

# Relay-Based Deployment Concepts for Wireless and Mobile Broadband Radio

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## ABSTRACT

In recent years, there has been an upsurge of interest in multihop-augmented infrastructure-based networks in both industry and academia, such as the seed concept in 3GPP, mesh networks in IEEE 802.16, and coverage extension of HiperLAN/2 through relays or user-cooperative diversity mesh networks. This article, a synopsis of numerous contributions to Working Group 4 of the Wireless World Research Forum and other research work, presents an overview of important topics and applications in the context of relaying. It covers different approaches to exploiting the benefits of multihop communications via relays, such as solutions for radio range extension in mobile and wireless broadband cellular networks (trading range for capacity), and solutions to combat shadowing at high radio frequencies. Furthermore, relaying is presented as a means to reduce infrastructure deployment costs. It is also shown that through the exploitation of spatial diversity, multihop relaying can enhance capacity in cellular networks. We wish to emphasize that while this article focuses on fixed relays, many of the concepts presented can also be applied to systems with moving relays.

## INTRODUCTION

The very high data rates envisioned for fourth-generation (4G) wireless systems in reasonably large areas do not appear to be feasible with the conventional cellular architecture due to two basic reasons. First, the transmission rates envisioned for 4G systems are two orders of magnitude higher than those of 3G systems. This demand creates serious power concerns since it is well known that for a given transmit power level, the symbol (and thus bit) energy decreases linearly with the increasing transmission rate. Second, the spectrum that will be released for 4G systems will almost certainly be

located well above the 2 GHz band used by the 3G systems. The radio propagation in these bands is significantly more vulnerable to non-line-of-sight conditions, which is the typical mode of operation in today's urban cellular communications.

The brute force solution to these two problems is to significantly increase the density of base stations, resulting in considerably higher deployment costs that would only be feasible if the number of subscribers also increased at the same rate. This seems unlikely, with the penetration of cellular phones already high in developed countries. On the other hand, the same number of subscribers will have a much higher demand in transmission rates, making the aggregate throughput rate the bottleneck in future wireless systems. Under the working assumption that subscribers will not be willing to pay the same amount per data bit as for voice bits, a drastic increase in the number of base stations does not seem economically justifiable.

It is obvious from the above discussion that more fundamental enhancements are necessary for the very ambitious throughput and coverage requirements of future systems. Toward this end, in addition to advanced transmission techniques and collocated antenna technologies, some major modifications in the wireless network architecture itself that will enable effective distribution and collection of signals to and from wireless users are required. The integration of multihop capability into conventional wireless networks is perhaps the most promising architectural upgrade. In the following, the terms *multihop* and *relaying* will be used to refer to the same concept; see also [1].

Multihop wireless networking traditionally has been studied in the context of ad hoc and peer-to-peer networks. The application of multihop networking in wide-area cellular systems has the following benefits.

While conventional cellular networks are assumed to have cells of diameter 2–5 km, a

relay will only be expected to cover a region of diameter 200–500 m. This means that the transmit power requirements for such a relay are significantly reduced compared to those for a base station (BS). This in turn permits economical design of the amplifier used in the relay. Furthermore, the mast on which the relay is placed does not need to be as high as for a BS, reducing operating expenses such as tower leasing and maintenance costs for the service provider.

Relays do not have a wired connection to the backhaul. Instead, they store the data received wirelessly from the BS and forward to the user terminals, and vice versa. Thus, the costs of the backplane that serves as the interface between the BS and the wired backhaul network can be eliminated for a relay.

If the density of relays in a cell is moderately high, most terminals are significantly closer to one or more relays than to the BS. This means that the propagation loss from the BS to such a terminal is larger than from a nearby relay to the terminal. This results in higher data rates on the links between the relays and the terminals, thereby potentially solving the coverage problem for high data rates in larger cells.

Since it is possible to have simultaneous transmission by both the BS and relays, capacity gains may also be achieved by either exploiting reuse efficiency or spatial diversity.

The relay-to-user links could use a different (unlicensed) spectrum (e.g., IEEE 802.11x) than the BS-to-user links (the licensed spectrum), yielding significant gains from load balancing through relays [2].

Compared to ad hoc networks, networks applying relaying via fixed infrastructure do not need complicated distributed routing algorithms, while retaining the flexibility of being able to move the relays as the traffic patterns change over time.

It is worth emphasizing the basic difference between the fundamental goals of conventional ad hoc networks and the described multihop-augmented infrastructure-based networks. While the defining goal of ad hoc networks is the ability to function without any infrastructure, the goal in the latter types is the almost ubiquitous provision of very-high-data-rate coverage and throughput.

In this article, BS is used for traditional cellular systems, while the term *access point* (AP) is used for wireless local area network (WLAN)-type systems. Both have in common the fact that they are directly connected to their backbone network, which distinguishes them from relay stations (RSs). However, it should be noted that future air interfaces and deployments could blur the distinction between BSs and APs and eventually lead to their convergence.

This article is organized as follows. First, an overview of the state of the art in current research on relaying topics is given. The next sections deal with performance benefits gained from relaying when combating heavy path loss and exploiting spatial diversity. Implications of relaying on routing and radio resource management are discussed next. Then we introduce the wireless media system (WMS), an example of a

new radio access network architecture based on fixed relays, and the conclusion gives a summary of the key research topics identified in the various contributions to this article.

