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Interference and QoS aware cell switch-off strategy for software defined LTE HetNets

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ABSTRACT

LTE-Heterogeneous Networks (HetNets) with dense deployment of small cells are expected to effectively meet unprecedented ever increasing data traffic demands and offer improved coverage in indoor environments. However, HetNets are raising major issues to Mobile Network Operators (MNOs) such as complex distributed control plane management and increased energy costs. Hence, MNOs are looking for flexible software defined mobile architectures to reduce their capital expenditure (CAPEX) and operational expenditure (OPEX). In this work, in order to reduce energy costs of the HetNets, we propose an interference and QoS aware cell switch-off strategy (IQ-CSOS) on a software defined LTE Radio Access Network (SD-LTE-RAN) framework. Unlike existing CSOSs, IQ-CSOS investigates both network energy costs and QoS satisfaction of sessions during CSOS decisions. In performance evaluation under various test scenarios, it is found that IQ-CSOS is able to provide 50–80% of network energy savings. Besides, it is able to provide 30% more energy savings compared to existing CSOSs with slight affect on network QoS.

1. Introduction

Proliferation of smart mobile devices and their applications demand Mobile Network Operators (MNOs) to expand their existing infrastructure to address coverage and capacity issues. In anticipation of these demands, MNOs started Heterogeneous Networks (HetNets) (Andrews et al., 2012) deployment with various small cells (Femto Base Stations (FBSs), pico, micro, *etc.*) for expanding network coverage and offering higher data rates. However, dense deployment of small cells increases complexity in handling Radio Access Network (RAN) control plane tasks like load balancing, interference management, handover management, and energy savings. In distributed Long Term Evolution (LTE)-RANs, in order to solve control tasks efficiently, small cells need to exchange lots of messages containing cells loads, scheduling and handover details over X2 interface with neighbor cells. And deployment of a lot of small cells increases capital expenditure (CAPEX) and operational expenditure (OPEX) of MNOs. Besides, energy consumption incurs 13–26% of OPEX while 65–75% of it is contributed by Base Stations (BSs or eNBs) deployed at cell sites (Richter et al., 2009; Alaca et al., 2012; Rao and Fapojuwo, 2014; Soh et al., 2013). Consequently, BSs higher energy consumption is alone contributing to 80% of carbon emissions from mobile networks (Rao and Fapojuwo, 2014; Ashraf et al., 2011). Aforementioned issues raised the need of simplification of control and management tasks of HetNets and efficient usage of network resources. For achieving these targets, MNOs are looking for programmable and flexible architectures, where hardware resources or software solutions can be dynamically scaled up or down based on traffic demands. And unused resources (*e.g., BSs*) can be switched-off to reduce energy consumption. Recent advances in Software Defined Networking (SDN) and Network Functions Virtualization (NFV) are promising to offer economical, open, flexible, and scalable solutions to MNOs (Zhou et al., 2016; Costa-Requena et al., 2015; Checko et al., 2015; Sun et al., 2015; Rost et al., 2014; Chen et al., 2014) and there by reduce their CAPEX and OPEX.

In general to effectively handle coverage and capacity issues in crowded places like shopping malls, airports or railway stations, MNOs deploy small cells under Macro eNBs as shown in Fig. 1. In proposed work, we used FBSs as small cells. These indoor FBSs are typically configured in Closed Access (CA) mode, hence only Closed Subscriber Group (CSG) User Equipments (UEs) can attach to them. Although FBSs are deployed to handle high traffic demands in crowded places, during late night hours or non busy timings most of the FBSs go idle. Moreover,

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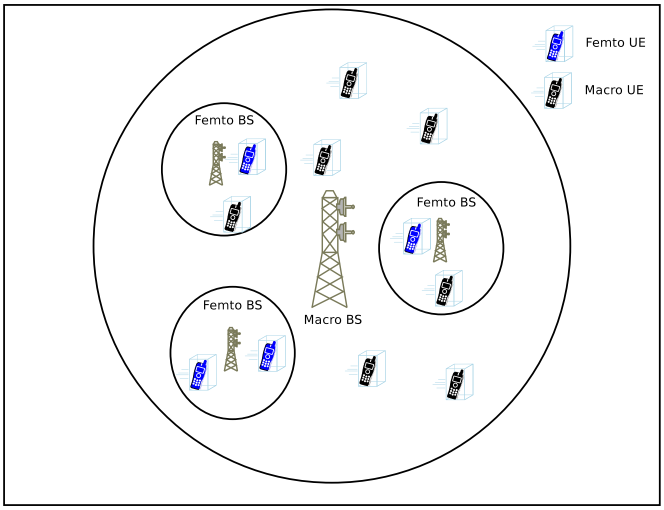

Fig. 1. A simple LTE-HetNet deployment.

some of Macro UEs can fall under FBSs coverage and suffer with low signal-to-interference-plus-noise ratio (SINR) due to interference from FBSs as frequency reuse one is employed in LTE HetNets. This particular issue can lead to higher resource blocks consumption of Macro eNBs. To address this issue, during non busy traffic hours, some of the FBSs can be switched-off to reduce interference and energy costs to MNOs.

In order to improve energy savings to operators, there are several CSOSs proposed, which are based on density of UEs, UEs positions, traffic load, and interference of the network (Alaca et al., 2012; Rao and Fapojuwo, 2014; Soh et al., 2013; Oh et al., 2011; Bousia et al., 2012a, b; Liu et al., 2014; Nabuuma et al., 2015; Oikonomakou et al., 2015; Dudnikova et al., 2015). Most of these solutions are evaluated in terms of active number of BSs, energy savings, and network coverage probabilities. But improper decisions of CSOSs during cell selection for switch-off can lead to network overload and Guaranteed Bit Rate (GBR) dissatisfaction to UEs. Hence, the CSOSs performance should also be evaluated in terms of network load and GBR satisfaction of UEs. In this work, we are addressing energy savings issues by Cell Switch-Off (CSO) operation in LTE HetNets using Software Defined-LTE-Radio Access Network (SD-LTE-RAN) framework (Rangisetti Tammaet al., 2016). The SD-LTE-RAN framework has been proposed to create centralized RAN with OpenFlow enabled eNBs (OFeNBs) and a centralized SDN controller. In (Rangisetti Tammaet al., 2016), we proposed a QoS Aware Load Balance (QALB) (Rangisetti Tammaet al., 2016) algorithm for addressing load imbalance issues of the RAN. In this work to reduce energy costs, an Energy Savings Module (ESM) is proposed on SD-LTE- RAN framework. A novel CSOS called interference and QoS aware CSOS (IQ-CSOS) is implemented at the ESM of SD-LTE-RAN framework. Further details of SD-LTE-RAN framework are discussed later in Section 3.

The main contributions of this work are summarised below:

- Proposed an ESM, which helps in realizing various CSOSs on SD-LTE-RAN framework.
- Proposed a novel CSOS called IQ-CSOS for improving total network energy savings with nominal affect on GBR satisfaction of UEs.
- Implemented three recent CSOSs: load aware-CSOS (LA-CSOS) (Nabuuma et al., 2015), interference and traffic aware-CSOS (IT-CSOS) (Dudnikova et al., 2015), and minimum RBU aware-CSOS (MinRBU-CSOS) (Oikonomakou et al., 2015) on the SD-LTE-RAN framework.
- Finally, we evaluated performance of all CSOs in various traffic load and interference variation scenarios. In evaluation, we found that IQ-CSOS is able to offer up to 30% of more energy savings compared to the existing CSOSs.

2. Related work

In order to reduce energy consumption in mobile networks, several Cell Switch-Off Strategies (CSOSs) have been proposed, which run periodically during low traffic load timings of the network and determine which cells to be switched-off. Some early works are based on density of UEs, distance between UEs and BSs, and traffic load of the network (Alaca et al., 2012; Rao and Fapojuwo, 2014; Soh et al., 2013; Oh et al., 2011; Bousia et al., 2012a, 2012b; Liu et al., 2014). Recent works proposed more intelligent solutions based on cell traffic load, UEs QoS, and interference (Zhang et al., 2017a, b, 2018; Le-The et al., 2017; Dolfi et al., 2017; Soliman and Song, 2017; Nabuuma et al., 2015; Oikonomakou et al., 2015; Dudnikova et al., 2015).

In (Zhang et al., 2017b), the authors proposed a load aware UEs association mechanism in the context of millimeter wave based ultra dense networks by considering load of neighbor BS, minimum bit rate requirement of UEs, and cross-tier interference. While minimizing energy consumption of BSs, the minimum SINR required by UEs to associate with BSs is determined based on UEs minimum bit rate requirement and load of neighbor BSs. The authors formulated UEs association with BSs as a mixed integer programming problem with constraints of cross-tier interference and QoS requirement of UEs. Besides, a practical iterative gradient UEs association and power allocation algorithm is proposed. However, the authors did not consider switching off small cells during less traffic load. But in our work, we focused on switching off small cells to save energy consumption of the network.

In (Zhang et al., 2018), the authors have studied energy efficient resource allocation in software defined heterogeneous Visible Light Communications (VLC) and RF Networks. Energy efficient resource allocation and power allocation problem is formulated as a mixed-integer programming problem with constraints of energy efficiency, inter-cell interference, QoS requirement, and backhaul capacity. Aforementioned constraints help to protect small cells from interference and guarantee reliable transmissions. Energy efficient resource allocation and power control distributed practical algorithms are proposed for both VLC and small cells.

In (El Morabit et al., 2017), the authors proposed a genetic algorithm to switch-off small cells during low traffic periods. This is a dynamically cell switch-off algorithm, considers traffic loads of a cell and its neighbor cells. Besides, it also considers coverage provided by multiple interfering cells. In (Lagum et al., 2017), the authors proposed a cell switch-off algorithm which maximizes spatial deployment regularity with remaining active base stations. Unlike most of the cell switch-off algorithms, this algorithm aims to maximize network coverage probability and energy savings. This approach is tested in highly irregular base stations deployment and observed better results compared to random cell switch-off algorithms. In (Bousia et al., 2012b), the authors proposed a distance aware base station (eNB) sleeping strategy to run off-peak traffic load periods. The idea is to switch-off an eNB not according to its traffic load, but according to the average distance of its UEs, because longer distances between UEs and the eNB can result into higher transmission power consumption. In (Oh et al., 2013), the authors proposed dynamic switch on/off strategies for green cellular networks, where BSs exchange network load and UEs signal strengths. A cell is switched-off, if it is not leading to network overload. During switch-on phase, it selects a neighbor BS (previously switched-off) to the loaded BSs to offload some load from the loaded BS. One more major contribution of this work is that the authors provided first order numerical analysis on number of BSs switched-off and energy savings with a naive switch-off approach. Performance of the algorithm is evaluated in terms of energy savings ratio, system load, and number of neighbor BSs required during various cell switch-off cases.

In (Nabuuma et al., 2015), the authors proposed a load aware small cell switch-off algorithm, which considers minimum traffic load or Resource Block Utilization (RBU) of the cell to choose a candidate cell for switch-off. To control traffic load from switched-off cell to neighbor cells, the proposed algorithm considers cells that are having RBU less than a threshold. This algorithm also considered UEs QoS during switch-off decisions. This algorithm performance was studied in terms of active number of base stations, energy consumption and UEs coverage probability.

In (Oikonomakou et al., 2015), the authors proposed a cooperative BS switch-off algorithm for HetNets. The algorithm considers the lowest traffic load cell as a candidate cell for switch-off. Before switch-off it tries to handover all UEs of the selected cell to neighbor cells, which can serve the UEs with the best signal strength and minimum number of RBs. In addition, the algorithm also considers, roaming cost to neighbor cell during handovers. Although the authors proposed that during UEs association their QoS also is ensured, results about UEs QoS affect and cell loads were not provided. The algorithm performance was studied in terms of active base stations, network energy efficiency, and network power consumption.

In (Dudnikova et al., 2015), the authors proposed a traffic and interference aware strategy. The proposed strategy considers less loaded cells as candidate cells to switch-off and selects the candidate cell which is causing highest interference to the neighbor cells. If all the UEs from the selected cell can be handovered to neighbor cells, then the cell will be switched-off. The algorithm performance was studied in terms of active FBSs and network energy savings. Recently in HyCell work (Zhao et al., 2015), the authors proposed green base station operations using software defined RAN. A separation scheme is proposed to realize the decoupled air interface for existing 3GPP standards so that BSs can be configured in Control Base Station (CBS) or Traffic Base Station (TBS) modes. The authors also proposed an algorithm for handling high traffic loads with help of CBSs. CBSs will monitor traffic load of various BSs and dynamically configure TBSs to handle higher traffic loads. In order to save energy of the network, during low traffic loads, CBSs will dynamically configure some of the TBSs in sleep mode. Feasibility of their work is studied in a real time testbed.

