COOPERATIVE COMMUNICATIONS WITH HARQ IN A WIRELESS MESH NETWORK BASED ON 3GPP LTE

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ABSTRACT

This paper presents some results of the FP7 ICT-LOLA (achieving LOw LAtency in wireless communications) project on the design of a clusterized wireless mesh network based on 3GPP LTE. First, we focus on the new MAC/PHY structure proposed. Then, the concept of virtual link is presented for inter-cluster communications combining MAC layer forwarding, hybrid automatic repeat request (HARQ) and cooperative communications with Decode and Forward (DF). The goal of a virtual link is to enable low latency data transfer in inter-cluster communications. The virtual link solution is studied by simulations thanks to OpenAirInterface which integrates LTE MAC and PHY layer procedures, as well as adaptations needed for the LOLA wireless mesh network. Simulation results show that the proposed distributed solution smoothly adapts to the link conditions. A loss in throughput efficiency is the price to be paid in certain configurations for the distributed operation of the virtual link. Nevertheless, the technique helps in reducing the average number of transmissions thus contributing to improve the latency of the system.

Index Terms— 3GPP LTE, wireless mesh networks, MAC layer forwarding, hybrid automatic repeat request (HARQ), cooperative communications, decode and forward (DF), low latency

1. INTRODUCTION

In the community of Private Mobile Radio (PMR) systems, an increasing research effort is undertaken for the definition of the future broadband PMR systems. Recently, a decision of FCC in the USA attributed a band to future PMR systems [1], imposing 3GPP LTE Rel. 8 as the base technology [2], in order to get an up-to-date and interoperable solution for public safety forces. FP7 project LOLA considers how to extend 3GPP LTE communication techniques, procedures and protocols for building rapid deployable nomadic clustered wireless mesh networks (WMNs) of small and medium size to be deployed in a crisis site. Low latency shall be achieved to enable emergency communications (voice or data transfer). WMNs are typically composed of mesh routers (MR) relaying data and mesh clients (MC) sending or receiving data. Each node can act as a host or as a router. Clustering nodes of a WMN into groups with a cluster head (CH) elected in the group can help to decrease the signalling overhead in the WMN. WMNs challenges are well known and have been investigated since a long time [3], [4].

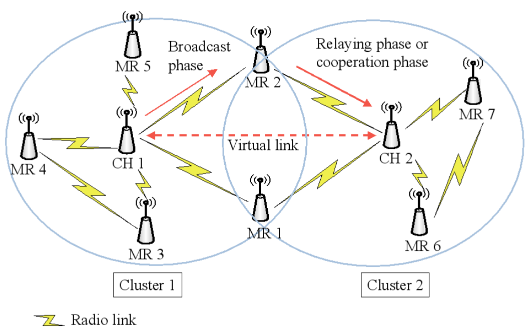

Fig. 1. Diamond topology with virtual link.

In this paper, a clusterized mesh network based on 3GPP LTE is described in Sect. 2. New features, with respect to the ones of 3GPP LTE, have been added to manage peculiar aspects of WMNs. In particular, the paper focuses on how inter-cluster communications can be efficiently implemented, with relatively small changes with respect to 3GPP LTE procedures, trying to increase link robustness while limiting latency. At this aim, Sect. 2.2 presents a virtual link for inter-cluster data transmission based on MAC layer forwarding, HARQ and cooperative communications with distributed Alamouti DF [5], [6]. 3GPP LTE networks typically use HARQ procedures to increase the reliability of the wireless links. However, in order to achieve low latencies in multi-hop WMN, the number of HARQ rounds needs to stay low,

This paper describes work undertaken in the context of the LOLA project - Achieving LOw-LAtency in Wireless Communications (www.ict-lola.eu) funded by the European Community 7th Framework Program under grant agreement No. 248993.

in this case cooperative communications can help to increase the robustness. Lot of works have been done on cooperative techniques, with or without HARQ, in cellular networks and WMNs. However, for the 3GPP LTE case and cellular networks, most of the literature focus on relaying inside a cell [7]. The main innovation of this work is to propose a distributed mechanism based on reasonable modifications of LTE procedures rather than proposing a brand-new cooperative protocol. The proposed solution is presented in Sect. 3. Sect. 4 reports simulation results obtained with the OpenAirInterface simulation environment [4].