## THE STATE OF THE ART

No smart relaying concept has been adopted in existing cellular systems so far. Solely bidirectional amplifiers have been used in 2G systems and will be introduced for 3G systems. However, these analog repeaters increase the noise level and suffer from the danger of instability due to their fixed gain, which has limited their application to specific scenarios.

Most existing and standardized systems were designed for bidirectional communication between a central BS and mobile stations directly linked to them. The additional communication traffic between a mobile terminal and a relay intermediately inserted into a link between mobile terminal and BS requires additional radio resources to be allocated — one of the factors that hitherto have hindered the deployment of smart relay concepts.

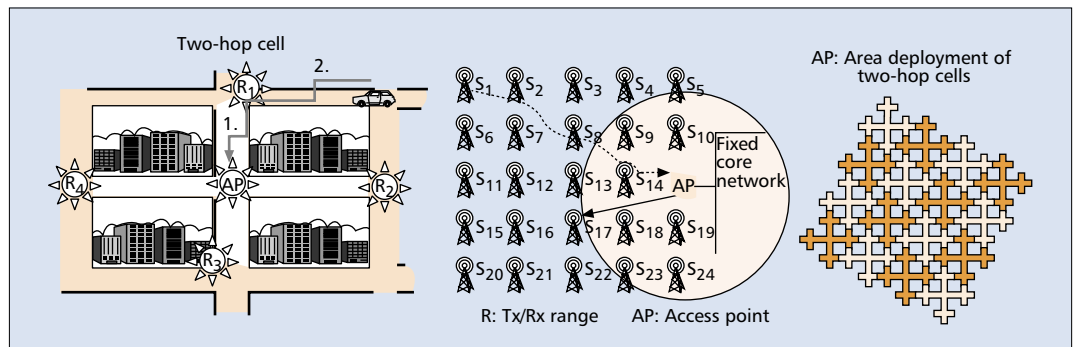
Time-division multiple access (TDMA)-based systems are especially well suited to introduce relaying, as this scheme allows for easy allocation of resources to the mobile-to-relay and relay-to-BS links. The first system based on time-division multiplex (TDM) and relays connecting mobiles to the fixed network was proposed in 1985 [3]. Another method proposed for F/TDMA (F: frequency) systems is to reuse a frequency channel from neighboring cells [4]. The European Telecommunications Standards Institute/Digital Enhanced Cordless Telephony (ETSI/DECT) standard in 1998 was the first specifying fixed relays (called wireless BSs) for cordless systems using TDM channels for voice and data communications. The ETSI/TETRA standard specifies a dual-watch function allowing the aggregate traffic of a number of mobile terminals connected in direct mode to be relayed by TDM channel-switching to a dispatcher panel connected to a BS. Relaying in cellular code-division multiple access (CDMA)-based systems has been investigated by Zadeh *et al.* [5]. Uplink and downlink are separated using frequency-division duplex (FDD), as is done in IS-95 and Universal Mobile Telecommunications System (UMTS) terrestrial radio access (UTRA) FDD. All these concepts can easily be extended to packet-based systems [6, 7].

A completely different approach is considered in [8], incorporating an additional ad hoc mode into the Global System for Mobile Communications (GSM) protocol stack to enable relaying. Similarly, [2] employs relaying stations to divert traffic from possibly congested areas of a cellular system to cells with a lower traffic load. These relaying stations utilize a different air interface for communication among themselves and with mobile stations, which could, for example, be provided by a WLAN standard.

ETSI-broadband radio access network (BRAN), high-performance LAN (HiperLAN/1), and IEEE 802.11x contain the elements to operate ad hoc networks. ETSI HiperLAN/2 in the home extension contains an ad hoc mode of

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ETSI-BRAN/HiperLAN/1 and IEEE 802.11x contain the elements to operate ad hoc networks. ETSI/HiperLAN/2 in the Home Extension contains an ad hoc mode of operation that allows the nodes to agree on a Central Controller (CC) to take the role of an AP in a cluster of nodes, but no multihop functions are specified so far in any WLAN standard.



■ **Figure 1.** Left: a city scenario with one AP (serving the white area) and four RSs covering the shadowed areas around the corners shown in grey. Middle: a schematic of the scenario. Right: wide-area coverage using the basic element (left) and two groups of frequencies (source: [10]).

