QoS-aware Resource Allocation for In-band Relaying in LTE-Advanced

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***Abstract*—Fulfilling the heterogeneous quality of service (QoS) requirements of individual users is a central theme in future wireless networks. The addition of relay nodes introduces some new challenges towards achieving this target. In this work, we study the problem of resource allocation in advanced-relay scenarios. To this end, we propose the design of an efficient QoS-aware scheduler that strikes a balance between the latency and the bit rate requirements of individual traffic flows. The proposed scheduler is implemented at the donor eNB and the relay node by adapting to the additional challenges introduced by the relay node's wireless backhaul link. Finally, via system level simulations for the downstream direction emulating traffic with different bit rate and latency requirements, we demonstrate that our algorithm is able to multiplex mixed traffic with small or no violation of the individual QoS requirements, thereby achieving significant gains over baseline approaches.**

***Index Terms*—Quality of service; QoS; Relay; LTE; Resource allocation; Scheduler; Backhaul link; VoIP; Video; Delay budget; In-band Relays.**

I. Introduction

One of the key functionalities to improve the cell-edge user throughput in the Long Term Evolution Advanced (LTE-A) is the support of relay nodes (RN), [1], which are low power transmitting nodes typically deployed at the cell-edge or coverage holes. Currently, LTE-A supports only non-transparent relays, or type-1 relays. These type-1 RNs appear to the User Equipment (UE) as an eNB with an independent coverage area whereas to the evolved NodeB (eNB), or base station, they appear as an UE with special capabilities.

In contrast to an eNB, the RNs do not have a wired connection to the core network, hence all data from/to the relay has to be forwarded through a wireless backhaul link established between the RN and a regular eNB, which, in this scenario is called Donor eNB (DeNB). Non-transparent (type-1) relays are classified depending on the way the backhaul and access links are multiplexed: When the backhaul and the relay access radio link use the same frequency band and they are segregated in the time domain, the relay is referred to as in-band relay. The relays are classified as out-band, when the backhaul link and the relay access links are allocated to different frequency bands. For in-band relays, special frames are reserved for the RN communication with the DeNB, the so-called MBSFN frames. During these frames, the RNs are only allowed to receive data from the DeNB, and they refrain from transmitting in order to avoid self interference.

In an advanced relay scenario, the eNBs and RNs have to host a mix of different traffic types. For instance, while some users are using Voice over IP (VoIP) services, some other are browsing, others have active FTP services or have active video streaming services. Each of these services has different requirements in terms of bit rate, latency, jitter, delay, etc. The presence of heterogeneous quality of service (QoS) requirements, call for the design of sophisticated resource allocation algorithms, that fulfill individual QoS requirements and ensure that they are not violated.

Although all architectural aspects are defined by the standard, the resource allocation is still an interesting topic for research. The fundamental questions that have to be answered by a resource allocation algorithm, especially in a relay enhanced scenario are:

- How to split/partition the resources at the DeNB between the macro UEs (M-UEs) and the wireless backhaul link?
- How to allocate resources at the DeNB and at RN, in order to satisfy the QoS constraints of the R-UEs accumulated over both hops?
- How to coordinate the resource allocation at the DeNB and the RN, so as to reduce the effect of interference on the access links?

In this work, via the design of our novel resource allocation algorithm, we focus primarily in answering the first two of these aspects. The last one is being considered for future work.

A. Related Work

Resource allocation for satisfaction of heterogeneous QoS requirements in presence/absence of relays has been an active area of research over the past few years. In [2], Liu *et. al.* propose a manner of scaling the delay influence on a QoS scheduler in a multi-hop wireless mesh network. However, this work does not consider the relay deployments in LTE-A, and its specific requirements.

The support of QoS in LTE-Advanced for mixed traffic is studied in [3] which divides the traffic types into two types: real-time traffic and non-real-time traffic. The flows belonging to the non-real-time traffic are scheduled based on a proportional fair metric which is scaled by the respective QoS requirements, and a scaled Max C/I approach is used to scheduled the real-time traffic. But this work also does not consider the resource allocation challenges in relay enhanced scenarios.

