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Advanced Relaying Concepts for Future Wireless Networks

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Abstract: Relaying is undoubtedly a key technology for future wireless networks as it can be applied to provide coverage extension and capacity increase in a cost-effective manner. This paper presents an outline of the major advanced relaying concepts that will be part of future systems from the viewpoint of the ARTIST4G European project. These concepts can be divided into three categories, those pertinent to type-1 relays, type-2 relays and moving relays. The characteristics of each of these concepts are presented and the challenges related to their implementation are discussed. Furthermore the paper proposes a set of solutions to address the discussed challenges. For type-1 relays, the paper presents solutions for the allocation of resources to the backhaul and the access links, the inter-relay interference mitigation, and the multi-hop transmission mode. For type-2 relays, our focus is on the design of distributed hybrid automatic repeat request (HARQ) protocols. More specifically, we propose that the conventional HARQ schemes are adapted to exploit the potentially better channel conditions provided by the relays. Moreover distributed turbo coding solutions are introduced for increasing transmission reliability with the aid of relays. Finally, moving relays are presented as an efficient solution to the ever-growing demand for wireless broadband by users within public transportation vehicles. We show that moving relays can very effectively overcome the vehicle penetration loss and boost the achievable capacities of the vehicular users. Overall, we conclude that the presented advanced relaying concepts are very promising and can significantly enhance the user experience in future wireless networks.

Keywords: Relaying, type-1 relays, type-2 relays, moving relays, in-band relays, out-band relays, resource allocation, inter-relay interference mitigation, multi-hop transmission, distributed hybrid automatic repeat request (HARQ), turbo coding with HARQ, ergodic capacity, vehicle penetration loss (VPL)

1. Introduction

For a long time positive user experience relied on the ubiquitous provision of basic services e.g., Voice and short message service (SMS), both indoors and outdoors. In recent years new types of mobile devices like smartphones, have introduced data hungry services that require far better radio channel qualities than conventional systems. However users are agnostic to the radio channel conditions and just experience undesirable fluctuations on their quality-of-service (QoS) when using high rate and/or data rich real time services [1].

This effect deteriorates for user equipments (UEs) located near the cell-edge. Hence designing solutions that guarantee a uniform user experience is a major research focus in the area of advanced radio systems [2] [3] [4].

To improve user experience at the cell-edge, it is necessary to employ modulation and coding of higher order. This requires high signal-to-noise plus interference ratios (SNIRs) which can be achieved by increasing the quality of useful channels and/or by mitigating co-channel interference (CCI) [2] [3] [4]. To this end, ARTIST4G considers the following three approaches to improve cell-edge performance: (1) *interference avoidance*, (2) *interference exploitation*, and (3) *node densification via relay deployment*. Interference avoidance relies on coordinated multipoint (CoMP) techniques, where several base stations (BSs) coordinate their transmission to minimize the detrimental effects of CCI [4] [5]. This requires the exchange of UE channel state information as well as user data between the involved BSs. Interference exploitation is based on the acceptance of interference at the receiver combined with suitable processing which improves the achievable SNIRs [3].

The third research approach involves the use of relay nodes (RNs) and will be the focus of this paper. Unlike interference avoidance and exploitation which mitigate CCI, the use of RNs boosts the achievable performance at the cell-edge by improving the quality of the useful radio channels [1] [2]. RNs are inexpensive nodes which can be seen as small BSs that utilize wireless backhaul to connect to the operators' network[1]. The deployment of RNs results in a densification of nodes in wireless systems, as relays will be part of the system infrastructure [1] [6]. It should be noted that relaying impacts upon the functions and architecture of the network and introduces challenges that ought to be addressed in order to bring the relaying concept into practice [1]. 3GPP Long Term Evolution (LTE) defined two different types of RNs, namely type-1 and type-2 RNs. Although type-1 RNs are part of LTE release 10, type-2 RNs are left for further study. Furthermore another type of RNs that is not included in LTE release 10 although it is very promising is moving relay nodes (MRNs), i.e., RNs mounted on top of public transport vehicles like buses, trams or trains [7] [8].

