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Multi-hop Relay Architectures for 3GPP LTE-Advanced

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***Abstract*— The next-generation wireless network is envisaged to incorporate multi-hop ad hoc characteristics into cellular network infrastructure. Multi-hop communication is viewed as an annexe to the cellular network infrastructure in order to increase coverage and capacity. Currently, the Third Generation Partnership Project (3GPP) is investigating multi-hop functionality as one technical component for LTE-Advanced. LTE-Advanced is the evolution of Long-Term Evolution (LTE). Even though multi-hop communication research has been ongoing for the past decades, research work on multi-hop cellular network is premature. This paper serves to provide a comprehensive review on state-of-the-art relaying strategies for LTE-Advanced. Two relaying strategies, namely amplify-and-forward and decode-and-forward are discussed. The relaying strategies are qualitatively compared against a set of criteria. The main conclusion drawn from the review is that each relaying strategy has its benefits and limitations. Thus, LTE-Advanced could deploy a mixture of amplify-and-forward and decode-and-forward relays depending on the needs and scenarios. We also discuss a new problem facing conventional channel-dependent scheduling mechanisms in LTE-Advanced with multi-hop links. Consequently, we propose a multi-hop aware channel-dependent scheduling mechanism to ameliorate the problem.**

***Keywords*— LTE-Advanced, multi-hop communication, relaying architectures, ad hoc, multi-hop cellular network, 4G**

I. Introduction

Multi-hop communication is a research topic that falls under the umbrella of Mobile Ad hoc NETworks (MANETs) which has been an active area of research for the past decades. The MANET research efforts are mostly concerted by the MANET Working Group [1] of the Internet Engineering Task Force (IETF). MANET considers generic and pure ad hoc networks without infrastructure. MANET mainly deals with routing issues. Recently, multi-hop communication is seen as an annexe to the next-generation cellular networks to increase coverage and capacity at cell borders. Such a network, which has ad hoc and cellular network characteristics, is referred to as Multi-hop Cellular Network (MCN) [2]. MCN combines the benefits of both ad hoc and cellular networks.

The first standard for MCN is the IEEE 802.16j [3] for mobile WiMAX. On the other hand, no standard for MCN has been ratified by 3GPP yet. However, multi-hop communication is being considered as one technology component for LTE-Advanced [4] which is currently under studied in the Third Generation Partnership Project (3GPP). LTE-Advanced is the next-generation of LTE (Long-Term Evolution) [5], which is set to provide data rates up to 1 Gb/s and 500 Mb/s in downlink and uplink, respectively. As WiMAX muti-hop architecture poses several limitations that drastically limited its capability, LTE-Advanced should learn the lessons from WiMAX and consider more sophisticated relaying strategies that fulfil the LTE-Advanced requirements. The paper reviews the state-of-the-art in relaying strategies for LTE-Advanced MCN, leveraging on relaying techniques that have been developed over the past decade. Each of the relaying strategies is qualitatively evaluated and compared against a set of criteria. The rest of the paper is organized as follows. In Section II, we present the use cases for MCN. Section III describes the envisaged LTE-Advanced MCN. Section IV gives a comprehensive review on pros and cons of the different relaying strategies for LTE-Advanced MCN. In Section V, the different relay strategies are compared. We outline the new problem facing dynamic channel-dependent scheduling in MCN and propose our solution in Section VI. Finally, Section VII concludes the paper.

II. Relay Usage Scenarios

A number of different usage scenarios can be envisaged. In general, these scenarios can be classified into two categories, namely coverage extension and capacity enhancement. The former usage scenario is illustrated in Fig. 1. In this scenario, multi-hop relays are used to extend the reach of LTE-Advanced terrestrial cellular network to a group of mobile users on an oil rig. Without the relays, the mobile users would rely solely on satellite communications which can be quite expensive.

