Relay-Based Deployment Concepts for Wireless and Mobile Broadband Radio

Ralf Pabst, Bernhard H. Walke, and Daniel C. Schultz, RWTH Aachen University
Patrick Herhold, Technical University of Dresden; Halim Yanikomeroglu, Carleton University
Sayandev Mukherjee and Harish Viswanathan, Lucent Technologies
Matthias Lott and Wolfgang Zirwas, SIEMENS ICM; Mischa Dohler and Hamid Aghvami, Kings College
David D. Falconer, Carleton University; Gerhard P. Fettweis, Technical University of Dresden

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].

TDMA-based systems are especially well-suited to introduce relaying, as this scheme allows for an 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.

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

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.

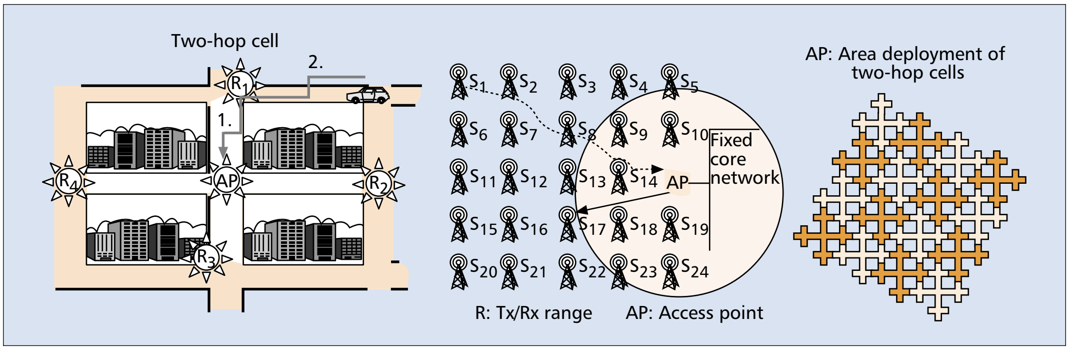


Figure 1. *Left: a city scenario with one AP (serving the white area) and four RSs covering the shadowed areas around the corners shown in grey. Middle: a schematic of the scenario. Right: wide-area coverage using the basic element (left) and two groups of frequencies (source: [10]).*