This paper presents an outline of the aforementioned advanced relaying concepts from the viewpoint of ARTIST4G [9] [10] [11] [12]. The research on relaying conducted by ARTIST4G focuses on solutions that enhance LTE release 10 in terms of capacity, QoS and coverage in order to pave the way towards future enhancements in the standards. To this end, the impact of relaying is studied from the physical layer, protocol and system architecture perspective. The paper discusses these aspects and proposes a multitude of solutions that greatly improve performance of type-1, type-2 as well as moving RNs.

The remainder of this paper is structured as follows. Section 2 provides an overview of all the considered advanced relaying concepts. Sections 3 and 4 describe the proposed solutions for type-1 and type-2 RNs respectively. Section 5 describes the potential of deploying MRNs and Section 6 concludes the paper.

2. Advanced Relaying Concepts and Challenges

Relaying is a promising technique for cell coverage extension and capacity increase [1] [2]. From the system viewpoint, relaying has an important impact on the system functions as well as the network architecture. Some of the advanced relaying concepts have been categorized by 3GPP LTE release 10 as those pertinent to type-1 and type-2 RNs. MRNs are not yet considered by this standard although scenarios for their use are under consideration.

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[1] Conventionally RNs use for backhauling the same spectrum as for wireless access (BS to UE connection).

1. **Type-1 relays**: they are non-transparent RNs, meaning that from the UE perspective an RN appears the same way as a regular evolved NodeB (eNB), i.e., it terminates all layer-2 and layer-3 protocols. Each RN has its own cell ID, synchronization and control channels as well as retransmission and broadcast processes. The UE communicates with the RN using the usual control information. On the other hand, the RN appears like a UE when attaching to the donor eNB (DeNB). It identifies itself as an RN by subsequent signaling. The wireless backhaul link between DeNB and RN is newly specified. In order to avoid the large amount of self-interference, sufficient isolation must be achieved between the transmitter and the receiver of the RN. It can be achieved in time (half-duplex mode), in frequency or by antenna configurations. Even though the basic concepts pertaining to type-1 RNs have been standardized by 3GPP, several issues related to the resource scheduling between the different links for two-hop relaying are still open. Moreover, when considering communication requiring more than two hops, the available cell resources that are constant regardless of the number of backhaul links should be optimized to avoid bottlenecks on the backhaul links.
2. **Type-2 relays:** they are not yet standardized by 3GPP. They are transparent and from the UE perspective, the RN just "expands" the cell spanned by the DeNB. Furthermore they do not have a separate cell ID and release 8 UEs should not be aware of their presence. As these RNs are not allowed to transmit control and common reference signals, they cannot be used for coverage extension but can be utilized for capacity and QoS increase within an existing macrocell. Their supported functionality is the implicit forwarding of information by means of amplify-and-forward (AF), decode-and-forward (DF), compress-and-forward (CF), estimate-and-forward (EF), Detect-and-Forward (DetF) etc. The transparency of type-2 RNs raises the question of how best to exploit them. By allowing cooperation with the BS, the use of adequate distributed coding between BS and RNs becomes possible. For two-hop RNs without cooperation, new evolved retransmission protocols can enable throughput enhancements.
3. **Moving relays:** the RN is positioned on top of a moving public transportation vehicle [7] [8]. The use of MRNs is expected to enhance the performance of vehicular UEs. In urban environments, a significant number of UEs use wireless broadband services within public transportation vehicles like buses, trains or trams. Furthermore, it is expected that the number of UEs requesting wireless broadband while in urban transport will greatly rise in the near future. This is due to the high penetration of smartphones and other compact devices that rely on wireless broadband. A significant advantage of MRNs is their potential to circumvent the high vehicle penetration loss (VPL) at the cost of the half-duplex loss[2].

3. Enhancements to Type-1 Relays

In this section, we focus on enhancements pertaining to the in-band and out-band RNs, primarily in the context of type-1 relays for LTE and similar cellular systems. To this end, we briefly describe three major innovations in the following.

