Fixed and Mobile Relaying Technologies for Cellular Networks

Halim Yanıkömeroğlu
Broadband Communications and Wireless Systems (BCWS) Centre
Department of Systems & Computer Engineering — Carleton University, Ottawa
halim@sce.carleton.ca

Abstract — In the last few years there has been quite an interest in multihop-augmented infrastructure-based networks in both industry and academia, such as the "seed" concept in 3GPP, coverage extension of HiperLAN2 through relayers, user-cooperative diversity, LMDS/MMDS mesh networks. This paper presents an overview of the concept of relaying, especially in cellular networks.

1 Multihop-Augmented Infrastructure-Based Networks: Motivation and Historic Perspective

The answer(s) to the following fundamental question is of utmost importance to the entire wireless community: how should the signals be distributed to and collected from wireless terminals in the most efficient manner. The developments in this direction will yield enhanced coverage, throughput, and QoS, as well as cost-efficient and compact wireless terminals.

Simple calculations indicate that the provision of the very high data rates envisioned in future wireless systems in reasonably large areas (i.e., beyond small disconnected pockets) does not seem to be feasible unless significant new spectrum is released or the density of the access points is increased dramatically. Currently, there is no indication that significant new spectrum will be available in the near future; and, a drastic increase in the number of access points is not economically justifiable.

In recent years, there has been significant advances in signal processing techniques (such as interference cancellation algorithms) and collocated antenna architectures which are generally referred to as smart antennas (such as MIMO and adaptive antennas). Although incorporation of these techniques in future wireless systems is crucial, for practical reasons, these techniques alone do not seem to be sufficient in enabling almost-ubiquitous very high data rate coverage. For instance, it may be infeasible to deploy complex antenna systems at wireless terminals; besides, in the presence of heavy shadowing, even the smartest antennas will not be of much help.

Therefore, more fundamental enhancements are necessary for the very ambitious capacity, throughput, and coverage requirements of future. Towards that end, in addition to advanced signal processing techniques, some major modifications in the wireless network architecture itself, which will enable effective distribution and collection of signals to and from wireless users, are sought. The integration of multihop capability in conventional wireless networks is one such promising architectural upgrade.

Towards that end, in the last few years there has been quite an interest in the generic multihop networks in both industry and academia, such as the "seed" concept in 3GPP, coverage extension of HiperLAN2 through relayers, user-cooperative diversity, LMDS/MMDS mesh networks. The intermediate relayers/routers in such multihop-augmented networks may be some fixed low-complexity entities (like "seeds" in the cellular multihop case [3GPP terminology]), or the other wireless terminals in the network (although routing through wireless terminals is not practical in the FDD mode unless non-trivial hardware changes/updates are made). Advanced antenna technologies can (and should) also be incorporated in these networks to increase the effectiveness in signal delivery further.

The interest in exploiting the "spatial" dimension, and thus in the inherent macrodiversity potential, of wireless networks (which cannot be achieved with collocated antenna technologies no matter how smart the antennas are) has been in various forms. In literature, the variants of such novel systems are referred to with the following keywords:

- mesh networks [1]-[6]
- cellular multihop networks [7]-[10]
- cellular ad-hoc networks [11]-[16]
- ODMA (opportunity-driven multiple access) [17],[18]
- user cooperative diversity [19]-[21]
- multiuser diversity [22]

While the first three keywords emphasize the architecture of such systems, the latter three emphasize their diversity capability; we will collectively refer to them as "intelligent relaying" (or simply as "relaying").

The concept of digital relaying has been studied as a theoretical problem from a network information theory perspective in 1970's and in early 1980's, and capacity regions of simple relaying channels have been evaluated [23]-[28]. But interestingly, to the best of our knowledge, there has been no other analytical study on this concept until very recently – most probably due to the fact that there were no foreseeable applications at that time. With the maturity of digital wireless technologies and with the overwhelming demand for high data rate coverage and throughput for wireless services, it seems that the time has finally arrived for the implementation of intelligent relaying in not-too-distant future. The very recent interest (starting in late 1990's) in this concept in both academia and industry confirms this observation.

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

There are many issues to be investigated towards a successful integration of the multihop capability in conventional wireless networks. For instance, the advantages and disadvantages of using fixed versus mobile relayers (routers), and of performing relaying in analog (amplify-and-forward) versus digital (decode-and-forward) form, have to be investigated. Other pertinent issues within the context of multihop-augmented networks include the load balancing capability (by diverting the traffic with relayers as necessary), signaling overhead, relaying interference, possible cap on the number of hops, incurred latency and its impact on QoS, relayer complexity and functionality, scheduling, radio resource management, and novel diversity techniques.

