Relay Technologies for WiMAX and LTE-Advanced Mobile Systems

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Abstract

Relay technologies have been actively studied and considered in the standardization process of next-generation mobile broadband communication systems such as 3GPP LTE-Advanced, IEEE 802.16j, and IEEE 802.16m. This article first introduces and compares different relay types in LTE-Advanced and WiMAX standards. Simulation results show that relay technologies can effectively improve service coverage and system throughput. Three relay transmission schemes are then summarized and evaluated in terms of transmission efficiency under different radio channel conditions. Finally, a centralized pairing scheme and a distributed pairing scheme are developed for effective relay selection. Simulation results show that the proposed schemes can maximize the number of served UE units and the overall throughput of a cell in a realistic multiple-RS-multiple-UE scenario.

Introduction

International Mobile Telecommunications-Advanced (IMT-Advanced) is the name, defined by International Telecommunication Union (ITU), for the next-generation (4G) mobile wireless broadband communication systems. The standardization process of IMT-Advanced systems will enter the technical proposal evaluation stage by the end of this year, and the first IMT-Advanced air interface standard is expected to be released in early 2011. The commercial deployment of IMT-Advanced systems and services is anticipated to be after 2015. According to the ITU's requirements [1], future IMT-Advanced systems can support peak data rates of 100 Mb/s and 1 Gb/s, respectively, in high-speed mobility environments (up to 350 km/h) and stationary and pedestrian environments (up to 10 km/h). The transmission bandwidth of IMT-Advanced systems should be scalable and can change from 20 to 100 MHz, with downlink and uplink spectrum efficiencies in the ranges of [1.1, 15 b/s/Hz] and [0.7, 6.75 b/s/Hz], respectively. The minimum requirements on voice over IP (VoIP) capacities in high- and low-mobility environments are 30 and 50 active users/sector/MHz. The latency for control and user planes should be less than 100 ms and 10 ms, respectively, in unloaded conditions.

In order to meet ever increasing requirements on higher wireless access data rate and better quality of service (QoS), the Third Generation Partnership Project (3GPP) initiated its Long Term Evolution (LTE) standardization work at the end of 2004 and successfully completed this task at the end of 2007. Immediately after that, 3GPP started its LTE-Advanced standardization process to address the requirements and challenges of IMT-Advanced systems by considering a series of new transmission technologies [2], such as carrier aggregation, coordinated multiple point transmission and reception, and relay. It is anticipated that 3GPP will submit this newly developed LTE-Advanced standard as a candidate technical proposal for IMT-Advanced mobile systems.

Through a different approach, the IEEE 802.16 Working Group has developed, since July 1999, several global standards of WiMAX for providing the first-mile/last-mile broadband wireless access in metropolitan areas, as well as backhaul services for voice/data communication hotspots. In October 2007 WiMAX was approved to become a 3G standard in the ITU IMT-2000 standards family. Recently, IEEE launched the 802.16j working group to develop relay-based multihop techniques for WiMAX standards [3]. For future evolution of WiMAX, IEEE 802.16m has been planned to meet the requirements and time schedule of IMT-Advanced standards.

As a hot research topic with great application potential, relay technologies have been actively studied and considered in the standardization process of next-generation mobile communication systems, such as 3GPP LTE-Advanced [2] and IEEE 802.16j [3]. Relay transmission can be seen as a kind of collaborative communications, in which a relay station (RS) helps to forward user information from neighboring user equipment (UE)/mobile station (MS) to a local eNode-B (eNB)/base station (BS). In doing this, an RS can effectively extend the signal and service coverage of an eNB and enhance the overall throughput performance of a wireless communication system [2, 3]. The performance of relay transmissions is greatly affected by the collaborative strategy, which includes the selection of relay types and relay partners (i.e., to decide when, how, and with whom to collaborate).

