Design and Evaluation of Cooperative Broadcast in a Wireless Mesh Network based on 3GPP LTE

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***Abstract*— This paper presents results of the Seventh Framework Programme (FP7) LOLA (achieving LOw LAtency in wireless communications) project about the design of a cooperative broadcast (CB) technique based on a decode and forward (DF) protocol, in the context of a clusterized wireless mesh network (WMN) based on 3GPP LTE PHY/MAC layers. The CB technique is compared to a baseline broadcast technique, obtained by packet propagation over a predetermined tree combined with local broadcasts inside the clusters. The novelty of the paper consists in presenting a design of CB which takes into consideration a number of practical issues set by the 3GPP LTE framework, like subframe design or MAC signalling. Moreover, simulation results are presented comparing the two techniques and presenting their advantages and drawbacks.**

I. Introduction

Broadcast has widely been studied by the research and standardization community in the area of mobile ad hoc networks (MANET) and static wireless mesh networks (WMN) [1]. Recently cooperative broadcast techniques have attracted interest, since they promise increased robustness, coverage and also important gains in terms of latency. The theoretical capacity of broadcast with cooperative relays has been studied in [2] (see also references therein). Under the name of barrage relay networks, authors [3] presented a practical way of implementing cooperative broadcast (CB) based on a decode and forward protocol (DF) which works in an autonomous and distributed way. Their joint design in Layer 2 and 3 not only reduces latency and increases robustness, but procedures work with a limited amount of signalling. The concept of autonomous cooperation over orthogonal channels was tested also in [4] for low-cost sensor networks for range extension. Authors in [5] investigate the performance of an autonomous cooperation via distributed space-time codes (virtual MIMO) and discuss issues at network level related to routing, power control, presence of retransmission protocols, network density, control overhead and selection of optimal group of relays.

In MANET and WMN, autonomous CB is seen with interest, especially for latency-constrained traffics with small packets, like short alarms and new applications emerging in the machine type communication (MTC) area. This paper presents part of the results of the European Community FP7 project LOLA on how to design and apply CB in the context of rapidly deployable nomadic clustered WMNs of small and medium size [6]. This kind of WMNs, studied in LOLA, are indeed private mobile radio (PMR) systems with stringent latency requirements for alarms and real-time traffic. Recently, a decision of FCC in the USA attributed a frequency band to future broadband PMR systems and recommended 3GPP Long Term Evolutions (LTE) Rel. 8 as their base technology [7]. The main contribution of this paper is to study and evaluate the extension of 3GPP LTE [8] for supporting autonomous cooperative broadcast.

The paper is structured as follows. Sect. II briefly introduces the LOLA WMN based on LTE. Sect. III details a baseline broadcast algorithm and a CB one, and briefly presents some implementation issues in the LTE framework, and proposes solutions with a special focus on physical (PHY) and medium access control (MAC) layers. Sect. IV presents the specific simulation setting investigated by simulations, while Sect. V show results and discuss them. Sect. VI draws conclusions and presents some perspectives for future work.

II. The LOLA Wireless Network

The LOLA WMN is composed of mesh routers (MR) and mesh clients (MC) and each node can act as a host or as a router. The WMN has been built with the intention to reuse as much as possible the 3GPP LTE standard, at least at PHY and MAC layers (we suppose in the following that the reader is familiar with LTE terminology). The LOLA WMN is clusterized at MAC level, with cluster heads (CHs) elected in the group. Clusters, which correspond to the concept of cell in LTE, take advantage of the LTE features for managing their spectral resources. The following associations between roles can be done inside a cluster: LTE eNodeB $\leftrightarrow$ mesh CH; LTE user equipment (UE) $\leftrightarrow$ MR. Moreover, subframes for downlink (DL) transmission are mapped to CH ones in the LOLA WMN, subframes for uplink (UL) transmission to MR ones. The previous associations indicate that PHY/MAC layer procedures, logical and transport channels of mesh nodes are inherited from those of the corresponding LTE entity. However, the MR role is completely different from the UE one: in the LOLA mesh, all nodes have the same hardware/software and they act as CH or MR according to the situation.

