Chapter 8

MULTI-ROUTE AND MULTI-USER DIVERSITY IN INFRASTRUCTURE-BASED MULTI-HOP NETWORKS

Keivan Navaie
Broadband Communications and Wireless Systems (BCWS) Centre
System and Computer Engineering Department, Carleton University
keivan@sce.carleton.ca

Halim Yanikomeroglu
Broadband Communications and Wireless Systems (BCWS) Centre
System and Computer Engineering Department, Carleton University
halim@sce.carleton.ca

Abstract: In this chapter multi-route and multi-user diversity in multi-hop infrastructure-based wireless networks are studied. We also propose a network coordinated relaying method, Cooperative Induced Multi-user Diversity Relaying (CIMDR), to overcome the fundamental limitations on the average achieved throughput per-user. In the proposed method, multi-user diversity is induced in a 2-hop forwarding scheme and then exploited in order to improve per-user achieved throughput. Simulation results show that by using the proposed method, the net throughput per-user and the packet-drop-ratio are significantly improved.

Keywords: multi-hop wireless networks, infrastructure-based wireless network, multi-user diversity, multi-route diversity, multiple access protocol.

1. Introduction

Relay-based deployment concepts will play an important role in the cost-effective provision of very high data rates in an almost-ubiquitous manner. Cost-effectiveness is a crucial point for the success of 4G cellular networks.

Frank H. P. Fitzek and Marcos D. Katz (eds.), Cooperation in Wireless Networks: Principles and Applications, 223–241.
© 2006 *Springer. Printed in the Netherlands.*

There has been an increasing interest in the infrastructure-based wireless multi-hop networks in academia, industry, and standardization bodies.

In the IEEE 802 Wireless World framework, a number of working groups are focusing on developing multi-hop standards:

- IEEE 802.11s - WLAN mesh networking: The goal is to develop a standard for auto-configuring multi-hop paths between access-points (APs) in a wireless distribution system. The standard is targeted to be approved by 2008.
- IEEE 802.15.5 - Wireless Personal Area Network (WPAN) mesh networking: This Task Group aims at determining the necessary mechanisms that must be present in the physical and medium access control (MAC) layers of WPANs to enable multi-hop networking. The standard is targeted to be approved by 2007.
- IEEE 802.16 - Wireless Metropolitan Area Network (WMAN): IEEE 802.16-2004 standard entitled “Air Interface for Fixed Broadband Wireless Access Systems” is approved in July 2004. The MAC layer supports a primarily point-to-multipoint architecture, with an optional multi-hop topology. The 802.16e standard amends the currently approved 802.16 standard in order to support mobility for the devices operating in the 2-6 GHz licensed bands. An optional multi-hop mode is also being considered in 802.16e. IEEE ratification of the 802.16e standard is expected in late 2005.
- IEEE 802.20 - Mobile Broadband Wireless Access (MBWA): The scope of this Task Group is to develop the specification of PHY and MAC layer of an air interface for inter-operable mobile broadband wireless access systems, operating in licensed bands below 3.5 GHz, optimized for IP-data transport, with peak data rates per user in excess of 1 Mbps. IEEE 802.20 standard is also expected to support the multi-hop architecture.

For the next generation of cellular networks, relay-based multi-hop cellular deployment concept has been considered as a potential air interface technology by Wireless World Research Forum (WWRF) as well as the Wireless world INitiative NEw Radio (WINNER) project supported by European Commission.

In addition to the above highlighted on-going standardization efforts, various proprietary multi-hop networks solutions in the unlicensed bands are being developed by the industrial players.

With the emergence of the relay-enabled standards in the IEEE 802 family, much higher interest and activity can be predicted in relay-based communications towards the end of this decade.

It is worth noting that the main goal in using the multi-hop architecture in the current proprietary solutions, as well as in the upcoming first generation relay-enabled standards, is to provide cost-effective high data rate coverage. However, once there is a relay-enabled standard it may be possible to achieve further benefits through the cooperation of the nodes in the network.

In this chapter, we study multi-user and multi-route diversity in multi-hop infrastructure-based wireless networks. We investigate the fundamental limitations on the throughput of single hop infrastructure-based networks. We then propose a simple two-hop relaying method, Cooperative Induced Multi-user Diversity Relaying (CIMDR), to overcome the fundamental limitations on the average achieved throughput per-user. We then present the CIMDR protocol details and investigate its performance. The presented simulation results also show that using CIMDR the throughput and packet drop ratio are significantly improved.

The organization of this chapter is as follows: In Section 2 we study route diversity and multi-user diversity. We also investigate the fundamental limitations of single-hop transmission. In Section 3 we present the CIMDR protocol. Simulation results are presented in Section 4. The chapter in concluded in Section 5.

2. Multi-route Diversity and Multi-user Diversity

A fundamental characteristic of wireless networks is the time variations in wireless channels. An important means to mitigate the destructive effects of the channel time variations is *diversity*, where the basic idea is to improve the system performance by creating several independent paths or, not significantly correlated, between the transmitter and the receiver.

In infrastructure-based wireless networks, the data packets are transmitted to the destination through intermediate relays. Such networks can be considered as a very rich *multi-route diversity* environment. Multi-route diversity is a potential form of diversity, which is achieved as a result of having independent wireless routes between the access-point and each user (see Fig. 8.1).

In a wireless network with multiple users, *multi-user diversity* is achieved as a result of having independent time-varying wireless channels between the access-point and different users in the coverage area (see Fig. 8.2).

