QoS Guarantee in Self-Backhauled LTE Mesh Networks

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***Abstract*—LTE is deployed in most countries and continuously evolving to match new use cases as well as requirements. While it is expected to evolve toward 5G deployments for outdoor and long range communications, it will also be used for Public Safety services in major countries. Among that, new scenarios call for wider networks relying on dynamic meshing of base stations. Leveraging the LTE air interface for base station meshing is an appealing idea but is not straightforward to guarantee quality of service (QoS). In this article, we study and evaluate scheduling strategies for multi-hop LTE mesh networks relying on the LTE relay channel. We firstly present the LTE relay channel and the scheduling problem for in-band LTE self-backhauling. We then propose a practical cross-layer method in order to fulfill the QoS requirements of real-time flows in such network. We finally evaluate the proposed method through extensive simulations. We show the effectiveness of the proposed approach compared to a legacy method in terms of both QoS requirement satisfaction of real-time flows and throughput enhancement of elastic flows.**

I. INTRODUCTION

Long Term Evolution (LTE) is now the 4G cellular network of reference. 3GPP LTE specifications are expanding its use-cases and increasing its features at every new release to become the 5G outdoor and long range radio access technology (RAT). Moreover, LTE is expected to be the next RAT for Public Safety (PS) communications and specifications items have emerged in this regard [1]. PS networks have several specific requirements including reliability and resiliency while demanding specific Quality of Service (QoS) requirements. In common PS scenarios, LTE Base Stations (BSs), called eNodeBs (eNBs), may lose access to the Evolved Packet Core (EPC) due to some outage or specific deployments. When that happens, they are unable to provide any service to their served users. This is an issue for PS networks and is addressed by 3GPP through the Isolated E-UTRAN concept that allows eNBs to continue providing minimal services for local PS users (TS 22.346, TR 23.797). In [2], we proposed an evolution of the Isolated E-UTRAN concept in the form of a new BS architecture for nomadic LTE networks called as enhanced eNB (e2NB). It embeds essential core network functions to ensure local services and has the ability to connect to other similar BSs leveraging the LTE relay interface to create a mesh network. Fig. 1 shows an example network topology. The e2NB can support new use cases where dynamic meshing among fix and/or moving BSs is highly required. In [3], we showed that the relay channel (called *Un*) performance is close to the legacy LTE eNB ↔ User Equipment (UE) interface (called *Uu*) and that it allows efficient transmissions between e2NBs. However, one of the main challenges when meshing e2NBs, especially when reusing a single frequency band, is that the transmission, reception and resource allocation between BSs shall be coordinated to avoid excessive blocking due to interference and to guarantee the performance of end-to-end connections.

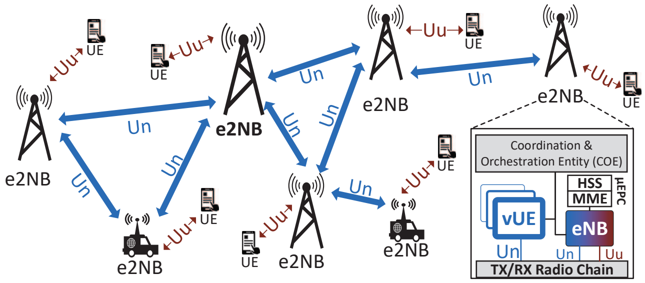

Fig. 1: LTE mesh network based on e2NB with LTE backhaul

In this paper, we exploit the relay channels and propose the genuine resource allocation algorithm to evolve LTE from a single-hop network to a multi-hop meshing of several fixed and/or mobile BSs. We briefly recall the properties of the LTE relay physical channels and the inherent problem to reuse a single frequency band to mesh a wireless network in Section II. In Section III, we present our target use cases and then state the associated problems, objectives and variables. In Section IV, we propose a cross-layer semi-centralized method to allocate resources of the network while taking into account the QoS requirements. In Section V, we evaluate the performance of the proposed method over several topologies via extensive simulations and we compare the results to other resource allocation algorithms. Finally, We conclude this work and present the next steps of our research.

II. BACKGROUND INFORMATION

Our considered problem is based on the LTE relay channel for in-band self-backhauling (i.e. single frequency networking) to mesh LTE BSs. Hence, we recall the background information and the inherent problem in this section.

