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On performance analysis of multioperator RAN sharing for mobile network operators

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Abstract: Enhancing the coverage and eliminating the poor performance is key to balance end-user experience and future network investments for mobile network operators (MNOs). Although vast amounts of infrastructure investments are provided by MNOs, there are still coverage and capacity planning problems at remote locations. This is because, in most cases, the population density and return-of-investments are low in those areas. In this paper, radio access network (RAN) sharing paradigm is utilized on experimental sites in Turkey to accommodate user equipment of multiple network operators under the same cell sites. We first investigate characteristics, benefits, and limitations of two different RAN sharing deployment scenarios. Then, a city-wide experimental RAN sharing study is conducted on live long-term evolution (LTE) networks between two MNOs in Turkey. Through experimental tests, we show overall performance gains of enabling RAN sharing feature in terms of observing various key performance indicators that are obtained from shared base stations. Our experimental results demonstrate that both downlink and uplink average user throughput values increased by 17.8% and 42.85%, respectively. After RAN sharing was enabled between MNOs, increase in the number of user equipment due to higher 4G coverage yielded a higher number of interradio access technology (inter-RAT) handover attempts. This caused inter-RAT handover out success rate to decrease by 70.66%. Intrafrequency handover out success rate, which indicates if the subscriber is using the same RAT type, increased by 358.33% and service drop rates dropped by 86.1%, respectively, after RAN sharing was enabled. Finally, we discuss and summarize the main takeaways of the outcome of the considered large-scale RAN sharing experiments.

Key words: Mobile operator, radio access network, transport, network sharing, real-world testbed

1. Introduction

5G has just begun to be installed in some countries and it is anticipated that installation will accelerate in the future. However, considering the investments in 5G devices in terms of operators, the costs of 5G infrastructure will be thought-provoking. One of the negative thoughts about 5G investments may seem to be that operators still do not make enough profits with their long-term evolution (LTE) investments (including newer devices, infrastructure, and operational costs)[1]. In addition to those mentioned among the costs to be paid for 5G, there are also costs for the spectrum, which can have a significant financial impact on operators. In this case, network sharing applications based on common usage of equipment can be a suitable solution. Among these,

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[1]GSMA (2019). 5G-era Mobile Network Cost Evolution [online]. Website https://www.gsma.com/futurenetworks/wiki/5g-era-mobile-network-cost-evolution/ [accessed 12 12 2019].

radio access network (RAN) sharing appears to be a solution that can provide reduced infrastructure and device costs for operators due to high utilization of different and advanced techniques in radio access [2].

The term RAN sharing was first introduced in The 3rd Generation Partnership Project (3GPP) Release-5 and at that time it was designed for 3G as multioperator core network (MOCN). RAN sharing is specified in 3GPP technical study (TS) [1] as multiple operators are operating their own core network (CN) and share a common RAN infrastructure. Until the introduction of the Release-14 by 3GPP, MOCN was realized by RAN connectivity to multiple CNs with a system information block (SIB) structure indicating a single cell identifier (ID) and tracking area code (TAC) associated with a list of public land mobile network (PLMN) IDs as detailed in TS of 3GPP [2]. A RAN node's identifier namely the eNB-ID contains the ID of the cells that are serving. Multiple CNs are connected to a single RAN operator with an associated Cell-ID/TAC numbering space dedicated to them as shown in Figure 1. For long-term evolution (LTE) as described in Rel-14 of 3GPP, a new SIB structure was introduced that allows RAN separation by broadcasting multiple Cell-IDs. Thus, each Cell-ID/TAC association is allowed to be dedicated to one mobile network operator (MNO) only. This enhancement in the SIB aims to support RAN-only service provider deployment use cases, where logical separation of RANs is needed. For 5G cases, MOCN with multiple Cell-ID broadcast was specified from the beginning the Release-15 of 3GPP. Each Cell-ID corresponds to a RAN node's identifier and multiple Cell-IDs correspond to multiple logical RAN nodes as shown in Figure 2. In cases where gNBs are disaggregated into gNB-distributed units (DUs) and gNB-central units (CUs), multiple Cell-ID allows logically separated F1 interface instances where each instance is established and maintained individually. For example, three 5G operators can use two broadcast Cell-IDs so that two operators can share the same Cell-ID/TAC space, which is different from the LTE-based deployment.