Unlike these works, we have focused on software defined HetNets with small cells only. Besides to maximize energy savings in HetNets, an IQ-CSO centralized cell switch-off strategy is proposed on SD-LTE-RAN (Rangisetti Tammaet al., 2016) framework in the ESM. Unlike existing CSOSs, IQ-CSOS proposed in this work considers both QoS (GBR details of UEs, RB Utilization (RBU) of BSs or cells) and victim UEs (VUEs) of Macro eNBs, which are suffering from Femtos interference. As a result it minimizes cross-tier interference effect on overlaying Macro BSs and co-tier interference among small cells and provides opportunity to switch-off more small cells to minimize total energy consumption of the HetNet. In Section 3.3, we discussed how cross-tier interference can effect resource block utilization of overlaying Macro BSs. IQ-CSOS periodically monitors network overload, RBU and number of victim UEs of Macro eNBs, which are suffering with poor SINR due to Femtos interference. And it uses aforementioned details during selection of a candidate small cell to switch-off and handover of its UEs. Performance of the CSOSs are evaluated in terms of network overload, GBR satisfaction, packets lost ratio, number of active BSs and total energy savings in terms of network energy consumption due to small cells and OPEX for energy consumption.

3. Proposed work

This section is organized as follows. Section 3.1 presents SD-LTE-RAN framework and how the framework is used for improving energy efficiency of LTE-HetNets. In Section 3.2, various parameters required for designing proposed IQ-CSOS are defined. In Section 3.3, motivational results for proposed IQ-CSOS are discussed. Finally, in Section 3.4 the proposed IQ-CSOS and some of the existing CSOSs are presented.

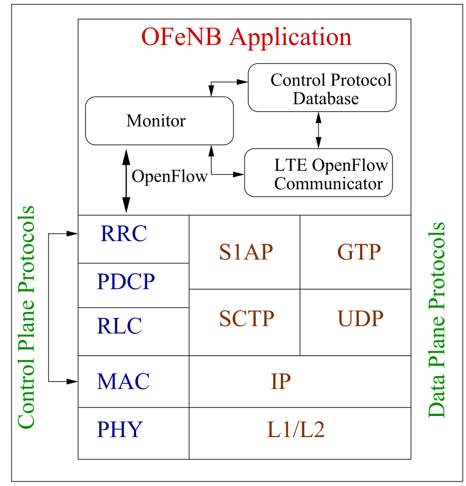

Fig. 2. Architecture of OFeNB.

3.1. SD-LTE-RAN framework for energy savings

Traditional LTE RAN and EPC components make use of various proprietary solutions from vendors for addressing issues related to interference management, load balancing, energy savings, handovers, pricing, and traffic engineering. Therefore, addition of new solutions or modification of existing solutions is expensive in traditional LTE deployments. There are a few existing software defined solutions (Zhou et al., 2016; Costa-Requena et al., 2015; Checko et al., 2015; Sun et al., 2015; Rost et al., 2014; Chen et al., 2014; Gudipati et al., 2013) to simplify LTE deployments. In (Rangisetti Tammaet al., 2016), we proposed SD-LTE-RAN framework with OpenFlow (OpenFlow Switch Specification 1.1.0) enabled eNBs (OFeNBs), in order to simplify complex RAN control plane tasks with minimal changes to legacy LTE-architecture and provide programmable, flexible and scalable solutions. Unlike existing works, in SD-LTE-RAN framework, data and control planes of eNBs are not separated or virtualized. However, an OpenFlow application is integrated with traditional eNB as shown in Fig. 2 to monitor necessary RAN details available at eNBs and control RAN with simplified network view provided by the SDN controller. Because of this approach, traditional procedures between LTE-RAN and EPC, like UEs connection management, bearer establishment or change procedures are not affected. Besides, eNB's system information broadcast functions, radio resources management functions, and UEs attach and detach procedures are also not changed. The SD-LTE-RAN framework offers abstraction of underlying complex RAN control plane and monitors necessary RAN information in a centralized way to implement network aware RAN applications like load balance, interference management, energy savings, *etc.*

The SD-LTE-RAN framework is realized using OFeNBs and a centralized SDN controller as shown in Fig. 4. Its main features are as follows:

- No changes to the existing interactions of eNB LTE data plane and EPC components.
- No changes to the existing tunnel management procedures between eNBs and EPC components.
- No changes to the UE protocol stack.
- An OpenFlow eNB application is installed over LTE eNB control plane protocol stack to help eNB to communicate with the controller.
- Monitors only necessary control signals between OFeNB and EPC components for required RAN applications like load balance, interference management, energy savings, *etc.*

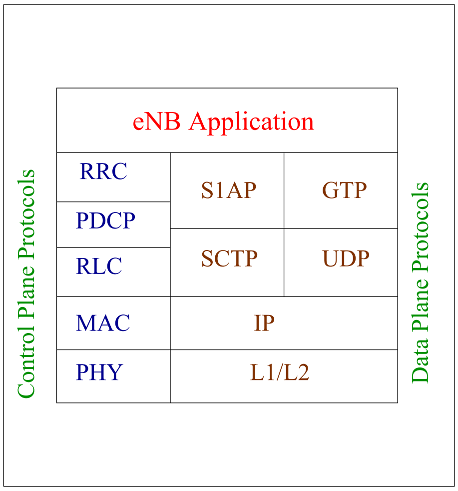

Fig. 3. Architecture of traditional eNB.

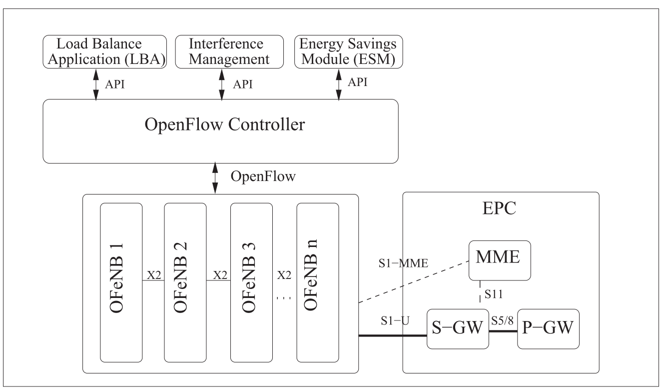

Fig. 4. Architecture of SD-LTE-RAN (Rangisetti Tammaet al., 2016).

- The SDN controller provides a simplified centralized view of underlying LTE-RAN to applications running over it.

In SD-LTE-RAN framework, various RAN applications can be deployed at the SDN controller. In order to provide centralized solutions for RAN applications, monitoring of eNBs for cell loads and scheduling details from MAC layer, and UEs connection, bearers details and handover measurement reports from RRC layer is necessary. The architecture of OFeNB as shown in Fig. 2, used in the SD-LTE-RAN framework, is designed with minimal changes to traditional eNB (FBS, pico, micro and Macro) architecture which is shown in Fig. 3. OFeNB application is used for monitoring RRC and MAC layers of eNB as shown in Fig. 2. Proposed OFeNBs send necessary RAN details to the SDN controller as per the need of applications deployed at the SDN controller. Hence, the SDN controller of the framework provides abstraction of underlying complex RAN by various APIs for accessing its control information by RAN applications.

In this work, for LTE-RAN we proposed an Energy Savings Module (ESM) with CSOSs, which is designed with help of the SDN controller to switch-off some of the small cells (FBSs) of LTE-HetNets to reduce energy consumption. The ESM monitors necessary messages from MAC layer of all OFeNBs to assist CSOSs with periodic load, scheduling details, and GBR satisfaction of UEs. And it also monitors RRC layer for UE's attach, detach, Reference Signal Received Quality (RSRQ), Reference Signal Received Power (RSRP) handover measurement reports, and QoS bearer modification messages. The ESM processes all these monitoring messages and maintains updated information related to OFeNBs and their connected UEs. In this work, various CSOSs from literature (MinRBU-CSO (Oikonomakou et al., 2015), LA-CSO (Nabuuma et al., 2015), IT-CSO (Dudnikova et al., 2015), and IQ-CSO) are also implemented with the help of the ESM.

The following SD-LTE-RAN OpenFlow messages (Rangisetti Tammaet al., 2016) are used in this work for exchanging necessary RAN details between OFeNBs and the SDN controller.

1. OFPT_LTE_ENB_ATTACH: This message is for ensuring successful attachment of OFeNB with the SDN controller. Each OFeNB sends its configuration details like bandwidth, transmission power, and CellID to the controller (ESM).
2. OFPT_LTE_X2_NEIGHBOR: This message is sent from an OFeNB to the ESM. It carries the list of neighbor OFeNBs that are connected to the current OFeNB over X2 interface.
3. OFPT_UE_ATTACH: This message is sent after a UE is successfully attached with an OFeNB. In this message, an OFeNB sends International Mobile Subscriber Identity (IMSI) and default QoS bearers information of the UE to the ESM.
4. OFPT_UE_DETACH: This message is sent after a UE is successfully detached from an OFeNB. In this message, an OFeNB sends UE details to the ESM, which helps it to maintain currently attached UE list of each OFeNB.
5. OFPT_UE_ACT_FLOW_RATE: This message is for informing configured GBR flow rates of UEs by OFeNBs to the controller. Whenever bearers of attached UEs are modified, OFeNBs send changes in bearer details to the ESM.
6. OFPT_UE_MEASUREMENT_REPORT: In LTE, RRC layer of each OFeNB is configured for receiving A2 and A4 events based neighbor cell RSRQ measurement reports from their connected UEs. Event A2 indicates that serving cell's RSRQ is lower than some given threshold. It indicates that the UE is experiencing poor signal quality from the serving cell. Event A4 indicates that neighbor cell's RSRQ becomes better than the threshold. OFeNBs use OFPT_UE_MEASUREMENT_REPORT messages for sending their connected UEs potential neighbor cells RSRQ measurement reports to the ESM at Measurement Report Interval (β). These messages are helpful to implement load balance and CSOS related handovers.
7. OFPT_ENB_LOAD: This message is used by cells for sending periodic load details to the ESM: Total UEs GBR Requirement (T-UGR), Total UEs actual Throughput (T-UETH), Total Used Resource Blocks (T-URB), and Total Resource Blocks Available (T-RBA) of OFeNB.
8. OFPT_CELL_CSO: This is a special message initiated by the ESM (IQ-CSO) to perform CSO and handovers in the network. During CSO, this message includes IMSI of the UE and CellID of the target OFeNB. CSO operation leads to handover of UEs from switching off OFeNB (source OFeNB) to a target OFeNB. OFPT_CELL_CSO message is delivered to the RRC layer of the source OFeNB. Then RRC layer of the source OFeNB starts standard X2-based handover (X2AP protocol 3GPP specification, 1364) signaling with the target OFeNB as shown in Fig. 5. ESM handles CSO related messages in RAN. IQ-CSOS or any CSOS runs on top of the ESM. As shown in Fig. 5, all remaining messages are standard X2 messages (X2AP protocol 3GPP specification, 1364) for handling handovers between source and target cells. We can also observe that our approach is not changing the standard X2 message exchange sequence, for handling handovers, among various standard LTE components like eNBs, MME, and S-GWs.
9. OFPT_CELL_CSO_SUCCESS: This message is for sending acknowledgment of successful CSO message from source OFeNB to the ESM.

   All the above messages can be created with the help of message structure shown in Fig. 6 (Rangisetti Tammaet al., 2016).