2. LOLA WIRELESS MESH NETWORK

2.1. General description

The LOLA WMN is organized in clusters, in order to take advantage of the LTE features for managing the spectral resources inside a cell. Two clusters cannot directly communicate between them by definition. Inside a cluster, the following associations between LTE and mesh roles can be done: LTE eNodeB ↔ mesh Cluster Head (CH), LTE User Equipment (UE) ↔ Mesh Router (MR). Concerning framing, subframes for DL transmission are mapped to CH ones, subframes for UL transmission to MR ones. The previous associations eNodeB/CH and UE/MR indicate that PHY/MAC layer procedures, logical and transport channels of mesh nodes are inherited from those of the corresponding LTE entity. However, the role of a MR is completely different from the one of a UE: in the LOLA mesh all nodes can have the same hardware/software, and they can assume the role of CH and MR according to the situation. This concept is schematically represented in Fig. 1.

Other substantial differences between the LOLA mesh and 3GPP LTE Rel 8 are described below. Firstly, the PHY technique is the same for CH-to-MR and MR-to-CH communications, Orthogonal Frequency Division Multiple Access (OFDMA) is always used. Secondly, an MR can be connected and active in more than one cluster, such an MR is called here a bridging MR. In Fig. 1, MR1 and MR2 are bridging MRs attached to both CH1 and CH2 (for more details on how this can be achieved, please refer to [8], [4]). Furthermore, direct MR (or MR-to-MR) communications are defined in the LOLA mesh, as well as multiple relay cooperation. For instance, MR1 and MR2 in Fig. 1 can cooperate for sending information to one of the CHs. Another important concept is the virtual link, which will be introduced in more details in the next section. For further details and additional features of the LOLA mesh, see [8].

In 3GPP LTE Rel. 10, relaying has been introduced for coverage extension. Non-transparent relaying (type 1) has been adopted while transparent relaying (type 2) has not [2]. The proposed solution in the LOLA WMN is related to transparent relaying since MAC forwarding and cooperative communications are performed. However, substantial differences still exist, since the MRs are connected to more than one CH.

2.2. Virtual link design

To lower the latency in inter-cluster transmission in the LOLA WMN, a virtual link between the different CHs is defined, by making use of LTE signalling or modifications of it. A virtual link is composed of one or more MRs cooperating in order to relay data between CHs. The MRs of a virtual link use DF to enable MAC forwarding and to perform cooperative diversity.

The 3GPP LTE MAC layer integrates three new functions: a MAC PDU building function, a forwarding function and a queuing function. The MAC PDU building function gets PDUs from the RLC layer to fit the MAC transport block size and builds the MAC PDUs. The forwarding function associates incoming cooperative links with outgoing cooperative links. Those cooperative links are identified by a newly defined cooperative Radio Network Temporary Identifier (CO-RNTI). There is a different CO-RNTI for each hop associated to a cooperative link (in fact, to a cooperative radio bearer). The queuing function stores the MAC PDU to be forwarded. In order to ensure data synchronization among the different MRs performing cooperative communications on a virtual link, the MAC PDUs to be forwarded integrate a newly defined identifier (MAC PDU ID). 3GPP LTE MAC layer legacy functions such as the controller or the HARQ function need modifications in order to interface with the newly defined functions. The newly obtained MAC layer is represented in Fig. 2.

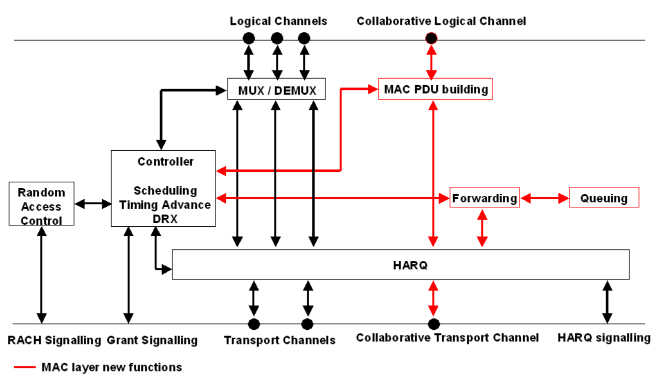

Fig. 2. 3GPP LTE MAC layer with forwarding, in red the new blocks and functional relationships.

The transmission in the first hop is scheduled by the source CH on the DL-SCH using CO-RNTI. The MRs then respond by transmitting HARQ ACK/NACK using on-off keying in the indicated PUCCH resource. The presence of the response indicates a NACK, whereas absence of the response indicates an ACK. If the source CH does not receive a NACK response, it continues with the next MAC PDU. Scheduling Requests (SRs) and Buffer Status Reports (BSRs) sent by the MRs of a virtual link to a CH integrate the IDs of the MAC PDU to be sent over the requested resources.