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

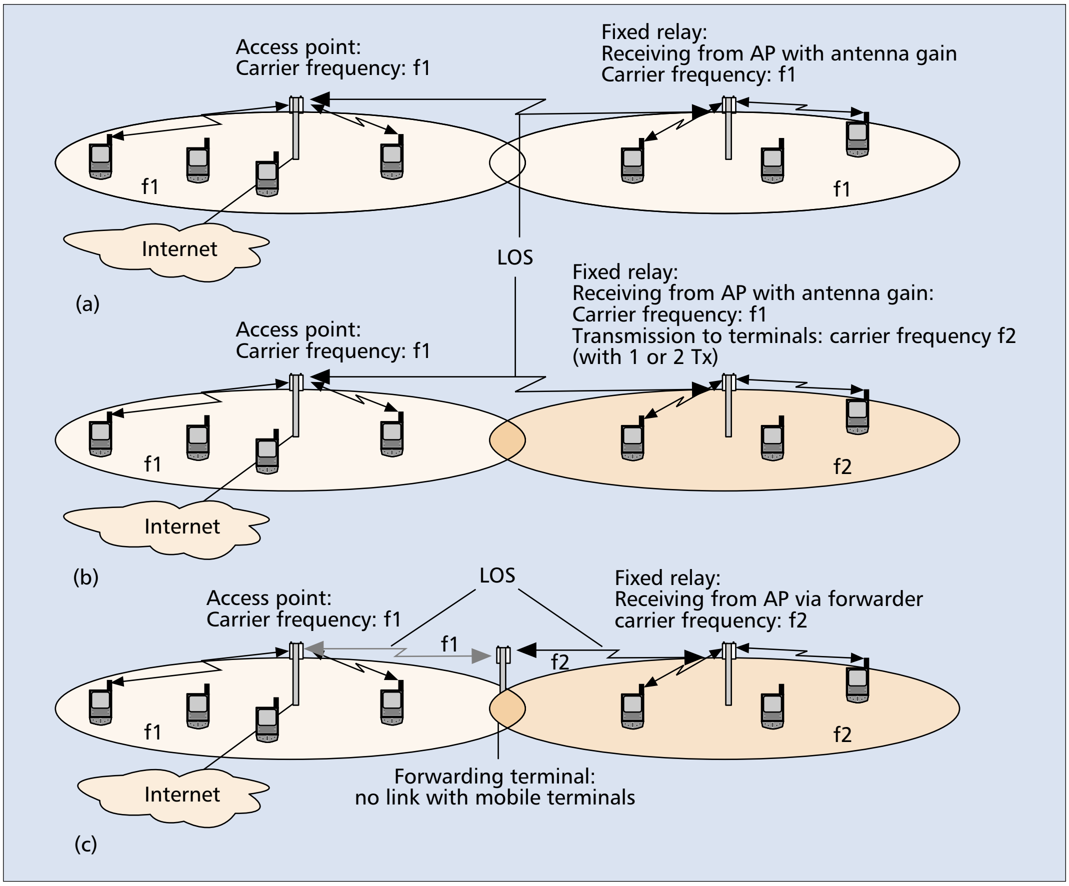


Figure 2. *Examples of relay concepts (source: [10]).*

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]:

a) Relaying in the time domain with the AP and RSs operating at the same carrier frequency, f1, while accessing the physical medium in time multiplex.

b) 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.

c) 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 f1 and f2. 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 interconnection (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.

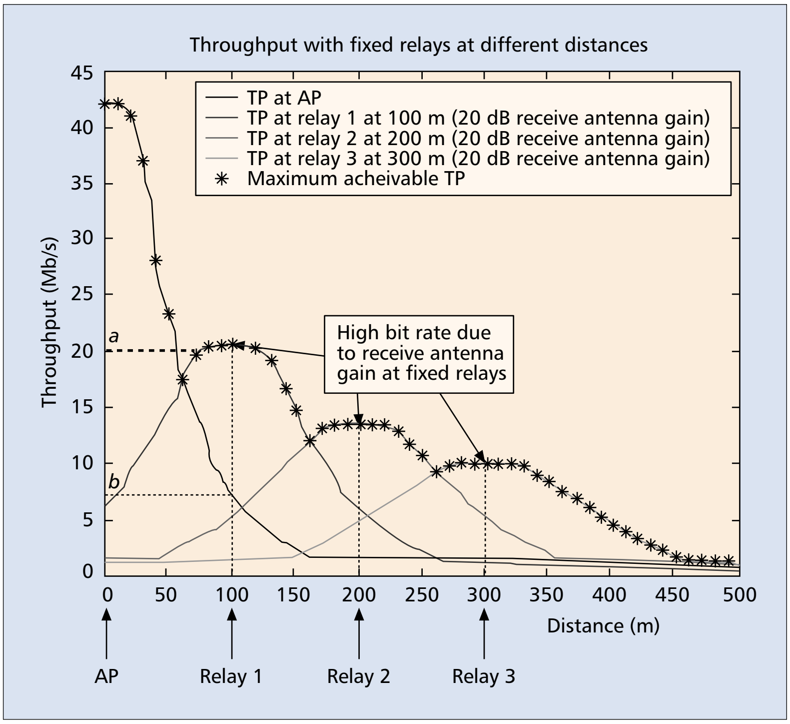


Figure 3. *Analytical estimation of the extension of the radio range of an AP by relays with receive antenna gain (source: [10]).*