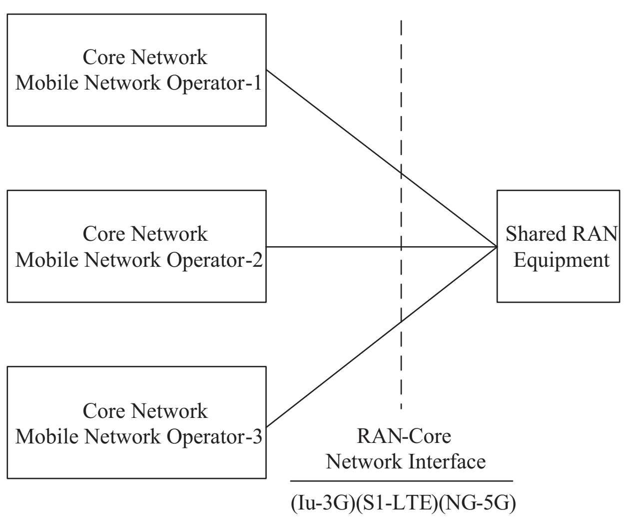

Figure 1. Multioperator-core-network-based RAN sharing scenario.

[2]GSMA (2018). Infrastructure Sharing: An Overview [online]. Website https://www.gsma.com/futurenetworks/wiki/infrastructure-sharing-an-overview/ [accessed 30 12 2019].

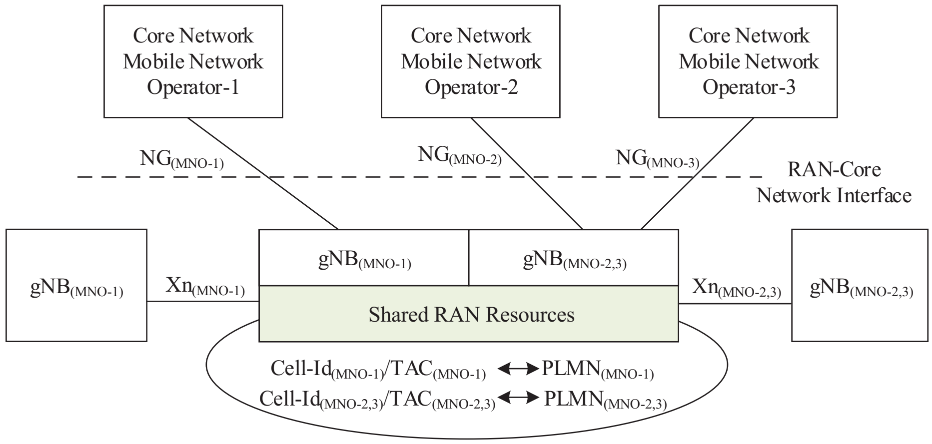

Figure 2. An illustration of RAN sharing for 5G use cases.

1.1. Related work

In real-world network deployments, RAN sharing is utilized by most of the major MNOs in the world. For example, Vodafone shares RAN in multiple regions of Spain and this collaboration covers a mixture of 2G, 3G, and LTE technologies. Another operator that shares RAN with Vodafone in Spain is Orange [3]. Another example of network sharing agreement is between Vodafone and O2 that covers the 5G deployment in Britain. [4] One of the important factors that affect the efficiency and economic gains of RAN sharing is providing a fairness between different MNOs [3–4]. If the fairness is provided, the shared equipment can cover all types of devices in the network such as femtocells, smallcells, and macrocells [5].

In the centralized or cloud RAN (C-RAN)-based scenarios which include the CU and DU split, RAN sharing deployment includes the sharing of the centralized resource computing elements [6]. The authors in [7–9] benefited from software-defined networking (SDN)-based C-RAN architecture to enable sharing of network resources among multiple MNOs. Efficient resource scheduling in multitenant environments is very important and scheduling functions need to be investigated [10,11] when user behaviors such as mobility change in different parts of the mobile networks. In multitenant environments, a robust procedure of leasing resources from infrastructure providers dynamically via signaling is needed [12]. Since cloud RAN is not standardized under 3GPP, 3GPP-defined sharing scenarios need to be studied for mapping these scenarios into the cloud RAN perspective. Marotta et al. [13] studied this mapping and evaluated the results obtained in simulation environment. Yu et al. [14] extended Marotta et al.'s study and investigated all the aspects of the cloud-based 5G networks.

