasize that our survey covers multihop routing and mesh systems but not more general forms of relaying and cooperation, in which multiple transmissions are combined at various receivers [3]. We conclude with an overview of recent standardization activities and remarks on remaining open problems and design challenges.

II. End-to-End Capacity

Consider the linear multihop network shown in Fig. 2 as a simple model to evaluate merits of relay-assisted multihop communication over cellular mesh networks. In this setting, source and destination terminals communicate with each other by routing their data through multiple intermediate relay terminals. In particular, we assume that the multihop wireless network consists

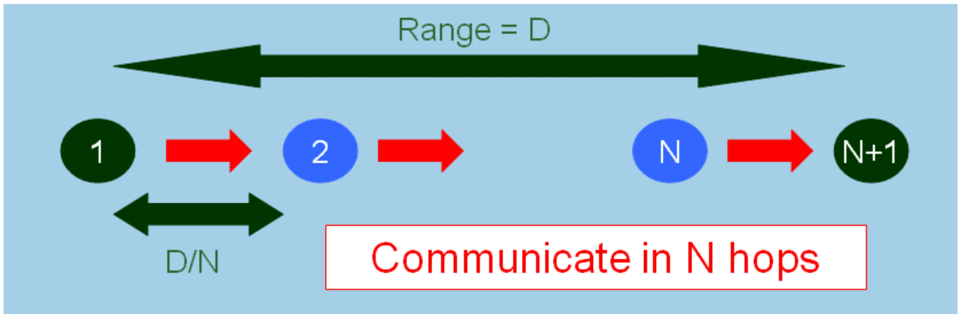

Fig. 2. Linear multihop network model.

of $N+1$ terminals, with a single active source-destination pair separated by a distance D and $N-1$ intermediate relay terminals located on the line between them; thus, N is the number of "hops" along the route. Because wireless terminals can often not transmit and receive at the same time in the same frequency band, we focus on time-division based, half duplex relaying, which orthogonalizes the use of the time and frequency resources between the transmitter and receiver of a given radio. Moreover, we consider *full decoding* of the entire codeword at the intermediate terminals, which is also called *regeneration* or *decode-and-forward* in various contexts. Finally, we will provide results for time-division multihop relaying protocols with no interference across different hops, as well as those with *reuse*, for which we allow a certain number of terminals to transmit simultaneously over the same time slot and frequency band. For purposes of this discussion, interference from other nodes in the system but not part of the multihop route is treated simply as additional noise.

Due to potential multipath scattering effects, each broadband wireless link over a given hop is modeled as a multipath fading channel with additive white Gaussian noise (AWGN). The frequency-selective fading includes a certain fixed line-of-sight (LOS) component and a randomly varying non-LOS component [4]. The relative strengths of these components in terms of signal powers is specified by the factor κ. In addition, we will consider propagation path loss variation with distance and slow lognormal shadowing of a certain standard deviation. Time-selectivity does not play a major role over the wireless backhaul links across the wired and wireless infrastructure terminals as these devices are stationary, however the radio access links from infrastructure terminals to the end users could be rapidly varying in time due to high mobility and Doppler spread.

Under quasi-static fading, the achievable rates over different hops become random and vary as the channel changes. We will denote by C_n the maximum achievable rate (assuming the use of capacity-approaching point-to-point codes) over hop n, where $n = 1, ..., N$, and by C the maximum achievable rate over the multihop route. We will examine performance in terms of the well-known spectral efficiency (in bits/second/Hertz or b/s/Hz), power efficiency tradeoff given in simplest form by [5]

$$\frac{E_b}{N_0} = \frac{2^C - 1}{C}, \tag{1}$$

where E_b is the energy per bit, and N_0 is the one-sided noise power spectral density. All receiving terminals are assumed to accurately estimate and track their channels and therefore possess full channel state information (CSI). The transmissions over multiple hops are performed according to two different strategies:

- **Fixed-rate relaying:** In this approach, a fixed-rate coding strategy is adopted over all hops; the rate over hop n equals $R_n = R, \forall n$ for some fixed value of R. Thus, in order to ensure reliable communication (i.e., codeword error probability approaching zero) under the time-division half-duplex multihop protocol, the condition $R \leq C_n$ must be satisfied over all hops. If $R > C_n$ for any $n \in \{1, ..., N\}$, the reliable transmission of the codeword over hop n is not possible even under large coding block lengths and the multihop link is considered to be in *outage* [6]. In this setting, the maximum end-to-end data rate C can be achieved by choosing R as $R = \min_n C_n$, which leads to

$$C = \frac{1}{N} \min_n C_n. \tag{2}$$

  For this approach, although we assume that receivers have perfect CSI, transmitters either do not possess CSI or do not exploit it due to the associated overhead in network protocols.
- **Rate-adaptive relaying:** More generally, each terminal can to some extent obtain transmit CSI on the link to the neighbor terminal along the multihop route, and thus can perform rate-adaptive relaying. In case of perfect transmit CSI at all terminals, this implies that rate adaptation can be performed such that $R_n = C_n, \forall n$. In this setting, provided the use of capacity-approaching codes, reliable communication can be guaranteed and the maximum

end-to-end data rate is given by [7]

$$C = \left(\sum_{n=1}^{N} \frac{1}{C_n} \right)^{-1}. \quad (3)$$

In practice, the collection of perfect transmit CSI at all terminals is difficult, due to finite-rate constraints over the feedback links, as well as channel variations under time selectivity, and therefore one would expect the end-to-end capacity performance under rate-adaptive relaying to lie between (2) and (3). Furthermore, due to the usage of finite coding blocklengths under delay constraints and suboptimal coding and decoding algorithms, $R_n < C_n$ for practical systems even under perfect CSI assumptions, where R_n is the maximum achievable rate that guarantees a certain level of reliability (e.g., packet error rate (PER)) and link adaptation mechanisms are designed to optimize performance under such reliability and delay constraints.

It should be noted that both relaying strategies are information-continuous in the sense that no data accumulation occurs at any of the intermediate relay terminals. In the fixed-rate relaying case, the same code rates and packet sizes are used over all hops. In the case of rate-adaptive relaying, the rates are chosen based on the channel quality of each hop and packet sizes are adjusted such that the same number of bits is transmitted over each hop. Consequently, the optimal rate-adaptive relaying technique that achieves (3) arranges the multihop transmissions such that the hops with poor channel conditions transmit relatively longer packets than the hops experiencing good channel conditions.

To implement the rate-adaptive relaying solution over random time-varying channels (e.g., fading wireless channels), where the maximum achievable rates $\{C_n\}_{n=1}^{N}$ become random variables, the transmit terminal over hop n only needs to know the value of C_n and the value of an end-to-end link quality parameter M, which is defined as $M = \sum_{n=1}^{N} \frac{1}{C_n}$. The knowledge of global CSI (i.e. CSI for all links in the multihop network) is not required at every terminal [8], which implies significantly reduced messaging overhead. The information on C_n can be obtained by each terminal through CSI feedback from only the neighboring terminal. Due to the stationarity of the infrastructure devices, the channels experienced over all hops are expected to be slowly time-varying (except possibly for the last hop involving the end user) and therefore it is realistic to assume that each node will be able to track its transmit/receive channels and perform rate-adaptive relaying. On the other hand, the parameter M depends on the channel conditions over all links, which may be computed in a distributed fashion using a routing algorithm (e.g., destination-sequenced distance-vector (DSDV) [9]) in which the cost of the link over hop n is represented by the metric $1/C_n$, which is also known as the *expected transmission time (ETT)* [10] in the networking literature. Such a distributed approach involves the end-to-end propagation of a single parameter, only requiring neighbor-to-neighbor message passing of the accumulated multihop link cost metric which is updated by each terminal with the addition of the cost of the last hop. Once the total route cost $\sum_{n=1}^{N} \frac{1}{C_n}$ has been determined by one of the end terminals, the value of M can be broadcasted to all the terminals in the linear multihop network. Again, due to slow fading, it can be safely assumed that the update broadcasts of this parameter do not need to be performed frequently, ensuring low complexity in the protocol overhead.