The transmission in the second hop is scheduled by the destination CH on the UL-SCH, based on BSRs (or SR) from the MRs. Resource grants integrate the IDs of the MAC PDU to be transmitted and the CO-RNTI of a virtual link. If a CO-RNTI is sent in the Downlink Control Information (DCI), each MR having the scheduled MAC PDU in its buffer will transmit according to a distributed Alamouti scheme. The MAC PDU(s) can be removed from the MAC buffer when the destination CH responds with a HARQ ACK.

2.3. Virtual link setup

The establishment of a virtual link follows a procedure similar to Data Radio Bearer (DRB) establishment (RRCConnectionReconf/RRCConnectionReconComplete) [9] and creates a newly defined Virtual DRB. New parameters such as the CO-RNTI are exchanged during this procedure. DRB used in the LOLA wireless mesh network begin/end on CHs/MRs.

During the set-up of a cooperative link, a virtual antenna role is assigned to each MR. In case of more than two MRs belonging to the virtual link, distributed Alamouti can be still used. In principle, for the MRs assigned to the same virtual antenna, cyclic delay diversity can be used to create additional frequency diversity. Fig. 3 illustrates the result of a virtual link setup.

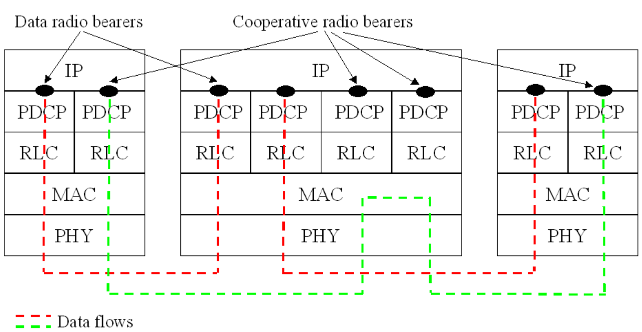

Fig. 3. 3GPP LTE protocol stack with cooperative communications.

3. HARQ AND DECODE & FORWARD STRATEGY

This section presents the coupling of hop-by-hop HARQ with the cooperative DF.

Each transmission from a CH over the virtual link is split into two separate hops (see Fig. 1). The first hop is a broadcast transmission from the source CH to all the MRs part of the virtual link. The transmission continues until all MRs have successfully decoded the MAC PDU or the maximum HARQ retransmission is reached. The second hop starts as soon as one of the MR has successfully received a MAC PDU. All MRs that have received the same MAC PDU will contribute to the transmission. So HARQ retransmissions of the same MAC PDU are allowed to be interleaved on the two hops.

Allowing the destination CH to schedule transmissions on the second hop before all MRs have decoded enables the possibility that the destination CH may successfully receive the MAC PDU before all MRs have received it from the source CH. In this case, in order to avoid wasting additional resources on the first hop, an MR will stop transmitting a HARQ NACK when a MAC PDU has been successfully received at the destination CH. The MRs get this knowledge by always listening to the PHICH from the destination CH, even if they have not participated in a cooperative transmission on the second hop.

4. PERFORMANCE AND RESULTS

4.1. Simulation settings

The simulations have been performed using a link simulator in a 5 MHz bandwidth with TDD configuration 1. The nodes encompass a source CH (CH1), two MRs acting as relays (MR1 and MR2), and a destination CH (CH2). The two MRs are assumed to be synchronized to both CHs, and configured to act as cooperative DF relays as described in Sect. 3. At the source CH, the data to be transmitted is encoded and modulated onto the Physical Downlink Shared CHannel (PDSCH) occupying the full 50 RBs over the whole subframe duration (25 RBs per slot). The channel realizations on the four links are independent. At MR1 and MR2, the DCI of the Physical Downlink Control CHannel (PDCCH) is assumed to always be correctly received. Channel estimation is performed, and the PDSCH data is received and decoded.

In the relaying phase, the BSRs and/or SRs and the DCI with the uplink scheduling grant are assumed to always be correctly received. The data is scheduled onto the PUSCH occupying the full 50 RBs over the whole subframe duration. When both MRs have decoded, the data is forwarded using distributed Alamouti encoding. In this case, orthogonal reference signals are used in order to enable the destination CH to accurately determine the channels from both MRs.

