IEEE Access
Multidisciplinary | Rapid Review | Open Access Journal

Received November 14, 2019, accepted December 2, 2019, date of publication December 5, 2019,
date of current version December 23, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2957940

Network Solutions for CoMP Coordinated Scheduling

ANDREA MAROTTA[1], (Member, IEEE), DAJANA CASSIOLI[1], (Senior Member, IEEE), CRISTIAN ANTONELLI[2], (Senior Member, IEEE), KOTESWARARAO KONDEPU[3], (Senior Member, IEEE), AND LUCA VALCARENGHI[3], (Senior Member, IEEE)

[1]Department of Information Engineering, Computer Science and Mathematics (DISIM), University of L'Aquila, 67100 L'Aquila, Italy
[2]Department of Physical and Chemical Sciences (DSFC), University of L'Aquila, 67100 L'Aquila, Italy
[3]Scuola Superiore Sant'Anna, 56127 Pisa, Italy

Corresponding author: Andrea Marotta (andrea.marotta@univaq.it)

This work was supported in part by the Italian Government through CIPE, in part by the Project innovating City Planning through Information and Communication Technologies (INCIPICT), and in part by the EC through the H2020 5G-TRANSFORMER Project under Project 761536.

ABSTRACT Demanding throughput, latency and scalability requirements of 5G networks may be addressed by relying on dense deployments of small cells. Coordinated Multipoint (CoMP) Coordinated Scheduling (CS) techniques are introduced to reduce inter-cell interference in case of dense deployment, given that local CoMP-CS information from the evolved NodeBs (eNodeBs) in the cluster are timely collected at the scheduling decision entity. This work studies how the distribution of CoMP-CS cell information is affected by the backhaul infrastructure in terms of both physical and logical topology. The differentiation between physical and logical infrastructure is justified in the context of new approaches like Software Defined Networking and Network Function Virtualization that enable the dynamic configuration of the network. We consider either a Packet Switched Network with three possible topologies (namely, ring, mesh and star) or a Time Division Multiplexing Passive Optical Network (TDM-PON), both carrying heterogeneous traffic. To improve the convergence time in the TDM-PON, we propose a novel bandwidth allocation scheme to prioritize the signaling traffic with respect to data traffic. Performance of both distributed and centralized CoMP-CS are compared in terms of convergence delay and traffic overhead. Finally, we analyze the impact of the periodicity of CS operations on mobile performance, in terms of average UEs throughput, in the presence of different cell loads.

INDEX TERMS CoMP coordinated scheduling, 5G, PON, RAN, NFV.

I. INTRODUCTION

5G networks target an unprecedented improvement of users' quality of experience (QoE). In practice, this aim is mapped onto ambitious requirements in terms of network capacity, latency, scalability and automation. Capacity and coverage can be improved by deploying dense small cells, but appropriate mechanisms for interference management must be adopted.

Coordinated Multi-Point (CoMP) techniques provide a significant reduction of inter-cell interference and increases the cell-edge throughput by coordinating the transmissions of multiple evolved NodeBs (eNodeBs) [1]. In the 3GPP standard, the CoMP is indicated as one of the functions of the Radio Resource Management (RRM) layer in both single and multi-cell environments [2]. Actually, RRM is placed above the Radio Resource Control (RRC) layer as an application of the eNodeB which interacts with both the RRC, the S1 Application Protocol (S1AP) and the X2 Application Protocol (X2AP). Hence, in the context of Software Defined Networking (SDN) [3], the inter-eNodeB CoMP is yet another network function that can be virtualized and orchestrated by the SDN controller jointly with the resource allocation in the backhaul network. In addition, optical network resources can be managed with the help of the software defined optical networking concept as described in [4].

Furthermore, it is possible to organize the eNodeBs in clusters, named CoMP cooperating sets, to make coordinated scheduling (CS) decisions per cluster. As the cluster size impacts its performance, it has been extensively studied in the

The associate editor coordinating the review of this manuscript and approving it for publication was Martin Reisslein.

literature [5], [6]. Scalability can be achieved by producing allocation masks lasting longer than the Transmission Time Interval (TTI) time-frame while the cooperating nodes are still in charge of scheduling per TTI [7].

The CoMP-CS decision process is based on up-to-date Channel State Information (CSI) shared between the eNodeBs in the cluster, which could be even heterogeneous [8], [9]. Efficient protocols for the timely sharing of scheduling hypothesis are still being devised.

Acceptable performance can be achieved if the coordinated decision for the eNodeB cluster is made by a centralized controller based solely on the gathered UEs' CSI reports defined in the 3GPP standard [10]. However, actual cooperation between neighbor eNodeBs is implemented by exchanging the cell information through the X2 interfaces. Therefore, it is clear that one of the main factors that limit the effectiveness of CS is the infrastructure of the Radio Access Network (RAN), because it determines the latency of the CS scheme.

The RAN can be valuably realised with the Passive Optical Network (PON) technology. Mobile backhaul and fronthaul based on Time Division Multiplexed (TDM)-PON can be suitable solutions for future radio access in terms of latency, capacity and cost effectiveness [11], if appropriate resources (bandwidth) allocation schemes are applied. Several Dynamic Bandwidth Allocation (DBA) schemes in 10 Gigabit Capable PON (XG-PON) addressing Quality of Service (QoS) requirements for different aggregated upstream applications in the LTE backhaul are proposed, with particular focus on user-plane traffic such as voice, live video and best-effort Internet traffic [12]. Latency aspects related to the adoption of PONs in fronthaul are mathematically analyzed in [13], using queuing theory to achieve minimal latency for constant bit rate fronthaul traffic.

However, to the best of the authors' knowledge, no work is present in the scientific literature that focuses on the evaluation and comparison of the time required by the CoMP hypothesis to be exchanged in a PON-based backhaul by tweaking the PON DBA or within different RAN topologies in a Packet Switched Network (PSN).

In this work, we extend our previous studies [14]–[16] by investigating how the backhaul infrastructure impacts the CoMP-CS performance in terms of convergence delay and throughput experienced by mobile users.

The reference architecture for our studies considers as the backhaul infrastructure either the TDM-PON or the PSN. Whereas the TDM-PON topology is fixed, for the PSN we consider the following topologies:

- MESH based either on SDN (MESH-SDN), or Spanning Tree Protocol (MESH-STP),
- STAR,
- RING.

Hence, a total of five different case studies are analyzed.

Our solution sees the CoMP-CS function extracted from the RRM and implemented as a VNF. We demonstrate that CS benefits from the application of SDN and NFV in cellular networks, where different virtualized CS deployments can be exploited by the orchestration layer. A comparison of such options in terms of convergence delay and traffic overhead is presented for both distributed and centralized CoMP-CS. We highlight that a virtualized CS deployment dynamically reduces the convergence delay and such reduction is most significant in the deployment at the macrocell. We provide guidelines for the design of optimal polices for virtualized CS deployment. Once analyzed the possible sources of the delay and its limitations, we quantify the throughput penalty of mobile users associated to such convergence delay, i.e. the delay in applying the CoMP-CS optimal plan.