A. LTE relay channel (Un)

LTE Relay is specified in 3GPP Release 10 allowing a relay node (RN) to serve UEs on its access link and reach the EPC through its backhaul link with its anchor eNB, called Donor

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eNB (DeNB). The LTE relay interface is denoted as *Un* [4] and is used to realize the in-band backhaul link between a LTE RN and its DeNB. As this link is in-band, it shares the same frequency band as the access link relying on a time division multiplexing mechanism. To ensure that the channel between RN and its UEs complies with the legacy access link interface (*Uu*), the *Un* interface relies on a property that is originally introduced in LTE eMBMS (enhanced Multimedia Broadcast Multicast Service, a.k.a. MBSFN) to differentiate multicast/broadcast subframes from the unicast ones. We recall that an LTE frame is made up of ten 1ms subframes (SFs) that carries a number of resource blocks (RBs) depends on the channel bandwidth. In an LTE FDD (Frequency Division Duplex) frame, a maximum of 6 MBSFN SFs are allowed. A relay can exploit properties of these MBSFN SFs to receive specifically formatted unicast RBs from its DeNB on the downlink (DL) channel instead of always being transmitting to its UEs on the access link [4]. This means that the maximum data rate on the *Un* interface is reduced to 60% of what can be achieved on the *Uu* interface.

B. *Single frequency wireless mesh network*

While there are several works regarding the use of LTE *Un* interface for self-backhauling [5], [6]; to the best of our knowledge, none of them considered meshing BSs that host their own EPC and that do not have a unique backhaul path towards a gateway. As indicated hereinbefore, we advocate that the *Un* interface can be reused to extend the eNB capability with in-band self-backhauling to realize self-organized LTE mesh network among BSs [1], [2]. The e2NB incorporates virtual UEs (vUEs) that are used to initiate and maintain connections to the adjacent e2NBs using the *Un* interface.

However, realizing an efficient wireless mesh network on a single frequency is still an open research problem. As all nodes share the resources within the same frequency band, each transmitter will potentially become an interferer to others. Thus, collisions among transmissions may happen if the channel access is not coordinated properly, which in turn limits the achievable rate. Further, there exist more issues in wireless mesh networks as surveyed in [7], including (a) topology control, (b) routing, (c) link scheduling, (d) interference measurement and (e) power control. These aforementioned problems are highly inter-dependent across layers and transmitting nodes.

To deal with these issues jointly, we propose a coordinated and cross-layer approach to unleash the performance barrier when meshing e2NBs in a single frequency band. In that sense, the per-flow QoS can be guaranteed by a jointly consideration on the topology control, path routing, link scheduling, and power control. Our proposed approach is based on an architecture relying on a logically centralized control entity that manages and orchestrates the induced mesh network across medium access control (MAC) and network layer through *policy enforcement*, as described in [1], [2]. Based on the results of such centralized entity, the distributed entities will do local scheduling for both access and backhaul links.

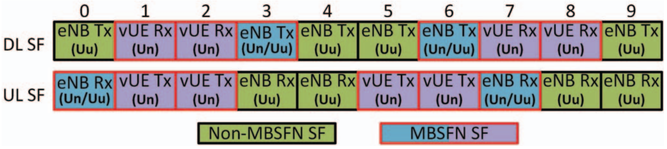


Fig. 2: Example of MBSFN SFs use for inband backhauling

III. PROBLEM STATEMENT AND OBJECTIVES

As mentioned in the previous section, it is necessary to define and enforce policies spanning across the relevant network layers and nodes to realize an efficient single frequency mesh network. We firstly define the objectives considering the use cases and then present the problem as well as its variables.

A. *Traffic flows*

In this work, we focus on public safety scenario with two types of traffic flow: real-time traffic with latency requirement (e.g. VoIP) and elastic traffic that is served in the best effort manner. As our considered scenario is extended from the Isolated E-UTRAN and each BS can provide services to other BSs through the self-backhaul LTE mesh network, hence the source and destination of traffic pattern can heterogeneously be composed of intra-cell and inter-cell UE-to-UE (U2U), eNB-to-eNB (e2e) and UE-to-eNB (U2e) communications. For the real-time traffic, we consider VoIP traffic with target maximum one-way-delay of 150ms for 95% of the packet to ensure a quality call with a Mean Opinion Score (MOS) of 3.5 using a G.729 codec [8]. For the elastic traffic, we consider multimedia data transfer with the objective to maximize its throughput.

B. *Problem statement*

We assume a single frequency FDD LTE network relying on e2NBs [3]. Each e2NB is equipped with a single omni directional antenna. Based on two entities (eNB, vUE(s)) and two interfaces (Un, Uu) in e2NB (see Fig. 1), the DL and UL SF allocation to either entity with corresponding interface is required as the example illustrated in Fig. 2 using all SFs (6 MBSFN SFs and 4 non-MBSFN SFs).