A base station (BS) is used for sharing purposes among different MNOs. The quality-of-service (QoS) requests coming from the user equipments (UEs) belonging to different MNOs are realized by that BS by keeping separate lists [15]. For the CN side, the load of the BS that is serving different CNs can be eased by using CN multiplexing [16]. Since each MNO has a separate PLMN identifier, the handling of broadcasting different PLMNs is critical [17]. In [18], simulation results show that information-centric wireless network virtualization

[3] Orange Press Release (2019). Orange and Vodafone strengthen their mobile and fixed network sharing agreements in Spain [online]. Website https://www.orange.com/en/Press-Room/press-releases/press-releases-2019/Orange-and-Vodafone-strengthen-their-mobile-and-fixed-network-sharing-agreements-in-Spain [accessed 30 12 2019].

[4] O2 Press Release (2019). O2 and Vodafone finalise 5G network agreement in the UK [online]. Website https://news.o2.co.uk/press-release/o2-and-vodafone-finalise-5g-network-agreement-in-the-uk/ [accessed 29 12 2019].

architecture outperforms the other existing schemes including RAN sharing. The network slicing can be thought as a different version of network sharing and this concept brings an end-to-end logical network that runs on a shared infrastructure. In the network slicing concept RAN, transport and CN resources for the network provider are abstracted and these abstracted resources can then be assigned to different MNOs in a dynamic or dedicated manner [19,20]. Evaluation of sharing in software-defined-radio-based deployment is discussed in [21], but it can be evaluated as a difficult use case when considering the current hardware capabilities of telecommunication vendors.

Guo and Arnott [22] investigated a novel effective scheduler and admission control mechanisms for shared RAN with system-level simulations. The authors in [5] built an emulation setup to connect a BS to multiple CNs via a RAN proxy (RANP) box to achieve RAN sharing. Fairness issues in RAN sharing between multiple MNOs were investigated in [3] and RAN sharing for public safety and railway networks was analyzed in [23] via simulations. The authors in [24] studied handover parameter optimization to overcome the network coverage problem of MOCN scenario in RAN sharing. The authors in [25] analyzed the benefits of RAN and spectrum sharing paradigms using a modified version of SimuLTE model to create a simulation environment. Nevertheless, these studies do not present a complete view on large-scale real network deployment use cases.

1.2. Main contributions

To the best of our knowledge, few studies have considered the experimental evaluations of RAN sharing and their corresponding key parameter indicator (KPI) results in a city-wide deployment scenario. Moreover, none of the works above evaluated different deployment options or scenarios of RAN sharing flavors and studied their characteristics, limitations, and advantages. Our main contributions in this paper can be summarized as follows: (a) investigating different configuration options and deployment scenarios for RAN sharing and studying their characteristics, benefits, and limitations, (b) investigating the challenges of deploying RAN sharing scenarios in both transport network and RAN domains, (c) analyzing the experimental KPI outcomes of one of the considered RAN sharing network scenarios (called MOCN as multioperator radio access network (MORAN)) for two MNOs in one of the pilot cities in Turkey in a realistic environment. Our experimental results demonstrate that both download (DL) and upload (UL) average user throughput values have increased by 17.8% and 42.85%, respectively, and the inter-RAT Handover (HO) out success rate and service drop rates have decreased by 70.66% and 86.1%, respectively, whereas intrafrequency HO out success rate has increased by 358.33% after RAN sharing is enabled in the network.

The rest of the paper is organized as follows. Section 2 presents the different architectures and deployment options for enabling RAN sharing among multiple MNOs. Section 3 provides the RAN- and transport-network-related important parameters that need to be managed and corresponding challenges that can be encountered during enabling RAN sharing among multiple MNOs. Section 4 provides the experimental results and discusses the outcomes of the shared RAN system based on the obtained results. Finally, Section 5 gives the conclusions and the future work.