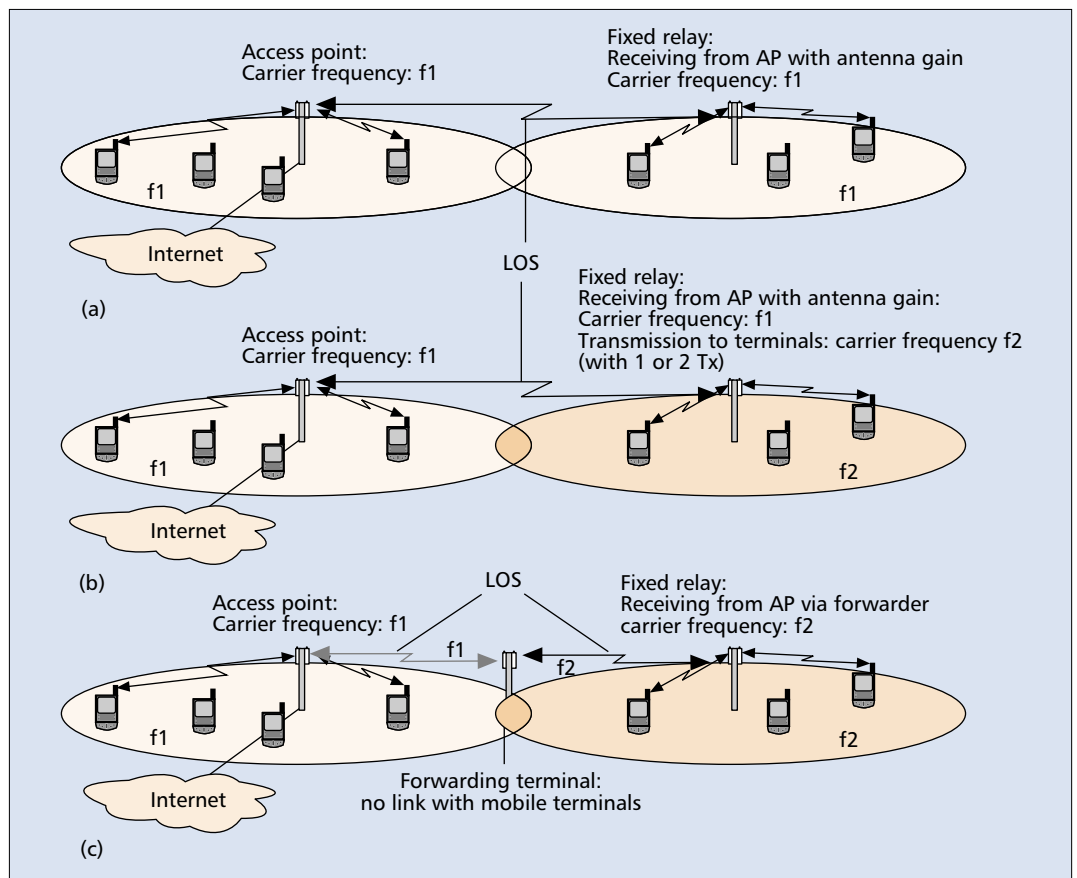
operation that allows the nodes to agree on a central controller (CC) to take the role of an AP in a cluster of nodes, but no multihop functions are specified so far in any WLAN standard. Multihop operation based on wireless relays that operate alternately on different frequency channels to connect neighboring clusters has been proven workable in [9]. In HiperLAN/2 basic mode (using an AP) it has been shown that multihop operation via forwarding mobile terminals is easy to perform within the framework of the standard [6, 7].

In general, relaying systems can be classified as either *decode-and-forward* or *amplify-and-forward* systems. In decode-and-forward schemes, where relays are also referred to as digital

repeaters, bridges, or routers, the relay nodes regenerate the signal by fully decoding and re-encoding the signals prior to retransmission. By contrast, in amplify-and-forward systems the relays essentially act as analog repeaters, thereby increasing the systems noise level. Unless otherwise stated, we consider decode-and-forward systems as the majority of proposed concepts are of this class, and they are generally considered to be more viable with respect to implementation.

## MULTIHOP OPERATION

This section presents examples of relay implementations and aims to point out the performance benefits multihop relaying can provide in



■ **Figure 2.** Examples of relay concepts (source: [10]).

broadband networks when applied in certain scenarios. Figure 1 (left) shows a city scenario with one AP (providing radio coverage to the areas marked white) and four fixed-mounted RSs to provide radio coverage to areas around the corner shadowed from the AP, shown in beige.

While the intersection can be covered well by the AP, nearby streets can only be served if line-of-sight (LOS) connectivity is available between a mobile terminal and its serving station, due to the difficult radio propagation conditions known, for example, in the 5–6 GHz frequency band. RSs allow extending radio coverage to these streets.

A schematic of this scenario (a multihop network with AP) is illustrated in Fig. 1 (middle) where the transmit/receive radius  $R$  is shown to be the parameter determining the connectivity of the nodes shown. RS  $S_1$  would have to route the traffic of the wireless terminals (not shown) it is serving via intermediate RS  $S_8$  using a low-rate but robust combination of modulation and coding (PHY mode), or via RSs  $S_2$  and  $S_8$  using a faster PHY mode and thus higher link capacity, and so forth from  $S_8$  either via  $S_9$  or directly to the AP. The interpretation of the multihop network in the middle of Fig. 1 is that all the nodes shown are either RSs or APs, and the mobile user terminals roaming in the area (not shown) are served by the nodes shown. The basic element of Fig. 1 (left) can be repeated to cover a wide area, as shown in Fig. 1 (right).