In our problem, we will allocate the (a) MBSFN SFs for backhaul transportation, (b) destination e2NB of backhaul relaying, and (c) transmission power. The resource allocation algorithm enforces policy to each e2NB on allocated transmission (Tx) and reception (Rx) SFs. Such policy depends on the traffic patterns on the mesh (which is a combination of U2U, U2e and e2e communications), on the diverse objectives (latency requirements and throughput maximization) of higher-layer applications, on the network topology, and on the selection of routing paths. Therefore, the main variables at the network level include:

- Tx/Rx SF allocation at each e2NB
- Power allocation of each SF at each eNB
- Traffic forwarding paths

During the allocation, a trade-off can be observed between allowing more e2NBs to communicate while in the mean time reducing the perceived interference by each node. Considering the aforementioned two types of traffic flow, our approach has two objectives:

- Guarantee the latency of real-time flows (i.e. VoIP)
- Maximize the throughput of elastic flows

IV. COORDINATED SCHEDULING

The proposed approach is based on a logically centralized coordinated and orchestration entity (COE) that schedules nodes and selects data forwarding paths by enforcing the policy at each BS (refer to Fig. 1). The COE follows a hierarchical design and is composed of a centralized entity that is connected to a number of COE agents [9], one per e2NB in a typical deployment. The COE agent can either act as a local COE with a limited network view handling control delegated by the centralized entity, or in coordination with other agents and the centralized entity. The communication between the centralized entity and agents is done through message exchanges allowing a bi-directional interaction between them. In one direction, the COE agent sends measured performance indicators and e2NB status to the centralized COE and other agents, while in the other direction the centralized entity enforces policies that define the operation to be executed by the agents and the underlying eNB and vUEs.

The aforementioned design provides the required flexibility in realizing the COE, and is able to reduce the control overhead by delegating more functions to the COE agent at the cost of less coordinated operation.

A. Topology Control

As we are using omni directional antennas, activating a link from a BS means interfering with all other links, regardless of the activated link. In order to remedy the interference from other links, we apply the power control and adaptive modulation and coding (AMC) scheme in *Un* interface that is already applied in *Uu* interface. To enable these two schemes, the received signal power and link quality shall be measured in the *Un* interface.

Moreover, LTE allows for multi point-to-point transmissions from a single BS using OFDMA to transport unicast data to several nodes in the same slot instead of communication to each other nodes in the per-slot basis. Via utilizing such property, the scheduler at each BS is responsible to (a) select which neighboring BS(s) to transmit to and (b) pick the applied modulation and coding scheme (MCS) rather than applying topology-dependent policy that requires a priori topology information.

B. Global routing

We apply the Dijkstra's algorithm at COE to find the shortest path to route traffic in backhaul. Such algorithm can minimize per-flow latency provided that the traffic load is below the maximum throughput to avoid congestion. Nevertheless, a better performance can be achieved if an adaptive distributed mesh routing is used to cope with different traffic pattern and network topology [10].

Algorithm 1: Coordinated Scheduling Algorithm

```
Input : $P_{SF}$ is the SuperFrame update periodicity
        $e2NB\_List$ is the list of e2NBs
begin
    while $networkrunning$ do
        $SF = SF + 1$ /* current subframe identifier */
        $TryNew = 0$
        if $event$ then
            $TryNew = 1$
        if $SF \equiv 0 \pmod{P_{SF}}$ $or$ $TryNew == 1$ then
            $get\_metrics()$
            $compute(L_{SF})$ (c.f. Eq. 1)
            $NeedMatched = 0$
            while $NeedMatched == 0$ do
                $compute(SF_{realtime})$ (c.f. Eq. 2)
                $compute(SF_{elastic})$ (c.f. Eq. 3)
                $[SF\_TX, NeedMatched] =$
                  $centralized\_NS(SF_{realtime}, SF_{elastic})$
                  (c.f. Alg. 2)
                $L_{SF} = L_{SF} + 10$
                if $L_{SF} > MaxLat \wedge TryNew == 1$ then
                    $reject(flow)$ /*Reject realtime flows*/
                    $compute(L_{SF})$ (c.f. Eq. 1)
                    $NeedMatched = 0$
        foreach $u \in e2NB\_List$ do
            $local\_LS(SF, SF\_TX[u])$ (c.f. Alg. 3)
```

C. Subframe scheduling

The main scheduling problem is to share the frequency (RBs) and time resources (MBSFN SFs) between e2NBs. Such scheduling is achieved at two different levels of different timescales. Algorithm 1 provides a high-layer scheduling approach that summarizes the two different levels. A centralized node scheduler (NS) (Algorithm 2) is executed periodically or on reaction to an event (for instance, a new real-time flow with latency requirements) and it defines which MBSFN SFs shall be utilized by each e2NB for transmission. Then, each e2NB utilizes the local link scheduler (LS) that is executed at every SF to perform the per-link scheduling (Algorithm 3).