Other substantial differences between the LOLA WMN and 3GPP LTE Rel 8 are: 1) the LOLA WMN PHY uses

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orthogonal frequency division multiple access (OFDMA) for all types of communications; 2) time division duplexing (TDD) is always used; 3) a MR can be connected and active in more than one cluster; 4) new logical and transport channels are defined for supporting broadcast and multicast inside the network; 5) MR-to-MR communications have been defined, as well as multiple relay cooperation; 6) a new subframe for CB has been specified, trying at the same time to minimize the impact on the rest of the LTE standard. Points 4) and 6) will be further explored in the paper. The interested reader can refer to [6] for further details on the other topics.

III. Broadcast Algorithms

A. Baseline Broadcast Algorithm

Flooding is a widely used technique for broadcasting data or control information over a WMN or a MANET [9], [10]. The baseline broadcast in the LOLA WMN is a simple algorithm which exploits the concept of connected dominating set (CDS). A dominating set is a subset of nodes of the WMN such that every node either belongs to the dominating set or it is adjacent to a node in the dominating set. The issue with CDS is that finding a CDS with minimal cardinality is a NP-hard problem. However, we notice that in the LOLA WMN any tree connecting all the CHs of the network is a CDS, although not necessarily of minimal cardinality. We suppose that such a tree is periodically generated. The baseline broadcast algorithm propagates the information along that tree. Once the packet reaches a CH, the latter will make a local broadcast inside the cluster.

B. Designs for Baseline Broadcast

The implementation of the broadcast baseline algorithm requires limited modifications of LTE PHY/MAC. We notice that in LTE a logical broadcast channel exists but it is used only for control information. Data broadcast can be implemented through multimedia broadcast/multicast service (MBMS), which however is designed thinking to single frequency networks. We propose to map the broadcast traffic on a DL shared channel (logical channel), mapped to the physical DL shared channel (PDSCH) with a new common Local Broadcast-Radio Network Temporary Identifier (LB-RNTI), for example in the range FFF4-FFFC which is reserved for future use. LTE implementation is not further detailed due to lack of space. For LTE notation and definitions please refer to [8].

C. Cooperative Broadcast Algorithm

The CB algorithm of the LOLA WMN is based on DF and it is completely autonomous in its operation. The transmissions are organized in CB sessions, which is a set of cooperative broadcast/multicast (CBM) subframes during which a given MAC payload data unit (PDU) is propagated. The number of CBM subframes in a CB session coincides with the maximum number of hops over which the MAC PDU can be relayed. CB sessions are semi-statically allocated by the radio resource control (RRC) when a request for such a service arises.

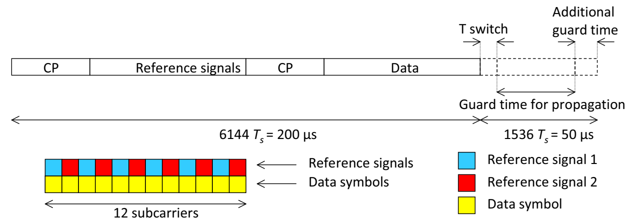

Fig. 1. The cooperative broadcast/multicast subframe

The cooperative protocol works as follows. At the source, after data extraction, fragmentation (if necessary), radio link control (RLC) and MAC headers insertion, the packets are sent on the air. The receivers listen: if there is no signal or it is missed or cyclic redundancy check (CRC) fails after decoding, they do nothing. Otherwise, the packet is correctly decoded, the MAC PDU number and the hop number are extracted:

1) if the MAC PDU number is lower than or equal to the latest received MAC PDU numbers, then the packet is a copy coming from a loop: discard it;
2) if the MAC PDU number is greater than the latest received MAC PDU numbers, then it is a new packet and it is sent to upper layers:
   i) if the hop number is higher than or equal to the maximum hop number: end of the CB session, do nothing.
   ii) Otherwise, a new MAC-header is generated and inserted on the received data for forming a new MAC PDU, which will be sent on the air during the next transmission opportunity of the CB session.