The rest of this article is organized as follows. In the next section different relay types and transmission schemes are introduced and analyzed to show the benefits of using relay technologies in cellular wireless networks (e.g., 3GPP LTE-Advanced and WiMAX mobile systems). In order to effectively adopt relay technologies, a centralized pairing scheme and a distributed pairing scheme are then developed and evaluated to maximize the number of served UE units, as well as the overall throughput of a cell, in a realistic multiple-RS-multiple-UE scenario. The final section concludes this article.

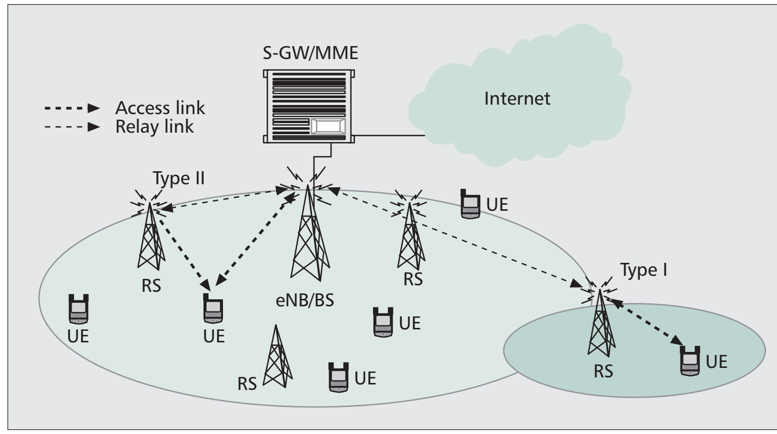

Figure 1. *A network scenario with multiple RSs and multiple UE units.*

	No RS	One RS	Two RSs	Three RSs
Throughput of local UE (Mb/s)	24.3	20.3	21.3	24.3
Throughput of remote UE (Mb/s)	0	5.8	11.6	14.7
Total throughput in a cell (Mb/s)	24.3	26.1	32.9	39.0
Throughput of edge UE (kb/s)	117.1	130.7	144.8	180.2

Table 1. *System performance of Type-I relay station deployment.*

Types and Benefits of Relay Technologies

Relay Types

Two types of RSs have been defined in 3GPP LTE-Advanced and 802.16j standards, Type-I and Type-II in [2], and non-transparency and transparency in [3]. Specifically, a Type-I (or non-transparency) RS can help a remote UE unit, which is located far away from an eNB (or a BS), to access the eNB. So a Type-I RS needs to transmit the common reference signal and the control information for the eNB, and its main objective is to extend signal and service coverage, as shown in Fig. 1. Type-I RSs mainly perform IP packet forwarding in the network layer (layer 3) and can make some contributions to the overall system capacity by enabling communication services and data transmissions for remote UE units.

On the other hand, a Type-II (or transparency) RS can help a local UE unit, which is located within the coverage of an eNB (or a BS) and has a direct communication link with the eNB, to improve its service quality and link capacity. So a Type-II RS does not transmit the common reference signal or the control information, and its main objective is to increase the overall system capacity by achieving multipath diversity and transmission gains for local UE units.

Consider a typical cell with an eNB located at the center and 50 UE units randomly deployed in this communication area. A selective decode and forward (DCF) relay scheme is used; Table 1 compares the throughput performance when different numbers of Type-I RSs are deployed in the cell. System bandwidth and the transmission power of an RS are set to be 25 MHz and 37 dBm,[1] respectively. As seen in Table 1, the deployment of Type-I RSs can effectively improve service coverage and throughput for remote UE units with weak communication links with the eNB. Compared to the case without RS, the total throughput of a cell can be improved by 7.4, 35.4, and 60.5 percent, respectively, when one, two, and three Type-I RSs are deployed. In practice, those UE units with very low throughput values (bottom 5 percent) ususally are located at the edge of a cell. Type-I RSs can effectively improve the total throughput of edge UE units: one, two, and three RSs can achieve throughput gains of 11.6, 23.7, and 53.9 percent, respectively.

Relay Transmission Schemes

Many relay transmission schemes have been proposed to establish two-hop communication between an eNB and a UE unit through an RS [3–5].

