Relay–Assisted Cooperative Communication Networks

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Abstract:
To facilitate the demand for a higher spectrum and power efficiency arising from the next generation mobile communication system, the introduction of relay–aided cooperative communication into the existing cellular infrastructure is considered as the most practical improvement under high rate and coverage. In comparison with the legacy cellular network, relay–aided cooperative communication network enjoys relative advantages over coverage efficiency, operation cost and transmission capacity. Transmission in relay–aided cooperative system falls into three types: the three–terminal transmission model, two–hop multi–relay parallel transmission model, and multi–hop multi–relay transmission model. For the extensive perspective of relay–aided cooperative communication in application, a profound research has been carried out in communication standards such as Worldwide Interoperability for Microwave Access (WiMAX) and Wireless World Initiative New Radio (WINNER).

International Mobile Telecommunications–Advanced (IMT–Advanced), the formal name of Beyond 3G (B3G) systems defined by the International Telecommunication Union (ITU), requires 100 Mb/s–1 Gb/s data rates for mobile communications, which are at least 10 times higher than the rate requirement of High Speed Download Packet Access (HSDPA) system, and hardly fulfilled in legacy cellular networks. It is unavoidable to reduce the coverage of legacy cells in order to implement such high rates, in other words, it is necessary to increase the number of Base Stations (BSs). However, the increase will definitely raise operator's networking cost and decline its competence in the market. The basic idea of radio relaying[1-3] is to employ relay nodes, reprocess BS signals and resend them out. Multi–hop relaying can, on one hand, expand the cell coverage to reduce dead spots during communications, and on the other hand, it can transfer traffic in hot spots to reach load balance. In additions, radio relaying saves the transmitting power of terminals, which may prolong battery life.

The relay–based architecture and its cooperation diversity and cooperative multipath technologies have attracted much attention worldwide. All the standards for future mobile communications systems (3GPP, 3GPP2, B3G and 4G), Wireless Local Area Network (WLAN) and broadband wireless networks (802.16j) introduce the concept of relaying, and take the problems of relay–assisted communications into account. Moreover, the Wireless World Initiative New Radio (WINNER) project has a detailed planning for ubiquitous broadband mobile radio relaying system.

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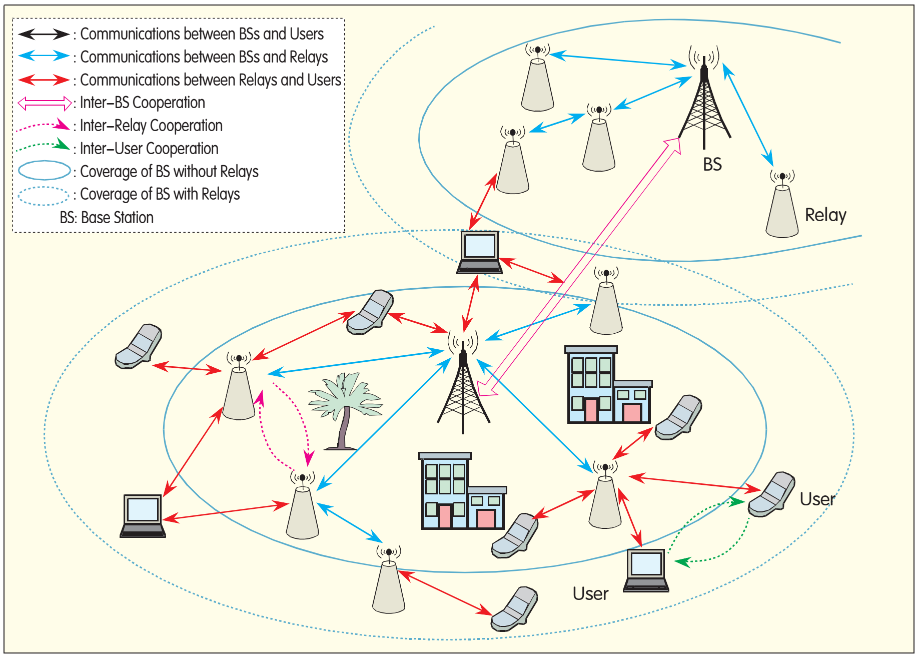
1 Overview of Relay–Assisted Communications System