In order to improve system throughput and connectivity performance, appropriate mechanisms should be adopted in appropriate time-scales to exploit multi-user diversity and multi-route diversity.

Multi-route Diversity

In an infrastructure-based multi-hop wireless network "source" and "destination" are defined according to the radio access network. Therefore, for the uplink (downlink) "destination" ("source") means the access-point, and "source" ("destination") means the mobile user.

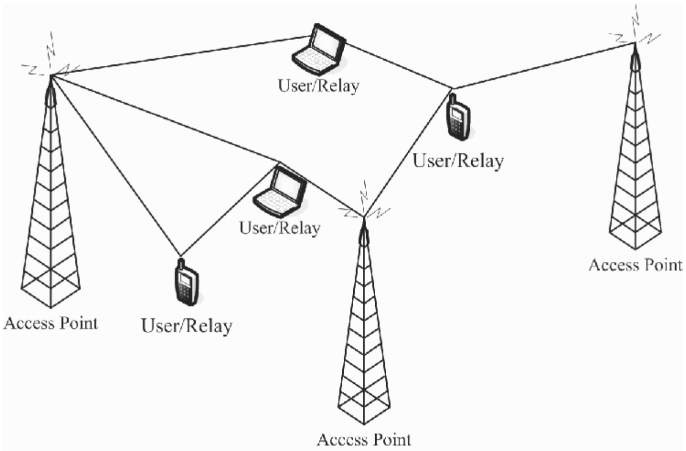

Figure 8.1. Multi-route diversity in infrastructure-based multi-hop networks.

Routing in an infrastructure-based wireless network is a functionality that recognizes, allocates, maintains, and manages wireless routes between the sources and the destinations.

Routing in multi-hop ad-hoc networks. In a wireless ad-hoc network in which there is no infrastructure, the network topology frequently changes. The time-scale of topology change is in the order of nodes' mobility. Therefore, routing in such networks is a challenging task. There are two general approaches for routing in ad-hoc networks: *topology-based* and *position-based routing* (see *e.g.*, [Mauve et al., 2001], and [Hong et al., 2002]).

In *topology-based routing* protocols the connectivity information that exists in the network is utilized for routing. Topology-based routing protocols can be further divided into *proactive*, *reactive*, and *hybrid* approaches. Proactive algorithms employ classical routing methods and maintain routing information of the available routes in the network even if these routes are not currently in use. Obviously, the main drawback of such approaches is the computational complexity and signaling overhead due to the maintenance of the routes that are not actually in use. In contrast, reactive routing protocols only maintain the routes that are currently in use. Reactive routing protocols also have some inherent limitations; these protocols need to perform a route discovery between communication peers before transmission. Obviously, performing route discovery may create a large delay in the transmission of the first packet. Moreover, even though route maintenance for reactive algorithms is restricted to the routes currently in use, it may still generate a significant amount of signalling overhead in cases that the network topology changes frequently.

In order to achieve a higher level of efficiency and scalability, a combination of a local proactive routing mechanisms and a global reactive one are considered as a hybrid routing protocol. However, even a combination of both methods still needs to maintain at least those routes which are currently in use.

The above mentioned limitations of topology-based routing are eliminated by using *position-based* routing protocols, which utilize the physical position information of the participating nodes. In these methods, each node determines its own position through the use of Global Positioning System (GPS) or some other type of positioning service. This position information is then included in the packet's destination address. The routing decision at each node is then being made based on the destination's position contained in the packet header and the position of the forwarding node's neighbors in such way that a performance metric is maximized. This performance metric indicates the efficiency of the routing algorithm in terms of the length of the route between the source and the destination and/or the transmission delay.

Note that due to the lack of network infrastructure, the main challenge for ad-hoc routing is to establish and maintain the connectivity between the source and the destination. This is not the case for infrastructure based wireless networks. In multi-hop infrastructure-based networks, selecting a particular route and transmission on it can be envisaged as a part of the resource management mechanism. Therefore, routing might be implemented jointly with or as a part of other radio resource control mechanisms ([Qiang and Acampora, 1999], [Tsirios and Haas, 2001], [Zhenzhen and Hua, 2004]).

Routing in multi-hop infrastructure-based network. For infrastructure-based multi-hop wireless networks, the stationarity (or low mobility) of the infrastructure nodes motivates the utilization of topology-based proactive methods. In this case, the routing information corresponding to the users within the coverage area of an access-point can be stored in and maintained by that access-point. Reactive routing methods can also be considered as a part of a hybrid method especially for providing ubiquitous network coverage for inter-system interconnection.

Routing techniques for multi-hop infrastructure-based networks should exploit the inherent characteristics of this network architecture:

- Network-oriented processing: Part of the routing in an infrastructure-based multi-hop network can be implemented in the infrastructure entities as these entities have more processing power. Having a network-centric routing technique not only simplifies the routing process but also provides the opportunity of performing routing jointly with other layers' functionalities.

- Position information and data flow direction: The position information and flow direction in both uplink and downlink are available. This information can be utilized for developing efficient position-based routing mechanisms.

- Cooperation incentive: Referring to the fact that the infrastructure deals with the charging issues, there could be a network coordinated framework, which promotes users' participation in cooperative communication schemes. Users' cooperation can also be very helpful in the process of routing particularly in the case of mobile relays.

Multi-route diversity can be exploited in different radio resource management mechanisms including, admission control, hand-over, load balancing, congestion control, and failure recovery.