1) Centralized node scheduling: Without loss of generality, we only consider a time-domain resource allocation (i.e. SF allocation) in DL direction (i.e. from eNB to vUE) among the neighboring nodes for self-backhauling, as the UL SFs are allocated correspondingly to these allocated DL SFs. The proposed node scheduling determines the active SFs for each BS within a superframe to schedule the transmission and reception in accompany with the corresponding vUE(s). Its goal is to allocate enough SFs to each e2NB to fulfill the real-time traffic transportation. However, if that is not possible, Algorithm 1 guarantees that each e2NB gets at least one SF per superframe through iteration in the superframe length.

The resource allocation within a superframe for each e2NB is repeated until the node scheduling gets updated, which is triggered by traffic load and/or channel variabilities in the superframe. The length of the superframe is determined in such a way to satisfy the latency requirement for real-time traffic flows, and remains the same for all e2NBs in the network (generally in the order of tens of millisecond). It is computed as a function of expected maximum number of hops, denoted as M_{hops} in Eq. (1), that a given flow may experience.

$$L_{SF} = \lceil MaxLat/((M_{hops} + offset)) \rceil \tag{1}$$

The $MaxLat$ represents the maximum acceptable latency for the real-time flows (e.g. 150ms for VoIP). The $offset$ is the stretch factor of M_{hops}, and it depends mainly on the mobility pattern (i.e. speed) and network size.

The algorithm relies on some a priori knowledge of real-time traffic flows in the network to proportionally allocate resources among BSs while respecting the QoS requirements. Some real-time flow control policy can further be applied to avoid accepting too many flows that could overload the network. The following inputs are required for each link:

- Expected traffic load of real-time flows;
- Expected link quality or the resulted MCS for each flow;
- Utilization ratio of the allocated resources during the last node scheduling period.

The first metric, denoted as $SF_{realtime}[u]$, is computed to determine the number of SFs during a superframe required by e2NB u to transmit the real-time flows. It is the main control variable and is also used to sort e2NBs in the descending order before allocating the SFs. It is computed centrally as follows:

$$SF_{realtime}[u] = \frac{\sum_{v \in N(u)} PRB_{u,v}(tpt_{u,v} \times L_{SF})}{N_{PRB}} \tag{2}$$

where $tpt_{u,v}$ is the sum of the throughput for real-time flows passing through link $u \rightarrow v$ (i.e. the transportation from node u to node v). $PRB_{u,v}(x)$ returns the number of PRBs required to transmit x bits given the current channel quality on link $u \rightarrow v$, $N(u)$ is a set that comprises all neighboring nodes of u and N_{PRB} is the total number of PRBs per SF.

A second metric is computed to increase the number of allocated SFs at e2NB u, denoted as $SF_{elastic}[u]$, for links that are saturated due to too many elastic flows passing through leading to a higher utilization ratio. We consider a link to be saturated if its ratio of saturated SFs (SFs that can transport less bits than what is queued) over allocated SFs is higher than a specified value.$SF_{elastic}[u]$ is a simple estimator that aims to catch the relative needs of extra SFs among e2NBs. Finally, eq. (3) details how it is obtained for a node u.

$$SF_{elastic}[u] = \left\lceil \frac{U[u]}{N_{freeSF} \times \sum_u U[u]} \right\rceil \tag{3a}$$

$$U[u] = \sum_{v \in N_{sat}(u)} TBS_{PRB}(u,v) \tag{3b}$$

$$N_{freeSF} = \frac{L_{SF}}{10 \times SF_{MBSFN}} - \frac{\sum_u SF_{realtime}[u]}{N_b/N_u} \tag{3c}$$

where $U[u]$ represents the sum of expected transport blocks per PRB among all outgoing links from node u, where $N_{sat}(u)$ comprises the neighboring nodes of u with saturated link along the direction from u, $TBS_{PRB}(u,v)$ is the expected transport block size (TBS) per allocated PRB over the link $u \rightarrow v$, N_b is the total number of e2NB while N_u is the average number of adjacent neighbors of each e2NB. Note the N_{freeSF} represents the potential number of free SFs within a superframe duration (cf. eq. (1)) after allocating $SF_{realtime}$.