In the relay–assisted communications system, multiple relays form a virtual array, and cooperate with one another to work, as shown in Figure 1. The relay–assisted broadband wireless communications networking enables diversified access modes, which is its major difference from legacy wireless access systems. Mobile terminals may access wireless networks either through relay stations directly or by cooperative relaying. As an effective technology for improving network coverage quality, radio relaying is a high–cost–performance solution to broadband wireless access at high frequency bands. Generally, the relay–assisted communications system has the following advantages as a new–type networking technology:

(1) Multiple relays can use the same time slots and frequency simultaneously, which saves radio resources;

(2) Space diversity and space multiplexing can be used between relays to improve system capacity for transmission;

(3) It is unnecessary for the system to greatly change the existing backbone architecture, which will enable the



▲Figure 1. Relay-assisted communications network.

smooth evolution of live communications networks.

1.1 Coverage

Owing to large-scale fading, the data transmission efficiency of BS-based cell-structured communications systems gets worse along with the distance increase between users and BSs. Therefore, users in legacy cellular networks cannot really enjoy high data rates at the edge of the networks. Moreover, a BS always fails to cover every inch of its cells, because signal transmission is always influenced by geographic conditions, such as buildings in cities and underground environments. If relay stations are deployed in the areas with both weak BS coverage and the cell edges, dead spots will be effectively reduced and cell coverage will be expanded through signal relaying during communications. Compared to legacy cellular systems, the system with relay stations has wider coverage and better communications quality, based on low networking cost.

1.2 Handover

The introduction of relay nodes, especially mobile relay nodes, forces legacy transmission topologies to make changes. BS is required to manage handover between relay stations, besides users' handover between cells. Single user's handover in legacy cellular networks is developed into handover of both users and mobile relay stations in the relay-assisted system.

There are two handover scenarios in relay-assisted communications: inter-cell handover and intra-cell handover. The former refers to user terminals or mobile relays moving from one cell into another, while the latter is user's handover between two relay stations in a cell or that between a relay station and the BS in a cell.

1.3 Transmission

This new wireless network integrating relay into the cellular network may send data to users through BS and relay stations simultaneously. Accordingly, capacity gains can be obtained through multiplexing or space diversity. Although the data transmission from BS to user via relay is a two-hop communications link, in which the relay requires certain frequency resources, data transmission to different users can use different relay stations. This may greatly compensate the capacity loss caused by the two-hop communications. When buildings and other geographic barriers hinder a transmission path from BS to user and lead to large-scale shadow fading, the capacity loss can even become a gain.

With different relaying models and different message feedback modes, the number of relays in the relay-assisted communications network has different impacts on system capacity. If both BS and mobile terminal in the system are equipped with M antennas, and if both relay and mobile terminal have known channel messages, the system capacity will have a linear increase with M, and a logarithmic increase with the number of relays.

2 Research Progress of Relay-Assisted Communications System

The relay-based channel model with three terminals is the original relay-assisted communications system, followed by the multi-relay parallel transmission and multi-hop models. A user, when located in different points, may get the cooperation of either one or multiple Relay Stations (RSs) to complete the communication with BS.

Three typical transmission models for relay-assisted communications system and their key technologies are discussed from the angle of network structure in this paper.