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

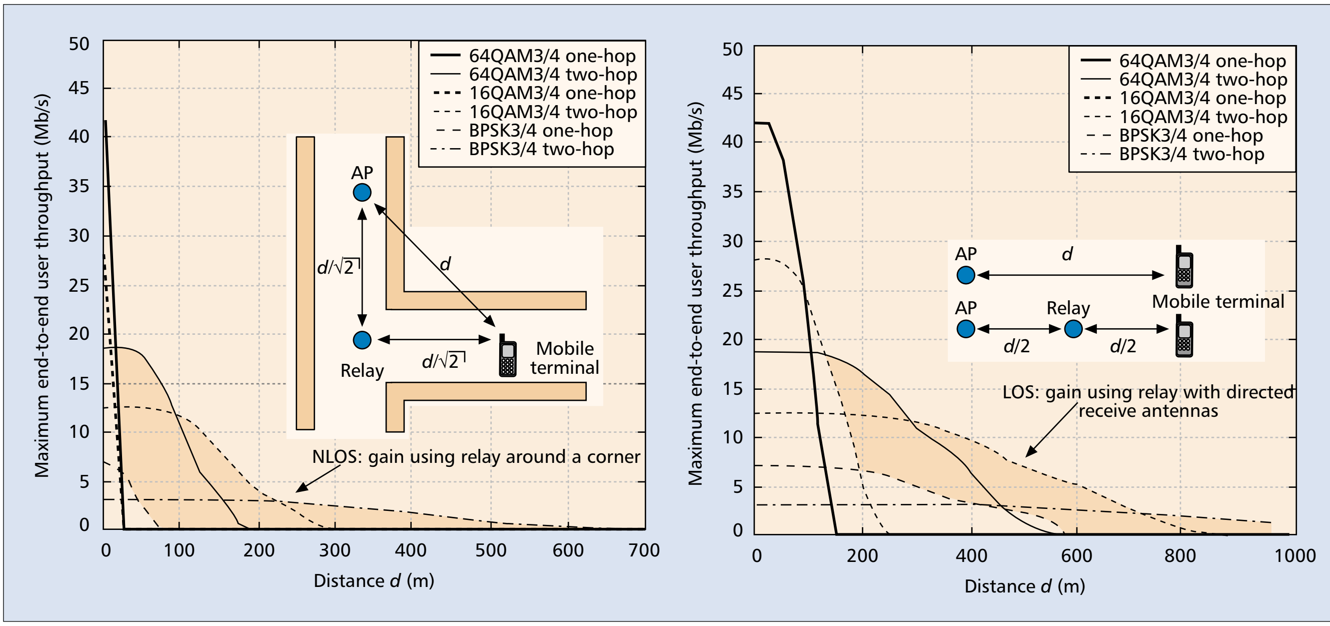


Figure 4. *Left: a fixed wireless router at an intersection to extend the radio range of an AP around the corner into a shadowed area to serve a remote mobile terminal. Right: maximum end-to-end throughput vs. distance for forwarding under LOS conditions with directed receive antennas having a gain of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