Finally, in the TDM-PON we enable the efficient exchange of CoMP-CS messages by proposing a novel DBA scheme which prioritizes the signaling traffic (i.e., X2 traffic). Simulation results show that the proposed scheme effectively achieves a significant reduction of the CoMP-CS exchange time. In addition some hints are drawn for dimensioning the PON in terms of number of eNodeBs (i.e., Optical Network Units (ONUs)) to achieve a given target exchange time for both distributed or centralized schemes [1].

The paper is organized as follows. Sec. II presents the CoMP-CS technique in details. The Sec. III describes the challenges related to practical implementations of CoMP-CS techniques over different backhaul infrastructures, namely, either the TDM-PON or the PSN with the three above-mentioned topologies. Sec. IV discusses the results obtained through extensive simulations. Finally, in Sec. V some conclusions are drawn.

II. CoMP COORDINATED SCHEDULING OVERVIEW

Inter eNodeB CoMP is a RRM function proposed to improve system throughput in both 4G and 5G mobile networks [17].

CoMP techniques comprise Joint Processing, which includes Joint Transmission (JT) and Dynamic Point Selection (DPS), Coordinated Scheduling/Beamforming (CS/CB), which includes Semi-static point selection (SSPS), or combinations of JP and CS/CB. CoMP can be applied to both homogeneous and heterogeneous networks [18].

The CoMP-CS allows the eNodeBs in the CoMP cluster to make coordinated decisions on user scheduling. CS between multiple cells, possibly heterogeneous, relies on up-to-date indicators shared, through the X2 interface, between the entities involved in the decision process by means of Load Information (LI) Messages [8]. Such messages contain several Information Elements (IEs) to support the LI Procedure to exchange load & interference coordination information between eNodeBs [19].

The CoMP-IE provides a list of up to a maximum of 256 CoMP hypothesis set, each one associated to a benefit metric. Each CoMP hypothesis set is the collection of CoMP hypothesis item(s) of one (or more) cells, up to a maximum of 32 cells. Each item is the pair {cell ID, CoMP hypothesis}, where the CoMP hypothesis is a **bitstring** of variable length, integer multiple of the number of Physical Resource Blocks (PRBs) contained in a subframe. Each bit represents the status of a PRB in a subframe: if set, it indicates an interference protected resource that should not be utilized because its use will generate a high level of interference.

The interference level is estimated based on the Channel State Information/Channel Quality Indicator (CSI/CQI) reports, which are sent, either periodically or aperiodically, to the eNodeBs by the served User Equipments (UEs) through the Physical Uplink Shared Channel (PUSCH) and the Physical Uplink Control Channel (PUCCH).

The periodicity of CQI transmission, expressed in terms of number of subframes, represents a critical design parameter for CoMP-CS and is set by RRC during RRC Connection Setup and RRC Connection Reconfiguration procedures [20].

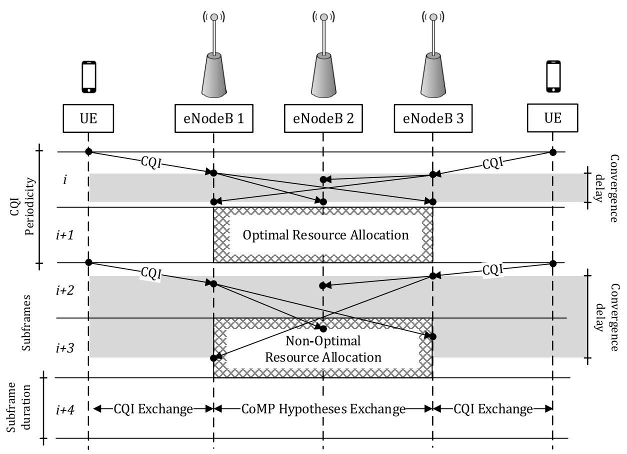

FIGURE 1. UE CSI/CQI measurements application.

The eNodeB produces a new CoMP hypothesis set only once it has received updated CQI from its served UEs (Fig. 1). Hence, the optimal scheduling must be released by the collaborating eNodeBs with a periodicity lower than CQI periodicity, in order to make the proposed scheduling optimally matching the current CQIs. The time required to apply the optimal scheduling is impacted by the time needed by the eNodeBs' cluster to share the CoMP hypothesis, thus it is referred to as the "convergence delay".

Fig. 1 shows the two cases: the upper part (subframes i and $i+1$) depicts the perfect scheduling of CQI transmission, CoMP hypotheses collection, and resource allocation release, which is optimal because the whole process is completed within the CQI periodicity. The lower part (subframes $i+2$ and $i+3$) presents the situation where the convergence delay exceeds the subframe duration, hence the resource allocation is non-optimal.

CoMP-CS can be implemented in either a distributed (i.e. Distributed Coordinated Scheduling (DCS)) or centralized architecture (i.e., Centralized Coordinated Scheduling (CCS)). In DCS, LI messages are exchanged between the eNodeBs in the cluster, whereas in CCS the Centralized Radio Resource Manager (C-RRM) is in charge of collecting the LI messages and enforcing the optimal CS by sharing the current scheduling decision within the cluster. The exchange of CoMP load information messages between eNodeBs in the two different scenarios is shown in Fig. 2. In DCS (Fig. 2a), the eNodeBs exchange load information messages through the X2 interface. In CCS (Fig. 2b), information messages are collected within the cluster by the C-RRM, which receives update messages by the cooperating eNodeBs and is responsible of making scheduling decisions.

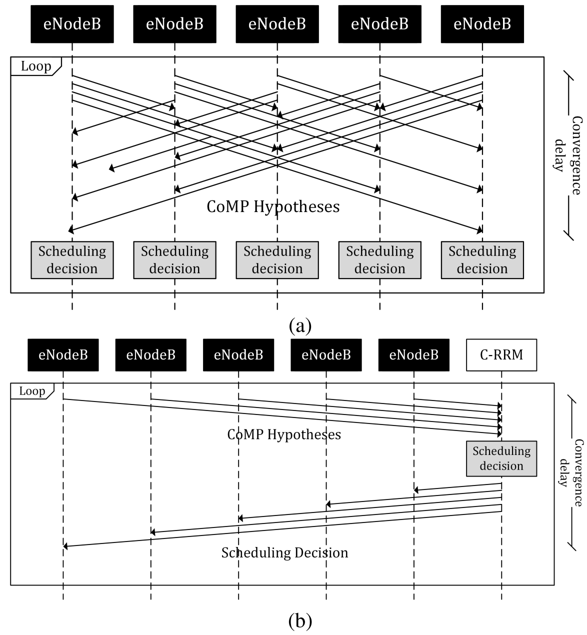

FIGURE 2. Distributed (a) Vs. Centralized (b) CoMP.

III. CoMP-CS PRACTICAL FEASIBILITY

The analysis of practical deployment scenarios for the CoMP-CS as a VNF is based on the generalized reference architecture shown in Fig. 3, which includes the Control and Orchestration Layer (top level) and the physical Network Function Virtualization Infrastructure (NFVI).

A. THE CONTROL AND ORCHESTRATION LAYER

The Control and Orchestration Layer has the role of coordinating and orchestrating the three network domains, i.e., Optical, Radio and Packet Networks. As indicated in Fig. 3, these domains refer each to a dedicated controller, i.e., the Radio Controller (RC) to operate over the mobile network, the Optical Controller (OC) and the Packet Network Controller (PNC) as responsible for the optimal management of the RAN's resources, including the VNFs deployment. The RC is interfaced with the PNC and OC by a dedicated protocol which enables the adaptive deployment of VNFs according to the instantaneous conditions and the current topology of the RAN.