Amplify and Forward — An RS receives the signal from the eNB (or UE) at the first phase. It amplifies this received signal and forwards it to the UE (or eNB) at the second phase. This Amplify and Forward (AF) scheme is very simple and has very short delay, but it also amplifies noise.

Selective Decode and Forward — An RS decodes (channel decoding) the received signal from the eNB (UE) at the first phase. If the decoded data is correct using cyclic redundancy check (CRC), the RS will perform channel coding and forward the new signal to the UE (eNB) at the second phase. This DCF scheme can effectively avoid error propagation through the RS, but the processing delay is quite long.

Demodulation and Forward — An RS demodulates the received signal from the eNB (UE) and makes a hard decision at the first phase (without decoding the received signal). It modulates and forwards the new signal to the UE (eNB) at the second phase. This Demodulation and Forward (DMF) scheme has the advantages of simple operation and low processing delay, but it cannot avoid error propagation due

[1] *In the latest LTE-Advanced standard development, a transmission power of 30 dBm is also under discussion for RSs.*

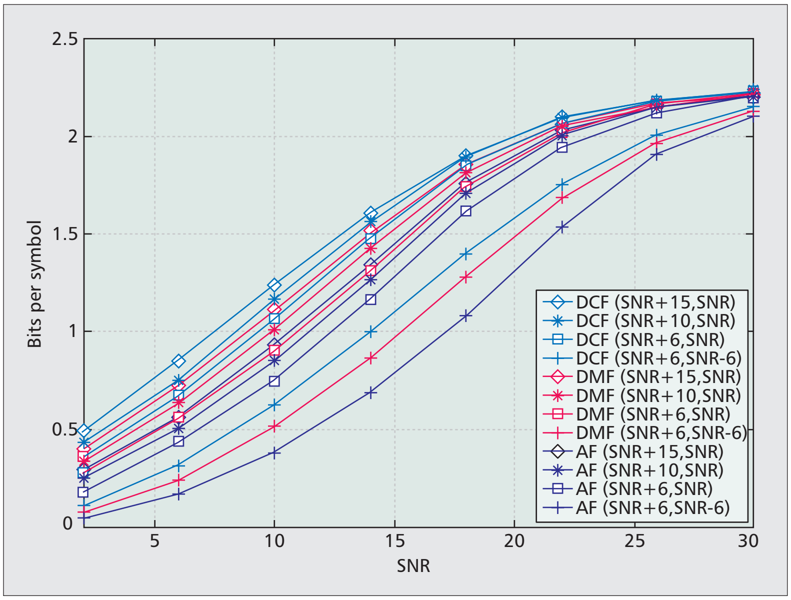

Figure 2. *Transmission efficiency of AF, DMF, and selective DCF relay schemes.*

to the hard decisions made at the symbol level in phase one.

Assuming each RS can accurately measure and estimate the instantaneous channel conditions of the links to an eNB and its neighboring UE units, this information enables the eNB, RSs, and UE to effectively perform link adaptation and maximize transmission efficiency in their two-hop relay transmissions. For performance comparison, our computer simulations adopt a block fading channel model, turbo channel coding, Max-Log-MAP decoding (eight iterations), four modulation schemes for dynamic link adaptation (i.e., binary phase shift keying [BPSK], quaternary PSK [QPSK], 16-quadrature amplitude modulation [QAM], and 64-QAM with the corresponding code rates 1/3, 1/2, 2/3, and 3/4), and a transport block size of 240 bits. Figure 2 shows the transmission efficiency performance of three relay transmission schemes under four combinations of two-hop channel conditions: (SNR + 15 dB, SNR), (SNR + 10 dB, SNR), (SNR + 16 dB, SNR), and (SNR + 6 dB, SNR – 6 dB), where the first and second elements represent the signal-to-noise ratios (SNRs) for the first and second hops in relay transmissions. The value of SNR in these conditions increases from 2 to 30 dB, as shown in the X-axis. From the simulation results, we can see that the AF scheme is most sensitive to the changes of two-hop SNR values; significant performance gains are achieved when the two-hop channel conditions are improved from (SNR + 6 dB, SNR – 6 dB) to (SNR + 15dB, SNR). Among these three relay transmission schemes, DCF can always offer the best transmission efficiency performance under different radio channel conditions. This is because the channel decoding and selective forwarding procedure in DCF can completely mitigate the channel fading effect at the first hop and then successfully restore the original signal for transmission over the second hop.