Using the capacity-based performance measures for the multihop routing protocols summarized in this section, in the next section we shall investigate merits of multihop relaying under several practically relevant cellular communication settings.

III. Numerical Results

The following four examples demonstrate some of the benefits of and design tradeoffs in multihop transmission in the context of a wireless backhaul application, where the objective is to enhance cellular link performance by the assistance of distributed wireless relay stations. These relay stations enable multihop routing of the packets from a (wired) base station to a (low-mobility) user, and vice versa. For purposes of illustration, we assume that the base station, relay stations and mobile station are perfectly aligned to form a linear multihop network as in Fig. 2, and the channel fading is assumed to be statistically independent and identically distributed over all hops. The models and results can be readily extended to more general scenarios.

In the first three examples, we illustrate various performance gains from multihop communication such as enhancements in capacity, power efficiency and reliability. In cellular communications, such benefits are critical, especially for users suffering from poor signal-to-interference-and-noise-ratio (SINR) conditions, which may arise from reasons such as high path loss due to distant positioning of the end user from the base station or coverage holes caused by high shadowing losses. The fourth example investigates the level of sensitivity of the gains from multihop routing with respect to wireless channel parameters.

Example 1: Path Loss Mitigation. In this example, we focus on the benefits of multihop for

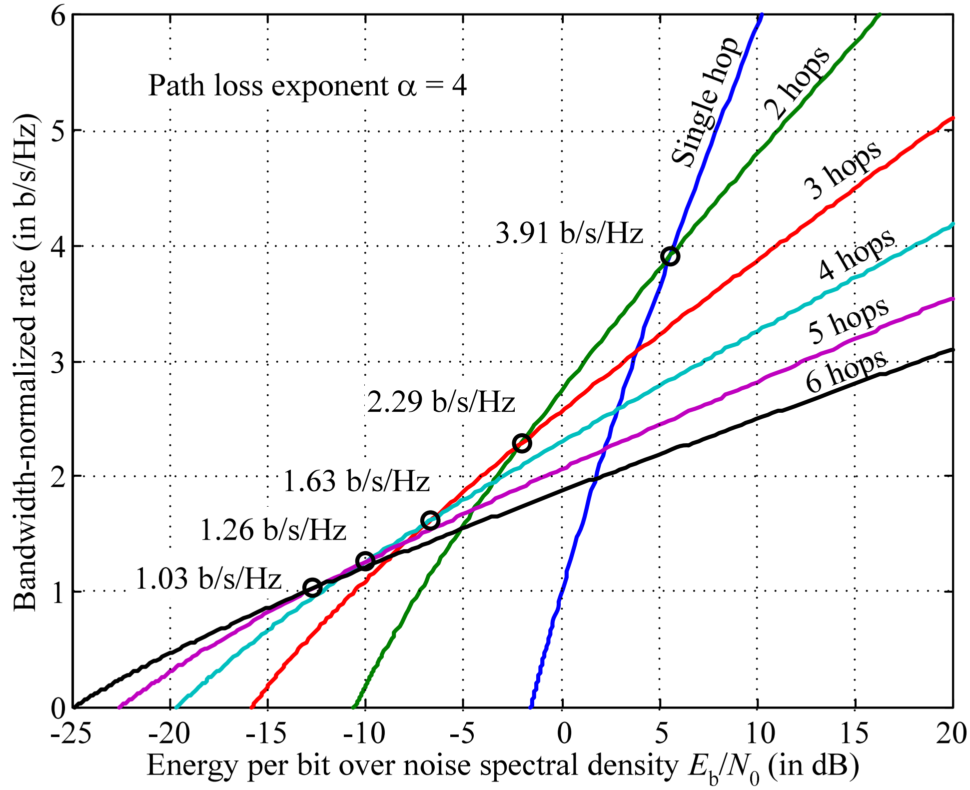

Fig. 3. Spectral efficiency C b/s/Hz vs. E_b/N_0 over frequency-flat AWGN multihop channels with path-loss of exponent $\alpha = 4$. Varying number of hops $N = 1, 2, \ldots, 6$ are considered. The results are normalized so that singlehop achieves the usual -1.59 dB corresponding to Shannon's limit on the minimal E_b/N_0.