For example, the RAN configuration (e.g., the number of active small cell sites, the distribution of VNFs, etc) may be varied by the PNC/OC upon the RC request based on the current traffic load for energy efficiency reasons. Here, RC sends a notification to the PNC/OC that the VNFs deployment on the NFVI has to be optimized. Thus, the PNC/OC

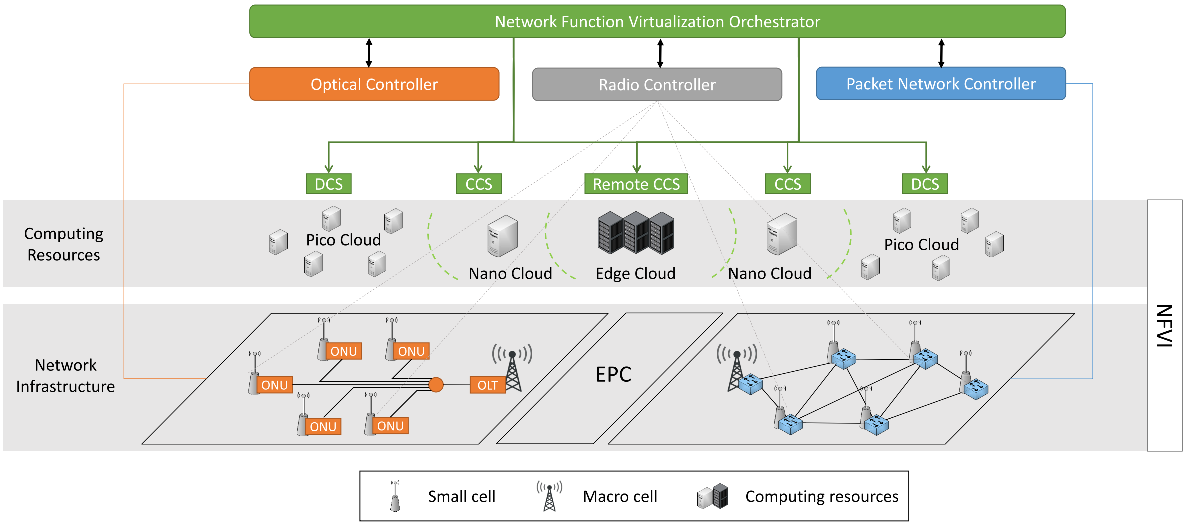

FIGURE 3. **Reference architecture.**

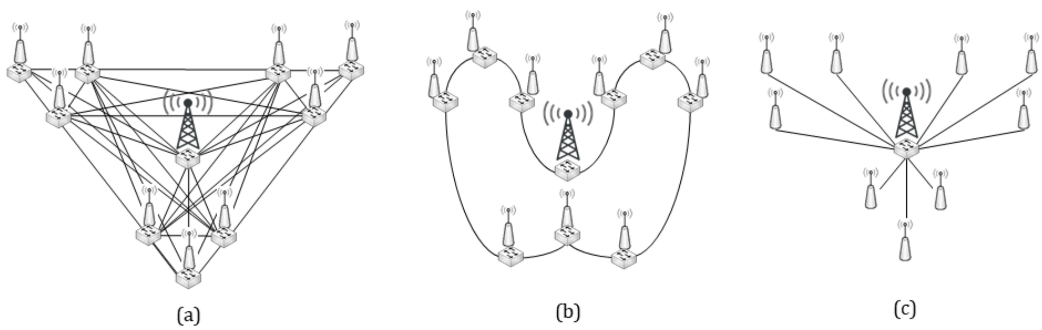

FIGURE 4. **Different PSN topologies: (a) full mesh, (b) ring, (c) star.**

informs the NFVO to optimize the deployment of VNFs on the NFVI, which promptly accommodates the forwarding plane accordingly.

B. THE COMPUTING RESOURCES

The NFVI is composed by "computing resources" and "network infrastructure". The network infrastructure consists of a number of forwarding devices, small and macrocell eNodeBs and computing resources that can be deployed at different places in the access network and managed by a control and orchestration layer. A typical categorization is the following [21]:

- multiple pico-cloud nodes at small-cell sites
- one nano-cloud node at the macrocell site
- an edge-cloud node at the higher level aggregation site, i.e. at the EPC.

The small cells are deployed to increase the capacity of the Radio Network within the macrocell area served by the macro eNodeB.

According to the above categorization, the CoMP-CS VNF can be instantiated in one of the following NFVI locations, as indicated in Fig. 3:

- at the pico-cloud: every small cell station runs its CoMP-CS application, which autonomously makes scheduling decisions - DCS;
- at the nano-cloud: scheduling decisions are managed at the macrocell - CCS;
- at the edge-cloud: decisions are made at the core network - remote CCS.

DCS schemes require that all application instances collect CoMP LI messages from all eNodeBs in the cluster. In CCS schemes, the CoMP information must be available at the VNF implementing the CS application in a centralized way, i.e., at the C-RRM placed at either the macrocell or Core and all nodes have a neighborhood relation with the C-RRM.

C. THE NETWORK INFRASTRUCTURE

The network infrastructure can be based on either a PSN or a TDM-PON, respectively shown on the right and left plots of Fig. 3.

In the PSN case, the macrocell site and the small-cell sites are connected through a packet switched network that could have a topology either mesh (Fig. 4(a)), ring (Fig. 4(b)) or star (Fig. 4(c)). The mesh topology may include either configurable switches via the SDN Controller or traditional STP

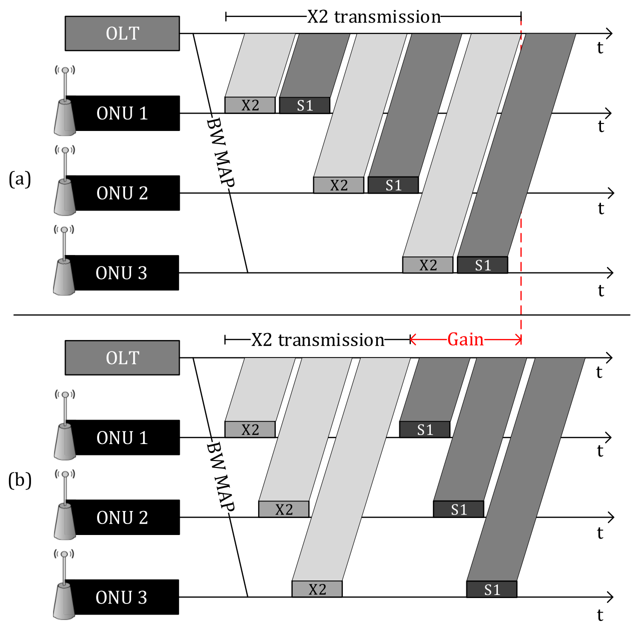

FIGURE 5. (a) Conventional DBA scheme; (b) Proposed DBA scheme with X2 prioritization.

switches (Fig. 4(a)), but is considered here as a benchmark scenario for delay evaluation because the high deployment cost prevents its use as a feasible infrastructure.