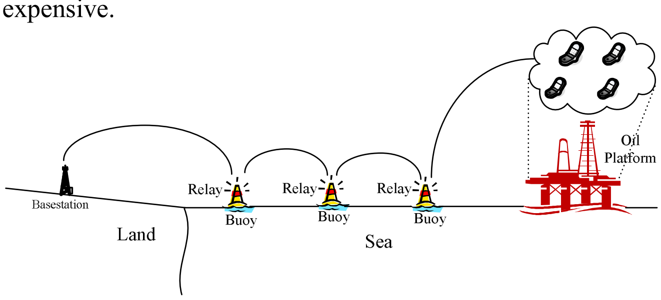


Fig. 1. Offshore Communications

Increased system capacity can be achieved through the use of multi-hop links, as opposed to a single-hop link. The intention of multi-hop links was to reduce the transmitter-to-receiver distance, thereby achieving higher data rates as compared to long single-hop links, see Fig. 2. Furthermore, multi-hop relays can ameliorate dead spots, shadowing, and support spatial reuse which can lead to increased overall system capacity.

III. MULTI-HOP RELAYING ARCHITECTURE IN LTE-ADVANCED NETWORKS

Since LTE-Advanced is evolved from LTE, the envisaged multi-hop relaying architecture for LTE-Advanced networks is composed of one or more relays between an evolved NodeB (eNodeB) and a User Equipment (UE) as shown in Fig. 3. A single eNodeB serves one or more multi-hop chains in its cell, which forms a tree structure with eNodeB as the parent. Note that a multi-hop chain can comprise two or more hops. The number of relays in a multi-hop chain is $n - 1$ for n number of hops. The complexity of MCN is strongly related to the number of hops. Thus, 3GPP has limited n to two for LTE-Advanced. The strategies used by the relays are discussed in Section IV.

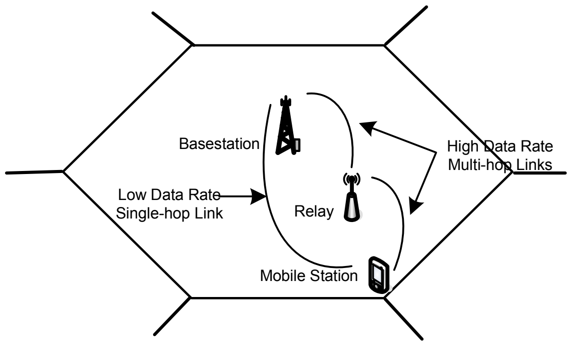


Fig. 2. Capacity Enhancement

The functional elements of LTE are UE and eNodeB, which correspond to the user terminal and base station, respectively. The remainder functional elements, namely Mobility Management Entity (MME), Serving Gateway, Packet Data Network (PDN) Gateway, and Policy and Charging Rules Function (PCRF), belong to the evolved packet core network. R*elay* is a new element introduced in the LTE-Advanced as compared with the network architecture of LTE.

Fig. 4(a) and (b) show the envisaged user plane and control plane protocol architecture for LTE-Advanced, respectively. Note that the protocol stack for the relay entity is shown as a black box because the protocol functions and layers vary with the relaying strategies used. The relaying strategies are described in Section IV. In the user plane, the Packet Data Convergence Protocol (PDCP) layer is responsible for compressing and decompressing the headers of user-level IP packets. Note that IP is also used at the transport-level for carry traffic and signalling between eNodeB and PDN Gateway. Unlike user-level IP, transport-level IP is transparent to the outside world. The Radio Control Link (RLC) layer provides three different reliability modes for transporting data between the UE and eNodeB. The Medium Access Control (MAC) layer provides the Hybrid Automatic Repeat reQuest (HARQ) and is responsible for logical-to-transport channel mapping, scheduling operation and random access. The Physical (PHY) layer is responsible for adaptive modulation and coding, and OFDM modulation. The GRPS Tunneling Protocol (GTP) layer is used to transfer IP datagrams between an eNodeB and a PDN Gateway. GTU operates on top of UDP, IP and various Layer 1/Layer 2 technologies.

In the control plane, the Non Access Stratum (NAS) protocol, which runs between MME and UE, is used for control-purposes such as session management, security control, and authentication. The NAS packets are carried by a reliable transport protocol, i.e., the Stream Control Transmission Protocol (SCTP), which is operated above IP. The Radio Resource Control (RRC) layer is responsible for setting up and maintenance of radio bearers, and mobility management. The PDCP, RLC, MAC and PHY layers of the control plane are the same as the user plane.