In admission control, network resources should be allocated to a call/session to support its Quality-of-Service (QoS) during its service time. In multi-hop infrastructure-based networks there should be a close cooperation between admission control and routing mechanism. As a part of admission control, there should be a mechanism to assign a certain network access entity (*e.g.*, an access-point or a fixed relay) to the corresponding user. For a user in the network coverage area, there are likely to have more than one route to a network access entity. Multi-route diversity can be exploited in admission control. Once a certain access-point does not have any available radio resources to accept a new call/session, call admission control mechanism may consider other available routes (even if they are not optimal), and a suitable access-point may then be assigned accordingly. The multi-route diversity also makes the hand-over process easier. Having multiple routes can also be utilized in load balancing and congestion control in which users' traffic is re-routed away from the congested area.

An appropriate routing method may consider "routes" as actual network resources that should be managed and utilized opportunistically to improve the system efficiency through utilizing the most available knowledge. Accordingly, there are a number of challenges for designing a routing mechanism which includes the followings:

- Complexity: Computational complexity and signalling overhead are the fundamental challenges for any radio resource management mechanism. Usually, computational complexity is a function of the number of parameters involved in making a decision or performing an action. However, because of the availability of high processing power in the access-points, the signalling overhead is more critical. Note, that in some circumstances the signaling overhead can be replaced by computational complexity through employing more complex decision making procedures.

- Measurements: Most of the routing methods are based on the assumption of the availability of perfect measurements in appropriate times (*e.g.*, channel state, upstream queue length, etc.). This may not be precisely the case in practice which should be taken into account in designing practical routing mechanisms.

- Supporting advanced communication techniques: Using advanced communication techniques such as multi-antennas, beam-forming and cooperative relaying, are very promising in designing and developing future communication systems. In multi-hop infrastructure-based networks using such techniques may be considered for improving transmission rates. Therefore, a routing mechanism should be flexible enough to be extendable such that one or more of the previously mentioned techniques can be incorporated in the physical layer. An appropriate extension of a routing technique is the one that can efficiently exploit advanced communication techniques to improve the system performance.

- Integration into other radio resource management functionalities: Basically, routing is a functionality located in the networking layer (layer 3). However, in multi-hop infrastructure-based networks, due to time variations in channel characteristics and network topology, routing may be considered as an important entity in a cross-layer design framework which has interaction particularly with resource scheduling, admission control, and handover. Examples of such routing methods are joint routing and scheduling ([Cruz and Santhanam, 2003]), joint routing and load balancing ([Pabst et al., 2005]), inter-system routing for ubiquitous coverage ([Ai-Chun et al., 2004]), and integrated power control and routing ([Yun and Ephremides, 2005]).

Multi-user Diversity in Multi-hop Infrastructure-based Networks

The delay tolerance of data services, alongside with wireless channel fluctuations in the physical layer have been opportunistically utilized to provide efficient resource allocation in data services (see *e.g.*, [Knopp and Humblet, 1995], [Tse, 1997], [Viswanath et al., 2002]). In such techniques, the packet transmission is scheduled when time varying channel capacity happens to be at (or near) its peak. The resulting throughput improvement is referred to as *multi-user diversity gain*. This approach has been employed in high-speed downlink standards for the third generation (3G) cellular wireless communications standards, HSDPA and 1xEV-DV.

In multi-hop infrastructure-based networks, the packets are transmitted to the destination through intermediate relays. An immediate potential advantage

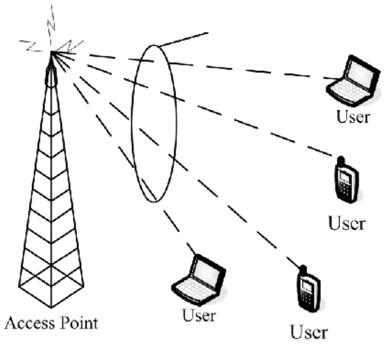

Figure 8.2. Multi-user diversity in an infrastructure-based network with multiple users.

of this architecture is the opportunity of exploiting multi-user diversity in each hop.

Here we consider an infrastructure-based wireless network in which access points with a maximum transmit power level of P_{max} are located at the center of their coverage area. An access-point transmits a signalling channel that can be received by all users in the coverage area.

In our modelling, there are n mobile users, indexed by i, distributed uniformly in the coverage area. Each packet has a large delay tolerance and includes the identity (*e.g.*, physical address) of the destination user. The wireless channel gain between the access-point and ith user at time t is given by the process $\{g_i(t)\}$ which is assumed to be stationary and ergodic. Moreover, for different users in the coverage area, the corresponding channel processes are assumed to be independent and identically distributed (i.i.d.).

At any time t, a resource allocation policy, Π, coordinates the data transmissions from the access-point to relays, or relays to destination users. For a resource allocation policy, $\Gamma_i^{\Pi}(t)$ is defined as the *achieved downlink throughput of user i at time t*, that is the number of bits received by user i at time t. For a resource allocation policy, we define *the feasible long-term achieved downlink throughput per-user*, $\Gamma^{\Pi}(n)$, such that

$$\lim_{T\to\infty} \inf_{i} \frac{1}{T} \sum_{t=1}^{T} \Gamma_i^{\Pi}(t) \to \Gamma^{\Pi}(n). \tag{8.1}$$

$\Gamma^{\Pi}(n)$ depends on various factors including the maximum supported bit-rate, number of users in the coverage area, and the wireless channel temporal characteristics. The definition in (8.1) is similar to that presented in ([Gupta and Kumar, 2000]), for ad-hoc networks.