A crucial task concerning in-band as well as out-band RNs is to optimize the allocation of resources among the macro-access and the backhaul link at the DeNB. As the underlying principles of resource partitioning are quite similar for the in-band and out-band RNs, we focus only on the out-band relaying scenario and describe our three main approaches for resource partitioning [13] [14]. In the first approach, referred to as "Fair-RU", we split the

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[2] The backhaul link between the MRN and the eNB has much better physical link quality on average than the UE-eNB link for vehicular UEs due to the avoidance of VPL. However, backhaul link quality is also varying in time and the half-duplex operational mode of MRN, requiring two slots for communication, can have a negative impact on the system capacity.

resource units (RU) in a static manner based only on the number of UEs served by RNs (R-UEs) as compared to the number of macro served UEs (M-UEs), while ignoring link qualities. A more sophisticated approach, referred to as “Fair-TP”, divides the resources dynamically so as to maintain a similar throughput (TP) per UE on the macro-access and the backhaul link. Finally, a third variant is an extended version of the conventional proportional fair scheduler (PFS) that works by treating the backhaul as a super-user with its metric scaled by the number of R-UEs. This approach is labelled as “Ext-Prop-Fair”. A performance comparison of the resource partitioning schemes is presented in Fig. 1 for the 3GPP case-1 with two RNs [15]. It is seen that the “Ext-Prop-Fair” performs best, while having similar structure with a regular PFS.

Secondly, we focus on handling interference from other RNs and eNBs in the in-band relaying scenario, and propose the use of two adaptive mechanisms: a long term scheduler to make bandwidth partitioning (each N radio frames) between nodes, and a fast link adaptation, operating on each transmission time interval (TTI), to allocate resources within the allocated bands. This takes into account low priority for bands that are shared among surrounding sectors. We design specific schedulers for in-band relaying, namely 2-TTI MCI (Maximum C/I) and 2-TTI EDF (Earliest Deadline First) schedulers. The 2-TTI structure relies on time split transmissions for the different links. While the macro-access link can be scheduled in all TTIs, the backhaul can be scheduled only on even TTIs and the relay-access only on the odd TTIs. Initial simulations have shown not only an SNIR improvement for cell-edge UEs, but also that the throughput (with MCI scheduler) of full-buffer traffic UEs and the packet delay (with EDF scheduler) for VoIP traffic are improved.

Finally, we consider multi-hop transmissions in the context of in-band RNs which are of practical relevance especially in networks with large cell radius. An important problem here is the reduced resource utilization efficiency due to the large resource cost of the multi-hop transmission with half-duplex relaying. To address this, full resource reuse schemes for three-hop relay transmission with both tree and mesh structures have been studied with the aid of graphs [16]. We propose that the transmissions on the backhaul links are multiplexed in the time domain, and all possible transmissions without conflict are assumed to reuse the same resource. Moreover, during the first backhaul transmission to the so-called Nested RN[3] we mute transmission of other RNs to reduce interference on the backhaul channel which could be a bottleneck for the network. Fig. 2 shows that with the full resource reuse schemes, three-hop transmission performs better in the cell-edge than two-hop transmission. Amongst all the three-hop transmissions, the tree structure case performs best.

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[3] Nested RN is defined as the only RN connected to DeNB and to which the two other RNs are connected.

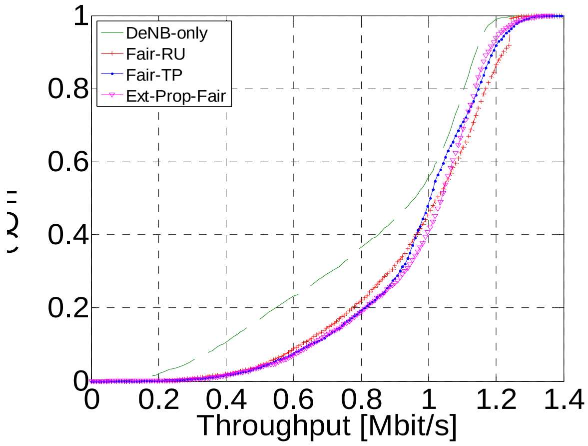

Figure 1: Throughput CDF for M-UEs and R-UEs combined: DeNB-only vs. out-band resource partitioning strategies.