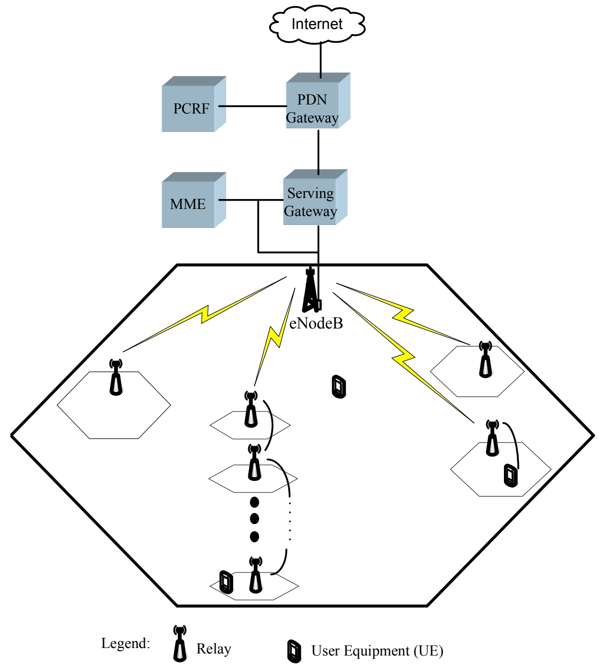
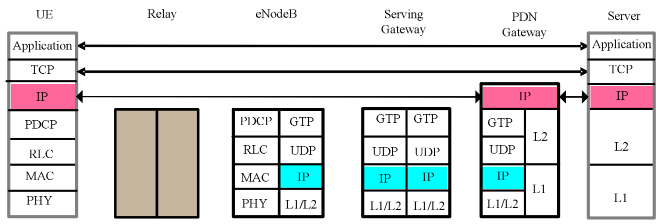
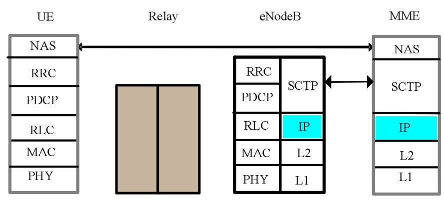


Fig. 3. LTE-Advanced Multi-hop Network Architecture



(a) LTE-Advanced Protocol Architecture – User Plane



(b) LTE-Advanced Protocol Architecture – Control Plane

Fig. 4.

IV. Relaying Strategies

A number of different relaying mechanisms have been developed in the past few years, namely amplify-and-forward and decode-and-forward strategies. In this section, we describe and review each of the relaying strategies to be used by LTE-Advanced relays.

A. Amplify-and-Forward Relaying Strategy

Amplify-and-forward relay [6] is also known as wireless repeater or Layer 1 (L1) relay. In LTE, L1 comprises the PHY layer. The repeater receives a signal, amplifies and reshapes it, then retransmits the signal to the destination. The transceiver at both sides of L1 relay can operate either on the same (inband) or on an orthogonal carrier frequency (outband). In the latter case, the repeated signal would not interfere with any direct signal received at the destination, but a frequency reuse factor of one is not possible. Additional radio resource management functionality is needed at eNodeB to allocate frequency bands for eNodeB-to-relay and relay-to-UE transmissions. For the inband case, directional antennas can be employed to mitigate the interference caused by simultaneous eNodeB-to-relay and relay-to-UE transmissions. Similarly, at the relay simultaneous reception from UEs and transmission by the relay also causes interference. L1 relay is suitable for mitigating coverage holes.

The main advantages of repeaters are simplicity, low cost and low delay. The disadvantage is that repeaters provide no means for isolating received noise and interference from the desired signals. In other words, noise and interference are also amplified and retransmitted together with the desired signals. As a result, the SINR of the signal is not improved at the output of the L1 relay.

B. Decode-and-Forward Relaying Strategy

The decode-and-forward relaying strategy [7] involves decoding of source signal at the relay node. The re-encoded signal is then forwarded to the destination. The major advantage of decode-and-forward relaying is that noise and interference are not propagated to the destination. The drawback is that the decoding and re-encoding process incurs a significant delay as compared with the Amplify-and-Forward relays.

Depending on which functions are included in the relay, the relay structures can be classified into a Layer 2 (L2) relay and a Layer 3 (L3) relay. For L2 or L3 relays, the eNodeB-to-relay and relay-to-UE transmissions can be inband or outband as in the case of L1 relays.