To exploit multi-user diversity, a resource allocation policy, $\Pi_{\mathcal{D}}$, is employed. This policy, in its simplest form, allocates the maximum access-point transmit bit-rate to a user i^* at each time t, where

$$i^*(t) = \arg\max\{g_i(t)\}. \tag{8.2}$$

Selecting $i^*(t)$ based on the channel condition may result in an unfair resource allocation. To resolve the fairness issue, some corrective scheduling methods are often used (see *e.g.*, [Viswanath et al., 2002], [Shakkottai and Stolyar, 2002], [Navaie et al., 2005]). Since our focus is on the multi-user diversity gain, we simply consider a long-term fairness requirement in which

$$\lim_{T\to\infty} \inf_{i,j} \frac{1}{T} \sum_{t=1}^{T} \left|\Gamma_i^{\Pi}(t) - \Gamma_j^{\Pi}(t)\right| \to 0;$$

that is a direct consequence of the i.i.d. wireless channels across different users in the coverage area.

Note that, in order to exploit multi-user diversity, according to $\Pi_{\mathcal{D}}$, a user's packets have to be delayed until the channel becomes the best relative to other users. Therefore, the time-scale of channel variations that can be exploited by $\Pi_{\mathcal{D}}$ is limited by the delay tolerance of the corresponding application.

It is shown that for the described resource allocation policy, $\Pi_{\mathcal{D}}$, the overall system throughput performance is significantly higher than that of simultaneous transmission ([Knopp and Humblet, 1995]). The greater the number of users in the coverage area, the higher is the probability of occurrence of a good channel, which results in a greater improvement in the access-point throughput. However, the achieved downlink throughput per-user is still limited by the maximum transmission bit-rate and coverage area, thus limited by fundamental architectural constraints.

Consider a CDMA-based radio interface; for transmission with a rate $R_i(t)$ bits/s to a user i, the basic bit-energy to the interference-plus-noise spectral density constraint should be satisfied. Thus

$$\frac{W}{R_i(t)} \frac{P_{max} g_i(t)}{I_0} \geq \rho_i(t), \tag{8.3}$$

where I_0 is the background interference plus noise power, and $\rho_i(t)$ is the minimum required bit-energy to the interference-plus-noise spectral density for the data transmission with bit-rate $R_i(t)$. For a user i selected for transmission, using (8.3) we write,

$$R_i(t) \leq \xi_0 g_i(t) \tag{8.4}$$

where $\xi_0 = \big(\rho_i(t) I_0\big)^{-1} W P_{max}$. Therefore, for user i,

$$\lim_{T\to\infty} \inf_{i} \frac{1}{T} \sum_{t=1}^{T} \Gamma_i^{\Pi_{\mathcal{D}}}(t) = \lim_{T\to\infty} \inf_{i} \frac{1}{T} \sum_{t=1}^{T} a_i(t) R_i(t) \tag{8.5}$$

where $a_i(t)$ is the selection indicator; *i.e.*, $a_i(t) = 1$, if user i is selected for transmission at time t, and 0 otherwise. Summing (8.5) over all users, we have

$$\begin{aligned}\Gamma^{\Pi_{\mathcal{D}}}(n) &\leq \frac{\xi_0}{n} \lim_{T\to\infty} \inf_{i} \frac{1}{T} \sum_{i=1}^{n} \sum_{t=1}^{T} a_i(t) g_i(t) &\quad (8.6)\\ &= \frac{\xi_0}{n} \lim_{T\to\infty} \inf_{i} \frac{1}{T} \sum_{t=1}^{T} g_{i^*}(t). &\quad (8.7)\end{aligned}$$

Eq. (8.7) shows that the downlink throughput per-user is upper-bounded by $g_{i^*}(t)$.

To increase multi-user diversity gain, in ([Viswanath et al., 2002]), multiple transmit antennas are used to induce large and fast channel fluctuations, *i.e.*, greater $g_{i^*}(t)$. Also in a multiple-cell scenario, the independent time variations of the wireless channels between a user and the neighboring access-points is introduced in ([Navaie and Yanikomeroglu, 2005]), as a new dimension in multi-user diversity. This form of diversity is exploited by joint access-point assignment and packet scheduling, which results in greater $g_{i^*}(t)$ and thus greater multi-user diversity gain per-user.

To exploit the multi-user diversity in a multi-hop network, a relaying method is proposed in ([Larsson and Johansson, 2005]). In this method, using a sequential optimization approach, multi-user diversity is exploited in each hop by selecting the next relay based on the instantaneous channel quality. However, selecting only one relay reduces the opportunity of capturing a good channel in the next hop. In the following section, we propose an access-point coordinated cooperative relaying method, Cooperative Induced Multi-user Diversity Relaying (CIMDR).

3. Cooperative Induced Multi-user Diversity Routing for Multi-hop Infrastructure-based Networks with Mobile Relays

CIMDR (Fig. 8.3) exploits the broadcast nature of wireless channel to induce multi-user diversity through a two-phase process. The basic idea is as follows. In the first phase, access-point broadcasts data packets with its maximum bit-rate. Some users in the coverage area are likely to receive the transmitted data packets. These users, act as potential relays in the second phase; each potential relay wait until the occurrence of a “good channel” to the destination user and then transmit the data packets. As soon as the transmission is carried out by one of the potential relays, the access-point manages to release the packets buffered in other potential relays.

We consider a 2-hop infrastructure-based network. Access-point is located at the center of the coverage area and its maximum transmit power is P_{max}.