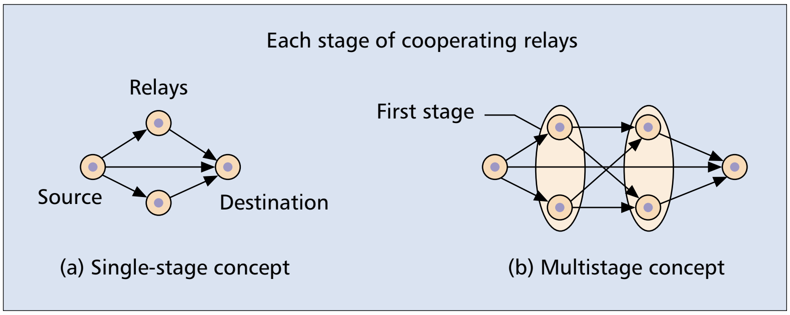


Figure 5. *The concept of cooperative relaying.*

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

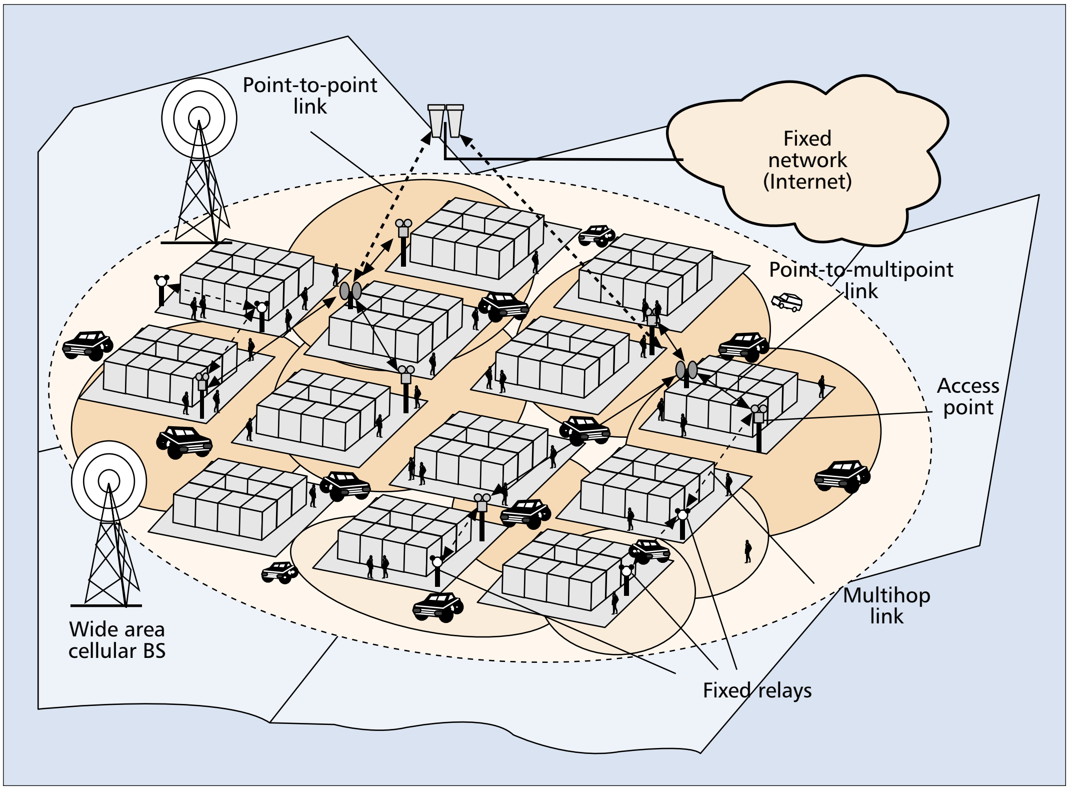
Routing and Radio Resource Management

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

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.



■ **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.

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.

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.

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."

ACKNOWLEDGMENTS

The authors would like to thank Shalini Periyalwar of Nortel Networks, Ottawa and Bassam Hashem of Saudi Telecom Company for support and inspiration for this article. Special thanks go to all the unnamed participants in the WG4 sessions of the WWRF who have added their thoughts and ideas to the discussion about relay-based systems.