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In [4] and [5], the issue of resource allocation for in-band relays was studied. However, both of these contributions focus on resource allocation only for flows with no QoS requirements.

B. Our Contribution

We focus on the problem of QoS-aware resource allocation in relay-aided future wireless networks. The description in this paper is oriented towards in-band relaying in LTE-A, however the proposed resource allocation mechanism is generic enough, and can be applied to other relay enhanced network deployments as well, with heterogeneous QoS requirements.

The remainder of this paper is organized as follows: In Section II, while highlighting the challenges associated with QoS-aware resource allocation in an enhanced relay scenario, we provide the description of the proposed algorithm. In Section III, a short description of the simulation setup is given, followed by the presentation and discussion of the main simulations results, including comparison with baseline approaches, in Section IV. Finally, a summary of the major achievements and outlook for future work in this area are provided.

II. Proposed QoS-aware Resource Allocation in Relaying Scenarios

A. Two-stage Scheduler Structure

We propose to employ a two-stage scheduler for the OFDM based downlink LTE system. Our LTE-A scheduler is therefore composed of two main stages: the time-domain (TD) stage and the frequency domain (FD) stage. The main function of the TD stage scheduler is set up a candidate list of users which are to be scheduled in a particular scheduling round. To this end, the users are sorted according to predefined rules (e.g., round-robin, proportional fair) or a metric computations based on their individual requirements. The TD scheduler also serves another propose: it reduces the number of users that will be forwarded to the next phase (the FD stage) thereby reducing the complexity of the resource allocation process. After the users are sorted, the created list is then forwarded to the FD stage scheduler. It is worth-mentioning here that we assign pending re-transmissions a higher priority so that they are always placed on the top of the TD candidate list.

The FD stage scheduler is responsible for the actual allocation of the frequency resource blocks to the users. All the resources are visited one by one, and the user with the highest metric is allocated the current resource block. After each allocation, the residual QoS requirements (urgency) of the scheduled user is updated. The allocation process ends when all the resources have been allocated, or no data is available.

B. QoS Requirements

The QoS requirements are specified in LTE-A typically via predefined Quality Class Indicator (QCI) [6]. QCI is an scalar which refers to a set of fix service parameters that are used in the packet forwarding decisions. Each one of the nine possible QCI values defines the

- delay budget: the maximum acceptable packet delay,
- maximum block error rate,
- service priority index: a scalar ranging from one to nine; the higher the index, the lower is the service priority.
- some QCIs also specify Guaranteed Bit-rate (GBR); the specification of GBR for a particular service is left open for the service provider.

In the following, we consider three of these QoS requirements namely, the delay budget, the GBR, and the priority index, while designing our QoS aware resource allocation algorithm.

C. Proposed Scheduling Metric

We start our studies by defining the QoS-scheduling metric which is used to sort the UEs according to the data urgency. The first step towards the definition of our scheduling metric is to define the delay coefficient $\omega_{\mathrm{d}}(n,t)$ which represents the effect of the packet delay on the metric computation: For a packet belonging to the flow n, we define the delay coefficient at the time instant t, as follows

$$\omega_{\mathrm{d}}(n,t) = \exp\left(\beta \frac{\mathrm{d}_{\mathrm{HOL}}(n,t)}{D_{\mathrm{Profile}}(n)}\right) \tag{1}$$

where $d_{\mathrm{HOL}}(n,t)$ is the head of line (HOL) delay of the flow n at time t, $D_{\mathrm{Profile}}(n)$ is the delay requirement of the flow n as specified in its QCI, and β is an scalar factor which pronounces the effect of the exponential function.

Using the delay metric from (1), we now define the overall QoS-scheduling metric as:

$$m_{\mathrm{QoS}}(n,t) = \max\left[\left(\frac{\mathrm{GBR}(n)}{\bar{\mathrm{R}}(n,t)}\right), 1\right]^{\rho} \cdot \frac{\omega_{\mathrm{d}}(n,t)}{\mathrm{P}(n)} \tag{2}$$

where $\bar{R}(n,t)$ is the average throughput of the flow n over past few intervals, while GBR(n) and $P(n)$ are respectively the guaranteed bit rate and the service priority index of the flow n as specified in its QCI. ρ is a factor which emphasizes the rate metric if their $\bar{R}(n,t)$ is lower then the required GBR(n).