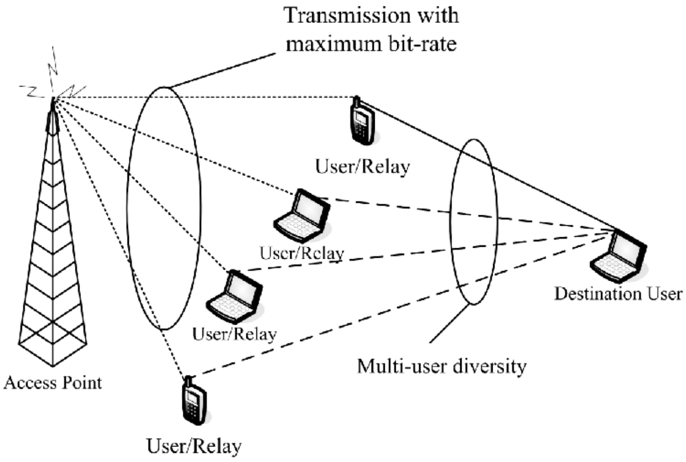

Figure 8.3. CIMDR for 2-hop transmission.

Packets can be transmitted directly from the access-point to the users, or they can go through another mobile user serving as a relay. Access-point transmits signalling on dedicated control channel(s) that can be received by all users in the coverage area.

There are n mobile users, indexed by i, distributed uniformly in the coverage area. Mobile users are able to receive, temporarily save and relay packets in the same frequency band of access-point transmission. They also transmit signaling information on an uplink signaling channel. Mobile terminals have a large enough buffer to store relay packets. Each packet has a large delay tolerance and includes the identity (*e.g.*, physical address) of the destination user. Each user in the coverage area broadcasts a pilot signal to indicate its identity. This pilot signal is also utilized by the relays for channel estimation. To decrease power consumption, broadcasting of users' pilot channel can be activated upon receiving a signal (from the access-point) indicating the existence of a data packet destined to that mobile user.

Since by this scenario we *induce* multi-user diversity through generating independent paths between the destination user and m relays, we name it Co-operative Induced Multi-user Diversity Relaying (CIMDR).

CIMDR Protocol

The proposed scenario, $\Pi_{\mathcal{I}}$, has two phases: the *feeding phase* and the *delivery phase*. These two phases occur sequentially in time (Fig. 8.4). The time-span of each phase (*i.e.*, τ_F and τ_D) is assigned based on the network

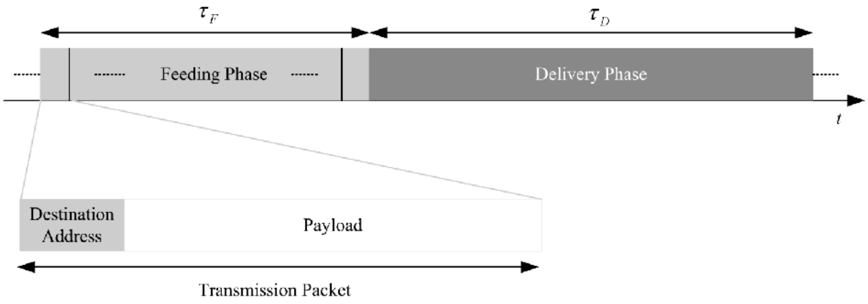

Figure 8.4. CIMDR two-phase protocol and packet structure.

traffic and the communication environment characteristics. Fig. 8.5 shows the signalling procedure of CIMDR protocol.

Feeding Phase: In the feeding phase, packets are broadcasted by the access-point with its maximum bit-rate; the total number of transmitted bits in the feeding phase would be $\tau_F R_{max}$, where τ_F is the time duration of the feeding phase. During the feeding phase multiple packets are transmitted using time domain scheduling. Any user which receives a data packet in the feeding phase acts as potential relays in the delivery phase.

The transmission order of the queued packets in the access-point is managed by a higher-layer functionality. If the destination user is among those who receive packets in the feeding phase, it sends a received acknowledge signal, R-ACK, to the access-point. Consequently, the access-point broadcasts a data release signal, D-REL, and all other relays release that data packet.

Here we assume that the number of users in the coverage area is high enough that in each time instant there is, at least, one user that can receive the transmitted data in the feeding phase. In cases where no mobile user in the coverage area can receive the transmitted packet in the feeding phase, the access-point should reduce its bit rate.

In the feeding phase, multi-user diversity gain comes from the fact that the access-point radio resource is only allocated for transmission with its maximum bit-rate. Note that for a large number of users in the coverage area, it is likely that some users will have a channel state that supports the access-point's highest bit-rate.

Delivery Phase: In the delivery phase, the access-point is kept inactive and only transmissions from relays to the final destinations are allowed. Each relay continuously tracks the quality of the wireless links to the neighboring users as well as their identity. If a relay is able to achieve a transmission bit-rate greater than or equal to a system parameter R_0 bits/s, then that relay transmits to the

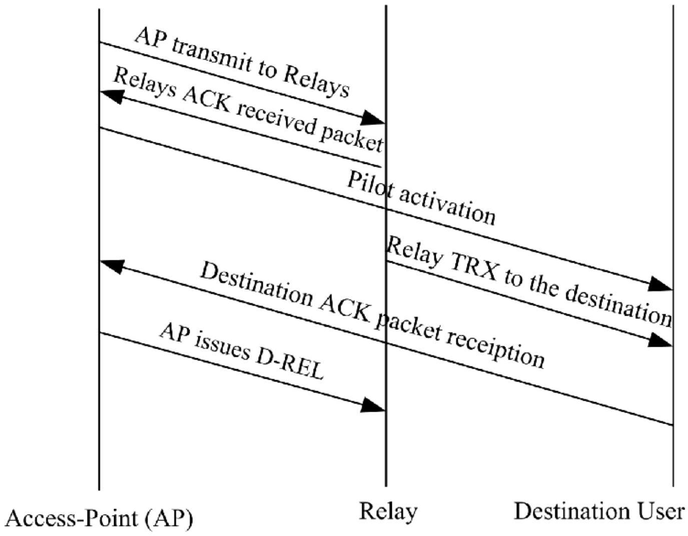

Figure 8.5. CIMDR signaling: Normal transmission.

destination user. The selection of R_0 critically affects the system performance and is elaborated in the Proposition given below.