3.2. IQ-CSOS parameters

IQ-CSOS uses the following parameters for its decision making: load of OFeNBs, QoS (GBR) of UEs, and number of Macro UEs that are suf-

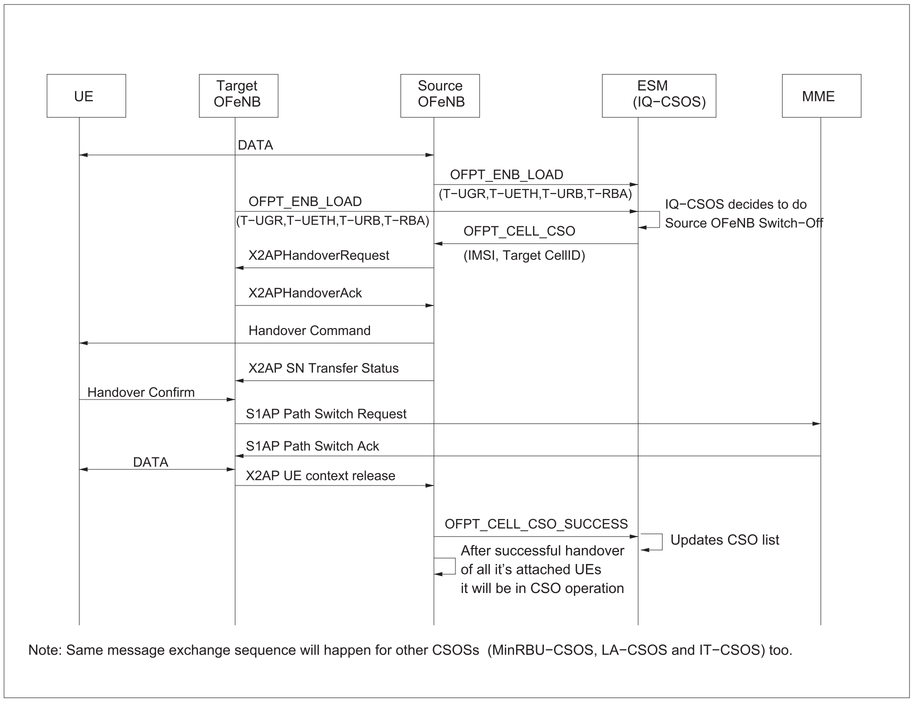

Fig. 5. Call flow diagram of CSO in SD-LTE-RAN framework.

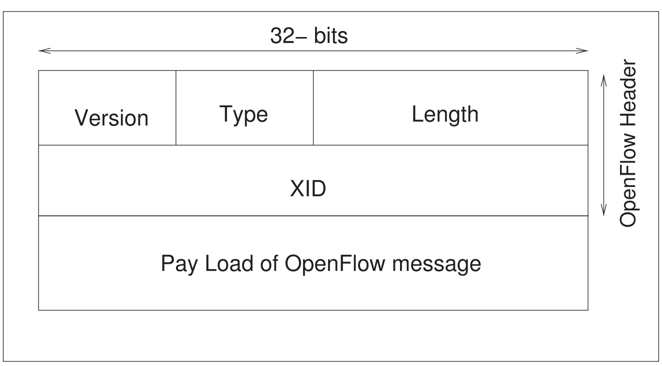

Fig. 6. Frame format of OpenFlow LTE messages.

fering due to cross-tier interference caused by FBSs. In rest of this work, the terms cross-tier interference and interference are used interchangeably.

IQ-CSOS considers both QoS parameters (GBR) of UEs and Resource Blocks Utilization (RBU) of the OFeNB to define overload of the OFeNB. RBU of the ith OFeNB (RBU_i) is given in Eqn. (1).

$$RBU_i = \frac{\sum_{j=1}^{k} URB_{i,j}}{TRBA_i} \tag{1}$$

Where, $URB_{i,j}$ is number of used RBs by jth UE which is connected to the ith OFeNB and k is the number of connected UEs to it. $TRBA_i$ is total number of resource blocks available at the ith OFeNB in a load reporting period (α). Due to reuse one in LTE networks, $TRBA_i$ is same in all periodic load reports from the ith OFeNB.

Load of an OFeNB is defined in terms of RBU of the OFeNB and GBR of UEs in every load reporting period (α). Load of the ith OFeNB ($eNBLoad_i$) is defined in Eqn. (2) (Szilágyi et al., 2012).

$$eNBLoad_i = \frac{\sum_{j=1}^{k} THT_{i,j}}{\sum_{j=1}^{k} GBR_{i,j}} \tag{2}$$

Where, $THT_{i,j}$ is the achieved/observed throughput of UE_j, $GBR_{i,j}$ is the GBR configured for UE_j when its bearer is established and k is the number of connected UEs to the $OFeNB_i$.

In order to consider both resource blocks utilization and QoS satisfaction details of UEs, for defining overload of an OFeNB, we used OverLoadRatio (OLR_i) of ith OFeNB as given in (Rangisetti Tammaet al., 2016). In a load report interval, even if RBU_i reaches above 95% and $eNBLoad_i \geq 1$, it indicates that all scheduled GBR UEs of the OFeNB are getting their configured GBRs and the cell is not loaded (IS_NOT_LOADED). Otherwise the cell is overloaded (IS_OVER_LOADED) because all the resource blocks are utilized but GBR UEs are still not getting their configured GBRs. OLR_i of ith OFeNB is defined in Eqn. (3). It takes values in the range of 0–1. It indicates overload percentage of $OFeNB_i$. From OLR, GBR satisfaction can be determined, for example, OLR = 0.5 of a cell indicates that UEs of the cell are getting only 50% of their configured GBRs *i.e.,* cell is 50% overloaded.

$$OLR_i = 1 - \min(1, eNBLoad_i) \tag{3}$$

As cell switch-off can lead to packet losses, we defined network Packet Loss Ratio (PLR) as follows:

$$PLR = \frac{TTXP - TRXP}{TTXP} \times 100 \tag{4}$$

Where TTXP is the total number of packets transmitted by all application level flows and TRXP is the total number of packets received by all application level flows.

In addition to above parameters, we define a new parameter called IQ_i of $OFeNB_i$ to estimate whether it is really facing interference or not. It is defined based on UEs GBR and their used RBs. To calculate IQ_i of ith OFeNB, the following inputs are taken into account:

- Macro UEs (which are getting RSRQ < $Threshold_{RSRQ}$), which are in interference region of neighbor FBSs are called VUEs. For a Macro $OFeNB_i$ with m VUEs, the total VUEs GBR requirement per second ($TV\,UGBR_i$) is defined as given in Eqn. (5) by summing up individual VUEs GBR. Similarly, the total VUEs RB used per second ($TV\,URB_i$) is defined as given in Eqn. (6) by summing up individual VUEs consumed RBs. Finally, VUEs RB consumption per bit ($V\,RBCPB_i$) is defined as given in Eqn. (7).

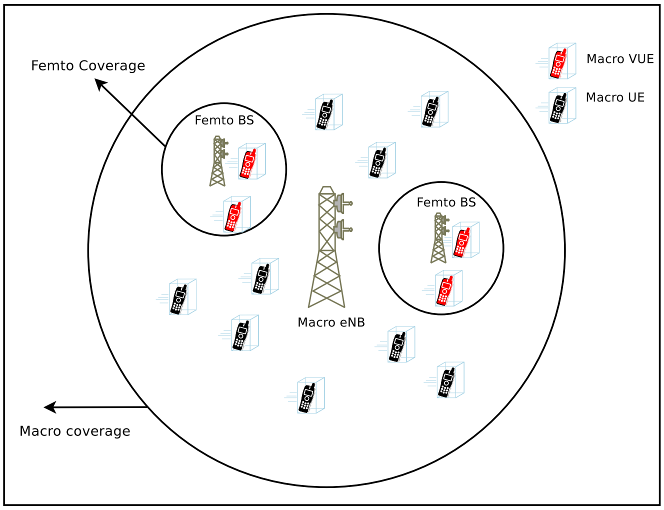

Fig. 7. HetNet topology considered for evaluating various test cases.

$$TVUGBR_i = \sum_{j=1}^{m} GBR_j \tag{5}$$

$$TVURB_i = \sum_{j=1}^{m} URB_j \tag{6}$$

$$VRBCPB_i = \frac{TVURB_i}{TVUGBR_i} \tag{7}$$

- Macro UEs which are in non-interference region are called non-victim UEs (N-VUEs). For a Macro OFeNB$_i$ with p N-VUEs, the total N-VUEs GBR requirement per second ($TNV\ UGBR_i$) is defined as given in Eqn. (8) by summing up individual N-VUEs GBR. Similarly, the total N-VUEs RB used per second ($TNV\ URB_i$) is defined as given in Eqn. (9) by summing up RBs consumed by N-VUEs. Finally, N-VUEs RB consumption per bit ($NV\ RBCPB_i$) is defined as given in Eqn. (10).

$$TNVUGBR_i = \sum_{j=1}^{p} GBR_j \tag{8}$$

$$TNVURB_i = \sum_{j=1}^{p} URB_j \tag{9}$$

$$NVRBCPB_i = \frac{TNVURB_i}{TNVUGBR_i} \tag{10}$$

IQ_i of a Macro OFeNB$_i$ is defined by using its $TV\ URB_i$, $TNV\ URB_i$, $V\ RBCPB_i$ and $NV\ RBCPB_i$. If ($TV\ URB_i > TNV\ URB_i$) and ($V\ RBCPB_i > NV\ RBCPB_i$), it means that VUEs of Macro OFeNB$_i$ are consuming more number of RBs due to poor SINR caused by cross-tier interference from FBSs and IQ_i is set to 1. Otherwise, IQ_i is set to 0. If $IQ_i = 1$, then strict total RB requirements condition (RBRC) check is relaxed for GBR UEs handovers. Otherwise strict RBRC is enforced for GBR UEs handovers. Strict RBRC will be true if the sum of TRBA$_t$ of the target Macro OFeNB$_t$ and T-URB$_s$ of the source Femto OFeNB$_s$ (which is going to be switched-off) is less than or equal to the maximum RBs available at the Macro OFeNB$_t$. Otherwise, it indicates that target Macro OFeNB$_t$ cannot satisfy GBR requirements of the Femto OFeNB$_s$.

3.3. Motivational result for IQ-CSOS design

In order to study the effects of cross-tier interference on network (neighbor Macro eNBs) performance in terms of OLR and RBU, we conducted a test scenario with following four cases:

1. Very High Interference (VH-INTF): In this case, 40% of Macro UEs are VUEs.
2. High Interference (HI-INTF): In this case, 30% of Macro UEs are VUEs.
3. Moderate Interference (MOD-INTF): In this case, 20% of Macro UEs are VUEs.
4. Low Interference (LOW-INTF): In this case, 10% of Macro UEs are VUEs.

The test scenario shown in Fig. 7 is configured with simulation parameters given in Table 1. FBSs are configured in CA mode, hence only CSG UEs can attach to FBSs. In each test case, according to interference level, Macro VUEs are spread in interference zones created by FBSs as shown in Fig. 7. Even in hotspots also during non business hours, most of the FBSs could be idle, however those FBSs could create cross-tier interference to Macro eNBs. Hence, aim of this scenario is to study FBSs (with no attached UEs) cross-tier interference affect on the Macro eNB in terms of OLR and RBU metrics.

In general before switch-off of any FBS, CSOSs should check whether any near by Macro eNB can meet RB requirements of all GBR UEs of the FBS. Otherwise too many FBSs switch-off can lead to network overload, *i.e.*, excessive traffic at Macro eNBs. Hence before switch-off of a FBS, if the Macro eNB can satisfy the RB requirements of GBR UEs of a FBS, then only the FBS will be switched-off. However, during interference conditions, the network RBU can vary drastically before and after FBSs switch-off. This effect can be clearly observed from Fig. 8. After switch-off of both FBSs, the neighbor Macro eNB consumes only 2% of RBs in the cell for meeting GBR requirements of its attached UEs. But, during interference situations RBU at Macro eNB varies from 24% (LOW-

Table 1
Simulation setup for interference test.

Simulator	NS-3.19 (NS-3.19; NS-3OpenFlow) with LENA and OpenFlow (OpenFlow Switch Specification 1.1.0)
# of Macro OFeNBs	1
# of Femto OFeNBs	2
# of Macro UEs	40
# of FBS UEs	0
LTE MAC Scheduler	Priority Set Scheduler (Monghal et al., 2008)
Default Handover Algorithm	A2A4Algorithm
OFeNB: Macro Tx Power	43 dBm
OFeNB: Femto Tx Power	23 dBm
PathLossModel	HybridBuildingsPropagationLossModel (NS-3.19)
Macro/FBS Bandwidth	50 RBs (Frequency Reuse-1)
Serving Cell Threshold	20 (3GPP RSRQ mapping (3GPP RSRQ Reference))
Hysteresis Threshold	5 (3GPP RSRQ mapping (3GPP RSRQ Reference))
UDP Application Traffic Downlink flow	64KBps GBR
Measurement Report Interval: β	125 ms
Load Report Interval: α	200 ms

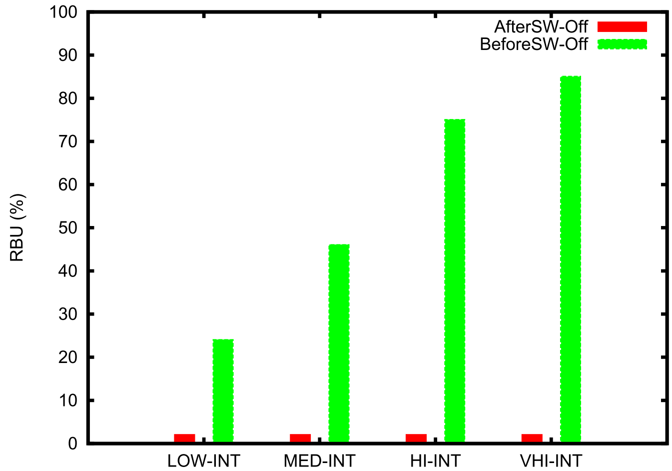

Fig. 8. Variation in RBU of Macro eNB for different interference levels: the plot shows as interference increases in the HetNet, the RBU of Macro BS also increases.