2 Salient Features of Intelligent Relayers

Conventional relayers have been used for decades to improve radio coverage in highly-shadowed areas [29]-[31]. However, the recently proposed intelligent relaying technologies are much more sophisticated and advanced in comparison to their dumb predecessors. The salient features of intelligent relayers are discussed below.

- **Selective Relaying**: The conventional blind relaying may create significant multiple access interference; therefore relayer site selection has been an important issue in conventional relaying. In intelligent relaying, on the other hand, only signals to/from users which need such an assistance are relayed.

- **Channel Selection**: Relayers use the most appropriate channel (frequency/time slot or code) with the right transmit power and/or modulation (and coding) level in order to reduce/minimize interference [9],[10].

- **Decoded versus Amplified Relaying**: The decoded relaying corresponds to the case where a relayer digitally decodes and re-encodes the relayed signal before retransmission. In the amplified relaying, on the other hand, a relayer simply amplifies the received signal before retransmission. In other words, the decoded relaying is regenerative, while amplified relaying is non-regenerative [32]-[40]. The decoded and amplified relaying are sometimes referred to as the digital and analog relaying, respectively.

- **Macrodiversity**: A terminal may communicate with more than one relayer, as well as with the base station, at the same time to achieve diversity benefits [35]-[37],[41].

- **Mobile (Peer-to-Peer) Relayers**: Relayers are not necessarily limited to radio transievers at some fixed locations (called "seeds" in 3GPP [17],[18],[42]-[45]); but rather, any mobile terminal can potentially act as a relayer.

- **Adaptation**: As the radio channel as well as the terminal and relayer locations change, the system connectivity is changed as well (such as relayer handoff) and the radio resources are redistributed (such as relaying channel re-selection) accordingly [46]-[48].

It is anticipated that the early intelligent relaying systems will only have a subset of the above features; for instance, it will be easier to implement fixed relayers in comparison to mobile relayers.

3 Two-Hop Mobile (Peer-to-Peer) Relaying in Cellular Networks

In this section the main results of our recent research on two-hop mobile relaying are presented (please refer to [9] and [10] for details). In this research peer-to-peer relaying in cellular networks is considered due to the great appeal of avoiding seeds (which has the obvious advantage of not necessitating any additional infrastructure). Various relayer selection algorithms are considered and their high data rate coverage levels are evaluated through extensive simulations.

3.1 Resource Management Problem in an Aggressive Relaying System

There are many challenges in realizing an intelligent relaying system; perhaps most of them are related to routing, protocols, and hardware issues. Yet, even if all these challenges are perfectly overcome, it is still not clear whether the system capacity (and throughput) will actually increase or not, mainly due to the radio resource management problem explained below.

Whenever relaying is performed, an additional channel will be required (for the second hop), since receiving and transmitting at the same channel will yield feedback loops. One strategy would be to reserve channels exclusively for relaying purposes. This is a conservative approach since each two-hop link will cost (in radio resources) the equivalent of two users to the system provider, which is obviously not desirable especially in busy systems.

If no channels are reserved for relaying, on the other hand, the system can search for a vacant channel whenever there is need for relaying, and relaying is performed only when such a vacant channel is available.

One may develop other such strategies as well. In this research we investigate the most aggressive relaying strategy: the relaying is always performed by employing already used channels in that cluster. This strategy will be the most desirable one (if it works) since the terminals with poor radio links will be served without consuming any extra radio resources. But the channel reuse pattern (in a fixed channel assignment scheme) will clearly be violated when this strategy is employed, and therefore there exists the danger of creating excessive co-channel interference. If that happens, one or more other terminals in the same co-channel set may be adversely affected. Now, if those affected terminals also initiate relaying processes for themselves in some other co-channel sets, they may as well bring down some further other users. This may lead to a chain reaction which may cause instability and may eventually bring down the entire system!

We considered a loaded cellular (square cells, omnidirectional antennas) TDMA system with the above described aggressive channel reuse scheme for the second hop. We investigated two types of systems, namely, noise-limited and interference-limited systems, which correspond to cell sizes (edges) 2 km and 400 m, respectively.

Radio resource management deals mainly with the following three assignment problems: base station assignment, channel assignment, and transmit power assignment. In view of this, our objective is to investigate the sensitivity of relaying systems to

- **relayer selection**,
- **relaying channel selection**, and
- **relayer power selection and control**.

Various relayer and relaying channel selection schemes, from random to smart selection, with and without power control, are considered.

In all relaying selection schemes, selection is performed from the channels used in the adjacent cells; in other words, no channel is used twice in the same cell (but some channels are used twice in the same cluster).

3.2 Observed Trends

In the early phase of this research our results indicated that with the proper relayer, relaying channel, and relayer power selection, a significant enhancement in high data rate coverage can be attained.