mitigating path-loss. For the purposes of this study, we consider frequency-flat link models with additive white Gaussian noise (AWGN) and path-loss of the form $d^{-\alpha}$, where d is the distance between two radios and $2 < \alpha < 5$ is the path-loss exponent [4]. The end-to-end capacity can then be studied as a special case of (2) and (3), which are identical in the case of equally-spaced terminals. More details can be found in [11], [12]. Fig. 3 illustrates capacity performance, in terms of the spectral efficiency, power efficiency tradeoff (1), for multihop transmission with path-loss exponent $\alpha = 4$ for varying number of hops $N = 1, 2, \ldots, 6$. In Fig. 3, transmissions employ fixed-rate relaying, and the number of nodes between simultaneously transmitting radios is $K = N$, i.e., there is no interference caused by simultaneous transmissions. For low E_b/N_0, or the *power-limited regime*, multihop with large N offers improved performance, because transmission over shorter distances corresponds to increased effective signal-to-noise ratios. For high E_b/N_0, or the *bandwidth-limited regime*, transmission with small N is preferable, at least for the time-sharing schedule without interference discussed so far, because increasing the number of hops corresponds to reducing the effective bandwidth in which transmissions occur on a given hop. For each E_b/N_0, or correspondingly for each target spectral efficiency, there is an *optimal number of hops*, which can be determined from Fig. 3 or using analytical solutions [11], [12]. Furthermore, it has been shown in [7] that the general power and bandwidth efficiency trends of multihop communication do not change with non-uniform channel qualities over different hops (e.g., under fading), and that the extra benefit from rate-adaptive relaying (i.e., with respect to fixed-rate relaying) over multiple hops comes in the form of improved power efficiency with no impact on bandwidth efficiency.

Example 2: Enhancements from Reuse. In this example, we illustrate improved performance in the power-limited regime through frequency or spatial reuse. Continuing with the scenario from Example 1, we allow every $K \leq N$ nodes to transmit simultaneously. As previously indicated, the case of $K = N$ corresponds to Example 1. Allowing multiple nodes to transmit allows more efficient use of bandwidth, but introduces intra-route interference. Fig. 4 illustrates the capacity performance, again in terms of the spectral efficiency, power efficiency tradeoff (1), for multihop transmission over AWGN channels with path-loss of exponent $\alpha = 4$ and varying number of hops $N = 1, 2, 3, 4, 6$. As N increases, the case of $K < N$ can offer better multihop performance for low E_b/N_0. Specifically, although the minimum E_b/N_0 does not change with K, the *slope* with which we approach the minimum increases. This so-called *wideband slope* is a figure of merit introduced in [5] to measure spectral efficiency in the power-limited regime.

Example 3: Outage Capacity and Reliability Enhancement against Fading. In this example, we focus on the benefits of multihop for mitigating fading, which may at first seem counter-intuitive. For the purposes of the following numerical study, we will consider a broadband channel model with frequency-selective multipath fading and path-loss, but without shadowing. Each multipath fading link has two independent taps with an exponential power delay profile (PDP) and complex Gaussian (Rician) distribution with mean $1/\sqrt{2}$ and variance $1/2$, i.e., $\kappa = 1$. The path loss exponent is assumed to be $\alpha = 4$, and the average received signal-to-noise ratio (SNR) between the mobile user and the base station is normalized to $0\,\text{dB}$. We plot in Fig. 5 the cumulative distribution function (c.d.f.) of the end-to-end capacity for both fixed-rate and rate-adaptive multihop relaying schemes with varying number of hops $N = 1, 2, 10$. We observe