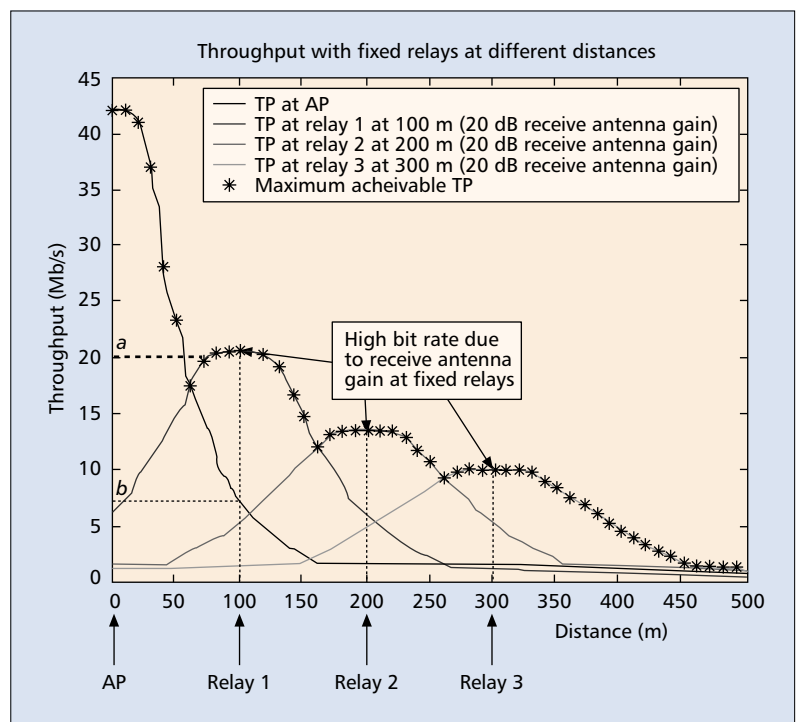
Figure 2 shows three examples of concepts for fixed or mobile relaying, see [10]:

- Relaying in the time domain with the AP and RSs operating at the same carrier frequency,  $f_1$ , while accessing the physical medium in time multiplex.
- Relaying in the frequency domain with the AP and RSs operating at two different carrier frequencies, one of them regularly switching between the two frequencies or having two transceivers.
- Two-stage relaying in the frequency domain, where a fixed mounted RS that is in the range of both the AP and a second RS connects the AP and the second RS by store-and-forward operation and dynamically switches between frequency carriers  $f_1$  and  $f_2$ . Unlike the second RS, which serves mobile terminals, the first RS's only role is to bridge the distance between the AP and the second RS where direct communication between the AP and the first RS is not possible due to lack of LOS (see also [9]).

In a and b the radio link is based on LOS radio with transmit and receive gain antennas at the AP and RS.

An analytical estimation of the bit rate over distance from an AP that is supported by RSs to extend the radio range is shown schematically in Fig. 3. This assumes a TDM approach according to Fig. 2a. Without receive antenna gain, RS 1 would have available only a bit rate equivalent to value  $b$  (Mb/s), while with receive antenna gain it achieves value  $a$  (Mb/s). A similar consideration applies to RSs 2 and 3.

In general, the relaying function could be performed according to the International Standards Organization open systems interconnec-



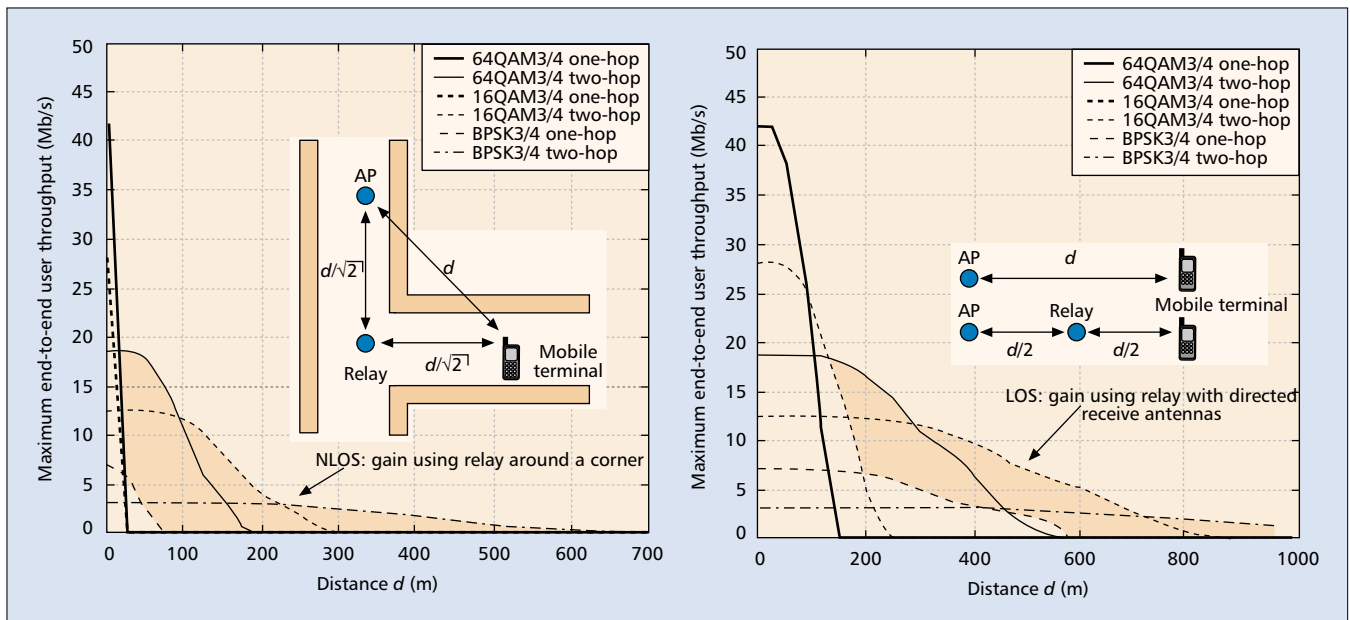
**Figure 3.** Analytical estimation of the extension of the radio range of an AP by relays with receive antenna gain (source: [10]).