We observe that the proposed scheduling metric in (2) consists of two main factors.

- The rate factor defined by the term inside max function forces the fulfillment of the GBR(n): While $\bar{R}(n,t)$ is smaller than GBR(n), the factor increases the metric, otherwise it has no effect on the metric.
- The second factor is $\omega_{\mathrm{d}}(n,t)$ which has small influence in the metric, if the delay is low, but increases the metric exponentially as the delay gets closer to the packet deadline.

We propose to employ the scheduling metric in (2) for sorting the users in the TD scheduling stage and also to assign resources in the FD scheduling stage, as discussed in Section II-A. For our simulation results in the next sections, we choose $\beta = 5$ and $\rho = 4$, respectively to pronounce the exponential effect of delay budget and GBR constraints.

D. Addressing Additional Challenges in Relaying Scenarios

The introduction of the second hop in a relay enhanced network introduces additional challenges for the support of QoS-aware services.

First and foremost, in such networks, the downlink resource allocation for the relay user equipments (R-UEs) has to be performed in two stages: In the first stage, while serving the M-UEs, the DeNB transfers the user data from its buffers to the serving relay node by scheduling resources to the backhaul link. Afterwards, each RN schedules the received data to their subordinate R-UEs. In other words, a packet destined to a R-UE has to undergo two scheduling process, and each of them results in extra packet delay. Therefore, a special attention has to be given to the flows that are multiplexed through the RNs. Hence, we define for the R-UEs the accumulated QoS requirements as follows:

$$T_{\text{DeNB-RN}} + T_{\text{RN-UE}} \leq D_{\text{Profile}}(n) \tag{3}$$

$$\frac{B_{\text{UE}}}{T_{\text{DeNB-RN}} + T_{\text{RN-UE}}} \geq \text{GBR}(n) \tag{4}$$

where $T_{\text{DeNB-RN}}$ is time interval between the packet arrival at the DeNB until it is received by the RN, $T_{\text{RN-UE}}$ is the interval between the reception in the RN and the time that the packet is received at the R-UE, and $D_{\text{Profile}}(n)$ is the delay requirement of the flow n. Moreover, B_{UE} is the volume of data transferred in the time interval $T_{\text{DeNB-RN}} + T_{\text{RN-UE}}$ and $\text{GBR}(n)$ is the rate requirement of the used flow.

Secondly, for in-band relays, the resources in the backhaul link must be scheduled only during the MBSFN frames. During these frames, the DeNB has to decide on how to partition the available resources between the wireless backhaul link and to the M-UEs. In this regard, we propose to bundle all the relay UEs (R-UEs) with the same QCI (similar QoS requirements) into a single flow with aggregate service requirements. Afterwards, the scheduler depending on the urgency of the M-UEs and the aggregated R-UEs flows decides whether a resource block is to be given to the backhaul link or to the access link.

As mentioned above, from the scheduling perspective of the DeNB, the backhaul link is a normal UE link, with QoS requirements of all underlying flows merged into single/multiple backhaul link "super flow". Based on (3) and (4), we define the GBR requirements for the backhaul link as:

$$\text{GBR}(B) \geq \sum \text{GBR}(n), \tag{5}$$

i.e., a sum of GBRs of all underlying flows. Furthermore, the delay requirement at each scheduling node for the virtual "super flow" is defined as:

$$D_{\text{QoS-B}} = \frac{D_{\text{Profile}}}{N}, \tag{6}$$

i.e., we split the QCI-specified delay budget equally among the N hops. Thus, we force the scheduler to send the packet earlier than what it would normally consider in a single hop scenario, thereby allowing the second hop scheduler the possibility of delivering the data before the packet deadline. In our scenario, a packet has to be forwarded through two hops, namely backhaul and RN access links, thus the maximum delay allowed at the first hop (DeNB) scheduler is restricted to be:

$$D_{\text{QoS-DeNB}} = \frac{D_{\text{Profile}}}{2}. \tag{7}$$

Note that, at the second hop (RN) scheduler, we extract the information of the delay that the packet has already went through, and adjust the packet HOL delay timer such that the total packet delay across both hops is still within the D_{Profile} as specified in the service QCI.