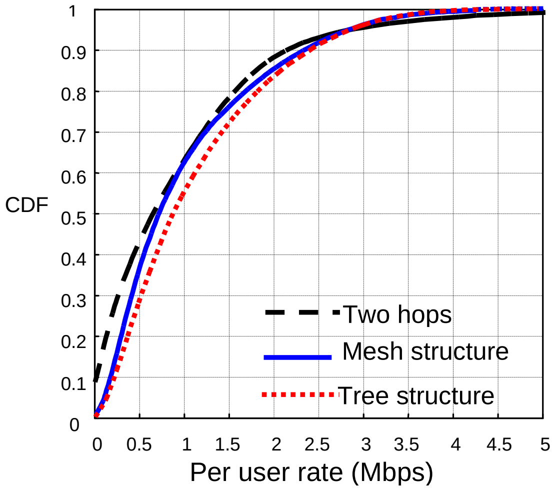

Figure 2: Throughput CDF curves for different relay layouts (3 RNs per Cell).

4. Enhancements to Type-2 Relays

In ARTIST4G, a type-2 RN is defined as any RN beyond type-1. Such class of RNs can significantly increase spectral efficiency throughout the cell. The proposals for type-2 RNs are very diverse and contain a large variety of approaches. In this paper we focus on different techniques for cooperative hybrid automatic repeat request (HARQ) [17]. The challenge is to design novel distributed HARQ protocols for cooperative transmission. HARQ is essential in wireless communication systems as it prevents packet losses in environments affected by signal fading. In addition, RNs are known to provide diversity gain in fading scenarios, so the combination of HARQ and RNs is very promising. It should be noted that the impact of such HARQ supporting RNs on the system architecture and signaling can be rather small, which is advantageous. HARQ schemes are usually divided into chase combining (CC) schemes, which provide an SNR gain, and incremental redundancy (IR) schemes, which achieve additional coding gain. These entail different requirements for the RN functionality. For CC techniques, the RN does not need to decode signals completely and can apply AF for instance. For IR schemes, the RN has to decode and re-encode the message and therefore employ DF.

4.1 – Adaptive HARQ with non-decoding relays

In a relay enhanced system, the typical HARQ schemes should be adapted to exploit the potentially better channel conditions provided by the RN as compared to the direct link. The HARQ adaptation should be optimized with respect to the trade-off between retransmissions and the required resources. It is crucial to optimize the allocation of resources in order to avoid further retransmissions with minimum resources. To this end, we propose an approach based on accumulated Mutual Information (MI) for relay networks applying different relay functions. We consider several memoryless relay functions without channel decoding, aiming for simple and cheap RNs. Besides the well-known AF and DetF schemes, we also consider the soft information relaying function EF as it provides higher MI than AF and DetF [18]. Some simulation results are given in Fig. 3 showing that our proposed HARQ retransmission scheme can improve the throughput significantly, especially if EF is applied by the RN. Here the achievable rate of the proposed scheme is normalized to the rate without RN. If the RN is located exactly between the source and destination and the path loss exponent is 4, we achieve 45% higher rate for the retransmission by the RN than without an RN. These results show the potential benefit of non-decoding type-2 RNs. More details and further results can be found in [19].

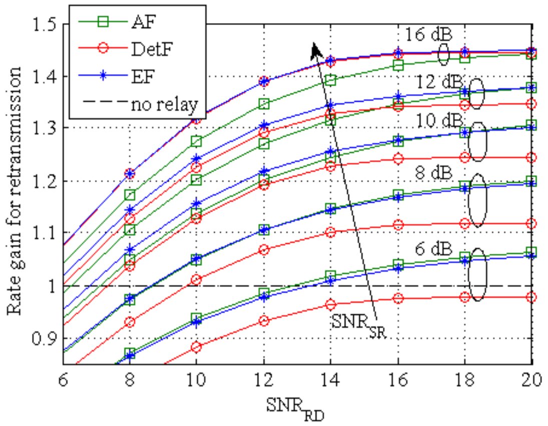

Figure 3: *Achievable rate of adaptive retransmission by type-2 RN normalized to system without RN, SNR on direct link 5dB, 16-QAM, R_c=0.66.*

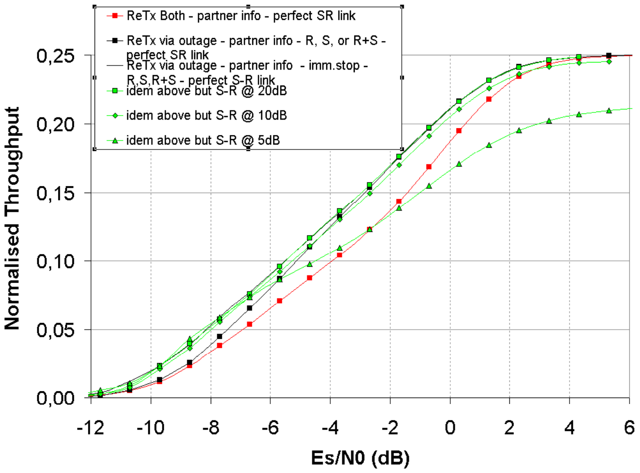

Figure 4: Normalized throughput vs. SNR (dB), asymmetric scenario.