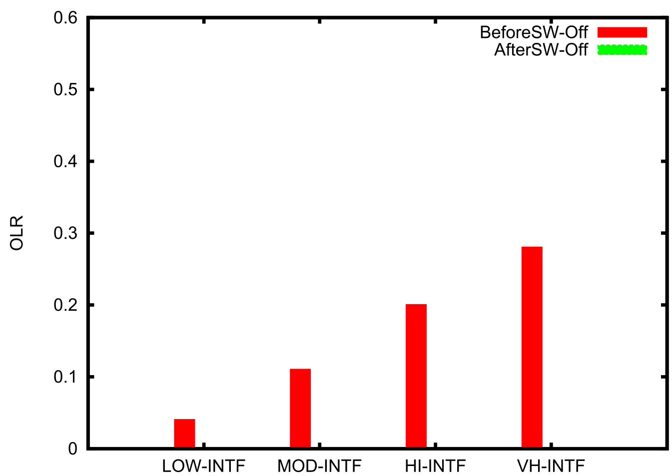

Fig. 9. Variation in OLR of Macro eNB for different interference levels: the plot shows that CSO can decrease interference in the network and reduces network OLR.

INTF) to 86% (VH-INTF) due to higher *TV URB* of VUEs compared to *TNV URB* of NVUEs. Especially, in HI-INTF and VH-INTF cases, RBU is very high (more than 72%) compared to actual RBU (only 2%) because VUEs with poor SINR are consuming more number of RBs. Similarly, OLR of the Macro eNB is also increasing drastically with increase in interference levels shown in Fig. 9. From Fig. 9, we can observe that before FBSs switch-off, network is overloaded due to cross-tier interference from FBSs but after FBSs switch-off network is not loaded (*i.e.,* OLR = 0). Hence in case of interference situations, OLR is over estimated and it is not accurate. As a result, strictly enforcing RB requirements of GBR UEs during CSO handovers could limit successful handover of UEs and there by affect maximum achievable energy savings. In order to solve issues related to interference situations, our proposed IQ-CSOS first selects high interference creating cells as target cells to switch-off. And during CSO-decisions, when neighbor cell's *IQ* is 1 *i.e.,* neighbor cell is really suffering from interference due to higher *TV URB* compared to *TNV URB*, then strict RB requirements condition for GBR UEs is relaxed for increasing the total energy savings. Otherwise, strict RB requirements condition for GBR UEs is enforced to limit the network overload.

3.4. IQ-CSOS

In this work, it is assumed that only FBSs can be switched-off for energy savings. Macro eNBs are not considered for switch-off for ensuring no coverage holes in network terrain. Hence, even after FBSs switch-off, their attached UEs can get connected to one of Macro eNBs. In the SD-LTE-RAN framework, Macro eNB and FBS are realized as OFeNBs.

Algorithm 1 Interference and QoS Aware Cell Switch-Off Strategy.

Initialization: IQ-CSOS configures all OFeNBs with load report in-terval
Inputs: Reads OFPT ENB LOAD messages from OFeNBs and updates their load estimates
Decision: Configure OFeNBs in CSO operation mode by OFPT CELL CSO command
IQ-CSOS runs periodically for every *t* seconds
loop
  hi_cellid ← *HICC()* {Returns the highest interference creating small cell in HetNet}
  can_ho_cnt ← 0 {Number of UEs that can be handovered}
  hicc_uescnt ← *T_AUEs(hi cellid)* {Number of attached UEs at hi-cellid}
  for each UE ∈ *hi_cellid* **do**
    ncell ← *MaxRsrqNeighborCell(UE_IMSI)* {Returns max RSRQ neighbor cell to the UE}
    NUERBs ← *U_RBS*(*UE_IMSI*, *hi_cellid*) {Number of RBs used by the UE from the hi_cellid}
    T_URB(*ncell*) ← *T_URB*(*ncell*) + *NUERBs* {In case of UE han-dover, estimating total RBs consumed at neighbor Macro by summing NUERBs}
    IQ_{ncell} ← 0
  {IQ is set to 1 when Macro VUEs are using higher number of RBs compared to NVUEs due to poor SINR because of FBSs cross-tier interfer- ence}
    if (($TVURB_{ncell} > TNV\ URB_{ncell}$) AND (V RBCPBncell > NV RBCPBncell)) **then**
      IQ_{ncell} ←1
    end if
    {In case of no cross-tier interference, checking RBs requirements for GBR UEs for determining number of UEs that can be handovered}
    if ($IQ_{ncell} = 0$) **then**
      if (*T_URB*(*ncell*) ≤ *MaxRBs*(*ncell*)) **then**
      can_ho_cnt ← *can_ho _cnt* + 1
    end if
    {Otherwise, relax RB requirements check for GBR UEs for determining number of UEs that can be handovered}
    else
      can_ho_cnt ← *can_ho_cnt* + 1
    end if
  end for
  {Handover all UEs of hi cellid to neighbor Macro BSs before switching it off}
  if (can_ho_cnt = *hicc_uescnt*) **then**
    for each *UE* ∈ *hi_cellid* **do**
      maxcell ← *MaxRsrqNeighborCell*(*UE_IMSI*) {Returns max RSRQ neighbor cell to the UE}
      Handover(*UE_IMSI*, *hi_cellid*, *maxcell*) {Handover the UE from hi_cellid to maxcell}
    end for
    Switch-off(*hi_cellid*)
  end if
end loop

Algorithm 2 High Interference Creating Cell (HICC).

1: **Initialization:** All OFeNBs configure their UEs with handover measurement reports A2 and A4
2: **Inputs:** Reads OFPT_UE_MEASUREMENT_REPORT messages and updates UEs neighbor cells information at the SDN controller
3: **Decision:** Returns CellID of HICC
4: **for each** $i \in$ {set of FBSs under Macro eNB} **do**
5: *NVUEs* ← *VUEsCntFromFBS*(i) {Get number of VUEs are suffering due to FBS_i}
6: *FBSVCNT*[i] ← *FBSVCNT*[i] + *NV UEs* {Count number of Macro VUEs that are having FBS_i as a neighbor cell in FBSVCNT[i]}
7: **end for**
8: *CellID* ← *MinRBUCell*(*FBSVCNT*) {Find CellID from FBSVCNT, which is having the least RBU and high Macro VUEs}
9: Return *CellID*

3.4.1. When to switch-on or switch-off BSs ?

In general, CSOSs will be active when network load is low (*e.g.,* non business hours) and indoor UEs traffic load can be borne by Macro eNBs. In proposed work, all FBSs will be **switch-on** during busy office/business working hours. Later, CSOSs will periodically monitor traffic loads of FBSs and try to switch-off maximum number of FBSs according to their CSO decisions.

3.4.2. IQ-CSOS description

In this work, in order to implement load aware handover decisions, we assumed that **total RB requirement of GBR UEs of a FBS is same before and after switching off of the FBS** in non interference scenarios. Hence before switch-off of a FBS, the CSOS checks that maximum RBs available at neighbor Macro eNB are sufficient to handle RB requirements of GBR UEs of the FBS. Pseudo code of the proposed IQ-CSOS is given in Algorithm 1 and the functions used in it are given in Table 2.

Cell selection for switch-off:

High Interference Creating Cell (HICC) (refer Algorithm 2) is used for selecting small cells/FBSs to switch-off. HICC considers both *RBU* of FBSs and interference effect of FBSs on Macro eNBs. For example, in HetNets with a Macro eNB and several FBSs, Macro UEs handover measurement reports can inform about their neighbor FBSs. Hence, it is possible to determine list of neighbor FBSs (*FBSV CNT*) of Macro UEs. HICC checks neighbor FBSs of each VUE of Macro eNB. Then, HICC updates number of VUEs that are affected by each FBS. Finally, it selects a FBS from *FBSV CNT*, which is affecting more VUEs and having minimum RBU as *hi-cell* (refer Algorithm 2). Finally, HICC returns the CellID of *hi-cell*.

Interference and QoS aware handovers during CSO:

IQ-CSOS runs periodically, and it uses periodic details *RBU*, *IQ* of OFeNBs, *T-UGR*, *T-URB*, and handover measurements of UEs. With the help of HICC (refer Algorithm 2), first selects a FBS (*hi-cellid*) with minimum RBU as a candidate cell to switch-off and checks whether all UEs of *hi-cellid* can be handovered to their *ncell* given by *MaxRsrqNeighborCell* (refer Algorithm 1). *MaxRsrqNeighborCell* returns CellID of the neighbor Macro eNB (*ncell*). To handover UEs of the *hi-cellid*, it checks neighbor Macro eNB *IQ* (IQ_{ncell}) and GBR requirements of UEs for handovers. If the IQ-CSOS checks and enforces both constraints strictly, it can end up with lesser energy savings. Hence, it needs to be aware of real interference situations and relax the RB requirements condition for GBR UEs to get the benefit after (*hi-cellid*) switch-off. Besides, it is necessary to ensure better GBR satisfaction to UEs without overloading neighbor Macro eNBs. To incorporate aforementioned two conditions into CSO decisions, *IQ* metric is used by IQ-CSOS. IQ_{ncell} metric is for confirming that really the neighbor Macro eNB (*ncell*) is suffering from interference due to the FBS (*hi-cellid*) or not. IQ_{ncell} depends on $TV\ URB_{ncell}$, $TNV\ URB_{ncell}$, $V\ RBCPB_{ncell}$ and $NV\ RBCPB_{ncell}$. If ($TV\ URB_{ncell} > TNV\ URB_{ncell}$) and ($V\ RBCPB_{ncell} > NV\ RBCPB_{ncell}$) then it means that VUEs are consuming higher number of RBs due to poor SINR and *ncell* is suffering from cross-tier interference from FBSs. Hence, IQ-CSOS by using *IQ*, if $IQ_{ncell} = 1$ then it relaxes the RB requirements condition for GBR UEs during handovers to the *ncell* (refer Algorithm 1, step 24), else it enforces RB requirements condition for GBR UEs during handovers (refer Algorithm 1, step 24). Finally, it checks that whether all UEs can be handovered and then it puts the *hi-cellid* cell in switch-off state, otherwise it selects next *hi-cellid* from the HICC algorithm for checking that for potential switch-off.

3.4.3. How IQ-CSOS differs from existing CSOSs ?

Unlike MinRBU-CSOS (Oikonomakou et al., 2015), IT-CSOS (Dudnikova et al., 2015) and LA-CSOS (Nabuuma et al., 2015), IQ-CSOS considers both interference and GBR for CSO decisions. In MinRBU-CSOS, it first chooses the set of lesser RBU FBSs as candidate small cells/FBSs to switch-off. In order to select minimum RBU FBSs, it sets a RBU threshold and selects FBSs which are less than the threshold. Hence during CSO operation, it leads to least amount of load offload from switching off FBSs to neighbor cells/Macro eNBs. Once a low RBU FBS is selected, it checks that all UEs of the FBS can be handovered to a neighbor Macro eNB, before switch-off the FBS. Drawback of this algorithm is that it is not enforcing RB requirements of GBR UEs during handovers. In case if it selects higher number of FBSs to switch-off, then the network can get overloaded.

In IT-CSOS, it first chooses a high interference creating FBS and checks that all UEs of the cell can be handovered to a neighbor Macro eNB. But it is not ensuring any GBR requirements of UEs during handovers, hence it can end up with severe degradation of GBR satisfaction. In order to avoid this issue by limiting number of FBSs to switch-off, IT-CSOS enforces low RBU threshold for selecting candidate small cells/FBSs to switch-off, but it could affect achievable energy savings.

LA-CSOS is enforcing load aware switch-offs and handovers. However, LA-CSOS is not considering interference into CSOS decisions. But it is enforcing RB requirements of GBR UEs during handovers to avoid overload to the network. But in case of interference scenarios, strict GBR requirements cannot be enforced, because after CSO operation, interference region created by FBS can be reduced and VUEs of the interference region can get higher SINR compared to their previous SINR. Hence after CSO operation, RBU of the network can be reduced. Because LA-CSOS is enforcing strict RB requirements check for GBR UEs handovers and not considering interference for cell selection for cells switch-off, it may not able to achieve maximum possible energy savings.