III. Simulation Setup

A. Deployment Scenario

The deployment scenario we have considered for our performance evaluations is a single macro-cell with 1 DeNB and 1, 2, or 4 relay nodes attached to it. Note that in the remainder of this work, we will only show results for the case of 2 relay nodes due to the limited space. The macro-cell is modeled as a hexagon with the DeNB at one corner and the RNs located along the opposite side. The hexagonal shape thus resembles one of the three sectors served by the DeNB, which corresponds to the reduced single-cell layout specified in [7]. The interference from all neighboring cells at non-negligible distance to the macro-cell is also considered in the model.

Within the macro-cell, a so-called "hot-spot" scenario is assumed: A total of 25 UEs are placed such that a pair of 2 UEs (the *R-UEs*) always ends up in the coverage region of a relay node and the remaining 21 UEs (the *M-UEs*) in the coverage region of the DeNB. In addition, all UEs are periodically relocated randomly within their respective coverage regions. Due to this automatic re-positioning, no explicit motion model or handover procedure has been considered in this work.

Finally, we would like to emphasize that the same sequence of UE positions is replayed when simulating the macro-cell without any relay nodes, such that the performance can be directly compared.

B. Macro-cell Configuration

The used channel model complies with the 3GPP *Case-1* for urban macro-cells with an inter-site distance (ISD) of 500 m, as specified in [1], Table A2.1.1-1. The respective configuration parameters for the DeNB-UE link are contained in this table and in the following table, Table A2.1.1-2. We will only recall the most important ones here for the sake of completeness:

- Carrier frequency: 2 GHz
- Duplexing and bandwidth: FDD with 10+10 MHz
- TTI duration: 1 ms
- Speed: 3 km/h
- Penetration loss: 20 dB
- Path loss: Only NLOS term (for macro to UE) used
- 3-D antenna pattern with 15 degree electrical downtilt

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- DeNB antenna height: 32 m
- UE antenna height: 1.5 m
- Minimum distance between DeNB and UE: 35 m
- DeNB Tx power: 43 dBm

While fast fading is considered in our model, we have omitted the log-normal shadowing for now, since the usual 1-D correlated model proposed in [1] does not lead to meaningful results when applied across a 2-D plane.

C. Relay Configuration

We also assume 3GPP *Case-1* here with 2 outdoor relays, thus complying with [1], Table A2.1.1.2-2. The respective configuration parameters for the RN-UE link are contained in Table A2.1.1.2-3 and A2.1.1.4-3. We will also recall only the most important ones here:

- Carrier frequency, duplexing, bandwidth, TTI duration, speed, and penetration loss: same as for macro-cell
- Path loss: Only NLOS term (for relay to UE) used
- 2-D omni-directional antenna pattern with 5 dBi gain, 2Tx and 2Rx antenna ports
- RN antenna height: 5 m
- UE antenna height: same as for macro-cell
- Minimum distance between RN and UE: 10 m
- RN Tx power: 30 dBm

Note that for the DeNB-RN link, we assume a gain of 5 dB to account for the quasi-stationary reception conditions. A typical signal to interference and noise ratio (SINR) map of the cell, indicating also the RN locations, is shown in Figure 1.

D. Traffic Model

In our evaluation, we employ two different traffic types with their distinct QoS requirements:

- VoIP traffic are emulated using a Constant Bit-rate (CBR) traffic generator which creates traffic at rate of 128 kbps. The QCI for this type of traffic is defined as QCI-1 [6]: The packets are allowed to have a maximum end-to-end delay of 100 ms, and the service priority is defined as 2.
- A second group of users are using video streaming services. Due to the limitations of the mobile devices, such as processing capabilities, we have chosen to limit this service to a rate of 256 kbps. The QCI for this type of traffic is defined as QCI-3 [6]: Maximum packet end-to-end delay is 300 ms, and the service priority is 5.