Next we investigated whether such returns are still valid when the selection criteria are not optimal; in other words, we studied the robustness/sensitivity of these results with respect to the relayer, channel, and power selection criteria used. Here is the summary of the results.

- Performance returns due to relaying increases as the number of users in the system increases.
- Relaying with no power control is still better than no-relaying with power control. Employing power control in a relaying system further enhances the performance, especially as the cells get smaller; the returns due to power control become substantial in 400-m cells (in comparison to 2-Km cells).
- The maximum relayer transmit power level is an important factor only in large cells, where the higher this level is the better the performance is; but in small cells most of the benefits are gained with relatively small power levels.
- The performance returns are quite sensitive to the relayer selection criterion. If the relayers are chosen randomly, the performance gets worse in comparison to the no-relaying case (this is analogous to the case where a user is connected to a *wrong* base station). Yet, highly suboptimal (with minimal intelligence) but implementationally feasible relayer selection schemes (such as relayer selection based solely on proximity) still yield significant coverage enhancements.
- On the other hand, the performance returns are quite insensitive to the relaying channel selection criterion; the difference in performance between the random and smart channel selection criteria is insignificant (provided that the relayers are selected properly).

From the above trends the following encouraging conclusions can be driven:

1. In systems with limited resources for monitoring and control purposes, the priority should be given to proper relayer selection rather than proper relaying channel selection. Since selecting the best relayer will most likely be much easier than selecting the best relaying channel, we may conclude that the relaying system will be quite robust. (For instance, through the use of the GPS data available at the base stations, distance-based relayer selection scheme can readily be implemented.)

2. Power control should be employed whenever possible. Since power control is a very well understood technique which has been used in cellular systems for at least a decade, its implementation will not be a problematic issue.

3. The impact of relaying on wireless terminals' batteries may not be that significant in microcellular systems.

The overall conclusion from the above stated trends is that equiping the wireless terminals with relaying (multihop) capability constitutes a very promising technology in delivering high data rates in a cost-effective manner in future wireless systems.

4 Future Research Areas

A thorough investigation of the concept of intelligent relaying is an enormously complex task due to the very many parameters involved, including propagation and physical layer issues, systems issues including multiple access and resource management, networking and protocol issues, and finally implementation-related issues. Moreover, since there is very little in the literature, the analytical understanding of the subject is also far from being comprehensive. Therefore, more research is needed to be conducted before making conclusive suggestions.

The two main design decisions to be made in a cellular multihop network are whether or not using additional **a)** air-interface, and **b)** infrastructure, for enabling relaying.

4.1 Air Interface: Single versus Dual

Whenever relaying is performed, an additional channel will be required for the second hop (relaying channel), since receiving and transmitting at the same channel will yield excessive interference. If a second air-interface is used in the second and subsequent hops, then the relaying part of the network will be orthogonal to the first hop (which constitutes the conventional cellular part of the composite network).

One possibility, for instance, is using the license-exempt bands for relaying. This seems to be a very promising idea due to the following two reasons: no expensive licensed band will be needed for relaying, and besides, if there happens to be major errors in relayer, relaying channel, and relayer power selection, this will only affect the terminal which is requiring relaying assistance but not the other terminals in the system who are using the licensed band. This appealing synergy between the concept of relaying and the efficient utilization of the license-exempt bands may result in considerable research in this area.

4.2 Network Architecture: Fixed versus Peer-to-Peer Relaying

The network architecture has a direct impact on the infrastructure since additional infrastructure will be needed if relaying is performed by using fixed relayers (seeds). Alternatively, relaying can in principle be performed by using wireless terminals which have good links with their BS. However, there are some important obstacles in, and concerns related to, the realization of peer-to-peer relaying within the upcoming cellular standards. The most fundamental obstacle is that with current technology, wireless terminals cannot transmit and receive in the same frequency band in the FDD mode. Therefore, if wireless terminals are to be used as relayers, TDD mode of operation will be required. Since almost all 3G cellular standards are using FDD mode, seeds have to be used as relayers in such networks. Also, wireless terminals with relaying capability may be substantially more complex; in CDMA systems, for instance, an almost linear increase in hardware with respect to the number of simultaneous relayings is likely since parallel transceivers will be required. Another concern with peer-to-peer relaying is that in such systems there is no guarantee for finding an adequate relayer especially when the active subscriber density happens to be low.

4.3 Other Issues

Here are some other issues which deserve rigorous investigation (the order in the below list is random):

• **Spectrum Allocation – Relaying Channel Reservation versus Reuse:** Some portion of the spectrum can exclusively be dedicated for relaying channels. Or, an already used channel (in that particular cluster) can be utilized as the relaying channel. This latter strategy is very appealing since no additional bandwidth is consumed for relaying, although it violates the standard channel allocation in cellular systems, and therefore may yield excessive interference.