Alternatively, as shown in the left plot of Fig. 3, the macrocell-site could be placed at the OLT and the small cells at the ONUs, both connected through a 10 Gigabit Capable PON (XG-PON). In XG-PON, the exchange of traffic between the OLT and ONUs is based on 10 GPON Encapsulation Method (XGEM) ports and Transmission Containers (T-CONTs). To avoid transmission collisions, a DBA procedure is used at the OLT to grant the transmission opportunities to the connected ONUs. Traditional DBA schemes grant transmission opportunities that comprise both X2 and S1 transmission as shown in Fig. 5(a). To achieve as rapidly as possible the convergence of CoMP hypothesis information among the eNodeBs in the network, i.e., to minimize the waiting time of X2 traffic, we propose a DBA scheme that adopts a T-CONT at the ONU side dedicated to each traffic type, either S1 or X2. At any request for transmission of T-CONTs associated to X2 traffic at the OLT, the DBA engine produces a bandwidth map that allocates first all resources to the X2 traffic generated by the ONUs followed by all S1 T-CONTs at the ONUs, as shown in Fig. 5(b).

Due to the X2 prioritization, the S1 traffic could experience an increased delay which grows with the number of co-located eNodeBs-ONUs, linearly for CCS and quadratically in DCS, as calculated in Appendix. Since the XG-PON capacity is asymmetric, the S1 waiting time is most severe in the upstream direction.

IV. RESULTS

In the following we evaluate the performance of the CoMP-CS developed as a VNF for the proposed RAN solutions: a PSN, with three topologies, and a TDM-PON. For each of them we evaluate the impact of resource management solutions. Finally, we evaluate the performance of the mobile network from the UEs perspective as a function of the CoMP-CS transmissions periodicity.

The CoMP-CS performance is measured in terms of the following metrics:

- the *convergence delay* of the LI messages calculated from the time of generation of the messages in all nodes and the time at which all collaborating nodes receive either the LI messages (DCS) or the C-RRM reply (CCS).
- the *traffic overhead* due to CS signaling measured as the number of bytes exchanged between all the nodes in the cluster.

A. EVALUATION OF CoMP-CS IN PSN

The three scenarios for deployment of CoMP-CS as VNF in the PSN correspond to the three network topologies described in the previous sections. We implemented them in NS3 simulation environment [22] by adding new features to the available LTE module [23].

The reference setup consists of an average number of 10 cooperating eNodeBs arranged as follows: one macrocell and three clusters of three small cells each located at the edge of the macrocell. Such scenarios with the eNodeBs interconnected by 10 Gbps optical Ethernet links according to the different topologies are shown in Fig. 4.

We assume 20 MHz system bandwidth, i.e., a length of 100 bits for each CoMP hypothesis. In addition, we simulate the generation of X2 LI messages carrying one single CoMP hypothesis. The simulation has been conducted running twenty simulations for each scenario with a confidence level of 95% to obtain the confidence interval depicted in Fig. 6. Three physical environments are studied: Urban, Suburban and Rural. The macrocell coverage ranges are 2 km, 7.5 km and 15 km, and the small-cell coverage radii are 200 m, 750 m and 1500 m, respectively for the three scenarios. Hence, the link lengths vary between 200 m and 3.4 km for urban scenario, 750 m and 13 km for suburban, and 1.5 km and 26 km for the rural one. The distance between the macrocell and the regional cloud data center is assumed to be equal to the inter-macrocell distance (i.e., twice the macrocell coverage radius). Links and switches for the connections towards the Core network are placed as dictated by the different RAN topologies. In the star topology all eNodeBs are connected to one switch at the macrocell. In the mesh and ring topologies, each eNodeB is connected to a switch and all eNodeB switches form respectively a mesh and a ring.

The three deployment schemes, DCS, CCS, and remote CCS, defined in Sec. III-C, are applied to different RAN topologies and scenarios (i.e. Urban, Suburban and Rural).

As shown in Fig. 6, the convergence delay of all proposed schemes increases with the increased length of links from Urban to Rural. Although the main contribution to convergence delay is the link propagation delay, most delays

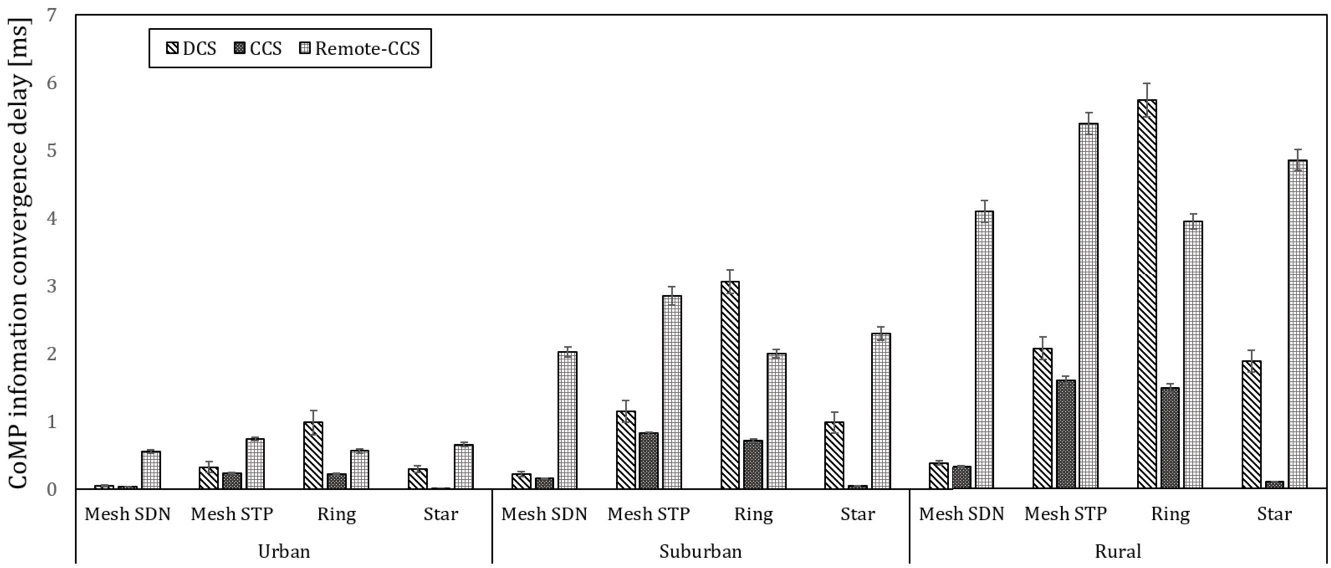

FIGURE 6. Convergence delays of CoMP VNF deployments in the PSN topologies for the different scenarios.

in Fig. 6 are by far larger than the simple one-way propagation time associated with the respective scenarios (urban, suburban, rural). The origin of this deviation is related to the fact that the Stream Control Transmission Protocol (SCTP) adopted for the X2AP messages' exchange does not support multicast transmission. Hence, load information messages, sent by an eNodeB to the nodes in the cluster, represent a set of unicast transmissions which are not simultaneous. In case of future evolution of scheduling periodicity requirements (for instance 1 ms subframe time) only urban scenarios could support CoMP-CS.