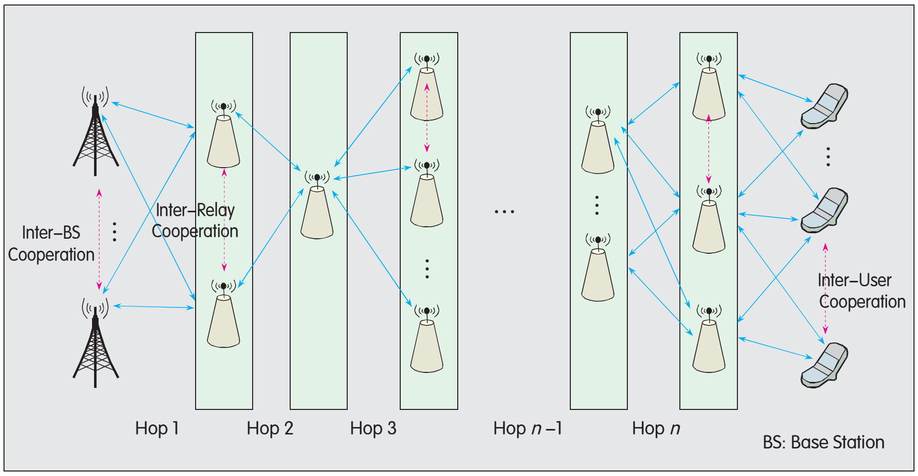
2.1 Three-Terminal Transmission Model

The three-terminal transmission model was first proposed by Van der Meulen. Cover and El Gamal gave its detailed theoretical derivation and performance analysis. Several researchers have made detailed analysis of three-terminal communications system under different channel fading environments in recent years.

In the three-terminal transmission model, specific channel fading characteristics influences system performance; the working mode of relays also plays a very important role.

According to signal processing models, relaying can be divided into the Amplify and Forward (AF), Decode and Forward (DF), Selection Relaying (SR) and Coded Cooperation (CC) models.

According to signal receiving and transmitting, relaying has two basic modes: analogue and digital. The analogue relaying is also called non-regenerative relaying, in which signals are not required to be digitalized



▲Figure 2. Multi−hop multi−relay transmission model.

before sent by relays. AF is a kind of analogue relaying. Oppositely, a relay, using digital relaying model, decodes and encodes signals before sending them out. Therefore, digital relaying is also called regenerative relaying, which DF and CC belong to.

The relay location should be used to select a proper relaying model to improve communications quality. For example, if a relay is near to user, it may select AF and use strong processing capability of BS or RS to make accurate detection and decoding; if a relay is near to BS, DF may be used to improve diversity for anti−fading.

2.2 Two−Hop Multi−Relay Parallel Transmission Model

In this model, BS communicates with multiple users through multiple parallel relays. The relays can be either user terminals or special relay stations. The user relays have their own demands on communications when they cooperate to transfer other users' messages; the relay stations just receive and send a minimum of control signaling for channel synchronizing and channel message transferring, besides transferring users' data. This is the biggest difference between user relays and RSs.

The relay−station−based two−hop multi−relay parallel transmission network can use the inter−relay space diversity to provide multiple users with multiple data links. The network may be regarded as a distributed multi−antenna system. Different from legacy distributed multi−antenna systems in which wired fiber networks are used for communications, RSs in the network use radio links to communicate with BS. Highly effective receiving/transmitting mechanism that guarantees the transmission performance of the first hop is important to the overall system transmission capability.

2.3 Multi−hop Multi−Relay Transmission Model

The abovementioned two models are two−hop relaying. Practically, the concept of Ad hoc network is always introduced to form a multi−hop multi−relay transmission model. The model can improve the coverage of BS in cellular network, and enhance survivability. The model is originated from Mesh network, but there exists difference between these two types of networks. Any nodes in Mesh network can communicate with each other directly. However, the multi−hop multi−relay transmission model, as shown in Figure 2, has different layers between hops. Therefore, each RS needs to search the communication destination among the nodes on upper and lower layers, and then to build a communication link with the destination node, which requires every RS to have routing function.

2.4 Distributed Space−Time Code

A distributed Space−Time Code (STC) allocates antennas of STC system at all relays, instead of at transmit and receive ends only. Space−time signals are built through inter−relay cooperation or the cooperation between BS and RSs. BS uses RSs to form virtual transmit antenna system to implement transmit diversity, so the RSs can be regarded as the remote antennas of BS. Figure 3 takes the distributed STC Multiple−Input Multiple−Output (MIMO) system as an example to illustrate the working principle of distributed STC.

In Figure 3, BS has two ways to send data through relays:

(1) BS first sends non−encoded data to RS_1, and then RS_1 sends STC to MS_1 in a traditional way.

(2) BS first sends non−encoded data to RS_2 and RS_3; RS_2 and RS_3 encode the data and then cooperate to send the encoded to MS_2.