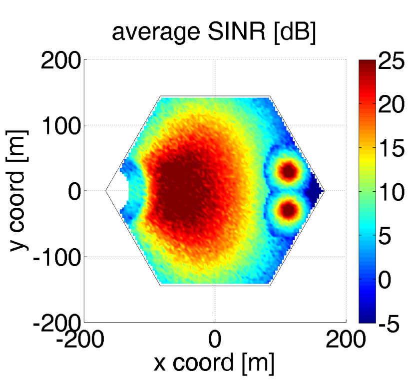


Fig. 1. Typical SINR map of DeNB plus 2 relay nodes (DeNB+2RN) scenario. Two dark red spots towards the far end of hexagon indicate the locations of the two relay nodes.

The desired CBR is created by our traffic generator using a fixed packet size of 256 bytes at appropriate time intervals: 8 ms for video and 16 ms for VoIP traffic.

IV. Performance Results

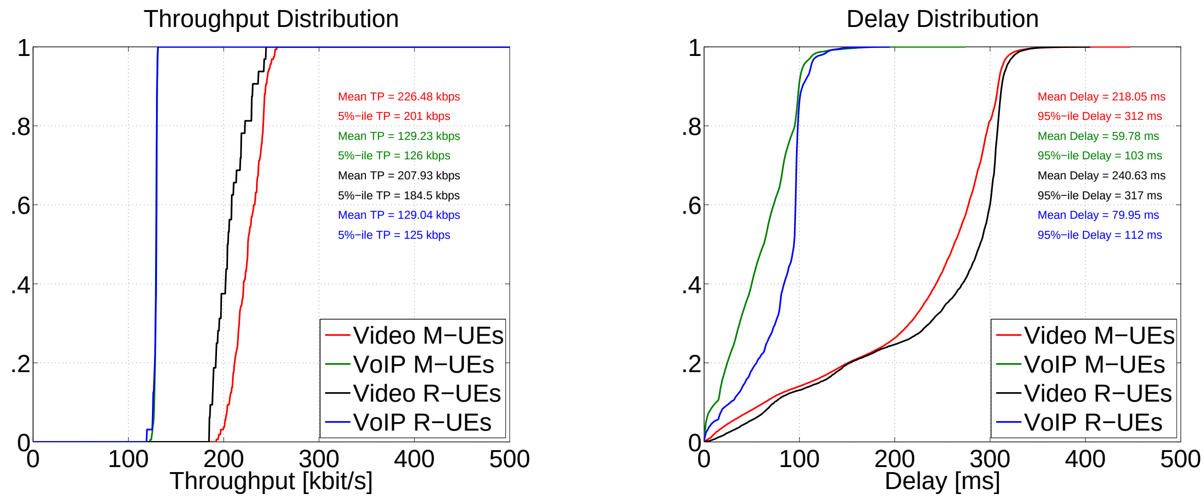
A. Baseline macro-cell-only scenario

We start our analysis by comparing the behavior of different flows for the case where DeNB is the only transmitting node serving the macro-cell. In order to provide a better understanding of the system behavior, we have divided the users into two groups:

- One group is formed by the users that would be in the coverage area of the RNs had they been activated, and we label these as R-UEs.
- The second group consists of the macro users (M-UEs) which always connect to the DeNB regardless of the simulated scenario (DeNB-only, or DeNB+2RNs).