The comparison between the convergence delays of the different virtualized CS deployment scenarios in Fig. 6, evidences that the centralized approach at the macrocell is the most advantageous. The Remote CCS performs worse, especially in the rural scenario, due to the large distance of the regional cloud data center from the cluster. On the other hand, the C-RRM at the Edge Cloud may enable a dynamic clusterization of CoMP-CS by controlling a huge number of cooperating clusters.

Due to the high X2 overhead traffic to achieve convergence, the performance of the DCS approach is low. This is in line with the proposed 5G-PPP physical architecture, which relies on a centralized approach at the macrocell for subordinate small cells, in order to avoid to equip the small cells with pico-cloud computing resources [21]. The SDN approach in mesh topology strongly reduces the convergence delay with respect to STP. This is easily explained by considering that the SDN controller has the knowledge of the whole topology, thus can optimize in real time routing and switching of flows to reduce the end-to-end delay. This results in a reduction of the CoMP-CS convergence time. Contrarily, STP maps the network mesh topology into a tree and forces the messages to navigate the tree through a non-optimal path, consequently increasing the convergence time[1]. Mesh topology generally experiences the lowest convergence delay due to the high number of available links, with the exception of virtualized CS deployment at macrocell, where the star topology outperforms the others, thanks to the low number of hops to reach the macrocell.

The ring topology experiences the highest convergence delay in the distributed case, because a high number of messages is exchanged over a small number of available links. In other words, the increased number of hops enlarges the convergence delay.

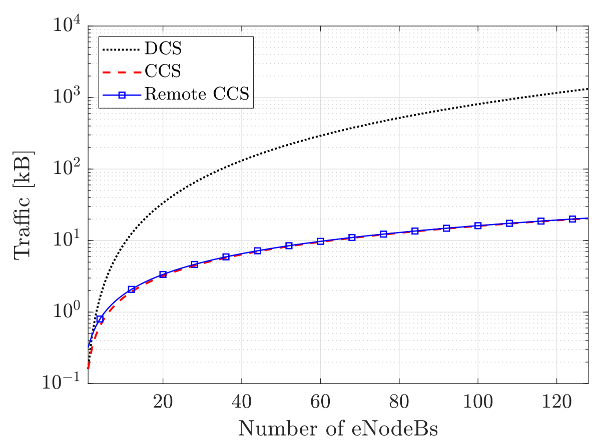

FIGURE 7. Overhead traffic of the different CS VNF deployments.

The comparison of the virtualized CS deployments in terms of overhead traffic is shown in Fig. 7 and evidences that:

- the high amount of exchanged data prevents the use of DCS scheme;

[1]We simulate STP protocol through a minimum spanning tree algorithm with equally weighted archs.

- centralized schemes experience lower overhead traffic, although the Remote CCS traffic level is slightly higher than CCS, because CoMP information are forwarded from the macrocell to the C-RRM.

B. CS PERFORMANCE IN TDM-PON

This evaluation is carried out by simulations in NS3 environment, by using LTE and XG-PON modules [23], [24] upgraded on purpose.

The reference scenario is represented by an OLT co-located at the macrocell and connected to the ONUs at the small cells by links 250 meters long. The link between the ONUs and the OLT consists of a 10-Gigabit-capable PON, providing nominal data rates up to 10 Gbps in downstream and 2.5 Gbps in upstream. We assume that all eNodeBs transmit S1 data in upstream at the maximum available capacity. In the comparison between different DBA schemes, the simulation is conducted running twenty simulations for each scenario. A confidence level of 95% was adopted to obtain the confidence interval depicted in Fig. 8. We simulate all eNodeBs in the cooperating set sending a single CoMP hypothesis each.

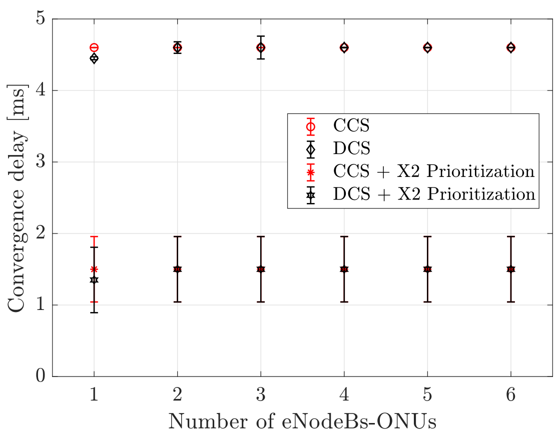

FIGURE 8. Convergence delay for different CoMP and DBA schemes vs. a small number of ONUs.

As anticipated in Sec. III-C, the CS convergence delay in a TDM-PON is strongly dependent on the DBA scheme applied to the X2 traffic in the optical links. Fig. 8 compares the convergence delay achieved by a small number of ONUs when DCS and CCS are supported by either a DBA that does not prioritize X2 traffic or a DBA prioritizing X2 traffic. In the presence of a small number of ONUs the convergence delay appears constant because the generated traffic is contained in a single upstream frame. In this case, the CS scheme, i.e., CCS or DCS, does not have any impact. Instead, it is evident that the proposed DBA scheme, which prioritizes X2 traffic over S1 traffic, plays a key role, reducing the convergence delay by 67% which passes from 4.6 ms to 1.5 ms. Despite the shorter link lengths, this delay is still higher than the delay observed in the star topology in PSN, which the TDM-PON can be in principle reconducted to. The higher convergence delay is mainly related to the grant-request procedure and bandwidth allocation calculation, as demonstrated in [25]. On the other hand, a PON infrastructure requires significantly lower capital and operating costs with respect to PSN.

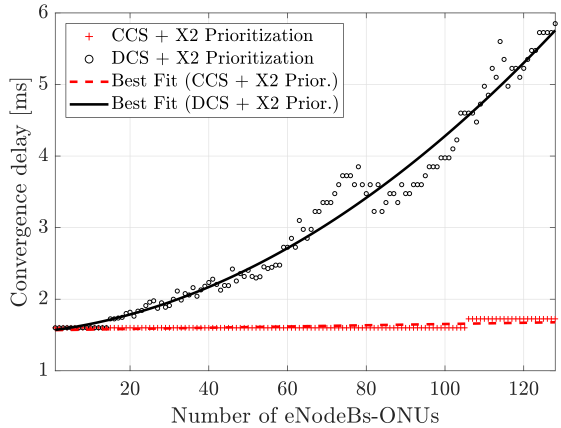

FIGURE 9. Convergence delay for CCS and DCS with X2 prioritization vs. the number of ONUs.

Increasing the number of ONUs from 1 to 128 for the proposed DBA scheme with X2 prioritization, the number of DCS exchanged messages among ONUs grows quadratically with the number of ONUs, while it grows linearly in the CCS case. This is reflected in the trend of the convergence delay for the two schemes as shown in Fig. 9. The increase of required upstream bandwidth for DCS saturates PON upstream available bandwidth, with consequent increase of the waiting time for the messages at the ONU. Hence, DCS does not represents a suitable solution in case of tight scheduling periodicity if the number of connected ONUs is greater than 20.