REFERENCES

[1] H. Yanikomeroglu, "Fixed and Mobile Relaying Technologies for Cellular Networks," *2nd Wksp. Apps and Svcs. in Wireless Networks*, Paris, France, 3–5 July 2002, pp. 75–81.
[2] H. Wu *et al.*, "Integrated Cellular and Ad Hoc Relaying Systems: iCAR." *IEEE JSAC*, vol. 19, no. 10, Oct. 2001, pp. 2105–15.
[3] B. Walke and G. Briechle, "A Local Cellular Radio Network for Digital Voice and Data Transmission at 60 GHz," *Proc. Int'l. Conf. Cellular and Mobile Commun.*, London, U.K., Nov. 1985, pp. 215–25; http://www.comnets.rwth-aachen.de/publications/~walke
[4] V. Sreng, H. Yanikomeroglu, and D. D. Falconer, "Relayer Selection Strategies in Cellular Networks with Peer-to-Peer Relaying," *IEEE VTC Fall '03*, Orlando, FL, Oct. 2003.
[5] A. N. Zadeh and B. Jabbari, "Performance Analysis of Multihop Packet CDMA Cellular Networks," *Proc. IEEE GLOBECOM 2001*, vol. 5, San Antonio, TX, Nov. 2001, pp. 2875–79.
[6] N. Esseling, H. S. Vandra, and B. Walke, "A Forwarding Concept for HiperLAN/2," *Proc. Euro. Wireless 2000*, Sept. 2000, Dresden, Germany, pp. 13–18.
[7] B. Walke *et al.*, "IP over Wireless Mobile ATM Guaranteed Wireless QoS by HiperLAN2," *Proc. IEEE*, vol. 89, Jan. 2001, pp. 21–40.
[8] G. Neonakis Agglou and R. Tafazolli, "On the Relaying Capability of Next-Generation GSM Cellular Networks," *IEEE Pers. Commun.*, vol. 8, no. 1, Feb. 2001, pp. 40–47.
[9] J. Habetha and B. Walke, "Fuzzy Rulebased Mobility and Load Management for Self-Organizing Wireless Networks," *J. Wireless Info. Networks*, Special Issue on Mobile Ad Hoc Networks: Standards, Research, Applications, vol. 9, Apr. 200, pp. 119–40.
[10] B. Walke, R. Pabst, and D. Schultz, "A Mobile Broadband System Based on Fixed Wireless Routers," *Proc. Int'l. Conf. Commun. Tech.*, 2003, Beijing, China, pp. 1310–17.
[11] N. Esseling *et al.*, "A Multi Hop Concept for HiperLAN/2: Capacity and Interference," *Proc. Euro. Wireless 2002*, vol. 1, Florence, Italy, Feb. 2002; http://www.comnets.rwth-aachen.de/cnroot_engl.html/~publication, pp. 1–7.
[12] W. Mohr, R. Lüder, and K.-H. Möhrmann, "Data Rate Estimates, Range Calculations and Spectrum Demand for New Elements of Systems Beyond IMT-2000," *Proc. 5th Int'l. Symp. Wireless Pers. Multimedia Commun.*, Honolulu, HI,, Oct. 2002.
[13] E. Zimmermann, P. Herhold, and G. Fettweis, "On the Performance of Cooperative Diversity Protocols in Practical Wireless Systems," *Proc. 58th VTC*, Orlando, FL, Fall 2003.
[14] W. Zirwas *et al.*, "Signaling in Distributed Smart Antennas," *Proc. 7th OFDM Wksp.*, Hamburg, Germany, Sept. 200, pp. 87–91.
[15] M. Dohler, A. Gkelias, and H. Aghvami, "2-Hop Distributed MIMO Communication System," *IEE Elect. Lett.*, June 2003.
[16] H. Viswanathan and S. Mukherjee, "Performance of Cellular Networks with Relays and Centralized Scheduling," *Proc. IEEE VTC*, Orlando, FL, Oct. 2003.
[17] M. Lott *et al.*, "Hierarchical Cellular Multihop Networks," *Proc. 5th Euro. Pers. Mobile Commun. Conf.*, Glasgow, U.K., 22–25 Apr., 2003.

BIOGRAPHIES

RALF PABST (pab@comnets.rwth-aachen.de) served student internships at SIEMENS ICN and D2 Vodafone before he received his Diploma in electrical engineering from RWTH Aachen University in 2001 and has served since then as a research assistant to the chair of Communication Networks (ComNets) of Aachen University, where he is working toward his Ph.D. degree. He has worked on various IST projects (WSI, WWRI, NEXWAY, ANWIRE, and WINNER) and is actively involved in the organization of WG4 in the Wireless World Research Forum (WWRF). His research interests include the performance of relay-based deployment concepts for next-generation wireless networks, associated resource management protocols, and spectral coexistence of wireless standards.