When the MRs are not cooperating, they are transmitting with power $P_{MR} = P_{CH}$, and when they are cooperating they are transmitting with $P_{MR} = P_{CH}/2$. The maximum HARQ transmissions per MAC PDU is 4, unless otherwise stated. HARQ ACK and NACK messages are assumed to be transmitted over error-free channels. Moreover a reference configuration with 1 bridging MRs is also investigated. In all configurations, the behaviour in terms of throughput efficiency and average number of transmissions is studied. The throughput efficiency is defined as the number of correctly received bits at CH2 divided by the total time-frequency resources used for both hops. Overhead due to pilots and PDCCH is taken into account. The latency of the communication

Config ID	Channel	$\text{SNR}_{CH1,MR2} = \text{SNR}_{MR2,CH2}$
Case 1	AWGN	9 dB
Case 2	AWGN	0 dB
Case 1	EVA	15 dB
Case 2	EVA	0 dB

Table 1. Average SNR in dB of MR2 links in different cases in the first scenario.

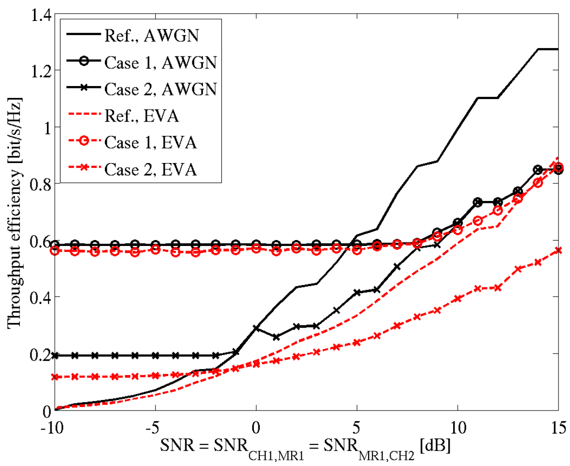

Fig. 4. Throughput efficiency for the configurations with 1 MR and 2 MRs in Table 1

is shown in terms of average number of transmissions on the two hops experienced by packets correctly received at CH2.

Simulation results are provided for the AWGN and Extended Vehicular A (EVA) channels [2]. The EVA channel is strongly time-correlated, with a correlation factor of 0.9 between channel realizations. Two scenarios are considered: 1) the SNRs of the links over MR2 are fixed while the SNR of the links over MR1 changes; 2) the SNRs of all four links are the same. Cooperation performance and its limits, when the links differ in quality, are shown in the first scenario. The second scenario is the most favorable to cooperation when distributed Alamouti is used. For the first scenario, the SNRs of the links over MR2 are shown in Table 1. In case 1, the links over MR2 have good quality, whereas in case 2 they have average quality.

The LTE modulation and coding scheme (MCS) that maximizes the throughput efficiency of the reference case (using 1 MR) has been determined through simulations, under the constraint that the same MCS is used for both hops. This gives a mapping between SNR and MCS. For the simulations with 2 MRs, the MCS is obtained by the same mapping, but using the SNR of the best link over either MR1 or MR2. The first and second scenarios were simulated respectively with at least 15000 and 5000 MAC PDUs for each point.

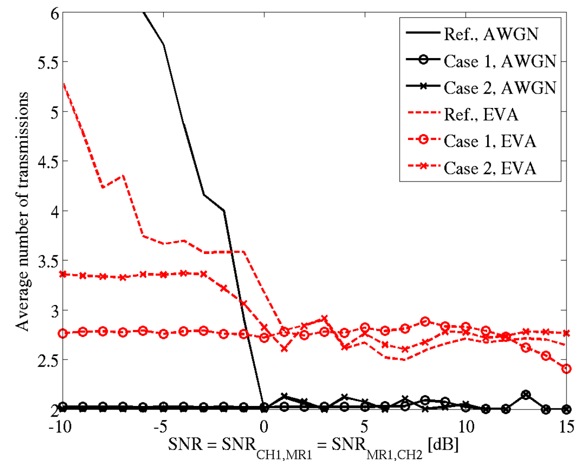

Fig. 5. Average number of transmissions for the configurations with 1 MR and 2 MRs in Table 1

4.2. Simulation results

Fig. 4 and 5 show throughput efficiencies and average number of transmissions for the first scenario. For the AWGN channel, cooperation is never better than best-relay selection. This can be seen, e.g., at SNR $=$ 0 dB where case 2 (using two 0 dB links) shows the same throughput efficiency as the reference case. Reducing the SNR of the MR1 links causes the efficiency to drop, as resources are wasted on retransmissions for the bad relay in the broadcast phase. Similarly, with increasing SNR a higher MCS is used and more retransmissions are needed for MR2 which causes the efficiency to drop. Considering the same case for the more realistic EVA channel, a significant decrease in the latency can be seen at 0 dB, with only a small penalty in the throughput efficiency. However, if the SNR of the links differ by more than 2 dB, using only the better relay is superior both in terms of latency and throughput efficiency.