Algorithm 2: Centralized Node Scheduler (centralized_NS)

```
Input  : $MBSFN$ is the list of MBSFN SFs during the
         scheduling period $L_{SF}$.
         $e2NB\_List$ is the list of e2NBs in the network.
         $N[u]$ is the list of neighboring e2NBs of e2NB $u$.
         $LINK(u,v)$ is a link between two e2NBs where
e2NB $u$ acts as an eNB and e2NB $v$ as a vUE.
         $SF\_RX[u]$ is the list of available RX SFs at $u$.
         $SF\_TX[u][v]$ is the list of available TX SFs at $u$
for each connected e2NB $v$.
Output: $SF\_TX$,$NeedMatched$
foreach $u \in e2NB\_List$ do
    $SF\_RX[u] = SF\_TX[u][v] = MBSFN, \forall v.$
    $haveOne[u] = 0.\ realtime[u] = SF_{realtime}[u].$
    $elastic[u] = SF_{elastic}[u]$
$NeedMatched = 0$
foreach $SF \in MBSFN$ do
    $sort\_descending(e2NB\_List, realtime)$
    $sort\_descending(u \in e2NB\_List \mid realtime[u] ==$
      $0, elastic)$
    foreach $u \in e2NB\_List$ do
        if $realtime[u] > 1$ or $elastic[u] > 1$ then
            if $SF \in SF\_TX[u][*]$ then
                $Transmit = 0$
                foreach $v$ such that $LINK(u,v)$ exist do
                    if $SF \in SF\_RX[v]$ then
                        $Transmit = 1$
                        $remove(SF, SF\_RX[u])$
                        $remove(SF, SF\_TX[v][*])$
                        foreach $w \in N_{interference}[u]$ do
                            $remove(SF, SF\_RX[w])$
                        foreach $w \in N_{interference}[v]$ do
                            $remove(SF, SF\_TX[w][*])$
                    else
                        $remove(SF, SF\_TX[u][v])$
                if $Transmit == 1$ then
                    $haveOne[u] = 1$
                    if $realtime[u] > 1$ then
                        $realtime[u] - -$
                    else
                        $elastic[u] - -$
    if $\forall u\ realtime[u] == 0$ then
        $NeedMatched = 1$
    if $\forall u\ elastic[u] == 0$ then
        foreach $u \in e2NB\_List$ do
            $elastic[u] = 1$
```

Algorithm 2 is used to allocate SFs between the e2NBs. $SF\_TX[u][v]$ is the list of SF on which e2NB u can transmit to e2NB v (i.e. v will be in reception). $NeedMatched$ indicates if the scheduler is able to give at least $SF_{required}[u]$ SF(s) to e2NB u for all e2NBs or not. $N_{interference}(u)$ represents the interference area around node u and can be adjusted to contain some neighboring nodes within the radio coverage depending on the scheduling policy (e.g. conservative for a reliable transmission). In either case, the link adaption shall cope with the induced interference at the local scheduler.

Algorithm 3: Local Link scheduler (local_LS)

```
Input : $u$ is the current e2NB identifier.
        $SF$ is the current subframe identifier.
        $UE\_List$ and $vUE\_List$ are the list of UEs/vUEs with non empty queues at $u$.
        $Q[x][p]$ is the queue size of UE/vUE $x$ for flows of priority $p$.
        $N_{PRB}$ is the number of available PRBs in $SF$.
        $SF\_TX[u][x]$ is the list of available Tx SFs at $u$ for each $x \in UE\_List \cup vUE\_List$.
Output: PRBs allocated for UEs and vUEs of e2NB $u$
Result: $u$ uses $PRB[x]$ to transmit to each
        $x \in UE\_List \cup vUE\_List$
$sort\_descending(UE\_List, Q[*][0])$
$sort\_descending(vUE\_List, Q[*][0])$
$List = append(vUE\_List, UE\_List)$
$prio = 0$ /* 0: real-time, 1: elastic */
while $N_{PRB} > 0$ and $prio < 2$ do
    $increase\_prio = 1$
    foreach $x \in List$ do
        if $SF \in SF\_TX[u][x]$ then
            if $N_{PRB} > 0 \wedge TBS[x] < \sum_{b=0}^{prio} Q[x][b]$ then
                $PRB[x] + +$
                $N_{PRB} - -$
                $TBS[x] = TBS(mcs[x], PRB[x])$
                $increase\_prio = 0$
    if $increase\_prio == 1$ then
        $prio + +$
```

2) Local scheduling: The local scheduler is priority-based dynamic round robin algorithm on per SF basis (see Algorithm 3) which takes into accounts the buffer status, priorities between flows, and the channel quality indicators. It firstly allocates resources for the backhaul links (i.e. vUEs) followed by the access links (i.e. UEs) for real-time flows. The remaining resources will be allocated to the elastic flows until all buffers become empty or there is no PRB left.

D. Local Routing

Within the proposed algorithm, we aim to provide DL SFs at each node. It means each node can reach all its neighboring nodes using DL, and can also be reached by these neighboring nodes using UL with the associated UL SF. Hence, every two adjacent nodes can reach each other in both UL and DL directions to each other. It also means that each incoming packet can go over the DL or UL direction toward the next hop. To this end, we use the expected waiting time of both UL and DL queues as the metric to decide whether the newly incoming packet shall go into the DL or UL queue to be delivered to the next hop.