BERNHARD H. WALKE (walke@comnets.rwth-aachen.de) is an internationally recognized expert (numerous publications, including several internationally published books) in the field of communication networks. His group's research work focuses on formal specification, modeling, mathematical and simulative analysis, and pilot implementation of protocols and services for communication networks. Having worked at AEG-TELEFUNKEN Research Institute, and later at Fern University of Hagen (Chair for Data Processing Techniques), he has held the chair of Communication Networks at Aachen University since 1990. He is member of various national and international expert groups and coordination boards (e.g., ITG, AG Mobikom, WWRF) and has frequently served as an advisor to the German national regulation body (RegTP).

DANIEL C. SCHULTZ (dcs@comnets.rwth-aachen.de) received his Dipl.-Ing. degree from Aachen University in 1999. He works for the chair of ComNets as research assistant since 2000. Before that he worked as a consultant for Vision Unltd. GbR, Germany. At ComNets he has worked on IST projects VIRTUOUS, FUTURE, and SAILOR. He was the responsible researcher at ComNets for the German government funded miniWatt project. His current research activities are in relaying technologies in a fixed and planned infrastructure.

PATRICK HERHOLD (herhold@ifn.et.tu-dresden.de) (S02) received his Dipl.-Ing. degree from Technische Universität Dresden in 2001, after having studied at TU Dresden and Virginia Polytechnic Institute and State University. During one of his internships he gained experience in radio network planning and optimization with Vodafone D2 GmbH in Munich. Since 2002 he is with the Vodafone Chair at Technische Universitt Dresden, where he is working toward his Ph.D. degree. His current research interests include the design of cooperative relaying networks and system-level performance evaluation of mobile communications systems.

HALIM YANIKOMEROGLU (halim@sce.carleton.ca) received a Ph.D. degree in electrical and computer engineering from the University of Toronto, Canada, in 1998. Since then he has been with the Department of Systems and Computer Engineering at Carleton University, Ottawa, where he is now an associate professor. His research interests include almost all aspects of wireless communications with special emphasis on cellular multihop networks, radio resource management, and CDMA multi-antenna systems. He has been involved in the steering committees and technical program committees of numerous international conferences in wireless communications; he has also given several tutorials in such conferences. He is Technical Program Co-Chair of the IEEE Wireless Communications and Networking Conference 2004. He is an editor for *IEEE Transactions on Wireless Communications*, and a guest editor for *Wiley Journal on Wireless Communications & Mobile Computing*. Currently he is serving as Vice-Chair of the IEEE Technical Committee on Personal Communications. He is a registered Professional Engineer in the province of Ontario, Canada.

SAYANDEV MUKHERJEE (sayan@lucent.com) (S'92-M'96) obtained a B.Tech. degree in electrical engineering from the Indian Institute of Technology, Kanpur, in 1991, and M.S. and Ph.D. degrees in electrical engineering from Cornell University, Ithaca, New York, in 1994 and 1997, respectively. Since 1996, he has been a member of technical staff in the Wireless Research Laboratory, Bell Laboratoriess, Lucent Technologies, New Jersey. His research interests include stochastic models, wireless system simulations, intelligent resource allocation in wireless systems, and scheduling and routing in wireless networks.

HARISH VISWANATHAN (harishv@lucent.com) received his B. Tech. degree from the Department of Electrical Engineering, Indian Institute of Technology, Madras, in 1992, and M.S. and Ph.D. degrees from the School of Electrical Engineering, Cornell University, in 1995 and 1997, respectively. He was awarded the Cornell Sage Fellowship during academic year 1992–1993. He is presently with Bell Laborato-

ries, Lucent Technologies, Murray Hill, New Jersey as a member of technical staff. He has worked extensively on design and analysis of performance enhancement schemes for wireless systems and in particular on the application of multiple-antenna technology to third-generation wireless systems. His research interests include information theory, communication theory, wireless networks, and signal processing.

MATTHIAS LOTT [M] (matthias.lott@siemens.com) received a Diploma in electrical engineering from the University of Braunschweig and a Ph.D. (Dr.-Ing.) degree from RWTH Aachen, Germany, in 1996 and 2001, respectively. Since 2000 he is an employee at Siemens AG in the Department of Future Radio Concepts, where he is involved in European and German research projects. He has published over 50 papers and holds several patents in the areas of channel modeling, modulation, and protocols for link and network layers. His recent research has focused on the problems of WLAN, ad hoc networks, and interworking of IP and the link layer. He received ITG's best paper award in 1999 and is a member of VDE.