Relay Technologies in WiMAX and LTE-Advanced Standards

According to the 3GPP LTE-Advanced technical report [2] and IEEE 802.16j technical specification [3–5], an RS can act as the BS for legacy UE units and should have its own physical cell identifier. It should be able to transmit its own synchronization channels, reference symbols and downlink control information. So an RS shall have the full functions of an eNB/BS (except for traffic backhauling), including the capabilities of knowing the radio bearer of received data packets and performing traffic aggregation to reduce signaling overhead. There should be no difference between the cell controlled by an RS and that controlled by a normal eNB.

There is little difference between Type-II and transparency RSs defined in 3GPP LTE-Advanced and IEEE 802.16j standards [2–5]. Table 2 compares the characteristics of Type-I and non-transparency RSs, which mainly perform IP packet forwarding in layer 3. As seen, the key differences are that IEEE 802.16j supports multihop communications in a cell and generates longer delay in relay transmissions, while 3GPP LTE-Advanced supports only two-hop relay transmissions with smaller latency. In order to guarantee backward compatibility, 3GPP LTE-Advanced [2] introduces a fake multicast broadcast singl-frequency network (MBSFN) technique to help legacy UE units access the advanced evolved Universal Mobile Telecommunications System (UMTS) terrestrial radio access network (E-UTRAN). LTE UE will not try to receive the common reference signal or measure the channel quality in an MBSFN subframe that has been allocated for eNB-to-RS transmission [2].

Pairing Schemes for Relay Selection

Consider a network with multiple RSs and multiple UE units in each cell (Fig. 1). One of the key challenges is to select and pair nearby RSs and UE units to achieve the relay/cooperative gain. The selection of relay partners (i.e., with whom to collaborate) is a key element for the success of the overall collaborative strategy. Practically, it is very important to develop effective pairing schemes to select appropriate RSs and UE units to collaborate in relay transmissions, thus improving throughput and coverage performance for future relay-enabled mobile communication networks.

This pairing procedure can be executed in either a centralized or distributed manner. In a centralized pairing scheme, an eNB will serve as a control node to collect the required channel and location information from all the RSs and UE units in its vicinity, and then make pairing decisions for all of them. On the contrary, in a distributed pairing scheme, each RS selects an appropriate UE unit in its neighborhood by using local channel information and a contention-based medium access control (MAC) mechanism. Generally speaking, centralized schemes require more signaling overhead, but can achieve better performance gains, than their distributed counterparts.

Some centralized and distributed pairing schemes have been developed for multiple-RS-single-UE and single-RS-multiple-UE scenarios [6–8], aiming at optimizing the throughput performance of a single two-hop link (or a single UE unit). Only limited work has been reported in the literature for the more general multiple-RS-multiple-UE scenario [9, 10]. Specifically, a centralized pairing scheme based on a min-max criterion and the bipartite graph theory is proposed in [9], which can minimize the maximal outage probability of all the UE units while guaranteeing fairness among them. In [10] another centralized pairing scheme is developed to enable every UE unit to measure the channel qualities toward its neighboring UE units and then identify a list of relay-capable neighbors by using a predefined threshold. This information will be sent to the eNB, which will make pairing decisions by sorting the orders in those lists from different UE units. To the best of our knowledge, no distributed pairing scheme has been published for the multiple-RS-multiple-UE scenario yet. In this section we develop and evaluate both centralized and distributed pairing schemes for achieving multipath diversity and optimizing the overall system performance in a realistic multiple-RS-multiple-UE scenario.