tion (ISO/OSI) reference model in either layer 1 (physical) “repeater,” 2 (link) “bridge,” or 3 (network) “router.” Figures 3 and 4 show analytical and simulation results according to the solution of a layer 2 relay as described in [6, 7] for the HiperLAN/2 standard.

Figure 4 (left) shows for the concept introduced in Fig. 2a the simulated end-to-end throughput between an AP and a mobile terminal located at distance  $d$  for different modulation and coding schemes known from the air interface of HiperLAN/2 or IEEE 802.11a [11]. The terminal is shadowed by a building at the street corner and is therefore connected around the corner with the help of an RS. The shaded area under the curves shows the gain in terms of throughput possible from the use of the RS without which the mobile terminal could not be connected to the AP. It can be seen that the range extension resulting from using the RS is substantial. It is worth noting that smart antenna technology at the AP or mobile terminal cannot provide radio coverage around an obstacle. A relay is currently the only way to achieve this.

It has been stated that the capacity of an AP when using a modem as standardized for HiperLAN/2 and IEEE 802.11a might be excessive compared to the rate requirements of mobile terminals roaming in its picocell area formed by omnidirectional or sectorized antennas and a maximum transmit power of 1 W equivalent isotropically radiated power (EIRP) [12].

The fixed relay concept can also be used to extend the range of an AP to nonshadowed areas beyond the regulatory EIRP limits as shown from the simulation results for HiperLAN/2 (Fig. 4, right) according to the scenario in Fig. 2a. It can be seen that the radio range can be dramatically increased, especially when



**Figure 4.** Left: a fixed wireless router at an intersection to extend the radio range of an AP around the corner into a shadowed area to serve a remote mobile terminal. Right: maximum end-to-end throughput vs. distance for forwarding under LOS conditions with directed receive antennas having a gain of 11 dB (source: [11]).

using receive antenna gain at both ends. The use of smart antennas and beamforming to improve the propagation characteristics between an AP and RSs and to connect multiple relays at the same time has been known for a long time [3].

Other benefits of relaying are the possibility of radio resource reuse within the area served by an AP and its related relays (e.g., frequency reuse within the area served by one AP), and the cost advantage. The cost to connect the radio access network to the infrastructure (core) network is reduced substantially by reducing the number of points of presence required, for example, to 20 percent for the example shown in Fig. 1 (left). In a Manhattan grid according to Fig. 1, a second tier of relays would enlarge the number of relays to 12, thereby covering 13 intersections. The infrastructure connectivity cost would then be reduced to about 8 percent of the cost of a purely AP-based system. The number of tiers is bounded by the capacity available from the AP, the capacity per area element required by the terminals roaming in the service area, and the delay requirements. It seems advisable not to exceed two tiers of relays in such networks.

## COOPERATIVE RELAYING AND VIRTUAL ANTENNA ARRAYS

### CONCEPTS

Common to all relaying techniques discussed so far is the store-and-forward operation of the nodes in a relay chain. Each receiver along this chain exploits solely the copy of the information that has been sent by its respective transmitter, while it discards emissions from other transmitters in the chain.

The basic idea of cooperative relaying is to go one step further by exploiting two fundamental features of the wireless medium: its broadcast

nature and its ability to achieve diversity through independent channels. While its broadcast nature is frequently considered a drawback as it leads to mutual interference in a wireless network, the concepts discussed in this subsection exploit the fact that a signal, once transmitted, can be received (and usefully forwarded) by multiple terminals.

In general, cooperative relaying systems have a source node *multicasting* a message to a number of cooperative (i.e., helping) relays, which in turn resend a processed version to the intended destination node (Fig. 5a). The destination node *combines* the signals received from the relays, possibly also taking into account the source's original signal. By performing this combining, the inherent diversity of the relay channel is usefully exploited. More advanced concepts additionally include successive interference cancellation to maximize throughput. In this context, such cooperative multihop scenarios can be regarded as virtual antenna arrays: each relay becomes part of a larger distributed array. This distributed nature naturally leads to a number of new challenges, among them synchronization, availability of channel state information, and appropriate cluster formation.

Like conventional relaying systems, cooperative schemes benefit from path loss savings; moreover, the following gains can be expected:

- Power gain due to the fact that each of the relays may add additional transmit power that is combined in the destination terminal
- Macrodiversity gain that allows combating shadowing
- Diversity gain in the presence of fading

Finally, it is worth noting that an integration of multiple-input multiple-output (MIMO) and so-called dirty paper coding techniques may lead to advanced multihop networks with high spectral efficiency.