2. System architecture for deployment options

In this section, we introduce different possible deployment options that are supported by the mobile network nodes. RAN sharing allows resource sharing between MNOs. Additionally, RAN feature enables each MNO to use their own PLMN over the same RAN. Without RAN sharing, a PLMN consists of a RAN and a CN, through which each MNO provides services to their subscribers, while subscribers of other MNOs can only receive services as national or international roamers. These configurations are standardized scenarios for network sharing as in 3GPP TS [1]. There are various types of deployment configurations for RAN sharing, as shown in Figure 3, which provide both 3GPP-compliant and non-3GPP configuration options. In all RAN sharing options, some parts of the network equipment are shared between MNOs (which are marked with red color in Figure 3). For example, in scenario #2, base band unit (BBU) is shared whereas in scenario #3, BBU, radio remote unit (RRU), and mobility management entity (MME) are shared among MNOs. Note that maximum amount of sharing units (therefore maximum benefit in terms of cost) can be accomplished in scenario #6 where network equipment of serving gateway (S-GW), MME, and BS (RRU and BBU) units are shared between MNOs. Shared spectrum can be achieved with scenarios #2, #3, and #4, separate spectrum is achieved with scenarios #6 and #7, and both spectrum sharing and separate spectrum options are available in scenario #5. 3GPP compliance and specifications are accomplished with five of the scenarios #2, #3, #5, #6, and #7 whereas scenario #1 and #4 are not 3GPP-compliant. Therefore, we can conclude that there are different consequences of deploying each of these scenarios for RAN sharing. The details of each deployment scenarios and options including their characteristics, advantages, and corresponding challenges for MNOs are described in Table given below.

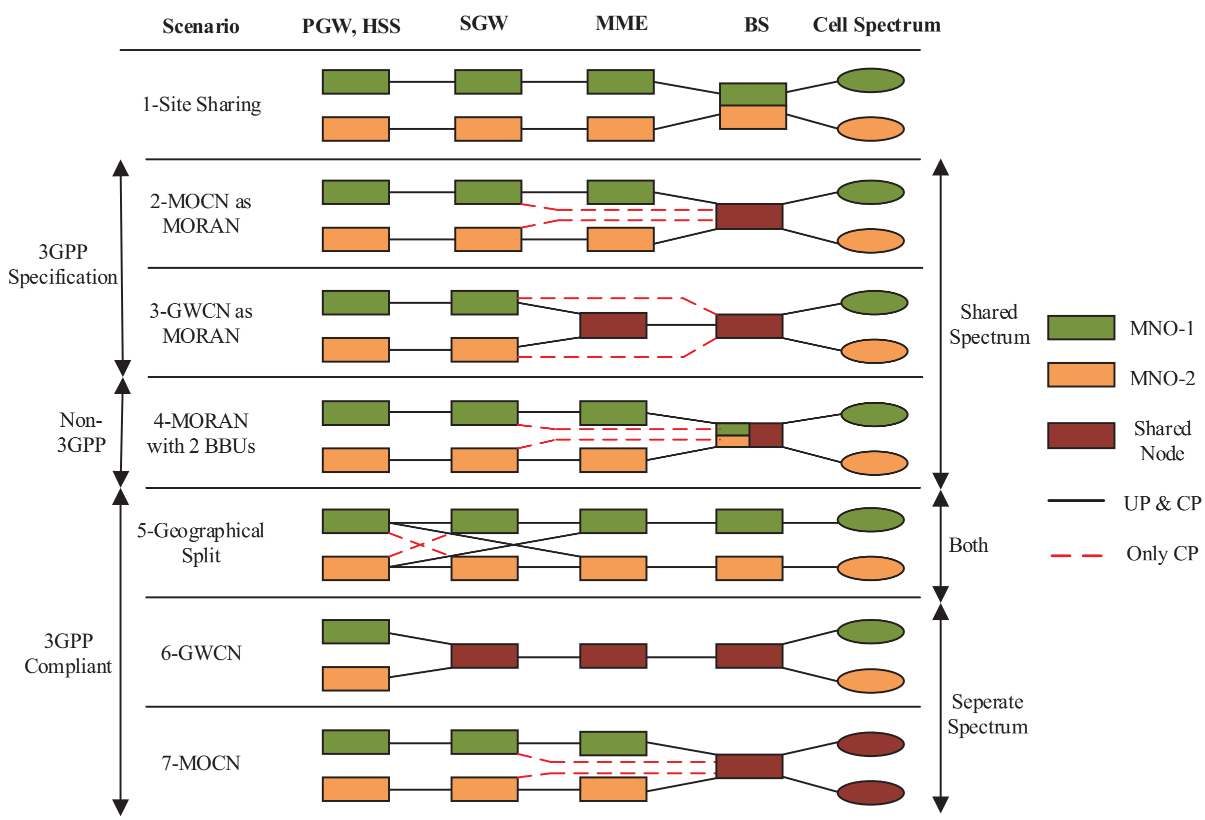

Figure 3. Different configuration options for RAN Sharing.