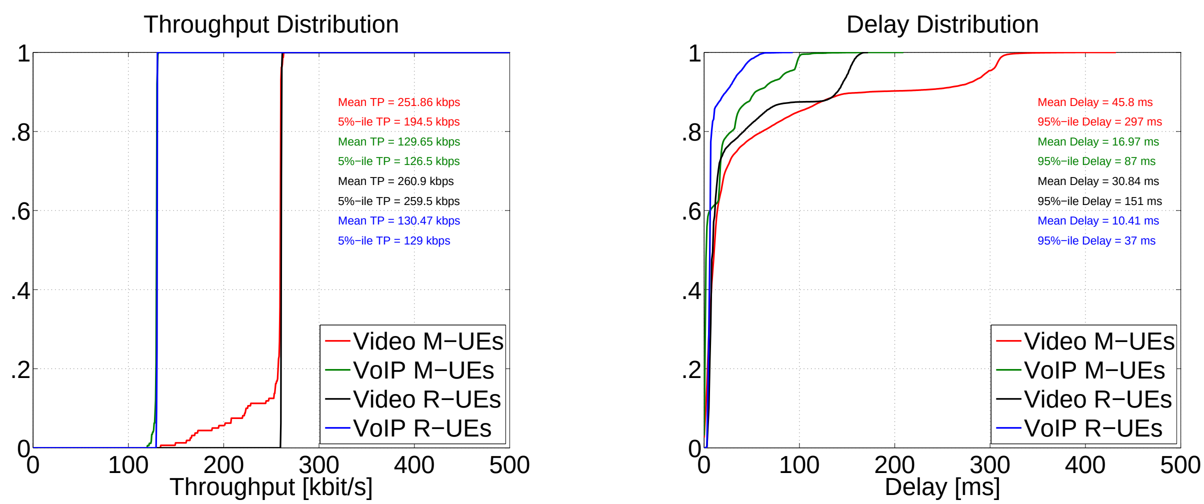
Figure 2 depicts the Cumulative Distribution Function (CDF) of the per-user throughput and delay for the two traffic types (VoIP and Video) in each user category (M-UEs and R-UEs) for the DeNB-only scenario with the proposed QoS-aware resource allocation strategy. From the throughput CDFs in Figure 2(a), we observe that VoIP users are able to achieve their designated GBR requirement to a large extent. The mean and 5%-ile TP values are 129 kbps and ca. 125 kbps for both M-UEs and R-UEs. However, the achieved throughput of the video UEs is significantly less as compared to the configured GBR. In contrast to the configured 256 kbps for video users, the mean and 5%-ile TP values for M-UEs are 226 kbps and 201 kbps respectively, while for R-UEs these are only around 208 kbps and 184 kbps respectively. We observe that R-UEs suffer more as compared to the M-UEs, and this owes to the fact that they are served over poorer radio conditions. The impact on M-UEs is basically a consequence of R-UEs throttling the performance of the overall system.

For the same scenario, we now focus on the end-to-end packet delay CDFs in Figure 2(b). In line with our observations regarding Figure 2(a), we note that the packet delays for both traffic types and for both UE groups is quite high, and quite often approaching the ultimate delay budget deadline, after which the packets are discarded at the scheduler. The VoIP 95%-ile delays being 103 ms and 112 ms respectively for M-UEs and R-UEs. Similarly, the video 95%-ile delays are around 312 ms and 317 ms respectively for M-UEs and R-UEs indicating that there is non-negligible network congestion and packet discard ongoing in the system. Note that the slight overshoot of delays beyond the delay budget can be attributed to the extra delay caused by re-transmissions.



(a) Throughput CDFs (b) Delay CDFs

Fig. 2. DeNB-only scenario with proposed QoS-aware resource allocation. Throughput and delay CDF comparisons for different UE groups (M-UEs and R-UEs) and traffic types (VoIP and Video).