1) Layer 3 (L3) Relay

In LTE, L3 only exists in control plane, that is, the RRC and NAS layers. The IP layer is L3 in the user plane. Hoymann et al. [8] proposed an L3 solution called self-backhauling. Self-backhauling relay can be viewed as a mini base station. In other words, the self-backhauling relay has the same functionality as base stations except for lower transmit power and smaller cell size. Unlike an ordinary base station, a self-backhauling relay is connected to an eNodeB via the LTE radio interface. Thus, the relay must support the LTE radio interface protocols for communicating with eNodeB. The radio link between the relay and eNodeB is referred to as backhaul link. Even though new dedicated radio technologies can be employed for the backhaul link, it is more cost-effective if the relay uses the same radio interface technology as UE. In addition, no new protocol standards need to be defined for including self-backhauling relay in the network. The user plane control and plane protocol stack for self-backhauling relay is shown in Fig. 5.

The self-backhauling configuration affects the protocol stack configuration of eNodeB, which is also shown in the figure. In the user plane, eNodeB functions like a wireless IP router between the self-backhauling relay and the Serving Gateway/MME. This means, standard routing protocols can be employed but the eNodeB must differentiate between self-backhauling IP packets and non-self-backhauling IP packets. In the case of self-backhauling IP packets, the packets are bypassing GTP and UDP at eNodeB for both the uplink and downlink directions. Instead the de/encapsulation process of GTP is performed at the self-backhauling relay. This has resulted in GTP-encapsulated IP packets being transmitted over the radio interface between the self-backhauling relay and the eNodeB [8]. Thus, the traditional method of IP packet classification based on GTP tunnel end-points is not feasible. Therefore, a different Quality of Service (QoS) mechanism is required at the self-backhauling relay and eNodeB [8]. In the control plane, eNodeB is functionally equivalent to the user plane. It routes IP packets carrying control plane data.

The self-backhauling solution is attractive because it reuses existing LTE radio protocols. However, such a solution can lead to performance issue because the LTE radio protocol stack is designed and optimized for single-hop rather than multi-hop transmission.

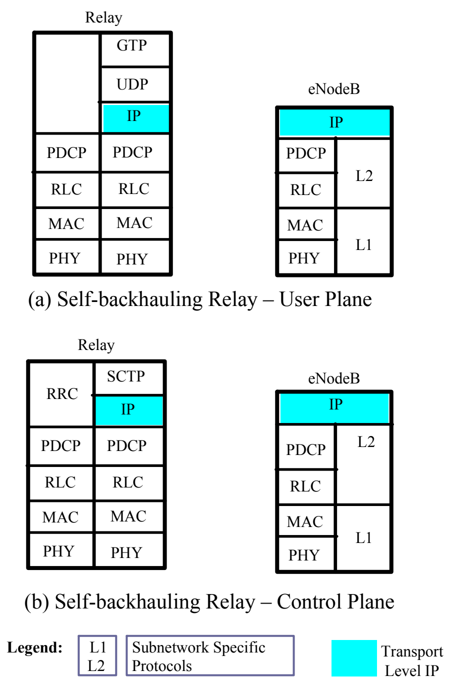
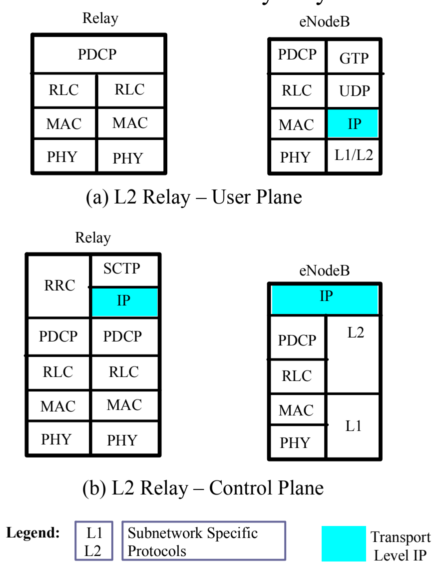


Fig. 5. L3 Relay – Self-backhauling Approach [8]