E. Interference measurement and link adaptation

The induced interferences are multi-facet: between neighboring e2NBs happening during the backhaul SFs, between e2NBs at UE in DL, and between UEs at e2NB side in UL during the access SFs. They are caused mainly due to the neighboring e2NBs being unaware of the resource allocation policy of each other. There are two ways to deal with it. First of all, interference can be handled locally by each e2NB, simply by using AMC to adapt the MCS of transmissions based on the reported CQIs (for DL) and its own measurement (for UL) as done by legacy systems. However, it can be improved for the backhaul link by taking into account the fact that the interference power will most probably be at the same level during the repeated SFs within the superframe as the other scheduled nodes will be the same.

Secondly, it can be handled through cooperation between nodes to achieve a better performance by dynamically enforcing the resource allocation policy based on the eNB status information. This is in contrast to (semi-)statically resource allocation policy with no or little interactions among eNBs (as in the case of X2 signaling to support inter-cell interference coordination (ICIC)). Through self-backhauling capability, eNBs can share the status information with the COE and neighboring eNBs including:

- the DL channel quality indicators (CQI), frequency and time resources;
- the UL interference status for each frequency resource (RB) experienced by the neighboring eNBs.

These above information allows to adapt the MCS, frequency resources, and the transmit power for both legacy UEs and newly-added vUEs so as to coordinate the resources and transmissions across access and backhaul links. For instance, an e2NB A is using high Tx power on frequencyresources f_1 to transmit to e2NB B. With COE, e2NB C allocates a different frequency resources f_2 to transmit to e2NB D which suffers less interference from e2NB A.

V. SIMULATION RESULTS

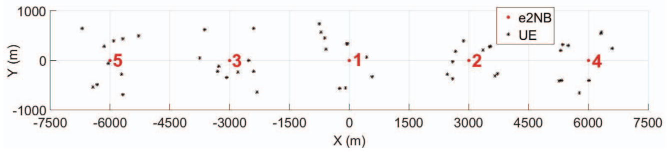
This section provides the performance evaluation of the proposed coordinated scheduling and compares the results to a classical mesh network link scheduling algorithm in [11].

A. Simulation environment

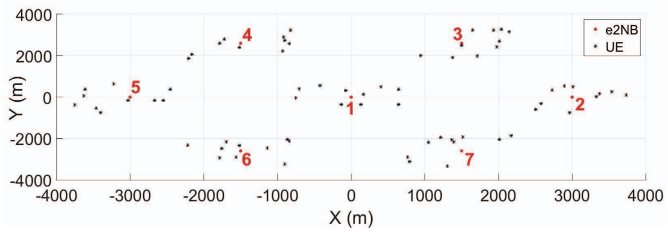
A complete LTE simulator is developed in MATLAB allowing to create a 2D-map of an arbitrary network of e2NBs with their associated UEs and to generate arbitrary flows between every type of nodes (e.g. U2U, e2U, e2e traffic). We assume that it takes 5ms for a eNB to process an incoming RF packet before pushing it to the output DL or UL queue to be transported toward the next hop as introduced beforehand.

1) Channel models: Between e2NBs, a freespace path loss model of coefficient 2.1 is applied with Claussen shadow fading and EPA multi-path channel. Between e2NBs and UEs, a rural (TR 36.942) path loss model is used with Claussen shadow fading and EPA multi-path channel. No further assumption is made on the interference coordination and mitigation for UEs. Moreover, e2NBs and UEs are assumed to be fixed and equipped with an omni directional antenna. All interferences caused by concurrent transmission are taken into account at each receiver.

2) Topologies: We define two different topologies as shown in Fig. 3(a) and 3(b). In both topologies, each BS has 10 attached UEs and is connected to the closest adjacent e2NBs through the co-located vUEs.



(a) Line Topology with 5 e2NBs



(a) Hexagonal Topology with 7 e2NBs

Fig. 3: Considered network topologies

3) Traffic patterns: Two traffic patterns are considered. First of all, all UEs are randomly paired with each other and establish a bi-directional real-time VoIP call with a packet size of 20 bytes (40 bytes on PHY using RoHC) with an arrival rate of 20ms. Secondly, two fixed e2e elastic traffic flows are added. Each elastic traffic aims to maximize its throughput and behaves as a connection-oriented acknowledgment service in that the new packet will be only generated if the maximum number of non-acknowledged packets is not reached. This type of flow represents the inter-site (i.e. BSs) data transfer that often happens in military and public safety application scenarios and is not directly generated by UEs.