In a given CBM subframe different relays send copies of the same signal. Since the propagation delays from the transmitters to a given receiver are in general different, the receiver will see many delayed signal replicas, i.e. a multipath channel. This is the same principle of cyclic delay diversity techniques for localized multiple antenna systems: spatial diversity is converted to frequency diversity by creating a multipath channel. This diversity can be recovered by OFDMA with a sufficiently robust error correcting code.

D. Designs for Cooperative Broadcast

At PHY layer, since CB is a multi-point-to-multi-point technique, standard LTE timing advance procedures can not be applied. Contrarily to many articles in the literature, in which ideal synchronization is considered, we designed the CBM subframe (see Fig. 1) in order to support a feasible synchronization at PHY layer in presence of multiple transmitters. First, at the end of the CBM subframe a guard time is inserted for absorbing propagation time and allowing switching of the hardware. Considering a switching time of 5 μs, the guard time covers propagations of more than 13 km. Second, in a CBM subframe the cyclic prefix (CP) must cover the largest propagation time between any two nodes able to communicate, plus the maximum delay spread of the channel (typically around 10 μs) and inaccuracies due to imperfect network

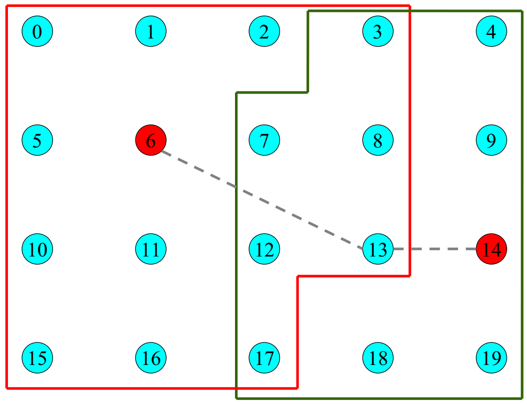

Fig. 2. Network used in the simulations: 20 nodes, 2 clusters

synchronization (typically less than 10 μs). Notice that, with a proposed CP of 33.3 μs, differential propagation times between transmitters up to 4 km are supported. Finally, the first OFDM symbol is a reference symbol used for synchronization and channel estimation. The refererence signal supports also distributed space-time coding schemes with two antennas. A CBM subframe is long 250 μs, i.e. a standard LTE subframe can contain 4 CBM subframes.

CB implemented as in Sect. III-C requires a completely new MAC mode with specific procedures, not specified in LTE as of today. A new MAC control element (CE) inside the LTE MAC header has been defined for supporting the CB algorithm. Its fields are: 1) a CB-RNTI of 16 bit which indicates the CB algorithm and is also used for masking the CRC used for checking the integrity of the data; 2) a MAC PDU number of 10 bits, to identify the MAC PDU; 3) a hop number of 4 bits, which contains the current hop number of the CB session; 4) the total number of hops of 4 bits, which states the length of the CB session. The MAC CE is 5 bytes long (6 bits are unused) and contains information which depends only on the hop number. For more details, please see [6].

Scheduling of CB sessions sets also significant issues. CB sessions could be accessed by random access (RA) with contention: a node wanting to broadcast a packet just sends it in the next CB session. RA is particularly adapted for event-driven traffic with small payloads like the one considered in this paper. The drawback of RA is the possible presence of collisions. In Sect. V we will study the performance of collision-free RA, i.e. an upper bound on really achievable performance. Centralized resource allocation is also possible (see e.g. [3]). In this case, a request and a confirmation logical channel must be defined and managed by a central entity so that there is no collision in accessing the resource. This scheme however adds latency and signalling overhead.