3.4.4. Controller overhead

Because of SDN and NFV based architectures evolution, the SDN controller can run on cloud platforms with abundant and elastic resources (Zhou et al., 2016; Sun et al., 2015). Hence, controller overhead and scalability may not be serious issues. How to configure the controller with required network bandwidth and processing resources were discussed in our previous work (Rangisetti Tammaet al., 2016). For instance, to implement energy saving CSOSs, all the cells in the network need to exchange eNBs transmission power, load, RBU reports and UEs GBR, RBU details among them. These periodic message exchange among huge number of small cells could lead to a lot of signaling overhead in traditional LTE-RAN distributed control plane. But in proposed centralized SD-LTE-RAN framework, signaling overhead is minimal compared to distributed LTE network with X2-based signal message exchanges, as each OFeNB or cell needs to send its details only to the central SDN controller. In order to estimate the total control signal overhead of the controller, we need to identify all signaling messages generated by cells present in the network and their connected UEs. Once

Table 2
List of functions used in IQ-CSO Algorithm.

HICC ()	Returns the highest interference creating CellID
T_AUEs (CellID)	Returns number of UEs attached with the given CellID
MaxRsrqNeighborCell (UE_IMSI)	Returns the max RSRQ neighbor cell to the given UE
T_URB (CellID)	Returns total used RBs of the given CellID
U_RBS(UE_IMSI, CellID)	Returns total RBs used by the given UE from the CellID
MaxRBs (CellID)	Maximum RBs configured for the CellID
Handover (UE_IMSI, SCellID, TCellID)	Handovers the UE from the source cell to the target cell
Switch-off (CellID)	Puts the cell in switch-off mode
MinRBUCell (ListOfCellIDs)	Returns the CellID which is having the minimum RBU
VUEsCntFromFBS(CellID)	Returns number of Macro VUEs under given Femto CellID

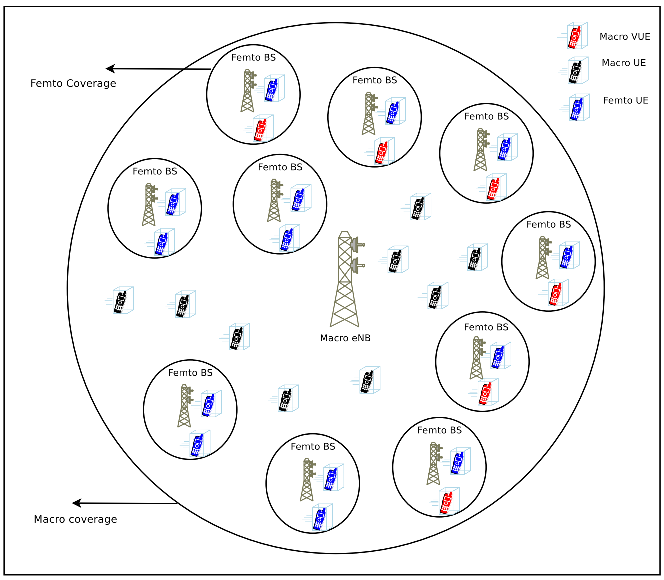

Fig. 10. HetNet used in test scenarios.

these messages are identified with their periodicities, it is possible to determine the total control signal overhead (TCSOH) based on their message lengths and periodicities as given in (Rangisetti Tammaet al., 2016). Based on TCSOH, it is possible to configure the controller with required network bandwidth and I/O processing capabilities.

In this work, all CSOSs are implemented using the same SD-LTE-RAN framework and all of them require to monitor RBU of eNBs and handover measurements reports of UEs. Hence, the TCSOH would be same for all CSOSs.

4. Performance results

In order to evaluate the performance of various CSOSs *i.e.,* MinRBU-CSOS, LA-CSOS, IT-CSOS, and IQ-CSOS), LTE-HetNet topology shown in Fig. 10 is configured with simulation parameters given in Table 3. All four algorithms are evaluated with various scenarios by varying traffic of UEs and number of VUEs. In test topology, FBSs are not suffering from co-tier interference. In test scenarios we refer cross-tier interference as interference and interference levels are varied by number of VUEs. In test scenarios Macro eNBs will not be switched-off and only FBSs can be switched-off. In test scenario high traffic means, UEs are accessing high traffic applications but network is not loaded hence FBSs could be switched-off and their UEs can be served by Macro eNBs. All UEs are configured with GBR flows. In order to generate fixed GBR traffic UDP application is used, because with TCP application fixed rate traffic flows cannot be generated. FBSs are configured in CA mode, hence only CSG UEs can attach to FBSs.

4.1. Energy savings metrics

Power consumption of a FBS can be modeled as given in (Richter et al., 2009; Soh et al., 2013; Wu et al., 2015; Auer et al., 2011; Debaillie et al., 2011). In this work, we assumed that the power consumption of the network is directly proportional to active FBS power consumption (Richter et al., 2009). Energy Consumption of a FBS (EC_{FBS}) in terms of *Joules or watts-hour (W-H)* is defined as given in Eqn. (11), based on the total power consumption in *watts* (P_{FBS}) during its total operational time in *hours* (T). Similarly, Total Network Energy Consumption (*TNEC*) is sum of energy consumption of all active FBSs except Macro eNBs as they are not considered for switch-off by CSOS in this work and *TNEC* is defined for a network with ***n*** FBSs as given in Eqn. (12). Total OPEX in terms of *TNEC* ($OPEX_{TNEC}$) is defined as given in Eqn. (13), where C is the price of power/energy in \$/watt.

$$EC_{FBS,i} = P_{FBS,i} \times T_{FBS,i} \tag{11}$$

$$TNEC = \sum_{i=1}^{n} EC_{FBS,i} \tag{12}$$

$$OPEX_{TNEC} = TNEC \times C \tag{13}$$

Total Energy Savings (*TES*) of a HetNet is defined in terms of active BSs (*ActBSs*) as given in Eqn. (14). Where, *B_ActBS* is active FBS count before CSO operation and *A_ActBS* is active FBS count after CSO operation. More specifically, *TES* in terms of *TNEC* is defined, TES_{TNEC}, as given in Eqn. (15) and *TES* in terms of operators OPEX (TES_{OPEX}) is defined as given in Eqn. (16).

$$TES = \frac{B\_ActBSs - A\_ActBS}{B\_ActBSs} \times 100 \tag{14}$$

$$TES_{TNEC} = TES \times TNEC \tag{15}$$

$$TES_{OPEX} = TES \times OPEX_{TNEC} \tag{16}$$

All four algorithms are evaluated with the following key metrics: network wide total energy savings, *TES* in terms of *TNEC*, *OPEX*, network level OLR, Packet Loss Ratio (*PLR*), and GBR satisfaction. Network level OLR and GBR satisfaction metrics are calculated by averaging OLR and GBR satisfaction of all cells in the network, respectively.

4.2. Scenario #1: High Interference and High Traffic (HIHT)

In this test scenario, all four algorithms are evaluated under HIHT conditions. From this test scenario, a common RBU threshold is determined for non load-aware CSOSs: IT-CSOS and MinRBU-CSOS. This is done because setting higher RBU threshold for non load-aware CSOSs can lead to network overload by switching off more number of small cells. For example, setting RBU to 0.9 means that the cells with RBs utilization ≤0.9 are selected as candidate cells for switch-off. Hence, to determine RBU threshold for non load-aware CSOSs, IT-CSOS-1 (0.65), MinRBU-CSOS-1 (0.65), IT-CSOS-2 (0.95), and MinRBU-CSOS-2 (0.95) are tested. However, LA-CSOS and IQ-CSOS are load aware CSOSs and

Table 3
Simulation setup for test scenarios.

Simulator	NS-3.19 (NS-3.19), (NS-3OpenFlow) with LENA and OpenFlow (OpenFlow Switch Specification 1.1.0)
# of Macro OFeNBs	1
# of Femto OFeNBs	10
# of Active UEs	3 per Femto
# of Active UEs	20 per Macro
LTE MAC Scheduler	Priority Set Scheduler (Monghal et al., 2008)
Handover Algorithm	A2A4Algorithm
OFeNB: Macro Tx Power	43 dBm
OFeNB: Femto Tx Power	23 dBm
Femto access mode	Closed Access
PathLossModel	HybridBuildingsPropagationLossModel (NS-3.19)
Macro/FBS Bandwidth	50 RBs (Frequency Reuse-1)
Serving Cell Threshold	20 (3GPP RSRQ mapping (3GPP RSRQ Reference))
Hysteresis Threshold	5 (3GPP RSRQ mapping (3GPP RSRQ Reference))
Application Traffic	UDP Client-Server Application
Rate of High traffic Downlink Flows	64KBps GBR
Rate of Low traffic Downlink Flows	16KBps GBR
High Interference	40% of Macro UEs are VUEs
Low Interference	10% or less Macro UEs are VUEs
Measurement Report Interval: β	125 ms
Load Report Interval: α	200 ms
Femto Energy consumption	80 Watts/hour (Liu et al., 2016)
VUEs Threshold$_{RSRQ}$	5
Power/Energy Charges (C)	C-$/Watt

they are enforcing strict RB requirements condition for UEs handover during cell switch-off to limit load of switching off cell to the neighbor cells. Hence, LA-CSOS and IQ-CSOS are configured with higher RBU threshold (0.95) for selecting candidate cells to switch-off. From results, each CSOS performance is explained according to its CSO decisions. Initially, HetNet has 10 active FBSs (ActBSs) which is represented by No-CSOS bar in Fig. 11. Once cell switch-offs are initiated by CSOSs, number of ActBSs has decreased and network is operating with fewer number of FBSs. Among four CSOSs shown in Fig. 11, LA-CSOS resulted in 7-ActBSs while IQ-CSOS resulted in the least number of 5-ActBSs. However, as shown in Fig. 12, LA-CSOS is ensuring lower network OLR (0.2) and 80% of GBR satisfaction to UEs as shown in Fig. 13 with additional cost of 2-ActBSs energy consumption. As given in Table 4, although IQ-CSOS is affecting GBR satisfaction of UEs, it is offering 20% more *TES* compared to LA-CSOS.

Another efficient CSOS is IT-CSOS-1, which is performing better compared to MinRBU-CSOS-1. Although both algorithms resulted in equal number of 6-ActBSs as shown in Fig. 11, IT-CSOS-1 is offering lesser network OLR (0.29) compared to MinRBU-CSOS-1 (0.36) as shown in Fig. 12. Similarly, as shown in Fig. 13, IT-CSOS-1 is offering higher GBR satisfaction (71%) to UEs compared to MinRBU-CSOS-1 (64%). To measure non-load aware IT-CSOS performance, we tested the IT-CSOS with two different RBU thresholds. In case of IT-CSOS-1, in order to limit load from switching off cells on other cells in the network, at first a few cells are selected based on RBU threshold (<65%) of cells. And then it selects the highest interfering cell as a candidate cell to switch-off. Hence, it may end up with only fewer number of candidate cells to choose for switch-off. Variant of IT-CSOS is IT-CSOS-2, which uses higher RBU threshold (<95%). As given in Table 4, although IT-CSOS-2 is able to provide 80% of *TES*, it is causing severe GBR (<55%) dissatisfaction to UEs. Besides, as shown in Fig. 14, it is also causing higher network *PLR* (15%).

Similarly, to measure non-load aware MinRBU-CSOS performance, we tested the MinRBU-CSOS with two different RBU thresholds. MinRBU-CSOS-1 is also limiting number of candidate cells to choose for switch-off based on RBU threshold (<65%) and not enforcing any GBR UEs RB requirements conditions during handover. Variant of MinRBU-

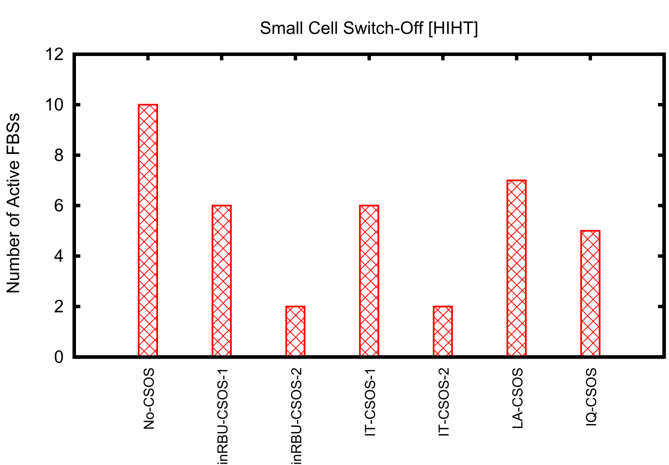

Fig. 11. Scenario #1: Comparison of number of active FBSs in various CSOSs. The plot shows number of ActBSs needed by CSOSs to handle HIHT. Since IT-CSOS and IQ-CSOS are considering the interference in the HetNet, they are able to switch-off more FBSs.