4.2 – Distributed Turbo Coding techniques with HARQ

We focus on a relay channel in which source and RN cooperatively construct a distributed turbo code (DTC) [20]. It should be noted that the proposed strategy could be extended for other forward error correction (FEC) schemes. We propose to exploit the instantaneous mutual information knowledge at the receiver. In order to select the node that retransmits we check the quality of both the relay-to-destination and source-to-destination channels. Moreover, outage probability is considered to evaluate the link quality between RN and destination and to estimate or predict if a retransmission will fail. Fig. 4 shows that the proposed distributed HARQ protocols can significantly enhance UE throughput. In this figure, we compare the performance of the different proposals in terms of normalized link throughput in an asymmetric scenario where the SNR of the relay (R) to destination (D) link is 10 dB higher than that of the source (S) to destination link. Retransmission via outage with immediate stop achieves the highest link throughput for the whole range of SNRs for the R-D link, showing the advantage of outage prediction even for very low SNRs. The same conclusion is drawn for the case of non-perfect S-R link (from 20 dB to 10 dB). Furthermore, our approach performs better than the case without immediate stop and perfect S-R link. More details and further results can be found in [21].

5. Moving Relays

A major factor that limits the achievable throughput for UEs inside vehicles is the vehicle penetration loss [7] [22]. Measurements have shown that the experienced VPL for cars can be as high as 25 dB at the frequency of 2.4 GHz [22]. However for highly isolated vehicles, like buses or trams, we foresee a much higher VPL. UE performance can be boosted in public transportation vehicles by deploying MRNs. In order to circumvent VPL, MRNs consist of outdoor and indoor antenna units that are connected via a cable that introduces negligible losses. This concept effectively creates a small cell within the vehicle with the potential to provide very high data rates to the connected UEs [7].

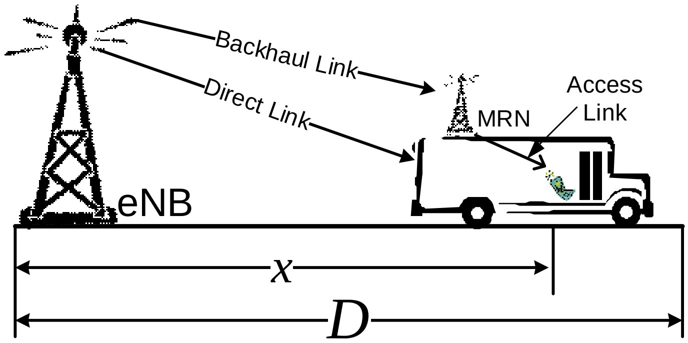

Figure 5: The studied MRN scenario.

To show the potential of MRNs we evaluate the ergodic capacity in a general scenario where the vehicle moves along a highway, as shown in Fig. 5. We compare the achievable ergodic capacity of the direct conventional transmission with that of a dual-hop transmission via the MRN. We define the link between eNB and MRN as the backhaul link, and the link between MRN and UE as the access link. In the MRN-assisted case, the eNB always transmits to the UE in a dual-hop fashion via the half-duplex MRN and communication is corrupted by Rayleigh fading. Wireless channels are assumed to be frequency non-selective and the DF scheme is employed for relaying.