IV. Simulation Settings

The static WMN used in the simulation is composed by 20 nodes deployed over a Manhattan grid with inter-node distance of 500 m, see Fig. 2. The traffic source is node

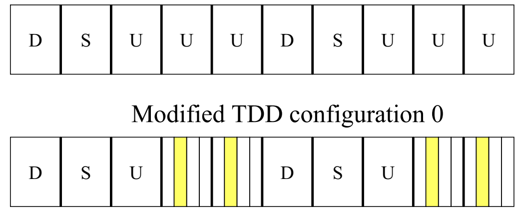

Fig. 3. 3GPP LTE frame in TDD UL/DL configuration 0 and its modified version for CB

TABLE I
Parameters of the WMN and of the simulation settings

Parameter	Value
TDD configuration	0
Channel bandwidth	5 MHz
Carrier frequency	400 MHz
Signalling	error-free
HARQ	no
Synchronization	propagation delays are considered
Traffic type	event-driven short alarms
CH/MR heights	3 m
CH/MR transmission power P_T	23, 33 dBm
Transmit antenna gain	6 dB
Receive antenna gain	6 dB
Implementation losses	2 dB
CH/MR antenna type	single, omnidirectional
Path loss model	ITU-R P.1411-4 [11]
Shadowing	no
Channel model	Extended Typical Urban (ETU) [8]

6. In the baseline case, the tree connecting the two CHs is shown by grey dashed segments in Fig. 2. Notice that design of CBM subframe in Fig. 1 is even overdimensioned for this deployment (see Sect. III-D): synchronization does not set additional difficulties. The multipath channels at the receivers are never longer than the CP, such that there is no harmfull interference.

Fig. 3 presents at the top the frame in TDD UL/DL configuration 0 for the baseline scenario, and at the bottom its modified version used for CB simulations. In the simulations, 4 parallel CB sessions are used, each one has 4 hops (one session is shown in yellow).

The traffic type is event-driven and composed by short packets with stringent latency constraints, like alarms. In order to better exploit the characteristics of the transport channels, RLC segments incoming packets in 25 and 30 bytes respectively for the baseline and CB algorithm. RLC and MAC headers take a total of 6 bytes. Then, the MAC PDU is 31 and 36 bytes long respectively for the baseline and CB case.

A fixed modulation and coding scheme (MCS) is used for all the transmissions during the broadcast. Advanced strategies, like the ones based on fountain codes, have not been studied here. In the baseline case, the MAC PDU is mapped to a MCS QPSK with 248 information bits, coded according the 3GPP LTE standard with code rate $r = 0.43$ (TS 36.211 v10), and occupying 3 resource blocks. In the CB case, the MAC PDU is mapped to a MCS QPSK with 288 information bits, with

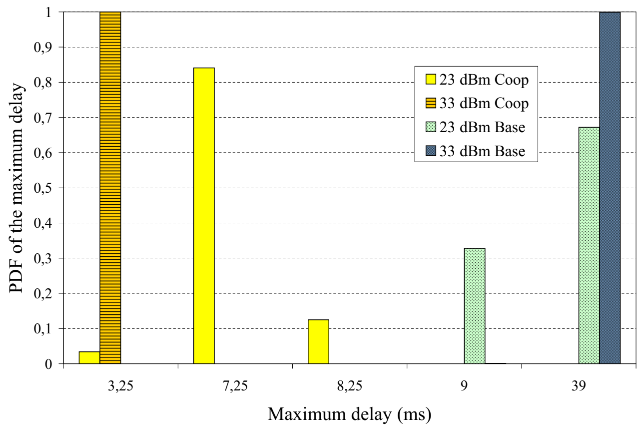

Fig. 4. Probability density function of the maximum network delay

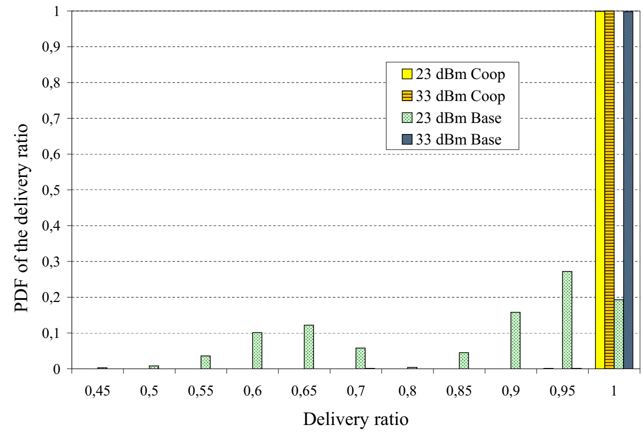

Fig. 5. Probability density function of the delivery ratio

code rate $r = 0.48$ (see TS 36.211 v10), and occupying one CBM subframe. The two MCSs' block error rate (BLER) vs SNR curves differ of 0.5 dB in additive white Gaussian noise.