4) Other settings and parameters: HARQ mechanism is not implemented in the simulator. UEs are only scheduled in UL/DL transmission in non MBSFN SFs. Expired VoIP packets (one-way-delay larger than 200ms) are discarded from the queue to improve the transportation efficiency. A link is considered to be saturated if the utilization ratio is larger than 80%. Each e2NB is configured with 10MHz channel bandwidth in band 4 (2.1GHz). For the BSs, the minimum transmit power is set to 20dBm and the maximum to 40dBm for DL UE transmissions and 46dBm for inter-e2NB transmissions. For UEs, maximum UL transmit power is set to 23dBm.

5) Li and Ephremides algorithm: In [11], Li and Ephremides propose a joint scheduling, power control and routing algorithm for TDMA wireless mesh networks. Their approach relies on a centralized scheduler that is executed at each time slot and decides which links should be activated as well as the transmission power. Their algorithm firstly sorts all possible links according to the link metric, which is based on the queue size of itself and all other links blocked by this link to prioritize the large queues while handling the congestion. For instance, a link i is considered to be blocked by a link j if its source or destination is identical to either the source or destination of link j. Then, an iterative algorithm can find the set of links with the highest priority that can be concurrently activated while respecting their power limitation and SINR requirements given all induced interference. In addition, their method periodically updates the routing paths based on the link quality and the relative queue size of each link to allow packets being redirected towards less congested links when queue buffer occupancy increases.

One of the main drawbacks of the Li and Ephremides approach is that the link scheduling is done in per-slot basis and thus it requires a perfect knowledge of queue sizes of all nodes and channel behavior between all nodes. Moreover, each activated node is used for a single point-to-point link which is inefficient in LTE system as the multi-point to point transmissions are allowed in both DL and UL directions within the same slot.

6) Improvement on Li and Ephremides algorithm: The following improvement is implemented to be applied by the Li and Ephremides algorithm in LTE for a fair comparison. We update the link metric and take into account both DL and UL queues of each link. Moreover, inter-node link scheduling is done for both DL and UL directions. The iterative power allocation algorithm is modified to incorporate the adaptive modulation and coding of different SINR regimes.

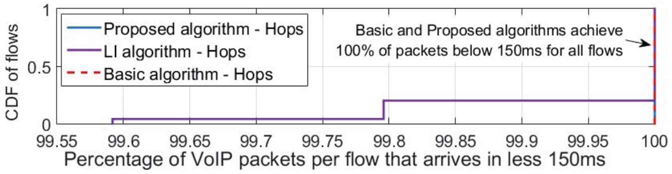
B. Algorithms considered

In following, we consider three mixed combinations of global and local approaches. In terms of the global approach, we consider three algorithms to be compared: (1) the Li and Ephremides algorithm with the aforementioned modifications (denoted as Li algorithm), (2) Algorithm 2 that uses the same and fixed number of MBSFN SFs between nodes for both real-time ($SF_{realtime}$) and elastic ($SF_{elastic}$) traffic among all e2NBs (denoted as the basic algorithm), and (3) the full proposed Algorithm 2 as described in section IV. Moreover, we consider two different variants on the local scheduler, (1) uses Algorithm 3 for UE scheduling but allocates all RBs of inter-e2NB links to a single vUE at one time while (2) and (3) use Algorithm 3 to allocate RBs in a fine-grained manner. In all cases, the incoming packets are classified into either real-time VoIP traffic or elastic traffic and are sorted and prioritized at the local vUE queues based on two manners: (a) the number of hops to reach the destination, labeled as *Hops* in following, or (b) the shortest deadline, labeled as *AirTime*. These two different metrics will affect the number of dropped VoIP packets, and consequently the throughput of elastic traffic.

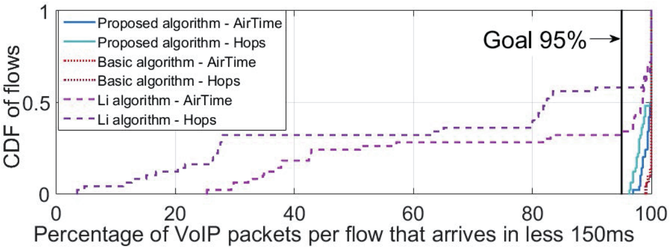
C. Results

Firstly, we consider two scenarios: (a) only VoIP traffic, and (b) both VoIP and elastic traffics. Then, we show the results in two forms: (i) the CDF plot in the percentage of VoIP packets that are within the pre-defined delay requirement (150ms) and (ii) throughput of elastic traffic flows.