3. Challenges of RAN sharing

There are multiple challenges of establishing RAN sharing between multiple MNO over multiple network domains. In this section, we will detail some of the related constraints in both RAN and transport network.

Table . Comparisons of the different scenarios for RAN sharing deployment.

Scenario	Characteristics	Challenges	Advantages
1. Site sharing	— Both MNOs position their eNodeBs at the same location. — All the CN equipment are separate. — All the cells and frequencies belong to the MNOs.	— OPeX saving is questionable. — Two sets of operations under the same physical space. — Agreement is needed among MNOs for suitable site selection.	— The energy resources and site leasing costs are shared. — No software configurations are needed for BBUs. — The least complex sharing scenario in terms of network configuration.
2. MOCN as MORAN	— Separate carriers can be used at the RAN side. — Cells are connected to the operator-owned carriers and one shared BBU is used for transport traffic aggregation.	— A highly capable BBU is needed to operate with the different carriers. — Complexity in management of BBU — Ownership of BBU is questionable — It needs agreements on QoS policies due to single BBU.	— Fully compliant with regulation authority rules. — Each MNO aggregates mobile traffic in their own carrier frequencies. — No additional BBU investment. — QoS configuration is relatively less complex when compared with other MORAN scenarios.
3. GWCN as MORAN	— Both eNodeB and MME are shared by two or more MNOs. — By network configuration nonshared cells can be enabled (dedicated frequency for each operator.)	— Authentication of BS is done at shared MME (can bring security issues). — Agreement issues on parameter adjustments of CP signalling among MNOs.	— Reduces the number of CP signalling. — No additional MME & BBU investment.
4. MORAN with 2BBUs	— Two DUs or BBU units that belong to different MNOs can share radio units and the support system. — Operators have their own carriers and individual configuration of all parameters.	— Not compliant with 3GPP standards. — Spectrum configuration is hard due to shared RRUs. — Interconnection between BBUs brings operational complexity	— No additional RRU investments. — Agreements on QoS configuration is possible due to separate BBUs.
5. Geographical split	— Two or more MNOs serve in different geographical locations across the country. — Collaborative large-scale network deployment among MNOs.	— MNOs need to obey each other's site selection and deployment policies. — Providing QoS and cost saving are questionable due to different MNO subscriber distributions in different regions across the country.	— Spectrum sharing can be selected or not based on the implementation and regulative constraints.
6. GWCN	— The eNodeB and the MME are shared by two or more MNOs. — SGW can also be shared based on deployment. — All the cells and frequencies are shared.	— More suitable to MVNOs not for MNOs (due to high number of virtualized nodes). — Regulation license of MVNOs may be required for MNOs.	— Best scenario for OPEX and CAPEX saving (due to shared MME, SGW and BBU). — No additional interconnection needed between MNOs.
7. MOCN	— Two or more MNOs share one eNodeB while the core network is dedicated for each operator.	— Operation is diffucult since ownership of BS is questionable. — Regulation difficulties due to traffic aggregation at same nodes (both in BBU and carrier).	— No additional carries and BBU investments. — Relatively easy configuration when compared to MORAN (scenarios 2 and 4).

3.1. RAN-related constraints

There are some important features and their corresponding challenges that need to be reconsidered during RAN sharing deployments. These are described as follows:

3.1.1. PLMN handling

Many MNOs can share a single LTE RAN. Thus, PLMN handling is important to provide correct PLMN information. Mobility candidate selection determines a set of frequencies in LTE or other radio access technologys (RATs), to which the connected UE can be transferred when it encounters poor coverage in the current cell. In the shared RAN scenario, different UE are connected to networks belonging to different MNOs. To avoid UE belonging to one operator being redirected or handed over to another operator network, an allowed PLMN list is added to each frequency relation of MNO for all RATs. If the list is empty, the frequency relation is allowed for UE belonging to any PLMN. If the list contains at least one PLMN, the frequency relation is only allowed for UE that has at least one of the listed PLMNs as serving PLMN or equivalent PLMN. In this way, PLMN interconnection problem can be solved easily [26].