Medium access control can be either a contention-based method or an access-point coordinated non-contention based method. Upon successful transmission, destination user sends an R-ACK signal to the access-point. Consequently, the access-point broadcasts a D-REL signal and other relays release that packet. If the access-point does not receive an R-ACK corresponding to a packet in a predefined time interval, τ_{max} seconds, that packet is considered lost and a D-REL signal is broadcasted by the access-point (see Fig. 8.6). That packet may be considered for retransmission in a later time.

Multi-user diversity in the delivery phase is exploited by transmission on channels with the achieved bit-rate greater than or equal to R_0. Note that in practice the transmit bit-rate may be adjusted based on the channel status which is fed back into the access-point by the users.

For a given medium access control technique, $0 < \gamma \leq 1$ is defined as the medium access control gain, which shows the average portion of the radio resource (*e.g.*, transmission time) that can be allocated to the competitors for a shared media. For non-contention based medium access control mechanisms $\gamma = 1$. Let R be the average access-point transmission bit-rate for single hop transmission with multi-user scheduling. The following proposition provides the condition on the system parameters for CIMDR.

Proposition 1: For a large number of users in the coverage area, by using CIMDR the access-point throughput is increased compared to the single-hop

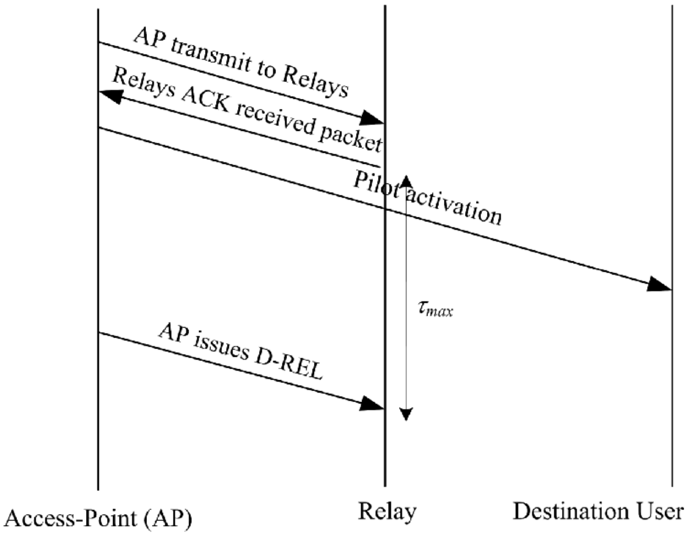

Figure 8.6. CIMDR signaling: Lost packet.

transmission if

$$\frac{1}{R_0} < \gamma\Big(\frac{1}{R} - \frac{1}{R_{max}}\Big). \tag{8.8}$$

Proof: Let $\Phi_D(t)$ and $\Phi_F(t)$ be the indicator functions for delivery and feeding phases, respectively. Therefore, $\Phi_D(t) = 1$ ($\Phi_F(t) = 1$) when the system is in delivery (feeding) phases and $\Phi_D(t) = 0$ ($\Phi_F(t) = 0$), otherwise. The total data bits in the system at time t, $\Theta(t)$, can be calculated as

$$\Theta(t) = \int_0^t \Big(\gamma R_0 \Phi_D(\alpha) - R_{max}\Phi_F(\alpha)\Big) d\alpha.$$

For system stability

$$\lim_{T\to\infty} \Theta(T) \to 0, \tag{8.9}$$

thus

$$\tau_D \gamma R_0 = \tau_F R_{max}. \tag{8.10}$$

On the other hand, compared to the single-hop transmission, the total access-point throughput will be increased if

$$\tau_F R_{max} > (\tau_F + \tau_D) R. \tag{8.11}$$

Hence, using (8.10) and (8.11),

$$\frac{1}{R_0} < \gamma\Big(\frac{1}{R} - \frac{1}{R_{max}}\Big). \tag{8.12}$$

This proves the proposition ■.

On one hand, if R_{max} is very large, then a smaller number of users in the coverage area will receive the data packets in the feeding phase. On the other hand, decreasing R_{max} will increase the number of potential relays but will decrease the overall rate. The transmission rate R_{max} may also be adjusted based on the number of potential relays; if data packets are not received by a reasonable number of mobile users, then R_{max} may be decreased.