	IEEE 802.16j	3GPP LTE-Advanced
Scheduling mode	Distributed	Distributed
PHY mode	Channel decoding	Channel decoding
Backward compatibility	Yes	Yes
Coverage enhancement	Yes	Yes
Throughput enhancement	Yes	Yes
Number of hops	Two or more	Two
Transmission latency introduced by RSs	Largest	Larger

Table 2. *Comparison of Type-I (3GPP LTE-Advanced) and non-transparency RSs (IEEE 802.16j).*

Centralized Pairing Scheme

In a centralized pairing scheme, each RS identifies a set of UE units it can serve in its vicinity and checks the channel condition (service quality) for the links between the RS and the eNB and between the RS and every UE unit in this service set. This information needs to be periodically updated and reported to the local eNB to capture dynamic changes of neighborhood and channel conditions at each RS. After receiving timely updates from all the RSs in the same cell, the corresponding eNB will generate a two-dimensional matrix $\mathbf{C} = [c_{i,j}]$ with its rows and columns corresponding to UE IDs and RS IDs, respectively. In matrix $\mathbf{C}$ the element $c_{i,j}$ ($c_{i,j} \geq 0$) represents the achievable data rate over a two-hop relay transmission when the ith UE is served by the jth RS. If the ith UE is not in the service set of the jth RS, $c_{i,j}$ is set to zero. Otherwise, $c_{i,j}$ can be calculated based on the instantaneous channel conditions between the ith UE and the jth RS, and between the jth RS and the eNB.

Under the condition that each RS can serve only one UE unit at a time, the optimization objective of a centralized pairing scheme is to maximize the number of served UE units. Specifically, the eNB will manipulate matrix $\mathbf{C}$ by keeping as many non-zero rows as possible (i.e., at least one positive element exists in each of these rows), while maintaining at most one non-zero element in each column because one RS cannot serve more than one UE unit simultaneously. To achieve the optimization objective, the eNB first searches and keeps those rows with only one non-zero element; that is, the UE units with only one RS in their vicinities are given high priority to be paired with their only RS. If several such high-priority UE units are sharing the same RS, the one with the maximal achievable data rate will be selected; as a result, the rows corresponding to the other UE units will be eliminated from matrix $\mathbf{C}$. Once an RS is selected for a UE unit, it cannot be used by any other UE units (if any) in its service set. Thus, the eNB will clear the values (i.e., set to zeros) along the column where the selected RS is located, except for the row corresponding to the paired UE. Following the same criteria, the eNB will iteratively check and keep the remaining rows, starting with those having fewer non-zero elements, and then continuously update the matrix $\mathbf{C}$ by setting zeros into the corresponding column each time an appropriate RS is paired with a new UE unit. Finally, all the columns contain only one non-zero element (i.e., the paired UE and RS), and this complete pairing result will be broadcast to all the RSs and UE units in the same cell. The overall throughput for the served UE units can be calculated by adding these non-zero values together.

Distributed Pairing Scheme

To reduce periodic information exchange and signaling overhead in the centralized pairing scheme, we propose here a simple distributed pairing scheme based on a contention-based MAC mechanism. Specifically, a common slotted communication channel is shared by all the RSs in the same cell. Every N slots are grouped into a pairing section, and a complete pairing procedure contains M pairing sections. In practice, these parameters N and M can be tuned according to the densities of RSs and UE units in each cell, thus to achieve a better performance tradeoff between collisions and delay in the proposed distributed pairing procedure.