2) Layer 2 Relay

In LTE, L2 protocol comprises three sublayers: PDCP, RLC and MAC for both the control plane and user plane. A number of different solutions are possible for L2 relay. The three sublayers can operate either edge-to-edge or on a per-hop basis [8]. The latter can reuse the L2 protocols and, in principles, similar to the self-backhauling approach, except the L2 relay forwards L2 PDCP packets instead of IP packets. Fig. 6 illustrates the user plane and control plane protocol stack. Unlike the self-backhauling case, IP packets are processed by GTP in eNodeB. That means, GTP tunnel end-points are used for IP packet classification as in the case for UE-eNodeB communication. For illustration purposes, we chose a full-fledge control plane. In principles, the L2 relay can realize a part of the control plane functionality.

In the end-to-end case, the LTE L2 protocols are located at the eNodeB and UE. New L2 protocols can be designed for multi-hop relaying. Although research is still in progress, a notable development that can be found in the literature is multi-hop ARQ schemes [9]-[11]. These ARQ schemes are optimized for multi-hop communications. Fig. 7 shows the user plane structure that includes a multi-hop ARQ scheme. The RLC protocol at sender, can be either UE or eNodeB, is responsible for end-to-end error recovery while the relay RLC is for local error recovery. On the contrary, the per-hop approach has local error recovery only as shown in Figure 7.



(a) L2 Relay – User Plane

(b) L2 Relay – Control Plane

Fig. 6. L2 Relay – Per-hop Approach

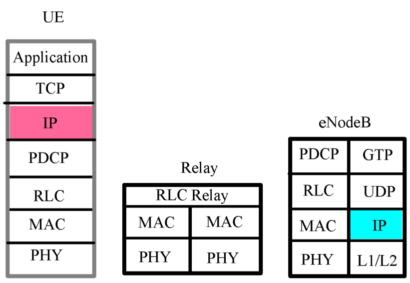


Fig. 7. L2 Relay – End-to-End Approach

V. Comparison

In Table I, L1, L2 and L3 relays are qualitatively compared against a set of criteria, namely cost, complexity, processing delay, mobility support, influence on standardization, protocol overhead, isolation of noise and interference, and the number of hops.

TABLE I: COMPARISON OF DIFFERENT RELAYING STRATEGIES

	Relay Type		
	L1 (Amplify-and-Froward [6]	**L2 (Decode-and-forward)**	**L3 (Decode-and-forward) [8]**
Cost	Low	Medium	High
Complexity	Low (Physical layer only)	Medium (Up to PDCP layer)	High (Full functionality up to IP layer)
Processing Delay	Negligible	Low	High
Mobility Support	No (Nomadic)	Limited	Full
Standards Influence	No	Major standardization efforts needed	Small
Protocol Overhead	Low	Medium	High
Noise and interference propagation	Yes, both noise and interference are amplified	No	No
Number of hops	Suitable for 2 hops	2 or more hops (rely on routing at the link layer)	2 or more hops (routing capability

VI. A Multi-hop aware channel-dependent scheduling

A scheduler dynamically controls the allocation of shared time-frequency resources among UEs at each time instant. The eNodeB MAC layer controls the uplink and downlink scheduling. A channel-dependent scheduler [5] is one that takes into account the instantaneous radio-channel conditions in the scheduling decision. Channel-dependent scheduling is employed in LTE, and similarly, it will be utilized in LTE-Advanced.

Among the relay strategies discussed in Section IV, only L2 and L3 relays can support scheduling since there is no MAC in L1 relays. In the rest of this section, L2 and L3 relays are simply referred to as relay because the proposed solution herein is applicable to both L2 and L3 relays. A straightforward solution is to employ conventional channel-dependent scheduling mechanisms in both the relay and eNodeB. Even though this solution is simple and cost-effective, it has dire consequences on performance. This is because conventional scheduling mechanisms were designed for single-hop links. In LTE-Advanced with multi-hop links, the communication between eNodeB and UE is via a relay as shown in Figure 8. The transmission bit rate (R) of each hop depends on the available bandwidth (BW) and instantaneous channel quality (CQ). The channel quality of the eNodeB-Relay (BR) link and the Relay-UE (RU) link may differ significantly, for instance, due to shadowing experienced by one of the links. Consequently, each individual link has a different transmission bit rate. In the downlink, the relay can be overwhelmed by data packets from eNodeB if the RU link quality is worse than the BR link. The received data packets are decoded and buffered while waiting to be forwarded to UE. Since the RU link is slower, buffers in the relay will eventually become overflowed. In order to avoid buffer overflowing, we propose that the eNodeB scheduling should take into account the buffer status of the relay in the scheduling decision in addition to the conventional parameters. The relay buffer status is fed back to eNodeB. Based on the relay buffer status, the eNodeB scheduler will decrease its transmission bit rate while the relay scheduler will allocate more resources to increase its transmission bit rate.