For the direct transmission, the experienced SNR at the UE is $\gamma = \frac{P_t |h|^2 \beta L^{-\alpha} \varepsilon}{N_0}$, where α denotes the pathloss exponent, β the pathloss constant and L the distance between transmitter (TX) and receiver (RX). ε denotes the VPL, where $0 < \varepsilon \leq 1$, and h represents the channel coefficient. N_0 is the one side noise power density at the RX. For the MRN assisted transmission, the capacities of the backhaul and access links can be expressed as $C_{bk} = \log_2\left(1+\gamma_{MRN}\right)$ and $C_{ac} = \log_2\left(1+\gamma_{UE}^{MRN}\right)$ respectively. The SNRs of the backhaul and access links are defined as $\gamma_{MRN}^{eNB} = \frac{P_t^{eNB} |h_2|^2 \beta_2 x^{-\alpha_2}}{N_0}$ and $\gamma_{UE}^{MRN} = \frac{P_t^{MRN} K}{N_0}$ respectively. K is a constant loss between the indoor MRN antenna and the UE, while P_t^{eNB} and P_t^{MRN} denote the transmit power of the eNB and MRN respectively. Under DF the ergodic capacity of the MRN assisted transmission can be expressed as $C_{DF} = \mathbf{E}\left[\frac{1}{2}\min\left\{C_{bk}, C_{ac}\right\}\right]$, where $\mathbf{E}[.]$ denotes expectation.

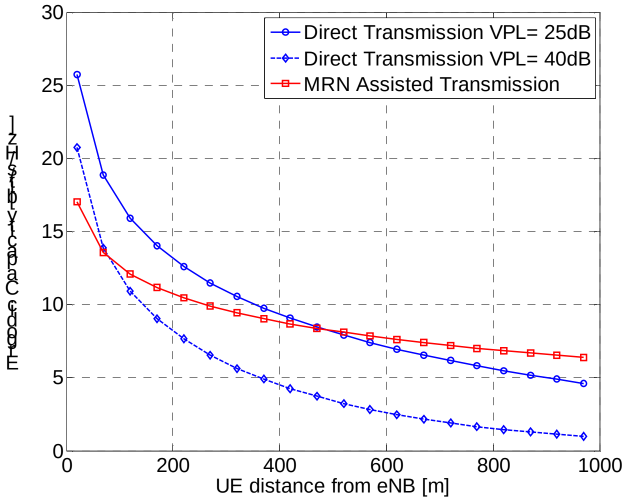

Figure 6: Ergodic capacity vs. UE distance from eNB and for different values of VPL.

Parameters	Values
Path Loss [dB]	PL =34.53 + 38 $\log_{10}(d)$
eNB transmit power	24 dBm
MRN transmit power	20 dBm
RX noise figure for MRN and UE	9 dB
Power loss between MRN and UE	34.53 + 38 $\log_{10}(20)$ = 83.969 dB

Table 1: The simulation parameters.

Fig. 6 presents simulation results of the system ergodic capacity for direct transmission and MRN assisted transmission under different values of VPL. The simulation parameters are given in table 1. It can be seen that as the vehicle moves away from the eNB, the ergodic capacity decreases. Furthermore as VPL increases, the achievable ergodic capacity of the direct transmission is severely reduced and the MRN assisted transmission shows its advantage. When the VPL is moderate (25 dB), the MRN assisted system outperforms the direct transmission when the UE is located at a greater distance than 550 meters from the eNB. Furthermore, as the VPL increases to 40 dB, the MRN assisted transmission overtakes the direct transmission even when the UE is quite near the eNB (smaller distance than 100 meters). Thus, using MRNs is very promising for increasing the system capacity of future wireless systems.

6. Conclusions

This paper presented an overview of advanced relaying concepts from the viewpoint of ARTIST4G. These concepts were divided into three categories, those pertinent to type-1, type-2 and moving RNs. The characteristics and the challenges associated with each of these concepts have been presented and discussed. More specifically, for type-1 RNs the paper addressed the problems of resource allocation, the inter-RN interference as well as the multi-hop transmission. In the area of type-2 RNs the paper proposed an adaptation of the conventional HARQ schemes that exploits RNs. Moreover, distributed turbo coding approaches have been presented that utilize RNs to boost transmission reliability. Finally, moving RNs have been presented as an efficient solution to the ever-growing demand for wireless broadband by users within public transportation vehicles. The paper showed through simulations that moving RNs can very effectively overcome the vehicle penetration loss and boost the achievable capacities of the moving users. It can be concluded that the presented advanced relaying concepts are very promising as they can significantly enhance the user experience in future wireless networks in a cost-effective manner.

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