Given the condition in (8.8) holds, within the interval $[0,\ T]$ for $T \to \infty$ all packets transmitted to the relays will be delivered to the users. Therefore, for CIMDR, it is simple to show that (8.7) is modified as

$$\Gamma^{\Pi_{\mathcal{I}}}(n) \leq \frac{\xi_1}{n}\breve{g}, \tag{8.13}$$

where ξ_1 is defined similar to ξ_0 in (8.7) and $\breve{g}$ is the minimum time-average value of the channel gain between the access-point and the relay with the maximum transmission bit-rate. Note that

$$\lim_{T\to\infty} \inf_i \frac{1}{T}\sum_{t=1}^{T} g_{i^*}(t) < \breve{g}, \tag{8.14}$$

which is a direct consequence of smaller path-losses because of multi-hop transmission. This directly results in $\Gamma^{\Pi_{\mathcal{I}}}(n) > \Gamma^{\Pi_{\mathcal{D}}}(n)$. In other words, using CIMDR, the achieved average throughput per user is increased.

Note that τ_{max} has an important role in the performance of CIMDR. If $\tau_{max} \to \infty$, then a packet can be kept waiting in a potential relay until the occurrence of a very high rate channel (*i.e.*, very large R_0). For moderate values of τ_{max}, the mobility is very important. The higher the users' mobility the higher is the probability of the occurrence of a high bit-rate channel in the second hop. For a given mobility profile, a larger value of τ_{max} results in the exploitation of the mobility in a more efficient way.

Incentive system for users' cooperation. In CIMDR users which act as relays, participate in the transmission process. However, there should be an incentive system to provide reasonable motivation to the users for cooperation in the relaying process.

This problem is heavily studied in the context of mobile ad-hoc networks (see *e.g.*, [Buttyan and Hubaux, 2003; Zhong et al., 2003]). In an infrastructure-based multi-hop system it is possible to have a network-based incentive system which makes this problem a lot easier.

Here, we propose a simple credit based incentive system. In this system a user i is granted a *participation credit* of $\mu(t)$ upon participating in relaying process at time t. This is due to the fact that the mobile user allocates a part of its processing power for tracking the neighboring mobile stations and for involving

Table 8.1. Simulation Parameters.

Parameter	**Value**
Physical layer	Based on UMTS
Cell radius	100 m
Access-points transmit power	10 W
Standard dev. of log-normal fading	8 dB
Background noise density	-174.0 dBm/Hz
Propagation loss exponent	4
Time-slot length	10 ms
R_{max}	2 Mbps
R	384 Kbps
Medium access control gain (γ)	≈ 1
Minimum required E_b/I_0	2 dB

in the corresponding signaling processes. As soon as finding the destination user and detecting a channel with available bit-rate greater than or equal to R_0, the relay transmits the data packet thus allocates a portion of its transmission power to relaying. In this case, the network grants a *relaying credit* of $\nu(t)$ to that mobile user. The values of $\mu(t)$ and $\nu(t)$ are related to the network charging strategy and can be varied in different times of the day based on the network traffic. In such a scenario with m mobile users participating in CIMDR, the total granted credit per packet transmission is $m.\mu(t) + \nu(t)$ which would be considered as part of the transmission cost for each data packet.

4. Simulation Results

We simulate a single-cell DS-CDMA system with n active users based on UMTS standard ([Holma and Toskala, 2000]). Users are uniformly distributed in the coverage area. The simulation parameters are presented in Table 8.1. A simple mobility model has been implemented, in which at each time instant, a user randomly located within a circle with its previous location in the center and a diameter of 2.5 meters.

To show the effect of multi-user diversity, we consider three different systems: in System I, for each user the access-point transmits packets in first-come-first-serve fashion using a time domain scheduling scheme. In System II, packets are scheduled based on $\Pi_{\mathcal{D}}$. Transmission in System III is based on $\Pi_{\mathcal{I}}$, with a non-contention based medium access control technique in the delivery phase.

System I is considered as the benchmark, and the average achieved net throughput of Systems II and III are normalized by the average achieved net throughput of System I. Fig. 8.7 illustrates the normalized average achieved net throughput versus the number of users in the coverage area for $\tau_{max} = 2$ s.

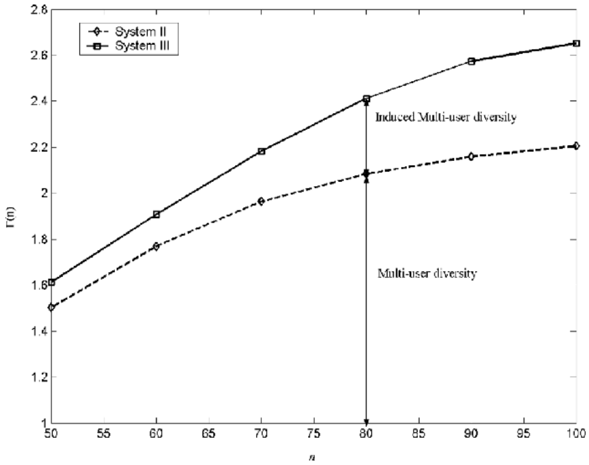

Figure 8.7. Normalized average achieved net throughput versus the number of users.

The difference between the throughput gains of Systems II and III indicates the achieved multi-user diversity gain resulting from exploiting the induced multi-user diversity by CIMDR. As it is expected, this gain is increased by the number of users. Note that normalized throughput curve will saturate because of the access-point total throughput constraint.

We also compare the packet-drop-ratio for System II and System III. Packets are considered lost when they cannot be transmitted within a delay threshold of $\tau_{max} = 2$ s. As it can be seen in Fig. 8.8, using CIMDR improves the packet-drop-ratio performance. The greater improvement in the packet drop ratio is archived by a larger number of users in the coverage area and a larger delay tolerance of 10 s.