When the CQ of the BR link quality is worse than RU, buffer overflowing could occur if the queues, which buffered packets to be forwarded to eNodeB, are full. Unlike the downlink case, the relay scheduler can control the amount of traffic sent by the UE. Thus, the relay scheduler should take into account its own buffer status in the scheduling decision in addition to the transmission bit rate of the RU link. The buffer status is obtained locally. Therefore, no explicit signalling is needed.

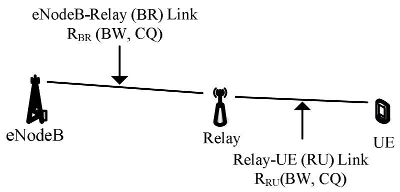


Figure 8: Multi-hop Links with different Transmission Bit Rates

Figure 9 shows the proposed channel-dependent scheduling framework of the relay. In the downlink, the eNodeB scheduler receives the buffer status report from the relay. In order to conserve radio resources, the sending of the buffer status report is triggered when the buffer occupancy reaches a certain threshold. We do not need to explicitly define new buffer status report since a similar buffer status report is used in the uplink as shown in Figure 9. The buffer status report for uplink and the channel quality report are already defined in LTE. In the uplink, the relay scheduler decision is based on UE and its own buffer status in addition to the channel quality. As mentioned, the relay buffer status is obtained locally.

VII. CONCLUSIONS

LTE-Advanced will include multi-hop communications in order to increase cell capacity and coverage. We conducted a comprehensive review on the amplify-and-forward and decode-and-forward relaying strategies. The relaying strategies were qualitatively compared against a set of criteria. For the decode-and-forward strategy, two different options, namely L2 and L3 relays were discussed. The main conclusion that can be drawn from the comparison is that each of the relaying strategies has its pros and cons. The choice of which relaying strategy to use depends on the context and requirements. For instance, if the main goal is to fill cell coverage holes without mobility support or capacity enhancement then the advantages of L1 relay would outweigh L2 and L3 relays. It can also be concluded that LTE-Advanced will deployed a mixture of L1, L2 and L3 relays for different needs.

Then, we proposed a channel-dependent scheduling framework for multi-hop links in LTE-Advanced. The proposed framework addresses the buffer overflowing problem in the relay, which is the result of differing channel conditions on each hop.

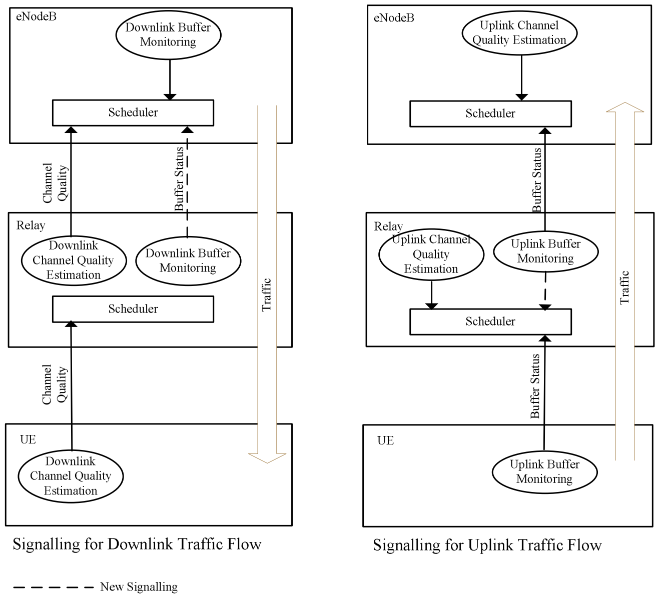


Figure 9: Multi-aware Channel-dependent Scheduling

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