The number of relays can be increased to form a distributed antenna array. Research results show that space diversity gain is in direct proportion to the number of relays when relays are used to send STC. Since the overall transmit power is in the inverse ratio of the

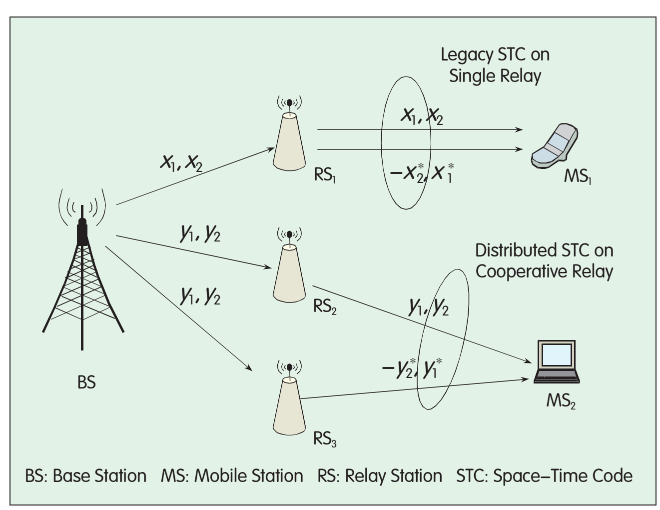


Figure 3.▶
Distributed STC.

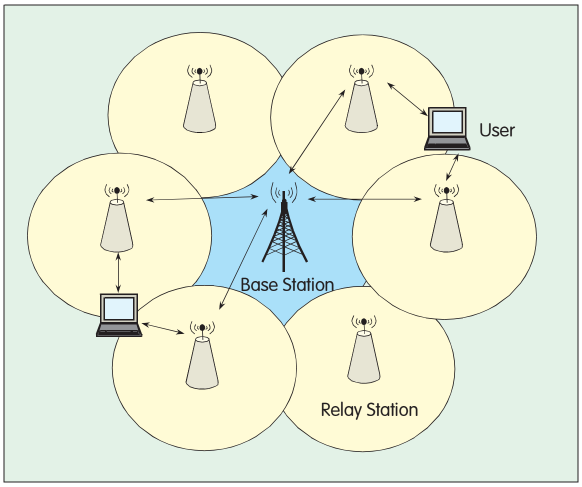


Figure 4. Relay-assisted cellular network architecture specified in IEEE 802.16j.

number of relays in a system with preset Quality of Service (QoS) requirements, such as Signal-to-Noise Ratio (SNR) and Bit Error Ratio (BER), the use of multiple relays helps save power.

2.5 Relay Management

Relay management is necessary for bringing relay-assisted cooperative network into full play. The management focuses on relay selection and power allocation. Choosing one or more out of all the relays for data transmission is relay selection. The selection strategy is mainly based on the physical distance, path loss, and instant channel status. Power allocation of the relay-assisted system fulfills reasonable distribution of power for the data source, relay and data destination to resist near-far effects, expand system capacity and improve BER.

3 Applications of Relaying Technology

3.1 Application in WiMAX System

In September 2005, the IEEE 802.16 working group established the Mobile Multihop Relay (MMR) task group to study the feasibility and implementation schemes of employing relay technology in IEEE 802.16 system. The task group fixed the research direction of relay-assisted cellular architecture, and finally adopted a cellular Point-to-Multipoint (PMP) based tree structure as the topology, giving up the Mesh architecture orignated from Ad hoc network. Figure 4 shows the relay-assisted cellular network architecture specified in IEEE 802.16j.

There are simple, complex and mobile relays in Worldwide Interoperability for Microwave Access (WiMAX) system. The simple relay only has power amplify function, supporting no control function. Therefore, it can be regarded as a power repeater. With signal function, it needs simple operation and low cost. The complex relay has control function, and can make route selection and resource scheduling. Both simple and complex relays are fixed, while the mobile relay can move freely. The mobile relay can solve such problems as load balancing and hotspot handover through its handover between adjacent cells. It also has routing function. All the three types of relays support multi-antenna system.

WiMAX uses transparent handover technology to manage users' inter-cell movement. BS employs the message set of RSs to cut its connection with the mobile terminals in its cells, which efficiently avoids its interaction with every mobile termnial, reducing signalling processes, decreasing multi-hop latency, and finally improving system performance.

WiMAX-related technologies were discussed much and deeply at the IEEE standard conference in July 2007, which included IEEE 802.16j on using relay-enhanced network topology to address dead spots in WiMAX network. As a solution to improving transmission and coverage efficiency of existing WiMAX networks, IEEE released Draft 1.0 on August 8, 2007. It is expected to release 802.16j standards in 2008 at the soonest.