For case 2, the overhead of cooperation over links with very different SNR is shown. This overhead is due to additional retransmissions in the broadcast phase (hop 1). As a matter of fact, CH1 continues to send retransmissions untill all the bridging MRs have sent an ACK. This is the price to be paid for having two fundamental advantages. The first one is that the proposed strategy is distributed and each CH is completely agnostic of the channel state and ACK/NACK messages of the other one. The second advantage is that this procedure allows to automatically select the best path.

Fig. 6 and Fig. 7 show the throughput efficiency and latency of the proposed technique for the second scenario, which is favourable to distributed Alamouti. In this situation cooperation of the two MRs is often triggered. The figures show performance with different number of HARQ transmissions: “max tx 1” is not using HARQ, whereas “max tx 2” and “max tx 4” are using 1 and 3 HARQ retransmissions,

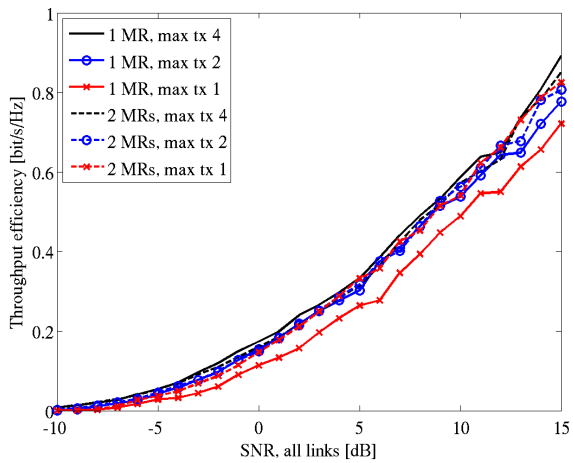

Fig. 6. Throughput efficiency in EVA channel. SNRs of all links are equal.

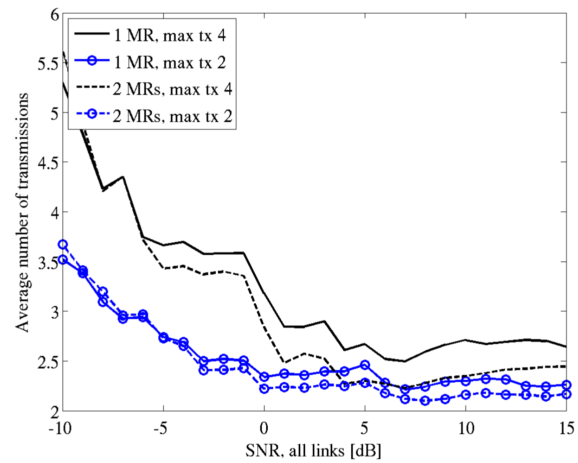

Fig. 7. Average number of transmissions in EVA channel. SNRs of all links are equal.

respectively.

For 1 and 3 retransmissions, cooperation gives a significant reduction in the latency whereas the penalty in throughput efficiency is low. On the other hand, without HARQ the latency for correctly received MAC PDUs is obviously two transmissions. Here, cooperation offers an increase in the throughput efficiency due to the extra diversity from the two relays.

5. CONCLUSIONS

In this paper, after having introduced the LOLA mesh network based on 3GPP LTE PHY and MAC layers, we described the concept of virtual link between two neighbouring cluster heads linked by one or more bridging mesh routers. In this context, a cooperative communication strategy with hop-by-hop HARQ over the virtual link has been described, and the necessary modifications to standard 3GPP LTE signalling have been presented. Simulation results were provided for characterizing the behaviour of the proposed strategy with one or two MRs and a variety of operational conditions. The proposed technique, which is distributed and does not need explicit signalling exchange between CHs, is able to lower the average number of retransmissions when two MRs are used instead of one. A penalty in throughput efficiency has to be paid in certain configurations due to the decentralized operation. A future research perspective for reducing this penalty is an adaptation of the signalling cycles in the two clusters.

6. REFERENCES

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