Simulations are done in an Omnet++ environment for CB, and in a Matlab environment for the baseline algorithm. Table I shows the main parameters used in the simulators. Both simulators use a PHY layer BLER predictor exploiting the so-called mutual information effective SNR metric [12]. When multiple transmitters cooperate in a CBM subframe, propagation delays are considered. The predictor uses the artificial multipath channel at the receiver, which is obtained by opportunely adding time-shifted realizations of the single-link channel impulse responses, including path loss.

V. Performance and Results

Results are obtained broadcasting 1000 alarm packets in the network. For simplicity and readibility of results, the delays are shown between the transmission of one RLC fragment and the reception of one RLC fragment. Spectral efficiency is calculated at RLC level. RLC and MAC headers are considered overhead, as well as all the guard times and pilots at PHY layer. The signalling required for transmission/scheduling procedures has not been taken into account in the spectral efficiency, but only in end-to-end delay.

Fig. 4 presents the probability density function (PDF) of maximum network delay calculated over all the nodes having correctly received the information, for two values of the transmission power P_T. For the baseline case, when $P_T = 33$ dBm, the maximum delay is practically constant at 39 ms and it corresponds to reception in the second cluster. At 23 dBm, there is a non-negligible probability that the maximum delay is 9 ms, corresponding to the cases in which the packet does not successfully propagate to the second cluster, due to transmission errors over the tree connecting the two CHs. As we will see later, a bad coverage corresponds to this good latency performance. These delays increase if the traffic source is not a CH (node 6). In the CB case, at 33 dBm the maximum delay for collision-free RA is constant and equal to 3.25 ms (i.e. two hops plus one CBM subframe, decoding delay of 1 ms and an average waiting time assumed equal to 1 ms). For a centralized CBM scheduler, we assume that the request and confirmation messages are error-free and transmitted via two separate CB sessions of 4 hops too, like the data. Then, the total delay with resource allocation, is around 25.5 ms which is still competitive with respect to the 39 ms of the baseline case. For the CB case at 23 dBm, the maximum delay can be as high as 8.25 ms with collision-free RA (or about 30.5 ms if we consider signalling for resource allocation).

In a WMN with N clusters in the worst configuration, the maximum delay of the baseline approach scales as $A+30(N-1)$ ms, where A is the time for accessing the first CH and for local broadcast, and 30 ms is an average value which depends on timing of LTE procedures in TDD. For CB, the maximum delay for collision-free RA scales as $B+(N+2)T_{cbs}$, where T_{cbs} is the average time between two consecutive CBM subframes in the same CB session and depends on the frequence and structure of the CBM session. In the current settings $T_{cbs} = 2.5$ ms. Two CBM subframes are added as redundancy for robust operation. The term B is a constant depending on the access, $B \approx 1$ ms for collision-free RA, but grows in case of collisions. $B \approx 2(N+2)T_{cbs}$ for centralized scheduling, representing serial request and confirmation messages. Notice that CB maximum delay gain with respect to the baseline grows with the number of clusters, as long as T_{cbs} is kept low, i.e. there is a sufficient number of CBM subframes in the LTE frame. As for the baseline, these results must be read together with the delivery ratio and spectral efficiency figures.