• **Analog versus Digital Relaying:** In digital relaying, the intermediate nodes (seeds) detect and decode the received signal before re-encoding and retransmitting it to the next node. In analog relaying, on the other hand, the seeds just amplify and retransmit the received signal. Although one may be tempted to think that digital relaying would be superior to analog relaying due to the elimination of the noise propagation, our recent research [38]-[40] on the physical layer performance comparison of various multihop channels indicates that this is not necessarily the case since a digital multihop channel may be limited with the hard detection at the worst hop which may cause a bottleneck. In this project both types of relaying (i.e., analog and digital) will be considered and contrasted.

• **Diversity and Scheduling:** Is it possible to develop novel diversity and scheduling techniques in relaying systems, especially for truly delay-insensitive applications where buffering signals for reasonable periods of time is permitted? The concept of "cooperative diversity" (receiving the same signal from two or more routes) has already been addressed in the literature. It should also be investigated whether the diversity gain justifies the signaling overhead.

• **Delay and QoS:** What impact will relaying have on satisfying the QoS requirements like delay constraints and BLER? Data communications are generally labeled as delay-insensitive, although, many such applications are indeed sensitive to relatively long delays, such as internet browsing. Is the inherent latency in multihop systems (especially in those cases with more than two hops) suitable for internet applications?

• **Number of Hops - Two or Many:** What are the advantages and disadvantages of limiting the number of hops to two? Can seeds cooperate among themselves?

• **Load Balancing:** Can a relayer be associated with many BSs? How effectively can relayers be used to divert traffic to other BSs to achieve load balancing [49]-[53].

• **Signaling Overhead and Interference:** Using protocols with low overhead is an essential factor in the successful operation of relaying systems. What is the required signaling for relaying in a cellular environment? Will the control signaling required for relayer selection, relaying channel selection, and power control if used, be at a feasible level, or will the pilot and feedback signals consume a relatively large portion of the available spectrum? How much interference will this overhead signaling cause? What is a good design strategy to minimize the overhead signaling?

• **Relayer Complexity:** What are the core functions of a relayer? How simple and how complex a relayer can be? What are the associated advantages and disadvantages? What is the incurred complexity at the wireless terminals for various types of relaying techniques with various levels of intelligence?

• **Capacity/Throughput Gain:** What is the expected capacity gain from relaying technologies in terms of number of users being served and in terms of aggregate data rates?

• **Power Consumption:** In a relaying system, each wireless terminal will presumably use less power to communicate with its base station; on the other hand, it will occasionally consume additional power for relaying other terminals' signals. So, is there an overall gain or penalty in power consumption at the wireless terminals?

• **Optimal Relayer and Relaying Channel Selection:** In any optimization problem, global optimization is better than (or at least equivalent to) the union of local optimizations. Therefore, finding the the optimal relayer and relaying channel in one shot is better than first finding the optimal relayer and then choosing the optimal relaying channel. But is the global optimization in this case an NP-complete problem? If this is the case, are there good heuristics which will still outperform optimizing the two components sequentially?

• **Relaying – Whenever Necessary or Whenever Possible?** How aggressive should the system be in relaying? It is expected that throughput increase can be achieved in a system which employs adaptive modulation and adaptive coding, if the relaying is performed aggressively.

• **Multiple Access Technique:** Is either CDMA, TDMA, or OFDM, inherently a more suitable multiple access technique for relaying systems?

• **Radio Resource Management:** Presumably, interference management, avoidance, and rejection will have great importance in relaying systems [46]-[48]. How can the vast body of knowledge available for radio resource management in conventional systems be expanded to relaying systems (feasibility analysis, call admission and resource allocation techniques, etc). For instance, does an optimal distributed power control algorithm exist in a relaying system (which does exist in conventional systems composed of only single-hops)?

• **Analytical Characterization:** Mathematical characterization of various types of relaying channels (such as the amplified relaying with and without diversity, and decoded relaying with and without diversity cases) is another area of interest [38]-[40]. For instance, what is the BER versus SNR characteristic with respect to the number of hops (say, when the total transmit power is kept constant)?

• **Relaying in WLANs:** How can relaying be effectively utilized in WLANs to increase high data rate coverage [42]-[45]?

5 Concluding Remarks

The almost-ubiquitous provision of the very high data rates envisioned for future wireless networks necessitates fundamental upgrades in the wireless network architecture.

It is expected that the incorporation of the multihop capability in third and fourth generation cellular networks, in WLANs, and in broadband fixed wireless networks, will facilitate the much sought high data rate coverage in an efficient manner. Towards that end, the interest in multihop-augmented infrastructure-based networks is growing rapidly.

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