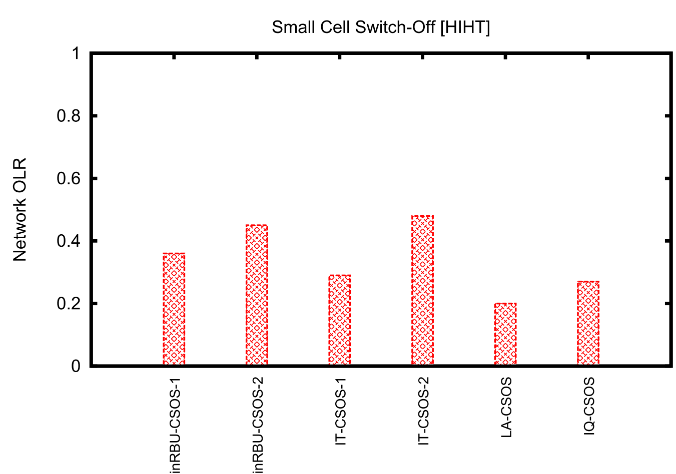

Fig. 12. Scenario #1: Comparison of network OLR in various CSOSs. The plot shows how network OLR is affected by various CSOSs. LA-CSOS and IQ-CSOS are considering network overload into CSO decision, hence they are able to maintain network OLR around 0.2.

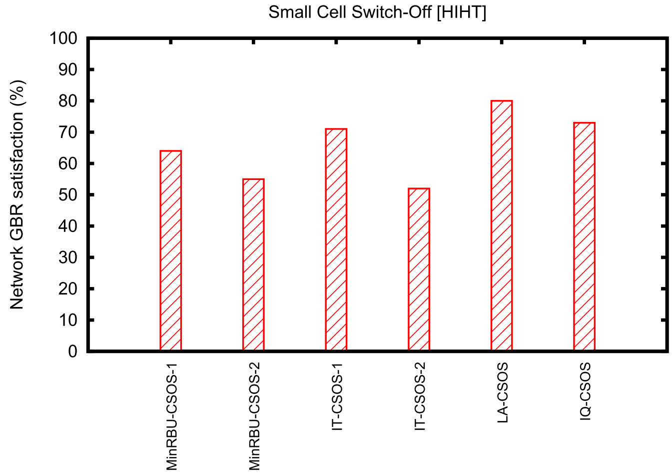

Fig. 13. Scenario #1: Comparison of GBR satisfaction in various CSOSs. The plot shows how UEs GBR is affected by various CSOSs. LA-CSOS and IQ-CSOS are considering network overload into CSO decision, hence they are able to maintain 80% or more GBR satisfaction.

Table 4
Comparison of various CSOSs in HIHT scenario.

CSOS	ActBSs	TES	Avg. OLR	Avg. GBR	PLR
MinRBU-CSOS-1	6	40%	0.36	64%	10%
MinRBU-CSOS-2	2	80%	0.45	55%	15%
IT-CSOS-1	6	40%	0.29	71%	9%
IT-CSOS-2	2	80%	0.48	52%	15%
LA-CSOS	7	30%	0.20	80%	6%
IQ-CSOS	5	50%	0.27	73%	7%
No-CSOS	10	0%	0	100%	2%

CSOS-1 is MinRBU-CSOS-2, which uses higher RBU threshold (<95%). As given in Table 4, because of setting higher RBU threshold, although MinRBU-CSOS-2 is able to provide 80% of *TES*, but it is causing severe GBR (<55%) dissatisfaction to UEs. Besides, as shown in Fig. 14, it is also causing higher network *PLR* (15%).

Considering HIHT conditions, IQ-CSOS is performing better in terms of GBR satisfaction of UEs and *TES*, compared to IT-CSOS-1 and MinRBU-CSOS-1. As IQ-CSOS is considering both interference and RBU during CSO, it is able to first reduce interference and minimize RBU of

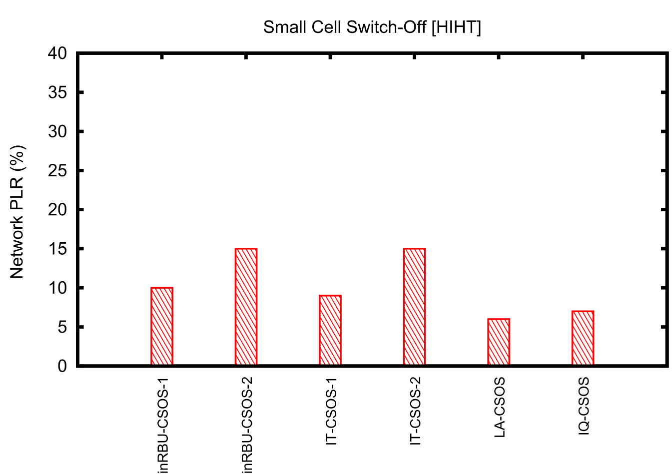

Fig. 14. Scenario #1: Comparison of PLR in various CSOSs. LA-CSOS and IQ-CSOS are considering network overload into CSO decision, hence they are causing lesser packet losses compared to other CSOSs.

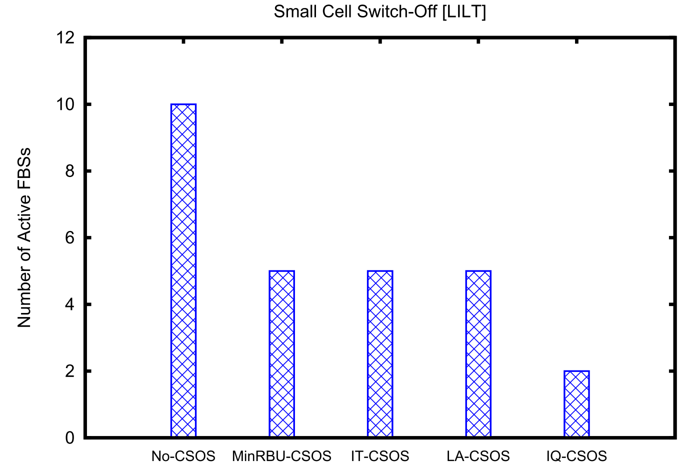

Fig. 15. Scenario #2: Comparison of number of active FBSs in various CSOSs. The plot shows that irrespective of interference in the HetNet, the IQ-CSOS is able to switch-off more small cells compared to other CSOSs.

Table 5
Comparison of various CSOSs in LILT scenario.

CSOS	ActBSs	TES	Avg. OLR	Avg. GBR	PLR
MinRBU-CSOS	5	50%	0	100%	7%
IT-CSOS	5	50%	0	100%	7%
LA-CSOS	5	50%	0	100%	7%
IQ-CSOS	2	80%	0	100%	4%
No-CSOS	10	0%	0	100%	0%

the network. And to ensure better QoS in the network, it makes interference and GBR UEs' RB requirement aware handovers to avoid overload to the neighbor Macro eNBs. Since LA-CSOS is not considering interference effect during CSO, it is not able to offer better energy savings. As given in Table 4, it is able to provide 80% of GBR satisfaction to UEs with only 20% of *TES*.

From Table 4, based on higher energy savings and UEs GBR satisfaction, for IT-CSOS and MinRBU-CSOS the RBU threshold is set to 65% and for IQ-CSOS and LA-CSOS the RBU threshold is set to 95%.

4.3. Scenario #2: Low Interference and Low Traffic (LILT)

In this test scenario, all four algorithms are evaluated under LILT conditions. In this test scenario, we mainly discuss about the need of selecting high interference creating cells as first choice for CSOS instead of enforcing strict RBU threshold. Initially, HetNet has 10 active FBSs. Once cell switch-offs are initiated by CSOSs, number of ActBSs has decreased and network is operating with fewer number of FBSs and *TES* is improved. Among four CSOSs, shown in Fig. 15, IQ-CSOS resulted in the least number of 2-ActBSs while other three CSOSs resulted in 5-ActBSs. In this particular case IQ-CSOS is able to save overall network energy savings upto 80% and 30% of more *TES* as compared to other three CSOSs given in Table 5. From this case, it is evident that restricting candidate cells to choose for switch-off based on only RBU or traffic load can affect total energy savings.

Although IQ-CSOS resulted in the least number of 2-ActBSs with no network overload it is able to ensure 100% of GBR satisfaction to UEs as shown in Fig. 17 (hence all values in Fig. 16 are zeros). Whereas MinRBU-CSOS, LA-CSOS, and IT-CSOS are able to switch-off only 5-ActBSs and network is not overloaded. Similarly, as shown in Fig. 17, MinRBU-CSOS, LA-CSOS and IT-CSOS also ensured 100% of GBR satisfaction to UEs with 50% of *TES* as given in Table 5. However, because LA-CSOS and MinRBU-CSOS do not take number of Macro VUEs due to FBSs cross-tier interference into consideration for CSOS, they may not get benefit of minimized RBU of the

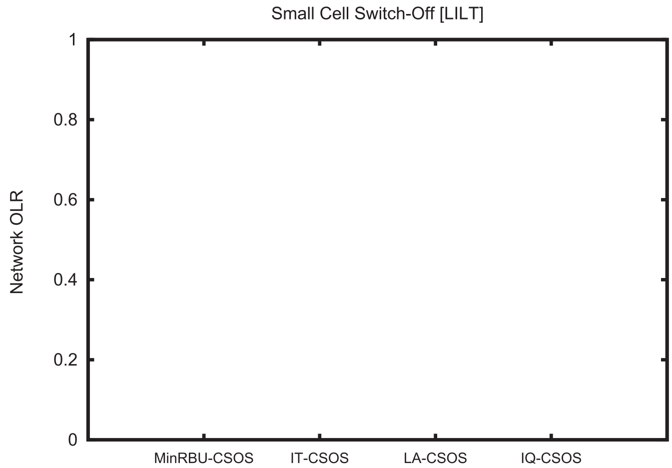

Fig. 16. Scenario #2: Comparison of network OLR in various CSOSs. The plot shows that irrespective of interference in the HetNet during low traffic load contrast to other CSOSs, the IQ-CSOS could switch-off more small cells and also ensures that network is not overloaded. Hence, it is showing all zeros in the plot.

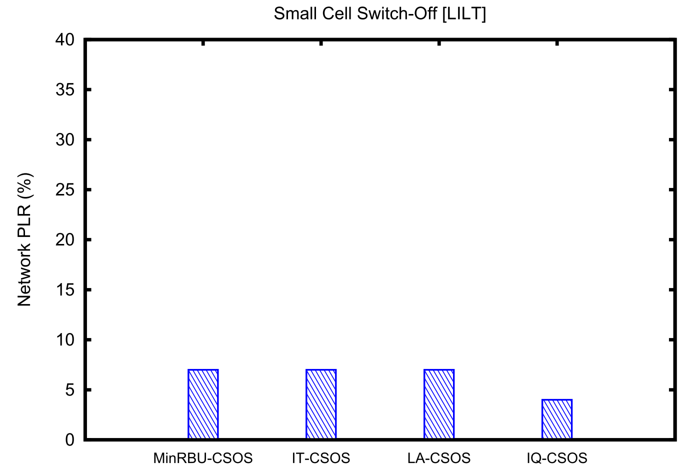

Fig. 18. Scenario #2: Comparison of PLR in various CSOSs. The plot shows that packet losses because of cell switch-offs in various CSOSs.

network after switching-off interfering cells. Besides, these CSOSs cannot switch-off more cells to avoid overload to the network and hence they do not achieve higher energy savings.

In case of IT-CSOS, it is taking interference into consideration for switch-off decisions but it limits number of candidate cells to switch-off to limit load to the network from switched-off cells. Hence, this algorithm also unable to achieve higher energy savings. Besides, as shown in Fig. 18, all CSOSs are causing lesser network *PLR* (≤7%).

4.4. Scenario #3: traffic and interference variation scenario

Aim of this test scenario is to compare performance of all four algorithms in the following network conditions in same experiment.

1. C1: High Interference and High Traffic load (HIHT)
2. C2: Low Interference and Low Traffic load (LILT)
3. C3: High Traffic Load and Low Interference (HTLI)
4. C4: Low Traffic load and High Interference (LTHI)

Few important assumptions about the test scenario are as follows:

- In this test scenario, we considered that network conditions vary on slow pace for every 3-h from C1 (HIHT) to C4 (LTHI).
- All C1, C2, C3, and C4 network conditions begin with all FBSs in switch-on state and the network traffic and interference conditions will be stabilized and identified in first few minutes for choosing cells for switch-off by CSOSs.
- In order to simulate various network conditions (C1, C2, C3, and C4) we ran experiment only for 120 s. But each network condition of 3-h duration is mapped to 30 s of simulation time.
- All evaluation metrics *TES*, *OLR*, *PLR* and GBR satisfaction are calculated for each network condition (C1, C2, C3, and C4) separately.
- Per day TES_{OPEX} and TES_{NEC} are calculated over entire simulation duration.