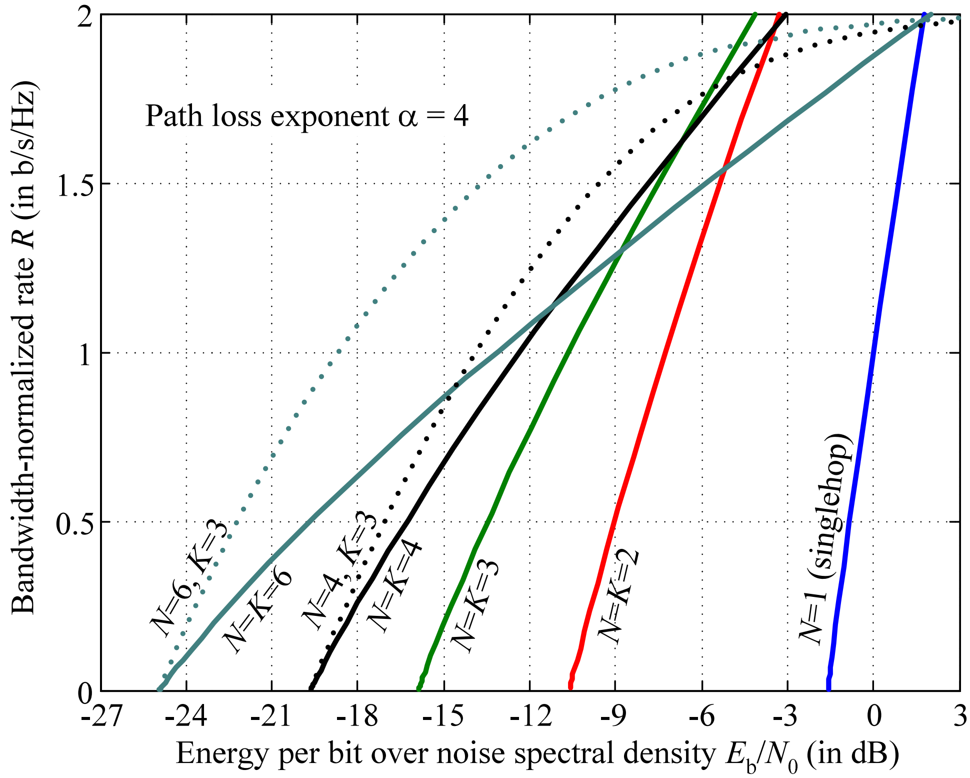

Fig. 4. Spectral efficiency C b/s/Hz vs. E_b/N_0 over frequency-flat AWGN multihop channels with path-loss of exponent $\alpha = 4$. Varying number of hops $N = 1, 2, 3, 4, 6$ and spatial reuse parameter $K \leq N$ are considered. Again, the results are normalized so that singlehop achieves the usual -1.59 dB corresponding to Shannon's limit on the minimal E_b/N_0.

that with increasing number of hops, the c.d.f. of capacity sharpens around the mean (i.e. the probability distribution function (p.d.f.) *concentrates*), yielding significant enhancements at low outage probabilities over single-hop communication. We interpret this improvement of the link robustness as *multihop diversity*, which serves to ensure higher reliability in diversity-limited fading environments as well as for QoS-constrained and delay-limited applications. Analogous to the results in Example 1, it is shown in [7] that, for any given desired level of end-to-end data rate R, there exists an optimal number of hops that minimizes end-to-end outage probability and this optimal number increases with decreasing R. Furthermore, [8] investigates the performance advantages from multihop relaying under an end-to-end delay constraint and identifies the conditions under which a better rate-reliability-delay tradeoff can be achieved over singlehop communication.