Cooperative protocols can be *static* or *adaptive*; the latter can be enhanced by allowing *feedback* and/or *signaling* between forwarding nodes. While in static protocols the relay nodes constantly retransmit a processed version of their received signals, in adaptive versions the relays resend signals only when they believe it to be helpful for the destination node. The adaptation may be done by each relay independently or jointly for all together if information is exchanged between the relays. Theoretically, the transmission in up- and downlink directions is fully symmetric, which follows from reversing the direction of the arrows in Fig. 5. In practice, however, the boundary conditions for up-/downlink will often be quite different, as the radio links between AP and RSs will exhibit typically good LOS conditions and may be enhanced by directional antennas in contrast to the relay-MS links, which are quite unpredictable. As a result, the optimum algorithms to be used in so-called single-frequency networks (SFNs) for up- and downlink may be different as well, and the benefits may not be entirely symmetric.

### EXAMPLES AND RESEARCH AREAS

Of the various approaches to cooperative relaying that have been investigated, we focus here on the concepts of SFNs and virtual antenna arrays.

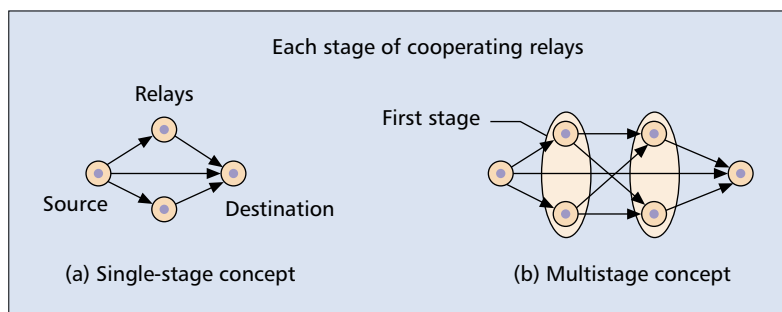
First, results for amplify-and-forward networks indicate that such systems indeed provide a degree of spatial diversity that is proportional to the number of distributed antenna elements, or, in our context, the number of involved relay nodes [13]. Even under strict power and bandwidth constraints, systems with one or two relays can achieve diversity gains over single-input single-output (SISO) and conventional relaying transmission for communication over a Rayleigh fading channel [13].

A mature concept of an SFN as well as MIMO concepts are presented in [14]. Fixed relays provide power gains and macrodiversity by forwarding signals from an AP to the destination terminal. Various protocol versions can be implemented based on the underlying orthogonal frequency-division multiplexing (OFDM) air interface. The potential of SFNs is illustrated in [14], where achievable performance gains of up to 9 dB for the ideal simultaneous operation of eight fixed relays are achieved. Specifically, three cases are compared:

- Random superposition of the individual subcarriers (classical SFN)
- Subcarrier selection based on strongest received power
- Ideal phase predistortion leading to constructive superposition at the terminal

Note that predistortion techniques require channel state information (CSI) at the relays, which leads to comparatively more complex system implementations.

While the former concept is a two-hop concept with one stage of intermediate relays, this can be generalized to a multistage concept as suggested in [15]. The idea is to group together closely spaced relays, thereby forming a stage that implements a virtual antenna array as



■ Figure 5. The concept of cooperative relaying.

depicted in Fig. 5b. More specifically, the source node transmits to the relays in the first stage, which then may use space-time coding techniques in a distributed manner to retransmit the signal to the next stage of relays. For example, each of the nodes in a stage can transmit a column of an orthogonal space-time code matrix, where the individual column indices have been chosen by the stage's nodes via a local exchange of information. This cooperation could possibly be done over an alternative air interface such as Bluetooth. Eventually, the destination terminal combines the signals transmitted by the last stage. It can be shown that up to 5 dB power savings are achieved with four distributed relays per stage compared to a conventional relay protocol.

Among others, important research areas are:

- The design of flexible protocols and forwarding strategies that allow integrating cooperative approaches in conventional relaying systems
- The question of availability of CSI at the transmitters and relays
- The trade-off between macrodiversity gains and usage of additional radio resources required by cooperative relaying