From results, we explain CSOSs performance during each network condition (C1 to C4). When network is in C1 (HIHT), among all CSOSs shown in Fig. 19, IQ-CSOS is able to provide 50% of energy savings with 5-ActBSs but it is suffering from network overload (refer Fig. 20) with 73% of GBR satisfaction to UEs as shown in Fig. 21. And IT-CSOS is able to provide 40% of *TES* with 6-ActBSs and 71% of GBR satisfaction to UEs. However, among all four algorithms only LA-CSOS is able to provide 80% of GBR satisfaction to UEs with only 30% of *TES* as given

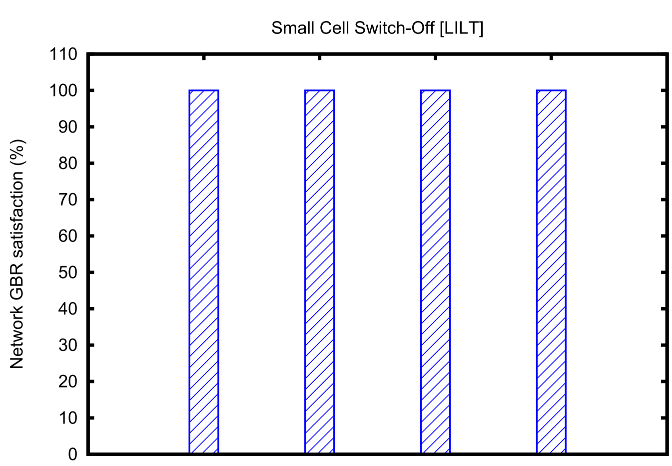

Fig. 17. Scenario #2: Comparison of GBR satisfaction in various CSOSs. The plot shows that irrespective of interference in the HetNet during low traffic load contrast to other CSOSs, the IQ-CSOS could switch-off more small cells and also ensures higher GBR satisfaction to UEs.

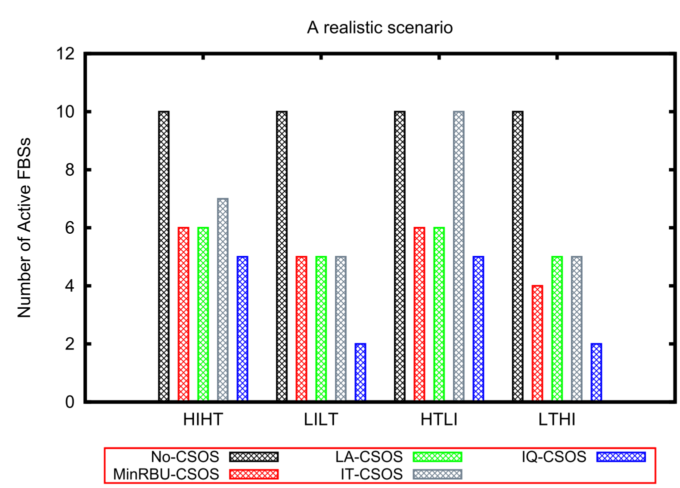

Fig. 19. Scenario #3: Network condition is varied from HIHT to LTHI, and observed number of active FBSs is plotted in various CSOSs. In a given HetNet, irrespective of interference during low traffic the IQ-CSOS needs only 2 ActBSs and during high traffic the IQ-CSOS needs 5 ActBSs. But, other CSOSs need 5 to 7 ActBSs based on traffic load.

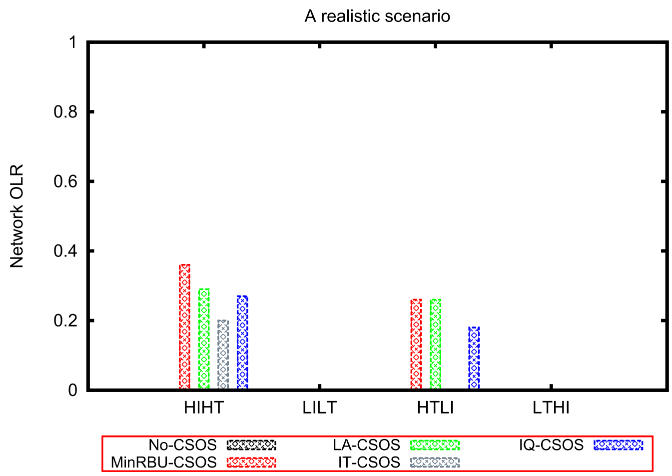

Fig. 20. Scenario #3: Network condition is varied from HIHT to LTHI, and observed network OLR is plotted in various CSOSs. In a given HetNet, irrespective of interference during low traffic the IQ-CSOS ensures network is not overloaded and during high traffic the IQ-CSOS ensures network overload is around 0.2. During high traffic, because of interference other CSOSs could able to ensure network OLR around 0.35 only.

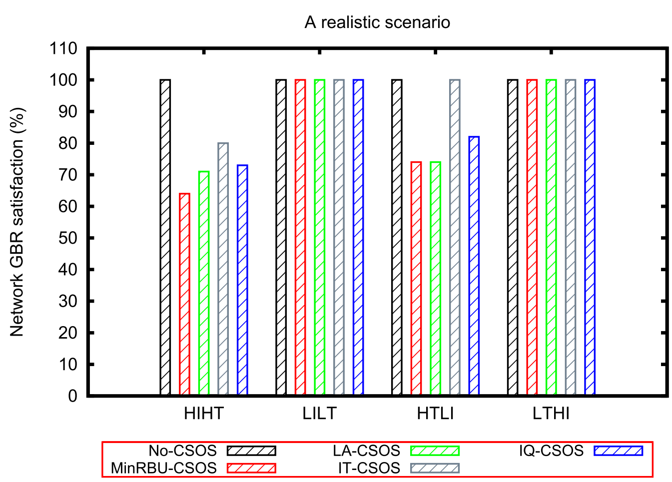

Fig. 21. Scenario #3: Network condition is varied from HIHT to LTHI, and observed network GBR satisfaction is plotted in various CSOSs. In a given HetNet, irrespective of interference during low traffic the IQ-CSOS ensures 100% of GBR satisfaction to UEs and during high traffic the IQ-CSOS ensures 80% of GBR satisfaction to UEs. During high traffic, because of interference other CSOSs could able to ensure only around 65% of GBR satisfaction to UEs.

in Table 6. MinRBU-CSOS is able to provide better 40% of *TES*, but it is causing higher network *PLR*, *OLR* and lesser GBR as given in Table 6.

Interestingly during C2 (LILT), as shown in Fig. 20, with no network overload, all four CSOSs are able to provide 100% of GBR satisfaction to UEs as shown in Fig. 21. However, in terms of higher *TES* as given in Table 5, IQ-CSOS is able to offer upto 80% of *TES* with fewer ActBSs-2

Table 6
Comparison of various CSOSs in HIHT scenario.

CSOS	ActBSs	TES	Avg. OLR	Avg. GBR	PLR
MinRBU-CSOS	6	40%	0.36	64%	10%
IT-CSOS	6	40%	0.29	71%	9%
LA-CSOS	7	30%	0.20	80%	6%
IQ-CSOS	5	50%	0.27	73%	7%
No-CSOS	10	0%	0	100%	2%

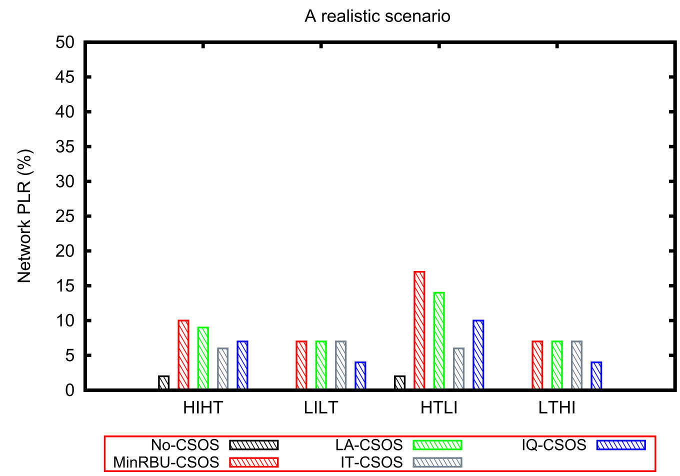

Fig. 22. Scenario #3: Network condition is varied from HIHT to LTHI, and observed PLR is plotted in various CSOSs. In a given HetNet, irrespective of interference during low traffic the IQ-CSOS is causing 4% of PLR and during high traffic the IQ-CSOS is causing 10% of PLR. During high traffic, because of interference other CSOSs are causing around 15% of PLR.

Table 7
Comparison of various CSOSs in HTLI scenario.

CSOS	ActBSs	TES	Avg. OLR	Avg. GBR	PLR
MinRBU-CSOS	6	40%	0.26	74%	17%
IT-CSOS	6	40%	0.26	74%	14%
LA-CSOS	10	0%	0	100%	6%
IQ-CSOS	5	50%	0.18	82%	10%
No-CSOS	10	0%	0	100%	2%

as shown in Fig. 19, whereas other three algorithms are able to provide only upto 50% of *TES* with ActBSs-5 as shown in Fig. 19. Overall network *PLR* is lesser in IQ-CSOS when compared to other three algorithms as shown in Fig. 22.

In case of C3 (HTLI), LA-CSOS is able to offer 100% of GBR satisfaction to UEs at the expense of savings (*TES*) as given in Table 7. Because of low interference in the network, even though traffic load is higher, both non load aware algorithms (MinRBU-CSOS and IT-CSOS) are able to perform equally well in terms of *TES* of 40% with 6-ActBSs (refer Fig. 19), and 74% of GBR satisfaction to UEs as shown in Fig. 21. Because of interference and QoS aware switch-off decisions IQ-CSOS is able to offer 82% of GBR satisfaction to UEs with *TES* of 50% with fewer ActBSs-5 as shown in Fig. 19. In terms of network *PLR* also, IQ-CSOS is performing better when compared to MinRBU-CSOS and IT-CSOSs as shown in Fig. 22.

Finally, during C4 (LTHI) network conditions as given in Table 8, IQ-CSOS is able to provide 80% of *TES* with fewer ActBSs-2 (refer Fig. 11) and 100% of GBR satisfaction to UEs as shown in Fig. 21. Whereas other three algorithms also able to provide 50% of *TES* with 100% of GBR satisfaction to UEs.

From these four cases results, given in Tables 5–8, in overall IQ-CSOS is able to offer around 88% of GBR satisfaction to UEs with 65% of *TES* in terms of *TNEC* and *OPEX*. Where as LA-CSOS is able to offer

Table 8
Comparison of various CSOSs in LTHI (C4) scenario.

CSOS	ActBSs	TES	Avg. OLR	Avg. GBR	PLR
MinRBU-CSOS	5	50%	0	100%	7%
IT-CSOS	5	50%	0	100%	7%
LA-CSOS	5	50%	0	100%	7%
IQ-CSOS	2	80%	0	100%	4%
No-CSOS	10	0%	0	100%	0%

Table 9
Comparison of various Cell Switch-Off Strategies.

	MinRBU-CSOS (Oikonomakou et al., 2015)	LA-CSOS (Nabuuma et al., 2015)	IT-CSOS (Dudnikova et al., 2015)	IQ-CSOS
When to Switch-Off	Low traffic	Low traffic	Low traffic	Low traffic
CSO Threshold	RBU	RBU	RBU	None
Interference	Not considered	Not considered	Considered	Considered
QoS	Not considered	Considered	Not considered	Considered
Network Load	Not considered	Considered	Not considered	Considered
Energy Savings Metrics	ActBSs, Power Consumption	ActBSs, Power Consumption	ActBSs, Power Consumption	ActBSs, Power Consumption
Evaluated QoS Metrics	None	None	None	GBR and PLR
Network Load Metric	None	Network load	Network load	OLR
Avg. Energy Savings	47%	32%	47%	65%
Avg. GBR Satisfaction	84%	95%	85%	88%
Avg. OLR	0.16	0.05	0.15	0.12
Avg. PLR	11%	6.3%	10%	7%

Table 10
Comparison of per day TES_{TNEC} and TES_{OPEX} metrics in (C1, C2, C3 and C4).