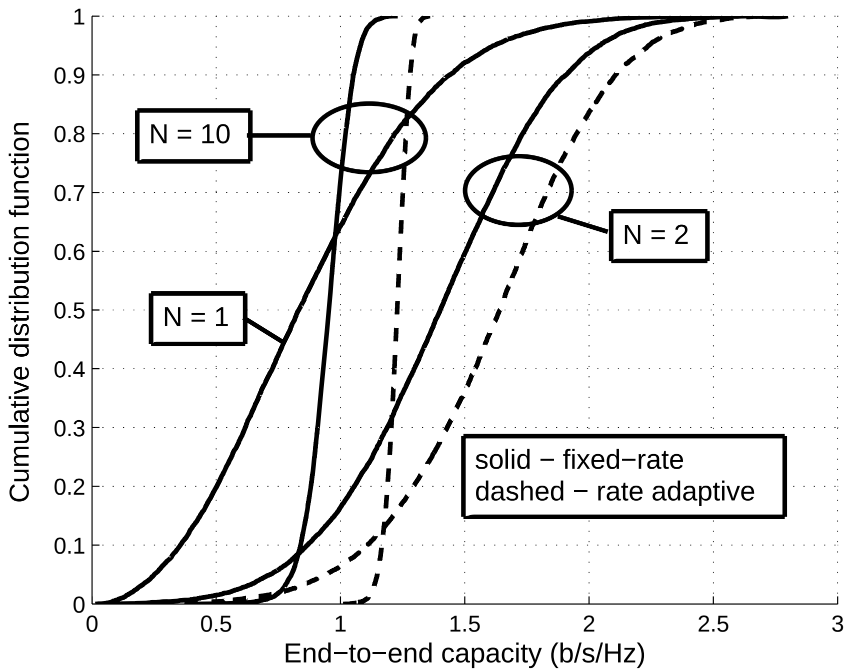

Fig. 5. Cumulative distribution function of end-to-end capacity for fixed-rate and rate-adaptive multihop relaying schemes for $N = 1, 2, 10$.

Example 4: Sensitivity of Gains to Channel Parameters. In this example, we consider the impact of varying path loss, which depends closely on range, antenna heights, terrain characteristics and carrier frequency. As the path loss characteristics of the network change with respect to the choice of these system design parameters, the optimal number of hops to maximize end-to-end capacity would also vary, and consequently an important question is the sensitivity of the optimal solution on the design parameters. Considering realistic broadband wireless channel models [13], preliminary simulation results (see [14] for further results) are sufficient to show the high sensitivity of gains from multihop communication to various channel parameters. In Fig. 6, we analyze the expected value of the optimal number of hops, denoted as N_{opt}, as a function of the path loss exponent α assuming rate-adaptive relaying, an end-to-end average received SNR of 0 dB between the base station and end user, lognormal shadowing of standard deviation values $\sigma = 0, 4, 8$ dB and a frequency-selective channel model with 2 independent exponential PDP taps and complex Gaussian (Rician) fading distribution with mean