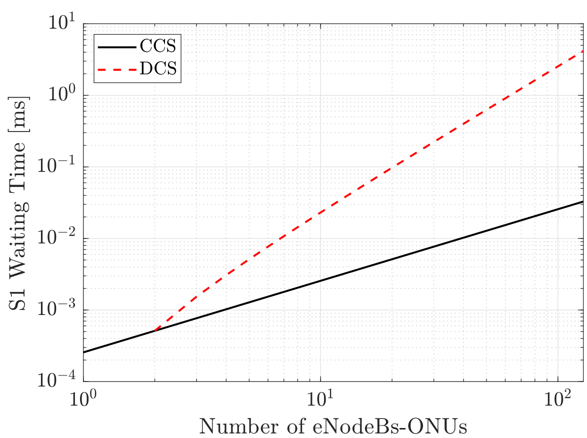

FIGURE 10. S1 Waiting time for CCS and DCS.

A similar behaviour is observed on the S1 waiting time when the prioritization of X2 traffic is applied. Fig. 10 shows the S1 waiting time in case of CCS and DCS as calculated in eq. (1) and eq. (2) in Appendix, respectively. In case of DCS, the S1 waiting time is higher than 1 ms for a number of cooperating eNodeBs-ONUs greater than 60. The S1 waiting time contributes to the delay experienced by the mobile users and grows with number of cooperating eNodeBs. Hence, the cluster size must be dimensioned according to the target S1 delay at the user plane.

C. ANALYSIS OF MOBILE USERS PERFORMANCE

We evaluate the impact of network performance on the throughput experienced by mobile users. Our simulations are based on the system level simulator included in the package of The Vienna LTE simulators [26]. It is possible to simulate a multitude of eNodeBs covering a specific area where many mobile terminals are located and/or moving around. Simplified models abstract the physical layer by capturing its essential dynamics with high accuracy at low complexity. The link quality is determined by the module *link measurement model*, which performs link adaptation and resource allocation based on the UE measurement reports. Based on the Signal to Interference and Noise Ratio (SINR), the UE computes the feedback (Pre-coding Matrix Indicators (PMI), Rank Indicators (RI), and Channel Quality Indicators (CQI)), which is employed for link adaptation at the eNodeB. Based on this feedback, a scheduler assigns PHY resources, precoding matrices, and a suitable Modulation Coding Scheme (MCS) to each UE attached to an eNodeB to optimize the performance of the system (e.g., in terms of throughput).

TABLE 1. Parameters for the system level simulations.

System Bandwidth	20 MHz
CQI feedback delay	5 TTI
Number of Resource Blocks	100
Number of users per eNodeB	25
UEs speed	100 km/h
Channel Model	3GPP TU [28]
Pathloss Model	TS36942
Number of transmit antenna ports	4
Number of receive antenna ports	1
eNodeB transmit power	46dBm
Inter-eNodeB distance	500m
Tx mode	Rank-1 CLSM
Receiver	Zero Forcing
Scheduler	CoMP-CS Round Robin DB
Simulation Duration	100 TTI

The set of parameters used in our system level simulations are summarized in Table 1. The network topology is a regular hexagonal grid composed of 7 transmission sites. To each transmission site, three eNodeBs are appended, i.e., sectors, each containing a scheduler. UEs are randomly disposed in the cell area, and a linear mobility model in random directions is assumed. Traffic modeling assumes full buffers in the downlink. The set of cooperating eNodeBs shares the CoMP hypothesis of all eNodeBs belonging to the cooperating cluster and defines the optimal scheduling for the current TTI, which is immediately applied to UEs. The CoMP periodicity is varied such that the optimal resource allocation plan is applied at a given time period, which varies from $t_{CSupdate} = 1$ to 10 TTI.

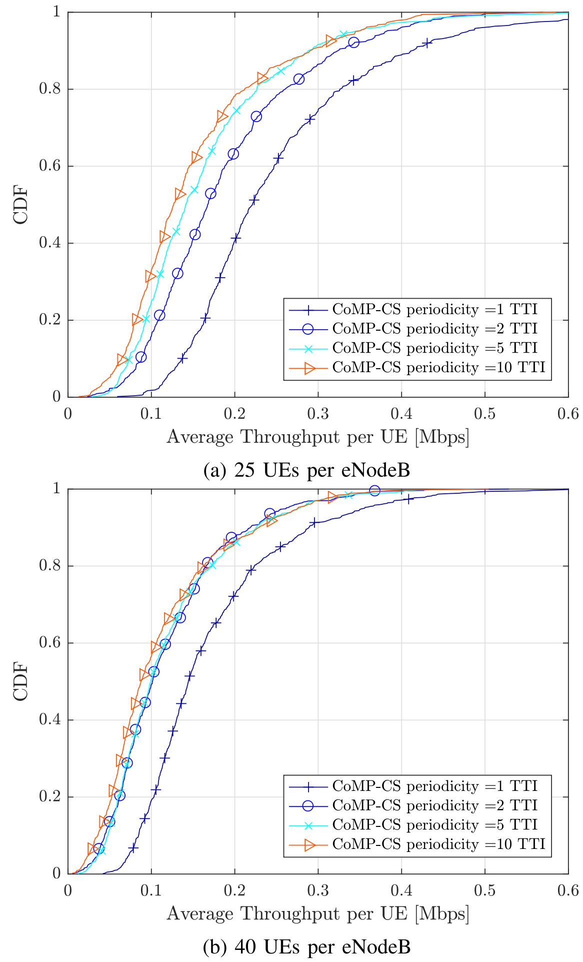

FIGURE 11. The CDFs of the average throughput per UE as a function of the CoMP-CS periodicity.

At every $t_{CSupdate}$, interfering transmissions are muted as soon as the CoMP-CS hypothesis are received. We assume that at every $t_{CSupdate}$ the CoMP-CS hypothesis convergence is achieved, thus $t_{CSupdate}$ is greater or equal to the convergence delay. During the time elapsing between two CoMP-CS updates, the regular scheduling, i.e. non CoMP-CS, is applied to serve new users requests, which can be allocated only non-muted PRBs according to the last applied CoMP-CS optimal plan. Among the different scheduling options offered by the simulator, we selected the CoMP-CS based on Round Robin [26].

The mobile network performance are measured in terms of average UEs throughput as a function of the CoMP-CS periodicity. The CDFs of the average UEs throughput as a function of the CoMP-CS plan application delay are plotted in Fig. 11 for two different values of average number of UEs per cell (i.e. 25 and 40). In both cases the curves present a very similar shape, however for the higher density cells the curves are stiffer. The CoMP-CS periodicity is relevant if the number of UEs per cell decreases to 25, as shown in Fig. 11 (a), where the timely application of CoMP-CS is an effective countermeasure to the increased level of interference, especially under the perspective of small cells densification with a low number of connected devices.

V. CONCLUSION

In this work we proposed two network solutions for the implementation of CoMP Coordinated Scheduling as a VNF in the RAN, i.e., a PSN, with three different topologies, and a TDM-PON. We evaluated the impact of resource management solutions and CoMP-CS periodicity on mobile network performance and UEs throughput.

The comparison of the three PSN topologies has been done in terms of both performance and traffic overhead with different deployment scenarios for CoMP-CS as a VNF in both centralized and distributed schemes. The most convenient choice appeared to be the centralized VNF instantiation of CoMP-CS function according to the CCS scheme over the star topology. Indeed, a real scenario of collaborating eNodeBs reasonably sees interfering nodes located at short distances and connected to the same switch. The star topology, however, has the drawback of being lowly tolerant to failure; this is even drastically increased by the full mesh topology.