CSOS	C1-TES_{TNEC} (Watt-Hour)	C2-TES_{TNEC} (Watt-Hour)	C3-TES_{TNEC} (Watt-Hour)	C4-TES_{TNEC} (Watt-Hour)	TES_{TNEC} (Watt-Hour)	TES_{OPEX} ($)
MinRBU-CSOS	960	1200	1200	720	4080	$4080 \times$ C
IT-CSOS	960	1200	960	1200	4320	$4320 \times$ C
LA-CSOS	720	1200	0	1200	3120	$3120 \times$ C
IQ-CSOS	1200	1920	1200	1920	6240	$6240 \times$ C

95% of GBR satisfaction to UEs with lesser *TES* of 32%. IT-CSOS is also able to offer better GBR satisfaction to UEs with 47% of *TES*. And MinRBU-CSOS is able to offer 84% of GBR satisfaction to UEs with 47% of *TES*.

From the results, we can conclude that in overall, IQ-CSOS is well suited on average in all network conditions to offer higher energy savings with minimal effect on GBR satisfaction of UEs. Whereas LA-CSOS is well suited in case of strict QoS enforcement with nominal energy savings. In case of higher interference case, IT-CSOS can offer reasonable energy savings with minimal effect on GBR satisfaction of UEs. Comparison of various CSOSs is given in Table 9.

Finally, we have given per day energy savings (12 h only as only night hours are considered) in Table 10. In case of there is No-CSOS, per day *TNEC* is 9600 (Watt-Hour), and *OPEX* is $9600 \times$ C ($).

5. Conclusions and future work

In this work, in order to improve energy savings in HetNets, we proposed a novel CSOS called IQ-CSOS on SD-LTE-RAN framework. Unlike existing CSOSs, IQ-CSOS considers both network traffic load and cross-tier interference to offer higher energy savings in HetNets. We implemented IQ-CSOS and three recent CSOSs: MinRBU-CSOS (Oikonomakou et al., 2015), LA-CSOS (Nabuuma et al., 2015), IT-CSOS (Dudnikova et al., 2015) on SD-LTE-RAN framework using NS-3 (NS-3.19) and OpenFlow (NS-3OpenFlow). We tested all four CSOSs in terms of network *OLR*, GBR satisfaction and *PLR*, and *TES* in terms of *TNEC* and *OPEX*. In evaluation, it is identified that IQ-CSOS is able to provide maximum energy savings with slight effect on network GBR due to its interference and GBR aware CSOS decisions. In our test scenarios, irrespective of interference levels in HetNets, when network traffic is low the IQ-CSOS is able to switch-off 80% of small cells, whereas other CSOS could able to switch-off only up to 50%. Hence, IQ-CSOS is able to provide up to 80% of total network energy savings and it also offers 30% more energy savings compared to other CSOSs.

In future work, various RAN control algorithms like load balance, interference management, handover algorithms, *etc.* can be developed on SD-LTE-RAN framework for HetNets. As current work is on simulations, we would like to study issues in implementation of proposed framework on a prototype testbed and how IQ-CSOS can be extended to consider other QoS parameters like delay and jitter in addition to GBR parameter of QoS, *OLR*, and *IQ*.

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References

3GPP RSRQ Reference: TS 36.133. http://www.3gpp.org/dynareport/36133.htm.

Alaca, F., Sediq, A.B., Yanikomeroglu, H., 2012. A genetic algorithm based cell switch-off scheme for energy saving in dense cell deployments. In: Proc. Of IEEE Globecom Workshops. IEEE, pp. 63–68.

Andrews, J.G., Claussen, H., Dohler, M., Rangan, S., Reed, M.C., 2012. Femtocells: past, present, and future. IEEE J. Sel. Area. Commun. 30 (3), 497–508.

Ashraf, I., Boccardi, F., Ho, L., 2011. Sleep mode techniques for small cell deployments. IEEE Commun. Mag. 49 (8), 72–79.

Auer, G., Giannini, V., Desset, C., Godor, I., Skillermark, P., Olsson, M., Imran, M.A., Sabella, D., Gonzalez, M.J., Blume, O., et al., 2011. How much energy is needed to run a wireless network? IEEE Trans. Wireless Commun. 18 (5), 40–49.

Bousia, A., Kartsakli, E., Alonso, L., Verikoukis, C., 2012a. Dynamic energy efficient distance-aware base station switch on/off scheme for lte-advanced. In: Proc. Of Global Communications Conference (GLOBECOM). IEEE, pp. 1532–1537.

Bousia, A., Antonopoulos, A., Alonso, L., Verikoukis, C., 2012b. “”green” distance-aware base station sleeping algorithm in lte-advanced. In: Proc. Of International Conference on Communications (ICC). IEEE, pp. 1347–1351.

Checko, A., Christiansen, H.L., Yan, Y., Scolari, L., Kardaras, G., Berger, M.S., Dittmann, L., 2015. “Cloud ran for mobile networks—a technology overview. IEEE Commun. Surv. Tutor. 17 (1), 405–426.

Chen, T., Zhang, H., Chen, X., Tirkkonen, O., 2014. Softmobile: control evolution for future heterogeneous mobile networks. IEEE Trans. Wireless Commun. 21 (6), 70–78.

Costa-Requena, J., Llorente Santos, J., Ferrer Guasch, V., Ahokas, K., Premsankar, G., Luukkainen, S., Ahmad, I., Liyanage, M., Ylianttila, M., López Pérez, O., et al., 2015. Sdn and nfv integration in generalized mobile network architecture. In: Proc. Of European Conference on Networks and Communications (EuCNC). IEEE, pp. 154–158.

Debaillie, B., Giry, A., Gonzalez, M.J., Dussopt, L., Li, M., Ferling, D., Giannini, V., 2011. Opportunities for energy savings in pico/femto-cell base-stations. In: Proc. Of International Conference on Future Network & Mobile Summit (FutureNetw). IEEE, pp. 1–8.

Dolfi, M., Cavdar, C., Morosi, S., Piunti, P., Zander, J., Del Re, E., 2017. On the trade-off between energy saving and number of switchings in green cellular networks. Trans. Emerg. Telecommun. Technol. 28 (11).

Dudnikova, A., Dini, P., Giupponi, L., Panno, D., 2015. Multi-criteria decision for small cell switch off in ultra-dense lte networks. In: Proc. Of International Conference on Telecommunications (ConTEL). IEEE, pp. 1–8.

El Morabit, Y., Mrabti, F., Abarkan, E.H., 2017. Small cell switch off using genetic algorithm. In: Advanced Technologies for Signal and Image Processing (ATSIP), 2017 International Conference on. IEEE, pp. 1–4.
Gudipati, A., Perry, D., Li, L.E., Katti, S., 2013. Softran: software defined radio access network. In: Proc. Of ACM SIGCOMM Workshop on Hot Topics in Software Defined Networking (HotSDN). ACM, pp. 25–30.
Lagum, F., Le-The, Q.-N., Beitelmal, T., Szyszkowicz, S.S., Yanikomeroglu, H., 2017. Cell switch-off for networks deployed with variable spatial regularity. IEEE Wirel. Commun. Lett. 6 (2), 234–237.
Le-The, Q.-N., Beitelmal, T., Lagum, F., Szyszkowicz, S.S., Yanikomeroglu, H., 2017. Cell switch-off algorithms for spatially irregular base station deployments. IEEE Wirel. Commun. Lett. 6 (3), 354–357.
Liu, H., Cui, H., Chen, J., 2014. Dynamic sleeping algorithm of base station based on spatial features. In: Proc. Of International Conference on Telecommunications (ICT). IEEE, pp. 333–337.
Liu, C., Natarajan, B., Xia, H., 2016. Small cell base station sleep strategies for energy efficiency. IEEE Trans. Veh. Technol. 65 (3), 1652–1661.
Monghal, G., Pedersen, K.I., Kovacs, I.Z., Mogensen, P.E., 2008. Qos oriented time and frequency domain packet schedulers for the utran long term evolution. In: Proc. Of Vehicular Technology Conference (VTC). IEEE, pp. 2532–2536.
Nabuuma, H., Alsusa, E., Pramudito, W., 2015. A load-aware base station switch-off technique for enhanced energy efficiency and relatively identical outage probability. In: Proc. Of Vehicular Technology Conference (VTC). IEEE, pp. 1–5.
NS-3.19. http://www.nsnam.org/news/ns-3-19-released/.
NS-3 and OpenFlow. http://www.nsnam.org/docs/release/3.13/models/html/openflow-switch.html.
Oh, E., Krishnamachari, B., Liu, X., Niu, Z., 2011. Toward dynamic energy-efficient operation of cellular network infrastructure. IEEE Commun. Mag. 49 (6), 56–61.
Oh, E., Son, K., Krishnamachari, B., 2013. Dynamic base station switching-on/off strategies for green cellular networks. IEEE Trans. Wireless Commun. 12 (5), 2126–2136.
Oikonomakou, M., Antonopoulos, A., Alonso, L., Verikoukis, C., 2015. Cooperative base station switching off in multi-operator shared heterogeneous network. In: Proc. Of Global Communications Conference (GLOBECOM). IEEE, pp. 1–6.
OpenFlow Switch Specification 1.1.0. http://archive.openflow.org/wp/documents/.
Rangisetti, A.K., Tamma, B.R., et al., 2016. Qos aware load balance in software defined lte networks. Comput. Commun. 97C, 52–71.
Rao, J.B., Fapojuwo, A.O., 2014. A survey of energy efficient resource management techniques for multicell cellular networks. IEEE Commun. Surv. Tutor. 16 (1), 154–180.
Richter, F., Fehske, A.J., Fettweis, G.P., 2009. Energy efficiency aspects of base station deployment strategies for cellular networks. In: Proc. Of Vehicular Technology Conference Fall (VTC). IEEE, pp. 1–5.
Rost, P., Bernardos, C., Domenico, A., Girolamo, M., Lalam, M., Maeder, A., Sabella, D., et al., 2014. Cloud technologies for flexible 5g radio access networks. IEEE Commun. Mag. 52 (5), 68–76.
Soh, Y.S., Quek, T.Q., Kountouris, M., Shin, H., 2013. Energy efficient heterogeneous cellular networks. IEEE J. Sel. Area. Commun. 31 (5), 840–850.
Soliman, S.S., Song, B., 2017. Fifth generation (5g) cellular and the network for tomorrow: cognitive and cooperative approach for energy savings. J. Netw. Comput. Appl. 85, 84–93.
Sun, S., Gong, L., Rong, B., Lu, K., 2015. An intelligent sdn framework for 5g heterogeneous networks. IEEE Commun. Mag. 53 (11), 142–147.
Szilágyi, P., Vincze, Z., Vulkan, C., 2012. Enhanced mobility load balancing optimisation in lte. In: Proc. Of Personal Indoor and Mobile Radio Communications (PIMRC). IEEE, pp. 997–1003.
Wu, J., Zhang, Y., Zukerman, M., Yung, E.K.-N., 2015. Energy-efficient base-stations sleep-mode techniques in green cellular networks: a survey. IEEE Commun. Surv. Tutor. 17 (2), 803–826.
X2AP protocol 3GPP specification.http://www.etsi.org/deliver/etsi_ts/136400_136499/136423/13.03.00_60/.
Zhang, S., Zhao, S., Yuan, M., Zeng, J., Yao, J., Lyu, M.R., King, I., 2017a. Traffic prediction based power saving in cellular networks: a machine learning method. In: Proceedings of the 25th ACM SIGSPATIAL International Conference on Advances in Geographic Information Systems. ACM, p. 29.
Zhang, H., Huang, S., Jiang, C., Long, K., Leung, V.C., Poor, H.V., 2017b. Energy efficient user association and power allocation in millimeter-wave-based ultra dense networks with energy harvesting base stations. IEEE J. Sel. Area. Commun. 35 (9), 1936–1947.
Zhang, H., Liu, N., Long, K., Cheng, J., Leung, V.C., Hanzo, L., 2018. Energy efficient subchannel and power allocation for the software defined heterogeneous vlc and rf networks. IEEE J. Sel. Area. Commun. 36 (3), 658–670.
Zhao, T., Wang, L., Zheng, X., Zhou, S., Niu, Z., 2015. Hycell: enabling green base station operations in software-defined radio access networks. In: Proc. Of International Conference on Communication Workshop (ICCW). IEEE, pp. 2868–2873.
Zhou, S., Zhao, T., Niu, Z., Zhou, S., 2016. Software-defined hyper-cellular architecture for green and elastic wireless access. IEEE Commun. Mag. 54 (1), 12–19.

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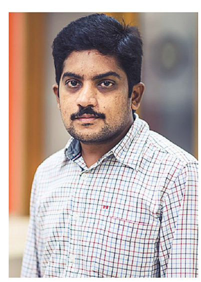

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