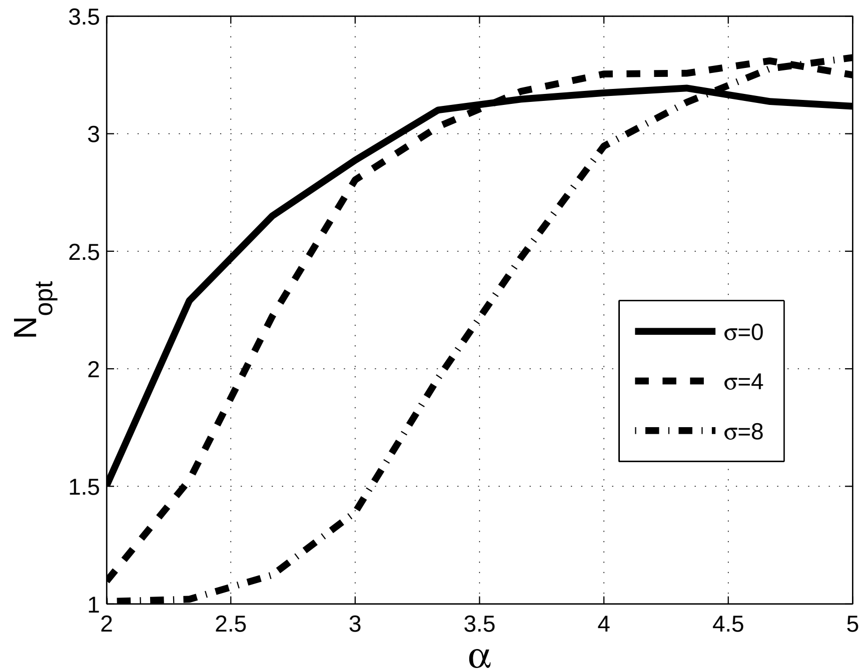

Fig. 6. The expected value of the optimal number of hops N_{opt} as a function of the path loss exponent α for different values of shadowing standard deviation, $\sigma = 0, 4, 8$ dB.

$1/\sqrt{2}$ and variance $1/2$, i.e., $\kappa = 1$, over each tap and each link. We average the optimal number of hops over various fading realizations using Monte Carlo simulations. Clearly, these results show the high sensitivity of N_{opt} with changing α and σ, necessitating the use of accurate channel models in order to extract the highest gains from multihop cellular system designs. The only regime in which N_{opt} appears to be robust with respect to α and σ is for high path loss exponent range, e.g., $\alpha > 4$.

In summary, the four examples illustrate that, although multihop relaying promises end-to-end performance enhancements in terms of capacity, reliability, latency, and power efficiency, the degree of gain can vary significantly with the system and channel parameters. This observation suggests that the system designer should carefully account for application requirements, hardware specifications, and terrain characteristics in choosing the optimal multihop network architecture.

IV. Multihop Relaying in Cellular Standards

Although multihop and mesh-based wireless networking techniques have been standardized in the context of local and personal area networks (e.g., 802.11s, 802.15.4), standardization efforts toward future cellular wide area networks have only recently begun. The multihop relay (MR) study group was formed in July 2005 to evalute merits of multihop relaying technologies for future 802.16-based wide area networks. The project authorization request (PAR) was approved in the March 2006 IEEE Standards meeting to initiate the 802.16j Relay Task Group; the standard is expected to be completed and approved in early 2008. The first phase of 802.16j is expected to be restricted to infrastructure relay stations that extend coverage of 802.16e base stations without impacting the subscriber station specification. These relay stations will be fully backward compatible in the sense that they will operate seamlessly with existing 802.16e subscribers. Key technical topics currently discussed in the 802.16j task group include general relay concepts, frame structures, network entry, bandwidth request, handover, construction and transmission of medium access control (MAC) protocol data units (PDUs), measurement and reporting, scheduling, routing, interference control and mobility management.

V. Future Challenges

The key technical goal to be accomplished in the design of multihop cellular mesh networks is end-to-end QoS optimization with the assistance of cost-effective relay architectures. Preliminary results as outlined above suggest that multihop relaying offers certain performance advantages; however, a number of specific challenges related to PHY/MAC-layer design of multihop systems remain. As a brief summary, these challenges include:

Resource allocation. As a natural consequence of communication over multiple hops, the allocation of resources in relay-assisted cellular mesh networks requires design of novel scheduling and routing policies, under certain QoS constraints such as reliability, fairness and latency. Broadly, resource allocation over multihop cellular mesh networks can be categorized as follows, as a function of the level of intelligence and amount of complexity at the relay terminals:

- *Centralized:* The base station is the sole decision-maker for allocating the time and frequency resources across users and the actions of the relay terminals are fully coordinated by the base station. This is the setting in which the relay terminals are used only as repeaters in order to enhance end-to-end link performance by multihop relaying. Although this approach is optimal under the assumption of global perfect CSI at the base station, it requires efficient design of joint centralized scheduling and routing algorithms and has substantial overhead for feedback which may become intractable if there is fast fading. Under moderately slow fading channel conditions, a novel resource allocation policy, *orthogonal frequency division multihop multiple access* ($\mathrm{OFDM^2A}$), was proposed recently in [15] as a low-complexity suboptimal solution for resource allocation over cellular mesh systems requiring reduced messaging overhead. This policy is based on centralized scheduling using end-to-end link quality metrics, under the principle of seperation of subcarrier allocation and multihop route selection, and was shown to simultaneously realize gains from both multiuser diversity and multihop relaying to enhance capacity and coverage, provided the availability of closed-loop transmission mechanisms.