5. Conclusion

In this chapter we study the multi-user diversity gain in the downlink of single-hop and multi-hop infrastructure-based networks. We propose an network coordinated cooperative relaying method, Cooperative Induced Multi-user Diversity Relaying (CIMDR), to overcome the fundamental limitations on the average achieved net throughput per-user. In the proposed method, multi-user diversity is induced in a 2-hop forwarding scheme and then exploited to improve per user achieved data throughput. We show that by using the proposed method, the throughput per-user and the packet-drop-ratio are significantly improved.

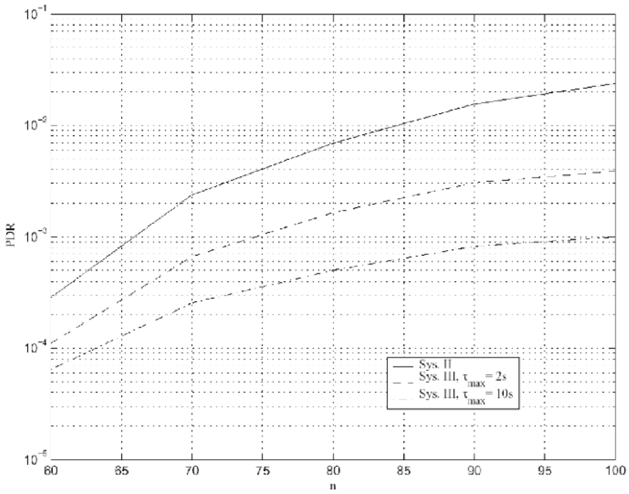

Figure 8.8. Packet-drop-ratio (PDR) of CIMDR and single-hop multi-user diversity scheduling for $\tau_{max} = 2$ and 10 seconds.

References

Ai-Chun, P., Jyh-Cheng, C., Yuan-Kai, C., and Agrawal, P. (2004). Mobility and session management: UMTS vs. cdma2000. *IEEE Wireless Communications*, 11(4):30–43.

Buttyan, L. and Hubaux, J. P. (2003). Stimulating cooperation in self-organizing mobile ad hoc networks. *ACM Mobile Networks and Applications*, 8(5):579–592.

Cruz, R. L. and Santhanam, A. V. (2003). Optimal routing, link scheduling and power control in multihop wireless networks. *in Proc. INFOCOM 2003*, 1:702–711.

Gupta, P. and Kumar, P. R. (2000). The capacity of wireless networks. *IEEE Trans. on Info. Theory*, pages 388–404.

Holma, H. and Toskala, A. (2000). *WCDMA for UMTS: Radio Access for Third Generation Mobile Communications*. John Willy and Sons.

Hong, X., Xu, K., and Gerla, M. (2002). Scalable routing protocols for mobile ad hoc networks. *IEEE Network*, 16(4):11–21.

Knopp, R. and Humblet, P. A. (1995). Information capacity and power control in single-cell multiuser communications. *in Proc. IEEE ICC'95*, pages 331–335.

Larsson, P. and Johansson, Niklas (2005). Multi-user diversity forwarding in multi-hop packet radio networks. *in Proc. IEEE WCNC'05*.

Mauve, M., Widmer, A., and Hartenstein, H. (2001). A survey on position-based routing in mobile ad hoc networks. *IEEE Network*, 15(6):30–39.

Navaie, K., Montuno, D., and Zhao, Y. Q. (2005). Fairness of resource allocation in cellular networks: A survey. In Li, W. and Pan, Y., editors, *Resource Allocation in Next Generation Wireless Networks*. Nova Science Publishers.

Navaie, K. and Yanikomeroglu, H. (2005). Optimal downlink resource allocation for elastic traffic in cellular CDMA/TDMA networks. *Preprint*.

Pabst, R., Walke, B. H., Schultz, D. C., Herhold, P., Yanikomeroglu, H., Mukherjee, S., Viswanathan, H., Lott, M., Zirwas, W., Dohler, M., Aghvami, H., Falconer, D. D., and Fettweis, G. P. (2005). Relay-based deployment concepts for wireless and mobile broadband cellular radio. *IEEE Communications Magazine*, 42(9):80–89.

Qiang, G. and Acampora, A. (1999). Routing and handoff support for a novel wireless broadband access network (UniNet). *in Proc. IEEE GLOBCOM'99*, 5:2788–2793.

Shakkottai, S. and Stolyar, A. (2002). Scheduling for multiple flows sharing a time-varying channel: The exponential rule. In Suhov, Yu. M., editor, *AMS Translations*, 2.

Tse, D. (1997). Optimal power allocation over parallel Gaussian channels. *in Proc. IEEE ISIT'97*, page 27.

Tsirios, A. and Haas, Z. J. (2001). Multipath routing in the presence of frequent topological changes. *IEEE Communications Magazine*, 39(11):132–138.

Viswanath, P., Tse, D. N. C., and Laroia, R. (2002). Opportunistic beamforming using dumb antennas. *IEEE Trans. on Info. Theory*, pages 1277–1294.

Yun, L. and Ephremides, A. (2005). Joint scheduling, power control, and routing algorithm for ad-hoc wireless networks. *HICSS '05*, page 322b.

Zhenzhen, Y. and Hua, Y. (2004). Networking by parallel relays: diversity, lifetime and routing overhead. *in Proc. of Thirty-Eighth Asilomar Conference on Signals, Systems and Computers*, 2:1302–1306.

Zhong, S., Chen, J., and Yang, Y. (2003). Sprite: A simple, cheat-proof, credit-based system for mobile ad-hoc networks. *in Proceedings of IEEE INFOCOM'03*, 3:1987–1997.