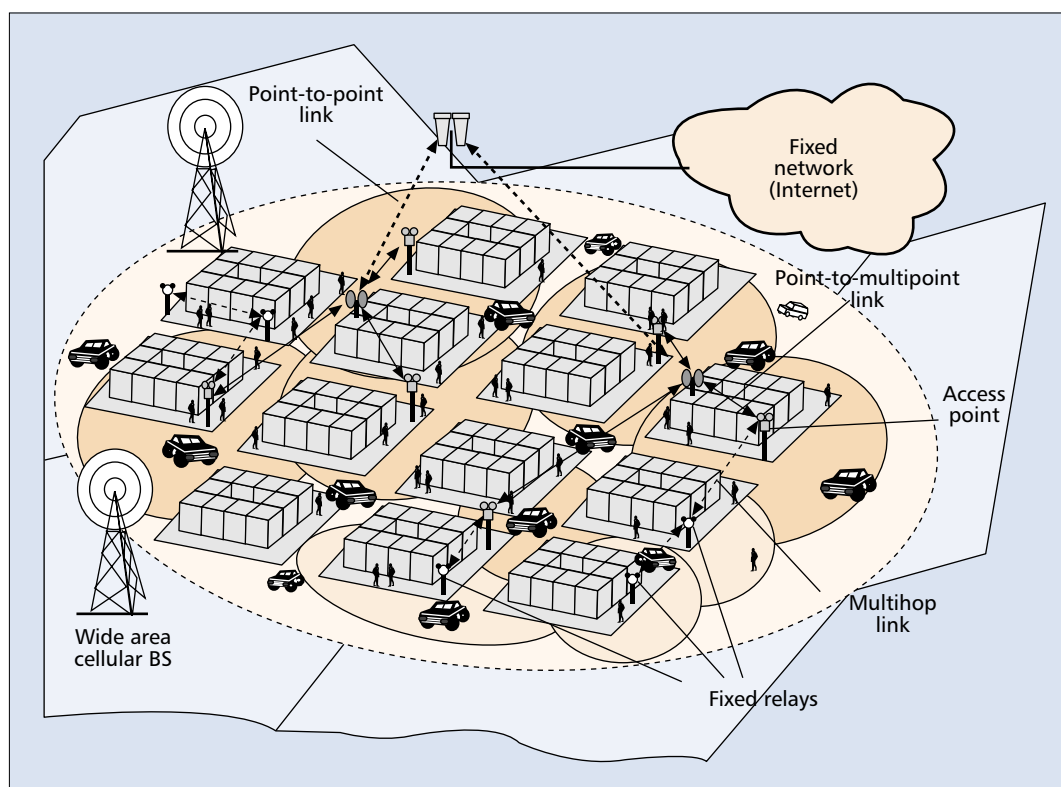
## ROUTING AND RADIO RESOURCE MANAGEMENT

### ROUTING

We consider routing in a multihop network supported by an infrastructure and communication relations limited to a few hops only. Multiple simultaneous routes become possible, making the choice of routing algorithm important. An algorithm ensuring that no queue at a relay node explodes for the largest possible set of packet arrival rates is called *throughput-optimal* [16].

Routing becomes more challenging when considering mobile relays. In the Mobile Ad Hoc Networks (MANET) subgroup of the Internet Engineering Task Force (IETF), several routing algorithms for MANETs have been investigated. Studies of these algorithms have shown high routing overhead and low efficiency in network throughput. Based on this observation, it is proposed that routing in the multihop network be supported by an area-wide cellular overlay network [17]. There, a hybrid routing scheme called Cellular Based Multihop (CBM) routing has been studied, where route requests are sent to the BS of the overlaying cellular network. This

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■ Figure 6. Wireless media system: integration with mobile radio (source: [10]).

central entity determines the route and responds with a packet comprising a series of mobile nodes willing to relay the data traffic between the source and destination. Service and route discovery is performed in the overlay cellular network and the packet data transmissions in the microrange multihop network. This exploits both the ability of the macro network to communicate with all of its nodes, and the throughput efficiency of multihop transmission in the microrange layer. Results have shown that CBM leads to low packet drops due to wrong route information and adds little overhead to network traffic [17]. Moreover, it allows fast packet delivery because of quick route establishments, and the routing overhead increases only linearly with the number of nodes, which indicates that CBM scales very well with network size.

It is known that the protocol overhead associated with establishing and maintaining the routes in multihop networks may become severe, thus reducing the potential efficiency of multihop techniques substantially. Limiting the number of hops (e.g., employing a single intermediate relay station on any route) would greatly simplify routing complexity.

#### RADIO RESOURCE MANAGEMENT

Radio resource management concerns the assignment of BS, channel, and transmit power. In view of this, the sensitivity of radio coverage to the selection of relay, relay channel, and relay power control are investigated in [4] for a cellular TDMA system where two-hop mobile relaying is employed whenever necessary.

Whenever relaying is performed, an additional time or frequency channel is required for the

second hop. In [4] an aggressive strategy that does not require any new channels for relaying is adopted: the relay channel is always selected among the already used channels in the adjacent cells.

Various selection schemes for the relay and relay channel, from random to smart selection, with and without power control, are considered in [4]. It is observed that with the proper selection of relay, relay channel, and relay power, a significant enhancement in high-data-rate coverage can be attained through two-hop mobile relaying. The observed trends and corresponding conclusions are as follows:

- Performance gains due to relaying increase as the number of wireless terminals in the system increases.
- Employing power control in both hops further enhances performance, especially as the cells get small; the returns due to power control become substantial for interference-limited cells.
- The maximum relay transmit power level is an important factor only in large cells; in small cells most of the benefits are gained with relatively small relay transmit power levels. Therefore, the impact of relaying on wireless terminals' batteries may not be significant in microcellular systems.
- Performance gains are quite sensitive to the relay selection criterion. If relays are chosen randomly, performance gets worse than for the no-relaying case (this is analogous to the case where a user is connected to a wrong BS). However, highly suboptimal (with minimal intelligence) but implementation-wise feasible relay selection schemes (e.g., relay selection based solely on proximity through the use of the Global Posi-

tioning System, GPS, data available at the BSs) still yield significant coverage enhancements.