3.2 Application in WINNER Plan

In its annual technical report of 2006, WINNER of European Union used more than 100 pages to introduce the concept of relay and the covergence of relay-assisted communication technology and legacy cellular networks. WINNER proposed to divide a cell into multiple micro-cells through adding fixed relay nodes into the traditional single-BS cell, as shown in Figure 5. The micro-cells include one using BS as Access Point (AP), and several using relays as APs. Users at different locations in a cell have different APs. Frequency allocation and frame structure design is also different for terminals using BS as AP and those using relays as AP.

This new-type relay-enhanced cell in WINNER supports Time Division Multiple Access (TDMA), Space Division Multiple Access (SDMA), and the combination of TDMA and SDMA. The WINNER-proposed communication system has heterogeneous frame structures for one-hop and two-hop communications, therefore, scheduling of Media Access Control (MAC) layer and resource allocation are extremely important.

Moreover, WINNER discussed the feasibility and application scenarios of multi-relay multi-hop communications system. In the system, signal transmission is implemented via the

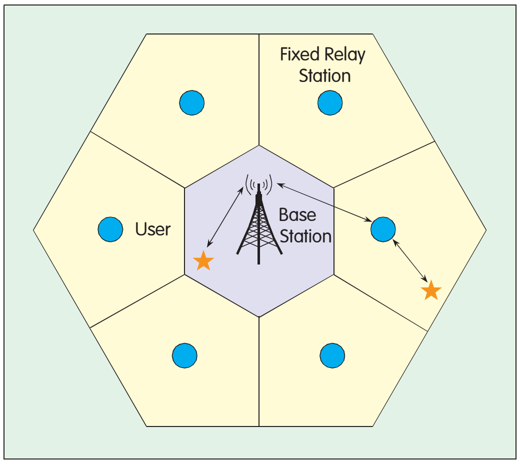


Figure 5. WINNER's system model with fixed relay stations.

cooperation of multiple relays, which has a higher requirement on the allocation and scheduling of frequency resources. Multi-relay multi-hop based transmission can improve communication survivability, facilitating the transfer of hotspot communications.

3.3 Application in 3GPP Systems

The 3GPP Long Term Evolution (LTE) project points out that, in order to improve coverage and system capacity of future evolved communication system, introducing the concept of multi-hop is an effective means. The multi-hop in LTE, different from two-hop fixed-relay networks proposed by WiMAX and WINNER, uses user terminals as relays to transfer signals to farther nodes, based on original network topology. In this way, network coverage can be expanded, and system capacity be improved. Moreover, any communication link in legacy PMP architecture is required to go through BS. That is to say, even for communications between two quite close terminals, signals from the source terminal shall first be sent to home BS, and then BS sends it to the destination terminal. Such a link, adding the overhead of signaling interaction, will consume much resource. In order to save resource consumption, LTE introduces the concept of multiple-point-to-multiple-point, which enables free communications between any two nodes in network to fulfill quicker, convenient and economical data transmission.

4 Conclusions

The network cooperation between BS and multiple relays is proposed for improving communication capacity. In order to fulfill the cooperation, distributed schemes are necessary for legacy physical-layer-based multi-user MIMO technologies (such as dirty-paper coding, linear precoding and decoding, multi-user detection and STC) to implement cooperative data transmission among various nodes in the network. Accordingly, MAC-layer-oriented cooperation strategies seem extremely important.

The relay-assisted communications system can use higher degree of freedom to improve resource allocation and optimize network performance. However, it also brings many non-convex optimization problems, which cannot be solved by traditional optimization algorithms. In fact, the heuristic interactive optimization and greedy search algorithms can achieve a good compromise between performance and complexity of computation.

It is also very important to synchronize BSs, RSs and multiple users in the relay-assisted communications system.

Moreover, robust distributed STC designed in the condition of reducing inter-relay message exchanges is an effective technology for making full use of multi-relay space gains.

Relay-based multi-hop transmission system has attracted much attention. The relay-assisted communications system, introducing relays into existing cellular networks, has been regarded as one of leading network architectures for next generation mobile communications.

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