WOLFGANG ZIRWAS (wolfgang.zirwas@siemens.com) received his Diploma in communication technologies in 1987 from the University of Munich. He started his work at Siemens Munich in the central research department for communication technologies with a focus on high-frequency issues and developed high-data-rate TDM fiber systems for data rates up to 40 Gb/s. Further research topics were broadband access systems over coax cable, twisted pairs, and finally radio-in-the-loop systems. Besides research topics he developed hardware trial systems and conducted related field trials. In 1999 he joined the Mobile Network Division at Siemens AG Munich, where he is project manager for the Bundesministerium fr Bildung und Forschung funded project COVERAGE in research of future radio systems based on multihop and OFDM.

MISCHA DOHLER [StM] (mischa@ieee.org) obtained his M.Sc. degree in telecommunications from King's College, University of London, England, in 1999, and his Master's and Diploma in electrical engineering from Dresden University of Technology, Germany, in 2000. He is currently lecturer at the Centre for Telecommunications Research, King's College London, where he works toward a PhD degree. Prior to telecommunications he studied physics in Moscow. He won various competitions in mathematics and physics ,and participated in the third round of the International Physics Olympics for Germany. He has published various research papers and holds four patents. He is the Student Representative of the IEEE UKRI Section and a member of the Student Activity Committee of IEEE Region 8.

HAMID AGHVAMI (hamid.aghvami@kcl.ac.uk) obtained his M.Sc. and Ph.D. degrees from King's College, University of London, England, in 1978 and 1981, respectively. He is currently a professor in telecommunications engineering at King's College and director of research in the Department of Electronic and Electrical Engineering. He has published over 150 research papers and has lectured on digital radio communications worldwide. He is a member of the U.K. IEE and Chairman of the Communications Chapter of U.K. and R.I.. He has served on the technical program and organizing committees of many international and European conferences, and founded the International Symposia on PIMRC.

DAVID D. FALCONER [F] (ddf@sce.carleton.ca) received a B.A.Sc. degree in engineering physics from the University of Toronto in 1962, and S.M. and Ph.D. degrees in electrical engineering from Massachusetts Institute of Technology (MIT) in 1963 and 1967, respectively. After a year as a postdoctoral fellow at the Royal Institute of Technology, Stockholm, Sweden, he was with Bell Laboratories, Holmdel, New Jersey from 1967 to 1980. During 1976–1977 he was a visiting professor at Linkping University, Sweden. Since 1980 he has been at Carleton University, Ottawa, Canada, where he is a professor in the Department of Systems and Computer Engineering. Since 1990 he has been active in a research project on broadband wireless communication at EHF radio frequencies, involving several universities, sponsored by the Canadian Institute for Telecommunications Research. From 1990 to 1998 he led the project.

GERHARD P. FETTWEIS (fettweis@ifn.et.tu-dresden.de) earned his Dipl.-Ing. and Ph.D. degrees from Aachen University of Technology (RWTH) in Germany. From 1990 to 1991 he was a visiting scientist at the IBM Almaden Research Center, San Jose, California, working on signal processing for disk drives. From 1991 to 1994 he was with TCSI Inc., Berkeley, California, responsible for signal processor developments. Since September 1994 he has held the Vodafone Chair at Technische Universität Dresden, Germany. He co-founded Systemonic as CTO, a startup acquired successfully in 2002 by Philips Semiconductors. The main focus is on broadband wireless chipsets. He has been an elected member of the IEEE Solid State Circuits Society Board (Administrative Committee) since 1999, and was associate editor for *IEEE Transactions on Circuits and Systems II* and the *IEEE Journal on Selected Areas in Communications* Wireless Series. He also serves on company supervisory boards, and on industrial as well as research institutes' advisory committees.

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.