(a) Throughput CDFs (b) Delay CDFs

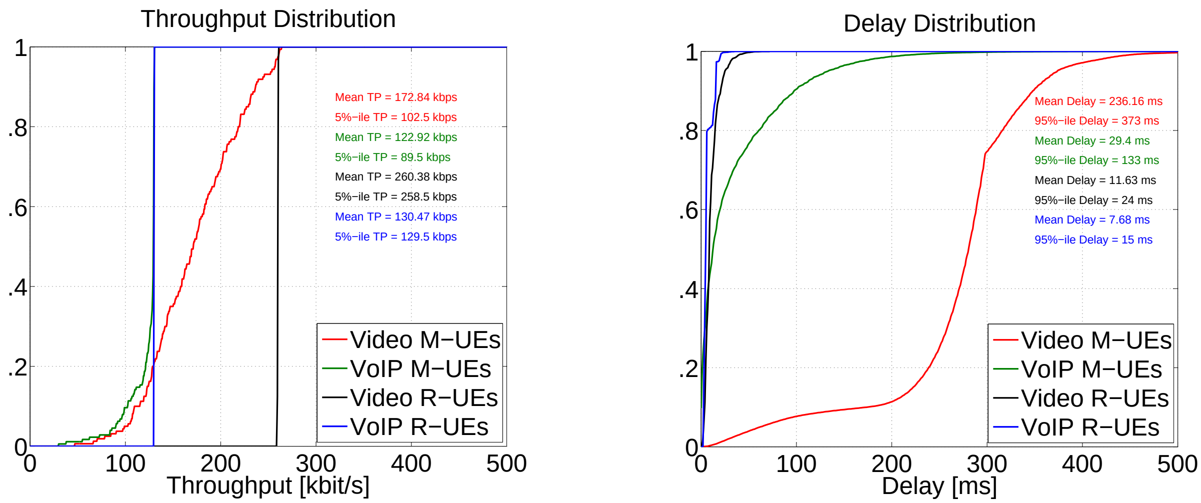
Fig. 3. DeNB+2RN scenario with proposed QoS-aware resource allocation. Throughput and delay CDF comparisons for different UE groups (M-UEs and R-UEs) and traffic types (VoIP and Video).

B. Relay enhanced scenario (DeNB+2RN) with proposed QoS-aware resource allocation

From results in last sub-section, we conclude that though the QoS-aware resource allocation attempts to fulfill the QoS requirements, the level of satisfied users is quite low owing to the congestion in network. In this sub-section, we consider the same traffic pattern, but now in a relay enhanced scenario, where two relay nodes are deployed to assist the DeNB.

In Figure 3, we present the throughput and delay CDFs for the DeNB+2RN scenario with the proposed QoS-aware resource allocation strategy. In contrast to Figure 2(a) for the TP CDF in DeNB-only scenario, in Figure 3(a), we observe that the rate requirements of both traffic types are fulfilled to a large extent for both UE categories. The mean and 5%-ile TP values for VoIP traffic type are 130 kbps and ca. 128 kbps for both M-UEs and R-UEs. For the video UEs, we observe that performance of R-UEs improve considerably as compared to that in Figure 2(a). The mean and 5%-ile TP values being 261 kbps and 260 kbps respectively. For the video M-UEs, we observe that there is still a fraction of M-UEs that are not able to achieve the designated GBR. The mean and 5%-ile TP values for video M-UEs are 252 kbps and 195 kbps respectively.

Next, in Figure 3(b), we plot the CDF of the end-to-end packet delays for proposed scheme in DeNB+2RN scenario. Note that the end-to-end packet delay in this scenario corresponds to a sum of packet delays experienced over both hops. We observe that adding relay nodes helps the system



(a) Throughput CDFs

(b) Delay CDFs

Fig. 4. DeNB+2RN scenario with conventional resource allocation (static resource partitioning plus proportional fair scheduler). Throughput and delay CDF comparisons for different UE groups (M-UEs and R-UEs) and traffic types (VoIP and Video).

significantly, in comparison to the DeNB-only case in Figure 2(b). The mean packet delays for both services are significantly reduced. The reduction for R-UEs delay comes from the fact that the RN is able to serve them over better radio conditions, while the reduction for M-UEs delay comes as a consequence of reduction in resource consumption for R-UEs. Besides the significant reduction of mean packet delays, 95%-ile delays are also reduced. The VoIP 95%-ile delays are reduced to 87 ms and 37 ms respectively for M-UEs and R-UEs. Similarly, the video 95%-ile delays reduce to around 297 ms and 151 ms respectively for M-UEs and R-UEs. The video R-UEs having 95%-ile delay of around 151 ms owes to the fact that the major fraction in end-to-end delay for R-UEs comes from the first hop, which in this case is assigned a delay budget deadline of 150 ms. Similar remark holds for the VoIP R-UEs.