In our distributed pairing scheme, each RS first identifies its service set of neighboring UE units. It also evaluates the channel conditions between itself and the eNB, as well as those UE units in the service set. Then, in the first pairing section of the distributed pairing procedure, those RSs with a single-UE service set each randomly selects a time slot from the N slots in this pairing section to broadcast its served/paired UE ID. If multiple RSs choose the same time slot to announce their served UE units, a pairing collision occurs, and those RSs involved will try again in the next pairing section. Other RSs with a ser-

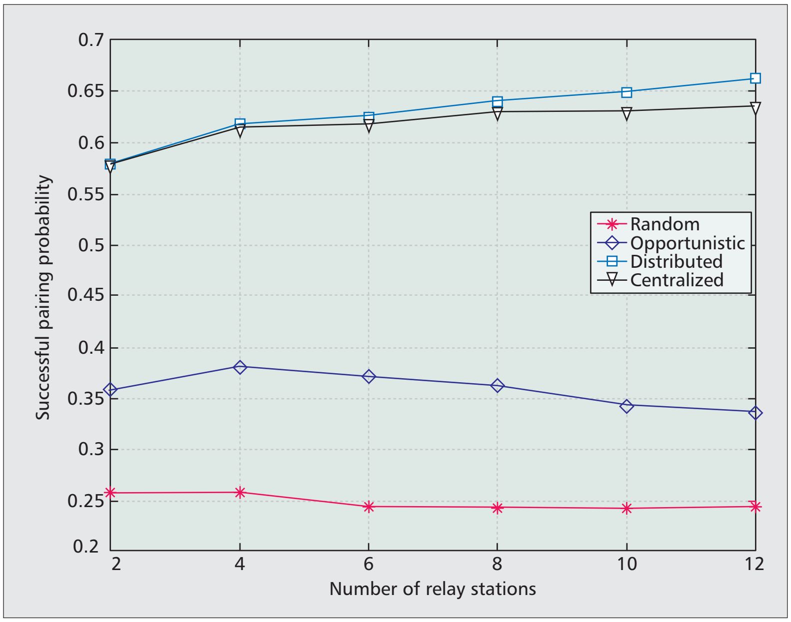

Figure 3. *Successful pairing probability of the UE units in a cell.*

vice set consisting of more than one UE unit will listen to the broadcast messages in the first pairing section and then update their service sets by removing those announced/paired UE units. The second pairing section is for those collided RSs (if any) in the first pairing section and some additional RSs, each having a newly updated service set of only one UE unit. These RSs will independently select their own time slot to announce their served/paired UE units in the second pairing section. Pairing collisions may occur, and the remaining RSs (with a service set of more than one UE unit) will update their service sets accordingly after hearing the successfully announced UE IDs. The same process continues in the following pairing sections, until the last (i.e., the Mth) section, wherein each remaining (unpaired) RS will select a UE unit from its current service set and announce its final pairing choice at a random time slot. Pairing collisions in this last section will not be resolved, and a new pairing procedure will start over again when an RS's neighborhood is changed due to user mobility or dynamic channel conditions.

By introducing high priority for the RSs with a single-UE service set in the pairing procedure, the proposed distributed pairing scheme can effectively reduce pairing collisions, increase successful pairing probability, and thus achieve the objective of serving as many UE units as possible in a multiple-RS-multiple-UE scenario.

Performance Evaluation

The performance of our proposed centralized and distributed pairing schemes are evaluated by computer simulations in a realistic single-cell scenario:

- The SUI-3 physical channel model is used with an attenuation factor of 2. A log-normal shadowing with a variance of 8 dB, and an additive white Gaussian noise (AWGN) with zero mean and a variance of 0.01 are also considered.
- Multiple RSs and multiple UE units are randomly deployed in the cell. The numbers of RSs and UE units range from 4 to 14 and from 2 to 12, respectively.
- Each UE unit has its arbitrary requirement on transmission data rate, $0.75R$, $1.5R$, or $3R$, where R denotes the average data rate between all the UE units and RSs. Note that the value of R will not affect the comparative performance between different pairing schemes.
- We choose to evaluate a three-section (M = 3) distributed pairing scheme with each pairing section consisting of four time slots (N = 4).
- Selective DCF is used.

A random pairing scheme and an opportunistic pairing scheme are also evaluated as two benchmarks for performance comparison against our proposed schemes. Specifically, as its name implies, the random pairing scheme pairs an RS with a randomly selected UE unit in its service set, without considering the UE location, the achievable data rate, or any other criteria. In the opportunistic pairing scheme, every UE unit sequentially chooses the closest RS (with the strongest signal) as its relay, until all the RSs are selected.