- *Distributed:* This form of resource allocation requires more intelligence at the relay terminals to allow them to contribute to scheduling, resource allocation and interference management. The relay stations perform resource allocation across users in their locality, with no influence from the base station. A fixed cellular reuse pattern may be enforced across micro cells. Alternatively, depending upon the quality of service (QoS) conditions (user load, fairness, throughput demands or changing channel conditions), the relay terminals can dynamically allocate resources (i.e., via distributed scheduling algorithms) to the users in their locality, in which case no static frequency reuse pattern is enforced across the micro cells. This approach requires close coordination among neighboring relay stations, where they may compete or cooperatively bargain for spectrum in order to optimize their respective radio access networks.
- *Hybrid or hierarchical:* In this form of resource allocation, the base station and relay stations work together such that the base station makes certain partial decisions on resource allocation across users (such as assigning a cluster of frequency bands or time slots to a relay station for user assignments) and each relay station makes the final decisions on the specific resource allocation among the users in its locality.

Sectorization, reuse and interference management. Spatial reuse through resource (time and frequency) sharing among relay terminals could be an important factor in enhancing throughput over multihop cellular networks. A static spatial reuse pattern can be enforced among the micro cells, or resource assignments can be performed dynamically. Especially under the centralized control of the base station, resource allocation allowing for controlled levels of intra-cell interference (i.e., interference within the coverage area of the base station due to spatial reuse by multiple active relay transmissions) may result in higher network capacity. On the other hand, under distributed resource allocation schemes, aggressive spatial reuse may cause undesired levels of intra-cell interference between the base station, relay stations and users due to lack of coordination, lowering capacity and reliability. However, with the development of advanced spectrum sensing mechanisms, distributed resource allocation and opportunistic spectrum usage may become attractive options for future relay deployments. Relay sectorization is another important degree of freedom that would enable higher capacity gains from more aggressive spatial reuse schemes. Micro cell planning could be based on the usage of omni-directional or directional antennas at the relay stations. Finally, a key question in optimizing mesh-based cellular architectures is quantifying the impact of inter-cell interference (i.e. interference caused by out-of-cell base stations, relay stations and end users) on network capacity.

Precise channel models. The presence of the relay terminals in cellular multihop mesh networks results in four different channel types: i) channels between the base station and users (as in conventional cellular architectures), ii) channels between relay stations and users and iii) channels between relay stations, and iv) channels between relay stations and the base station. Although the first channel type is specified by widely accepted channel models in several standards (e.g., see [13]), specifications and precise models for the channels involving relay terminals are necessary because the gains from multihop communication and end-to-end optimization criteria are found to be very sensitive to different model assumptions and channel parameters such as path loss exponent, carrier frequency, antenna heights, and terrain characteristics.

Mobility and handoff. The issue of mobility becomes more critical in multihop cellular mesh networks. One immediate difficulty arises with handoff, as each user may need to be associated with a relay terminal in addition to the usual association with a base station. Furthermore, besides the usual difficulties in reliable channel estimation and feedback experienced in conventional cellular networks, high mobility makes it impossible to realize the advantages of dynamic resource allocation, such as gains from bandwidth allocation, scheduling, and routing, due to the increases in the required frequency of route updates and the fact that channel state feedback has higher overhead. Under stringent end-to-end delay constraints, one can expect multihop systems to be impacted more severely from mobility than conventional cellular systems.

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