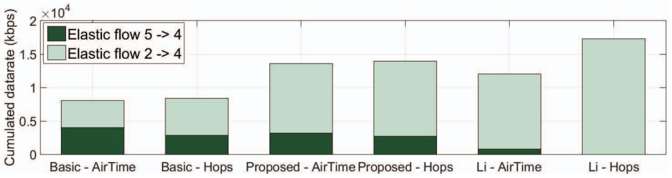
1) Line topology: In Fig. 4.(a), it can be seen that with only VoIP traffic, all three approaches satisfy the required 95% of packet with less than 150ms end-to-end latency among all VoIP flows. This is because there is sufficient capacity to transport all flows even without using the multi-point to point characteristic of LTE, particularly because the topology allows for a maximum of two point-to-point communications (two adjacent neighbors) from a given node at a time slot.



(a) CDF of VoIP flows. (50 VoIP flows)

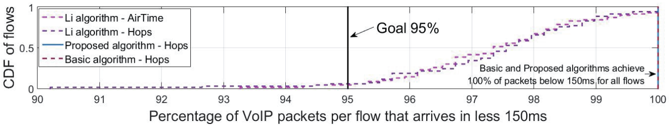


(b) CDF of VoIP flows. (50 VoIP and 2 e2e elastic flows)

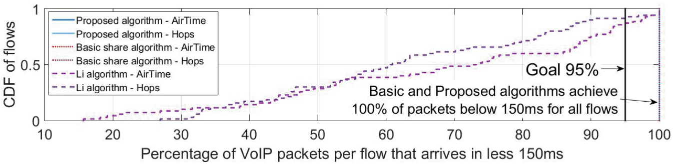


(c) Cumulated data rate of elastic traffic. (50 VoIP and 2 e2e elastic flows)

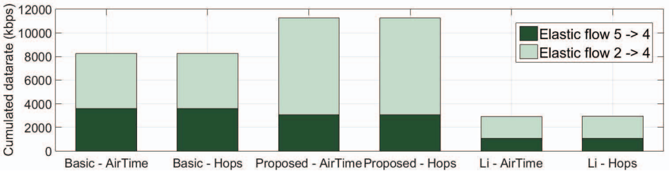
Fig. 4: Line Topology



(a) CDF of VoIP flows. (70 VoIP flows)



(b) CDF of VoIP flows. (70 VoIP and 2 e2e elastic flows)



(c) Cumulated data rate of elastic traffic. (70 VoIP and 2 e2e elastic flows)

Fig. 5: Hexagonal topology

Then, we add two extra e2e elastics flows ($5 \rightarrow 4$ and $2 \rightarrow 4$). In Fig. 4.(b), we can see that Li approach performs poorly regarding latency requirements as only 60% of flows meet the requirement when using *AirTime* as a sorting metric and only 40% of flows meet the requirement when using *Hops* as a sorting metric. On the other hand, both *Basic* and *Proposed* approaches allows all flows to meet their latency requirement. The *Basic* approach is comparable with the *Proposed* approach and the *AirTime* sorting metric is better than the *Hops* approach. From Fig. 4.(c), it can be observed that the *Basic* approach has the lowest cumulated throughput as it fixed global allocation which does not react to the needs of elastic flows, while the *Proposed* approach on average is comparable with the Li approach.

2) Hexagonal topology: For the hexagonal topology, we observe in Fig. 5.(a) that around 5% of VoIP flows cannot meet the latency requirement when using Li approach while all flows under *Basic* and *Proposed* approaches can fulfill the requirement. Then, two extra e2e elastics flows ($5 \rightarrow 4$ and $2 \rightarrow 4$) are added. In the Fig. 5.(b), both *Basic* and *Proposed* approaches perform perfectly regarding latency requirements but Li approach fall short with almost 90% of the VoIP flows that do not meet the requirements. From Fig. 5.(c), Li approach performs the worst while the *Proposed* approach achieves 35% throughput improvement over the *Basic* approach. The under-performance of Li approach is due to its lack of multi-point to point capability that is highly beneficial in networks with multiple adjacent nodes.

To sum up, the *Proposed* approach achieves the best latency-throughput trade-off for real-time and elastic traffics. Such merit is mainly due to its link adaptation capability and the use of multi-point to point link scheduling.

VI. CONCLUSION

In this article, we present a method to efficiently and practically realize an in-band LTE wireless mesh networks that leverages the LTE relay interface (*Un*) and takes into account QoS requirements of real-time flows. We then compare such approach to two other ones in different scenarios. The findings are dual: first of all, we show that the in-band meshing of LTE BSs is possible without requiring intense modifications on current standards while keeping legacy UE support. Secondly, we show that our approach is able to guarantee QoS requirements of real-time flows while improving the network throughput for elastic flows. In future, we plan to detailedly introduce the architecture to realize the autonomy of network based on the preliminary study in [12].

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