Fig. 5 presents the PDF of the delivery ratio, i.e. the percentage of nodes having correctly received the message. A delivery ratio of 1 represents the complete coverage of the network. For CB at 33 dBm and 23 dBm, the message is substantially received by all the nodes. Results (not presented here) show that in the 23 dBm CB case, the whole network is totally covered 3.43% of the times after 2 hops and 87.5% after 3 hops. On the contrary, the baseline strategy at 23 dBm covers

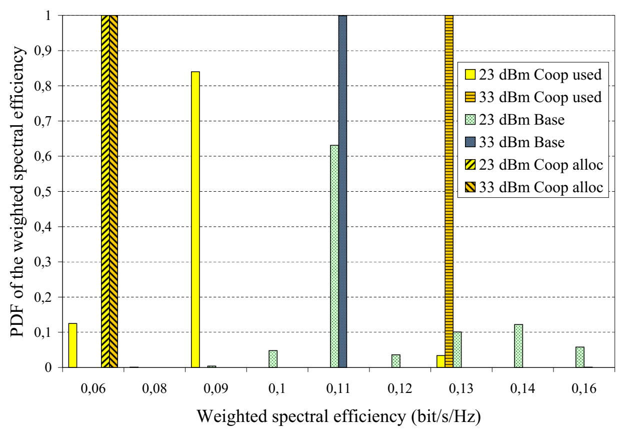

Fig. 6. Probability density function of the weighted spectral efficiency

the whole network only 19.3% of the times. This result is paid by the cooperative broadcast in terms of spectral efficiency.

Notice that, if the target metric of interest is global coverage coupled with delay, the baseline case needs a transmit power of 33 dBm, while the CB case requires only 23 dBm. Calculations show that, in this configuration, the total transmit power spent in the network for data transmission is around 4 W for CB, and in between 6 and 8 W for the baseline case, giving a slight advantage to CB.

Finally, Fig. 6 shows the PDF of the weigthed spectral efficiency, defined as the number of information bits correctly received in the network divided by the total number of resources used for their transmission and multiplied by the instantaneous delivery ratio. In the CB case we calculate the weighted spectral efficiency in two ways, one considering the allocated resource, i.e. 4 CBM subframes for each packet, the other considering the really-used CBM subframes, which can be less then 4 CBM subframes. The average weighted spectral efficiency calculated with respect to the allocated resources is of course the same for 23 dBm and 33 dBm and it is around 0.064 bits/s/Hz: the loss with respect to the baseline technique is about 44%, the average being around 0.11 bit/s/Hz. When the calculation is done over the used resources, the average weighted spectral efficiency of CB in the 33 dBm case rises over the baseline to 0.128 bit/s/Hz, which is paid by an higher network transmit power. In the CB case at 23 dBm, the average weighted spectral efficiency raises to 0.084 bit/s/Hz, reducing the loss to 25% with respect to the 33 dBm baseline case, but with better performance in transmitted power, same global coverage and lower maximum delays. This fact calls for advanced strategies which are able to exploit unused resources inside CB sessions, and which are left for future work.

VI. Conclusions and Perspectives

This paper presented an implementation of an autonomous cooperative broadcast algorithm in the framework of a clusterized WMN based on 3GPP LTE, for transmission of short, event-driven messages like alarms. Adaptations of the 3GPP LTE MAC and PHY layers have been proposed and discussed. Simulations were run in order to compare CB to a traditional baseline algorithm based on local broadcast. We showed that CB has a significant advantage in terms of delay (up to a factor of four) and delivery ratio when used together with ideal collision-free random access. The delay advantage is however significantly reduced in case of centralized scheduling for networks with few clusters. Moreover, given the autonomous operation of the CB scheme, spectral use of the resources is less efficient than for the baseline algorithm (loss up to a factor of two). The use of CB seems to be questionable for WMN composed by 1, 2 or 3 clusters, while its interest grows as soon as the number of clusters is higher than 3.

However, two important issues must still be solved before CB becomes a really attractive technique. First of all, the low CB spectral efficiency should be improved. One possibility is to optimize the CBM subframe design at PHY layer in order to recover part of the spectral efficiency loss. As a matter of fact, the current design is rather conservative. The impact of collisions in contention-based random access must also be further investigated, since it has a detrimental effect on spectral efficiency.

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