In the TDM-PON we proposed a new DBA scheme to prioritize the scheduling of the traffic belonging to the X2 interface, to effectively manage the increase of overhead traffic associated to the CS operation. The proposed scheme provides a reduction of the convergence delay of CoMP hypothesis up to 67% in both centralized and distributed CS implementations. Moreover, for a large number of ONUs the centralized CS appears to be preferred with respect to the distributed, because it has a lower impact on the increase of S1 traffic delay and a negligible growing rate of the CoMP hypothesis convergence delay with the increasing number of ONUs.

From the UEs perspective, the application of the CoMP-CS provides an improvement of the mobile network throughput for the lowest possible value of CoMP-CS periodicity, but for high user density the impact of increased periodicity is less significant. A reduction of the overall network capacity is observed for CS periodicity set at high values.

The considered approach focuses on centralized and distributed RRM. In future work we will evaluate CoMP-CS performance in centralized RAN with decoupled eNodeB into radio unit, distributed unit and central unit (i.e., next generation RAN).

APPENDIX

If we model the X2 transmission as a server vacation for the S1 traffic, the S1 waiting time, introduced by the vacation, can be expressed as half the average vacation time [28]. The X2 transmission time associated to the CoMP-CS process can be calculated as a function of the number of involved ONUs, thus it depends on the adopted CS scheme, either CCS or DCS. The entire CS process involves both upstream and downstream X2 transmissions. The XG-PON capacity is asymmetric, the downstream capacity is almost four times higher the one upstream. In light of the above considerations, the S1 waiting time is most severe in the upstream direction.

In the presence of N ONUs transmitting X2 CoMP hypothesis messages of length L (in bytes) each, with an available upstream bandwidth BW_{UP}, the S1 waiting time can be expressed in CCS as:

$$W_{S1}^{CCS} = \frac{8 \cdot N \cdot L}{2 \cdot BW_{UP}} \tag{1}$$

and in DCS case:

$$W_{S1}^{DCS} = \frac{[N \cdot (N-1) \cdot L \cdot 8]}{2 \cdot BW_{UP}}. \tag{2}$$

By comparing eq. (1) with eq. (2) it can be observed that while the W_{S1}^{CCS} grows linearly with the number of eNodeB-ONUs, the W_{S1}^{DCS} grows quadratically, because each eNodeB-ONU must transmit its CoMP hypothesis to the other $(N-1)$ eNodeBs, resulting in a total of $N \cdot (N-1)$ exchanged messages. Thus, in CCS S1 traffic is less impacted by the prioritization of X2 traffic than in DCS.

REFERENCES

[1] *RAN Evolution Project CoMP Evaluation and Enhancement*, NGMN, Frankfurt, Germany, Mar. 2015.
[2] *Evolved Universal Terrestrial Radio Access (E-UTRA) and Evolved Universal Terrestrial Radio Access Network (E-UTRAN); Overall description; Stage 2*, document 3GPP TS 36.300 Release 13, Dec. 2016.
[3] T. Chen, M. Matinmikko, X. Chen, X. Zhou, and P. Ahokangas, "Software defined mobile networks: Concept, survey, and research directions," *IEEE Commun. Mag.*, vol. 53, no. 11, pp. 126–133, Nov. 2015.
[4] A. S. Thyagaturu, A. Mercian, M. P. McGarry, M. Reisslein, and W. Kellerer, "Software defined optical networks (SDONs): A comprehensive survey," *IEEE Commun. Surveys Tuts.*, vol. 18, no. 4, pp. 2738–2786, 4th Quart., 2016.
[5] *RAN Evolution Project CoMP Evaluation and Enhancement*, NGMN, Frankfurt, Germany, Mar. 2015.
[6] F. Musumeci, E. D. Silva, and M. Tornatore, "Enhancing RAN throughput by optimized comp controller placement in optical metro networks," *IEEE J. Sel. Areas Commun.*, vol. 36, no. 11, pp. 2561–2569, Nov. 2018.
[7] G. Nardini, G. Stea, A. Virdis, A. Frangioni, L. Galli, D. Sabella, and G. Dell'Aera, "Practical feasibility, scalability and effectiveness of coordinated scheduling algorithms in cellular networks towards 5G," *J. Netw. Comput. Appl.*, vol. 106, pp. 1–16, Mar. 2018.
[8] G. Y. Li, J. Niu, D. Lee, J. Fan, and Y. Fu, "Multi-cell coordinated scheduling and MIMO in LTE," *IEEE Commun. Surveys Tuts.*, vol. 16, no. 2, pp. 761–775, 2nd Quart., 2014.
[9] K. Kwak, H. Lee, H. W. Je, J. Hong, and S. Choi, "Adaptive and distributed CoMP scheduling in LTE-advanced systems," in *Proc. IEEE 78th Veh. Technol. Conf. (VTC Fall)*, Sep. 2013, pp. 1–5.
[10] O. D. Ramos-Cantor, J. Belschner, G. Hegde, and M. Pesavento, "Centralized coordinated scheduling in LTE-Advanced networks," *EURASIP J. Wireless Commun. Netw.*, vol. 2017, no. 1, p. 122, Dec. 2017.
[11] S. Kuwano, "Operator perspective on next-generation optical access for future radio access," in *Proc. IEEE Int. Conf. Commun. Workshops (ICC)*, Jun. 2014, pp. 376–381.
[12] J. A. Arokkiam, K. N. Brown, and C. J. Sreenan, "Optimised QoS-aware DBA mechanisms in XG-PON for upstream traffic in LTE backhaul," in *Proc. IEEE 4th Int. Conf. Future Internet Things Cloud Workshops (FiCloudW)*, Aug. 2016, pp. 361–368.
[13] N. P. Anthapadmanabhan, A. Walid, and T. Pfeiffer, "Mobile fronthaul over latency-optimized time division multiplexed passive optical networks," in *Proc. IEEE Int. Conf. Commun. Workshop (ICCW)*, Jun. 2015, pp. 62–67.
[14] A. Marotta, K. Kondepu, F. Giannone, D. Cassioli, C. Antonelli, L. Valcarenghi, and P. Castoldi, "Impact of CoMP VNF placement on 5G coordinated scheduling performance," in *Proc. Eur. Conf. Netw. Commun. (EuCNC)*, Jun. 2017, pp. 1–6.

[15] A. Marotta, F. Giannone, K. Kondepu, D. Cassioli, C. Antonelli, L. Valcarenghi, and P. Castoldi, "Reducing CoMP control message delay in PON backhauled 5G networks," in *Proc. 23th Eur. Wireless Conf. Eur. Wireless*, May 2017, pp. 1–5.

[16] A. Marotta, K. Kondepu, F. Giannone, S. Doddikrinda, D. Cassioli, C. Antonelli, L. Valcarenghi, and P. Castoldi, "Performance evaluation of CoMP coordinated scheduling over different backhaul infrastructures: A real use case scenario," in *Proc. IEEE Int. Conf. Sci. Electr. Eng. (ICSEE)*, Nov. 2016, pp. 1–5.