In summary, we observe from Figure 3 that once sufficient radio resources are available, the proposed QoS-aware resource allocation mechanism facilitates to a very large extent the satisfaction of heterogeneous QoS requirements in terms of both latency and bit rate simultaneously.

C. Relay enhanced scenario (DeNB+2RN) with conventional resource allocation

Finally, in this sub-section, we present the throughput and delay CDFs for the same relay enhanced scenario (DeNB+2RN), as in last sub-section, but with conventional resource allocation in place of QoS-aware resource allocation. To this end, we pursue static resource partitioning [4] at the DeNB between the macro-access link and the backhaul link. This static resource partitioning incorporates the fact that the video users have twice the rate requirement of the VoIP users. A regular proportional fair scheduler is employed with in the partitioned spectrum to assign resources to various competing users.

From Figure 4, we observe an imbalance with regard to QoS satisfaction of users. In Figure 4(a), we note that though the TP requirements for R-UEs are easily met, the observed mean and 5%-ile values for M-UEs are only around 173 kbps and 103 kbps for video, and around 123 kbps and 90 kbps for VoIP users. Similar observations can be made from Figure 4(b) depicting the delay CDF; we note that though the delays for R-UEs are lower as compared to Figure 3(b), but the degradation in the performance of M-UEs is rather drastic.

D. Comparison between proposed and conventional resource allocation

In order to summarize the effectiveness of the proposed QoS-aware resource allocation scheme for relay enhanced networks, we present in this sub-section a comparison with the conventional scheme, in terms of the fraction of satisfied users. To this end, we define two alternative measures:

- μ_{TP} = Fraction of satisfied users w.r.t. throughput, defined as the fraction of users (or samples) that achieve up to 95% of the configured GBR.
- μ_{DLY} = Fraction of satisfied users w.r.t. delay, defined as the fraction of users (or samples) that are served within the configured delay limits.

For the DeNB+2RN scenario, the fraction of satisfied users w.r.t. TP and delay are presented in Table I for the proposed and conventional schemes. Note that the values are obtained respectively from Figure 3 and Figure 4. It can be seen that especially for M-UEs, the fraction of satisfied users is appreciably increased by employing the proposed QoS-aware resource allocation scheme. For instance, the number of satisfied video UEs increase from 8.1% to 88.8% w.r.t. the achieved throughput, and from 74.7% to 95.3% w.r.t. the experienced packet delay.

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TABLE I
DENB+2RN SCENARIO: FRACTION OF SATISFIED USERS μ_{TP} AND μ_{DLY} FOR THE PROPOSED QOS-AWARE (PROP.) VS. THE CONVENTIONAL STATIC RESOURCE PARTITIONING BASED (CONV.) RESOURCE ALLOCATION

UE type	Fraction of satisfied users w.r.t.			
	achieved throughput		experienced delay	
	Conv.	Prop.	Conv.	Prop.
Video M-UEs	8.1%	88.8%	74.7%	95.3%
VoIP M-UEs	80.0%	99.4%	90.5%	99.0%
Video R-UEs	100.0%	100.0%	100.0%	100.0%
VoIP R-UEs	100.0%	100.0%	100.0%	100.0%

V. CONCLUSION AND FUTURE WORK

In this work, we have analyzed the performance of a QoS-aware scheduler for in-band relaying scenario in LTE-Advanced systems. The proposed scheduler addresses two major issues. First, it guides on how to split resources between macro users and the backhaul link at the DeNB scheduler via the concept of "super flows". Secondly, it facilitates the satisfaction of QoS constraints for the R-UEs that are scheduled in two distinct hops. The advantage of the proposed resource allocation scheme in both these aspects has been confirmed via system level simulations, which show significant gains over conventional approaches, in terms of the fraction of satisfied users.

Further work in this area will target an extension of the overall resource allocation framework to interference coordination strategies for relays. We believe that coupling of the proposed scheme with an efficient interference coordination on access links [8] will lead to a better performance of the cell-edge users especially for scenarios with a large number of relay nodes (i.e., 4-10 RNs), where the interference inside the macro-cell can easily degrade the overall system performance.

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