Figure 3 compares the successful pairing probability performance of different pairing schemes. The number of UE units in the cell increases with the number of RSs, more specifically, it is equal to the latter minus two. Successful pairing probability is defined as the ratio between the served/paired UE units and the total number of UE units. As seen in Fig. 3, the proposed centralized and distributed pairing schemes have the objective to maximize the number of served UE units in a cell; they both can achieve similar but much higher successful pairing probabilities than the random and opportunistic pairing schemes. In addition, their successful pairing probability curves increase linearly with the number of RSs. This indicates that the proposed schemes can effectively exploit the newly added RSs to achieve better pairing performance.

Figure 4 shows the throughput performance of a cell under different pairing schemes. With the high successful pairing probabilities shown in Fig. 3, the proposed centralized and distributed schemes can maximize the usage of the RSs deployed in a cell and offer significantly better throughput performance (i.e., the total achievable data rate across the whole cell) in a multiple-RS-multiple-UE scenario than the random and opportunistic pairing schemes. As the numbers of RSs and UE units in the cell increase, most RSs will have a large-size service set. This leads to fewer pairing actions (announcements) in the first and second pairing sections, and more collisions in the third (last, as M = 3) pairing section of the distributed pairing scheme. As a result, its throughput performance is saturated when the number of RSs (and UE units) is large. This problem can be solved by dynamically adjusting the system parameters N and M according to the numbers of RSs and UE units in the cell.

Conclusions

This article gives an overview of relay technologies adopted in IEEE WiMAX and 3GPP LTE-Advanced mobile communications systems. It is shown that relay technologies can effectively improve service coverage and system throughput, especially when multiple RSs are deployed. With additional complexity and processing delay, a selective DCF scheme can achieve better performance than AF and DMF relay schemes under different radio channel conditions. In order to serve as many UE units as possible in a realistic multiple-RS-multiple-UE scenario, we have proposed and evaluated both centralized and distributed pairing schemes, which can achieve maximal numbers of served UE units and much higher cell throughput performance than random and opportunistic pairing schemes.

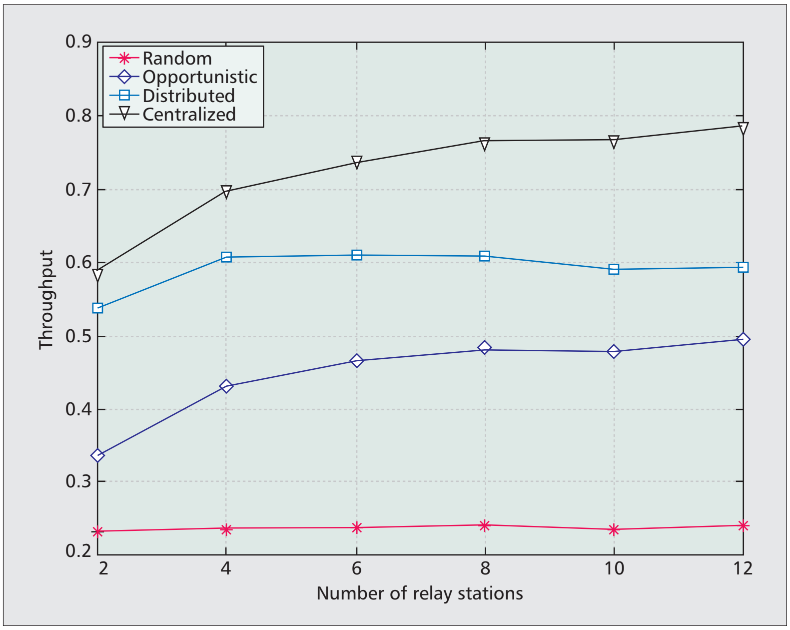

Figure 4. *Throughput performance of different pairing schemes.*

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Biographies

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