[17] *Evolved Universal Terrestrial Radio Access (E-UTRA) and Evolved Universal Terrestrial Radio Access Network (E-UTRAN)*, document 3GPP TS 36.300 Release 14, Sep. 2016.

[18] *Coordinated Multi-Point Operation for LTE Physical Layer Aspects*, document 3GPP TR 36.819 Release 11, Sep. 2013.

[19] *X2 Application Protocol (X2AP)*, document 3GPP TS 36.423 Release 15, Sep. 2018.

[20] *Evolved Universal Terrestrial Radio Access (E-UTRA); Physical Layer Procedures*, document 3GPP TS 36.213 Release 13, May 2016.

[21] 5GPPP Architecture Working Group. (Jul. 2016). View on 5G architecture. White Paper. [Online]. Available: https://5g-ppp.eu/wp-content/uploads/2014/02/5G-PPP-5G-Architecture-WP-July-2016.pdf

[22] *NS-3 Network Simulator*. Accessed: Oct. 14, 2019. [Online]. Available: https://www.nsnam.org/

[23] G. Piro, N. Baldo, and M. Miozzo, "An LTE module for the NS-3 network simulator," in *Proc. 4th Int. ICST Conf. Simulation Tools Techn.*, Brussels, Belgium, 2011, pp. 415–422.

[24] X. Wu, "An XG-PON module for the NS-3 network simulator," in *Proc. Workshop NS-3*, 2013, pp. 195–202.

[25] J. A. Arokkiam, X. Wu, K. N. Brown, and C. J. Sreenan, "Experimental evaluation of TCP performance over 10gb/s passive optical networks (XG-PON)," in *Proc. IEEE Global Commun. Conf.*, Dec. 2014, pp. 2223–2228.

[26] M. Rupp, S. Schwarz, and M. Taranetz, *The Vienna LTE-Advanced Simulators: Up and Downlink, Link and System Level Simulation* (Signals and Communication Technology), 1st ed. Singapore: Springer, 2016.

[27] *Technical Specification Group Radio Access Network, Deployment Aspects*, document 3GPP TS 25.943, Dec. 2008.

[28] L. Valcarenghi, M. Chincoli, P. Monti, L. Wosinska, and P. Castoldi, "Energy efficient PONs with service delay guarantees," in *Proc. Sustain. Internet ICT Sustainability (SustainIT)*, Oct. 2012, pp. 1–8.

ANDREA MAROTTA received the B.Sc. and M.Sc. degrees in computer engineering from the University of L'Aquila, Italy, where he is currently pursuing the Ph.D. degree with the Department of Information Engineering Computer Science and Mathematics, under the supervision of Dr. C. Antonelli. During his graduate studies, he was a Visiting Student with the Group for Research on Wireless (GROW), Instituto Superior Técnico/University of Lisbon, performing research on C-RAN deployment optimisation. He spent one year as a Visiting Ph.D. at the Research Institute of Communication, Information and Perception Technologies (TeCIP), Scuola Superiore di Studi Universitari e di Perfezionamento Sant'Anna, Pisa, performing research on 5G Radio Access Network design. He performs research on 5G fronthaul optimisation, CoMP Coordinated Scheduling, PON fronthauling for 5G, and 5G Software Defined Access.

DAJANA CASSIOLI was a Summer Manager with the Wireless Systems Research Department, AT&T Labs-Research, NJ, USA, in 2000. She was the Director of the Associated Laboratory of RADIOLABS, University of L'Aquila, Italy, from 2005 to 2012. She has been the Coordinator of the University of L'Aquila Node of the National Laboratory of Cyber-Security of the National Inter-University Consortium for the Computer Science (CINI), since 2015. She is currently an Associate Professor with the Department of Information Engineering, Computer Science and Mathematics, University of L'Aquila. She has also been involved in several European projects as a Local Scientific Officer or a WP Leader. Since 2009, she serves as an Expert for the European Commission, for Review and Evaluation of European Projects, and for several national institutions in different countries. She is author and coauthor of tens of publications on prestigious International Journals and Conferences. Her main research interests are in the fields of wireless communications, 5G, software defined networks, IP networking, and network security. She serves as a TPC Member of International Conferences, such as the ICC, PIMRC, VTC, and GLOBECOM. She is a member of ComSoc and CompSoc. She has also been awarded the ERC Starting Grant VISION (Video-oriented UWB-based Intelligent Ubiquitous Sensing) (five years; 1.2M*e*), in 2010, and the ERC Proof-of-Concept Grant iCARE, in 2016. She served as the CEO from 2014 to 2018, and the COO in 2018 for the spin-off of the University of L'Aquila SMARTLY: Natives of smart living s.r.l. She served as the Chair for the IEEE Joint VT06/COM19 Italy Chapter, from 2011 to 2017. She is also the Chair of the WIE AG of the IEEE Italy Section, in 2016. She is an Editor of the *IET Electronic Letters*, the IEEE Communications Letters, *Internet Technology Letters*, and *Transactions on Emerging Telecommunications Technologies*. She participated in the definition of the standard channel model for the IEEE 802.15.4, in 2005.

CRISTIAN ANTONELLI received the M.Sc. and Ph.D. degrees in electrical engineering from the University of L'Aquila, Italy, in 2002 and 2006, respectively. Since 2007, he has been a Senior Research Scientist first at CNISM, the Italian Inter-University Consortium for the Physics of Matter, and then at the University of L'Aquila. He is currently a Tenure-Track Assistant Professor with the Department of Physical and Chemical Sciences, University of L'Aquila (in early 2018, he qualified for the position of a Full Professor, and his tenure will be processed, in 2019). He performs research in the area of fiber-optic communications, with focus on the analysis and design of high-speed systems. These include primarily space-division multiplexing in multimode and multicore fibers and advanced direct-detection systems. Previously, he has worked on polarization-entanglement based QKD in optical fibers. He coauthored more than 120 articles in international journals and leading international conferences, where he gave numerous invited talks. He is a co-inventor of seven U.S. patents. He chaired sub-committee S5 ("Digital transmission systems") for OFC 2017, and served multiple years as a TCP Member for OFC, ECOC, and CLEO. Since 2014, he has been an Associate Editor of the IEEE/OSA Journal of Lightwave Technology.

KOTESWARARAO KONDEPU received the Ph.D. degree in computer science and engineering from the Institute for Advanced Studies Lucca (IMT), Italy, in July 2012. He is currently a Research Fellow with Scuola Superiore Sant' Anna, Pisa, Italy. His research interests are 5G, optical networks design, energy efficient schemes in communication networks, and sparse senor networks.

LUCA VALCARENGHI has been an Associate Professor with the Scuola Superiore Sant'Anna, Pisa, Italy, since 2014. He published more than 100 articles in International Journals and Conference Proceedings and actively participated in the TPC of several IEEE conferences, such as Globecom and ICC. His main research interests are optical networks design, analysis, and optimization; artificial intelligence optimization techniques; communication networks reliability; fixed and mobile network integration; fixed network backhauling for mobile networks; and energy efficiency in communications networks. Dr. Valcarenghi received a Fulbright Reaserch Scholar Fellowship, in 2009, and a JSPS "Invitation Fellowship Program for Research in Japan (Long Term)," in 2013.