- Once a good relay is selected, performance gains become fairly insensitive to the relay channel selection criterion. Therefore, in systems with limited resources for monitoring and control purposes, priority should be given to proper relay selection rather than proper relay channel selection.

For infrastructure-based solutions with fixed relays, the selection of relays is much simpler and more or less predefined. For this case, possible concepts can be based on centrally controlled heuristic methods for relay channel selection within a single multihop cell. Selection criteria involve the mutual interference between relay channels.

## WMS: A PROTOTYPICAL CELLULAR RELAY NETWORK

The wireless media system (WMS) is an example of a new radio access network architecture for a mobile broadband system using fixed relays to provide radio coverage to otherwise shadowed areas. Its goal is to ensure highest spectrum efficiency and lowest possible transmit power. WMS architecture makes use of a wireless or mobile broadband air interface to link low-power (1 W) pico BSs, APs, and RSs, trading the high capacity available at APs for radio coverage range. The WMS, illustrated in Fig. 6, is embedded in a cellular radio network providing medium-transmission-rate communication to high-mobility terminals. The low power requirement for the broadband air interface leads to a picocellular concept relying essentially on multihop communication across fixed relays and to some extent also on ad hoc networking, using mobile relays at the periphery of the WMS [1, 6, 7].

WMS is intended to have a very high multiplexing data rate of between 100–1000 Mb/s at the air interface for medium-velocity terminals and high deployment flexibility through the use of mass production building blocks for APs and relays. The candidate spectrum bands for operation of the WMS (e.g., beyond 3 GHz or even beyond 5 GHz) will allow very small equipment size for picocellular BSs/APs and RSs, including the antennas, so the infrastructure can be termed more or less “invisible.” RSs might use either central or distributed control of the nodes involved, as described in [3]. WMS is integrated into a 3G system, as shown in Fig. 6, by means of large hexagonal cells, sharing:

- An IPv6 based fixed core network
- Functions of the cellular system like subscriber identity module (SIM), authentication, authorization, and accounting (AAA), and localization

As shown in Fig. 6, the feeder systems connecting APs to the fixed network might be based on either wire/fiber or wireless, for example, point-to-multipoint (PMP) LOS radio systems. Both APs and RSs appear like a BS to a mobile terminal, and are henceforth referred to as *media points* (MPs). In Fig. 6 the radio coverage areas served by RSs are shown in a color different from the APs.

Figure 6 also illustrates by means of an example the discontinuous radio coverage available from WMS in urban areas. The small picocells highlighted around the MPs represent areas where broadband radio coverage is available via preplanned multihop communication.

From Fig. 4 it is apparent that the WMS architecture scales quite well and is able to provide the traffic capacity of an AP to a small (pico) or much larger (micro) cell built up from many picocells defined by the AP and its related RSs, resulting in a very cost-efficient and flexible infrastructure.

A mobile terminal must be able to support both mobile cellular radio and WMS air interfaces, but not at the same time. An operator of a WMS that is integrated into a cellular mobile radio system might apply a mixed cost calculation to be able to trade the low cost for transporting mass data via the WMS against the high cost of data transport across cellular systems. This concept, of course, is also applicable to indoor service. Furthermore, this operator may end up with a very attractive tariff for all of its services compared to an operator purely relying on 3G technology.

## CONCLUSIONS

Relaying is generally considered a method to ensure capacity and coverage in cellular systems. This article gives an overview of relaying, presenting two main concepts. The first is the cooperative use of relays forming virtual antenna arrays to exploit the spatial diversity inherent to multihop communications, leading to substantial increases in available capacity; the second is the wireless media system, a concept for a mobile broadband system based on fixed relay stations. Examples of forwarding techniques as well as a pattern for wide-area urban coverage using clusters of access points and relays are proposed. It is shown for different application scenarios that multihop communications can provide a substantial increase in link and network capacity when applied in areas suffering from heavy path loss. The benefit for broadband radio systems is that the very high capacity that can be expected from these systems can be traded for radio range that would otherwise be limited due to high attenuation at high radio frequencies. This allows meeting the expected capacity needs per unit area without danger of capacity overprovisioning as when relying on single-hop concepts only.

A thorough investigation of the relaying concept is enormously complex due to the many parameters involved, including propagation and physical layer challenges, system issues such as medium access and radio resource management, networking and protocol design, and finally, implementation-related issues. Moreover, a survey of the literature shows that analytical understanding of the subject is far from comprehensive at the present time. The overview of relaying concepts and problems highlights the importance of future research in the areas of virtual arrays and novel diversity schemes, multiple access and multiplexing schemes, and the combination of medium access and radio resource management protocols for multihop networks.

*WMS is an example of a new radio access network architecture for a mobile broadband system using fixed relays to provide radio coverage to otherwise shadowed areas. Its goal is to ensure highest spectrum efficiency and lowest possible transmit power.*

The candidate spectrum bands for operation of the WMS (e.g., beyond 3 GHz or even beyond 5 GHz) will allow very small equipment size for pico cellular BSs/APs and RSs, including the antennas, so that the infrastructure can be termed more or less "invisible."

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