3.1.2. SIB information

It contains relevant information when evaluating whether a UE is allowed to access a cell and also defines the scheduling of other system information. For each cell, the SIB can include more than one PLMN and it must include all active PLMNs. The primary PLMN must always be broadcast in the SIB. This is because it is used to construct the Cell Global Identity (CGI) and used by the UE to identify the cell. If the primary PLMN is excluded as the active PLMN, the primary PLMN is marked as reserved for MNO usage in the SIB.

3.1.3. Mobility and handover cases

When UE reports that it has found a set of suitable cells based on its LTE measurements, a handover evaluation process is executed. Handover evaluation decides whether a reported cell is suitable for that UE. The tracking area identifier (TAI) of the target cell is compared with the forbidden TAIs. If all the reported cells are forbidden for the UE, the report is discarded. If it is still valid, then the target cell PLMN or PLMN list is compared with the UE serving PLMN and equivalent PLMNs. If there is a match between them, the best cell is selected as target cell. In RAN sharing, since X2 handover signaling is only allowed if the eNodeBs are connected to the same MME pool, the target eNodeB MME pools must be compared with the UE serving MME before X2 handover is selected instead of S1 handover. If the target eNodeB is not connected to the MME pool to which the UE serving MME belongs, X2 handover is not allowed. In case of evolved universal terrestrial radio access network (E-UTRAN), the maximum number of frequencies depend on the compliance of the UE with 3GPP Release-12 below or higher. All PLMNs have a common configuration for S1-U and S1-MME. However, if multiple Internet Protocol (IP) addresses are needed, then it is possible to use different configurations for each PLMN independently.

3.2. Transport-network-related constraints

Along with the target transmission network architecture, RAN sharing is also aimed to create a shared transmission network, provide error isolation and load sharing and create an architecture ready for convergence of the shared network. The transport network for the shared RAN can also utilize network automation techniques as described in [27,28]. The transport network topology in RAN sharing is different than traditional transport network topology. Figure 4 shows the topology concentrated on the transport side. The overall traffic from/to the shared BS will reach the mobile Backhaul aggregation router (MBAR) of the first MNO (which is MNO-1 in Figure 4). Then, there are separate peering routers that are positioned between MNOs (i.e. between MNO-1 & MNO-2 and MNO-1 & MNO-3). Corresponding peering routers are in communication with the circuit switched (CS)-packet-switched (PS) CN of each MNO. Multiprotocol (MP)-Border Gateway Protocol (BGP) model is recommended for traffic transmission between two MNOs. BGP connection will be provided over local autonomous system (AS) numbers. In this case, each service will be carried through a separate Virtual Private Network (VPN). To prevent problems in case of ever increasing interconnections between regions in the future, a separate prefix list should be created for each service. Note that each user traffic belonging to different MNOs is separated by virtual LANs (VLANs) between the MBAR and the shared BSs. Thus, one leased line can be configured with three VLANs.

On the RAN side, the same scheduling rate should be set for QoS class identifier (QCI)-8 and QCI-9. On the transport side, the queue from QCI-8 and 9 must be carried within best effort priority. According to the traffic value from the opposite MNO, marking will be done in the peering router in the direction of ingress. Note that all of the MNOs will not have premium users in the sharing area. Secure tunnels are opened towards security gateway (SecGW) of the guest MNO with the certificate information received by the certification authority (CA) server. Certificate update should also be done automatically and certificate traffic must be carried over a separate VPN. After certification process is accomplished successfully, there will be separate IP security (IPSec) tunnels that will be established to the SecGWs of the different MNOs.

Another situation to be noted here is related to the number of interconnections. As an example, let us assume that there is one interconnection point for the whole country and this is in the center of the country. In this case, the traffic of the BSs in the cities that are located at the edge of the country comes to the center location and goes from there to the CN of the other operator. Hence, the transport network creates network-induced delays. Interconnection can be made in more than one place in the country, but it will require interconnection investments such as peering routers and leased lines.

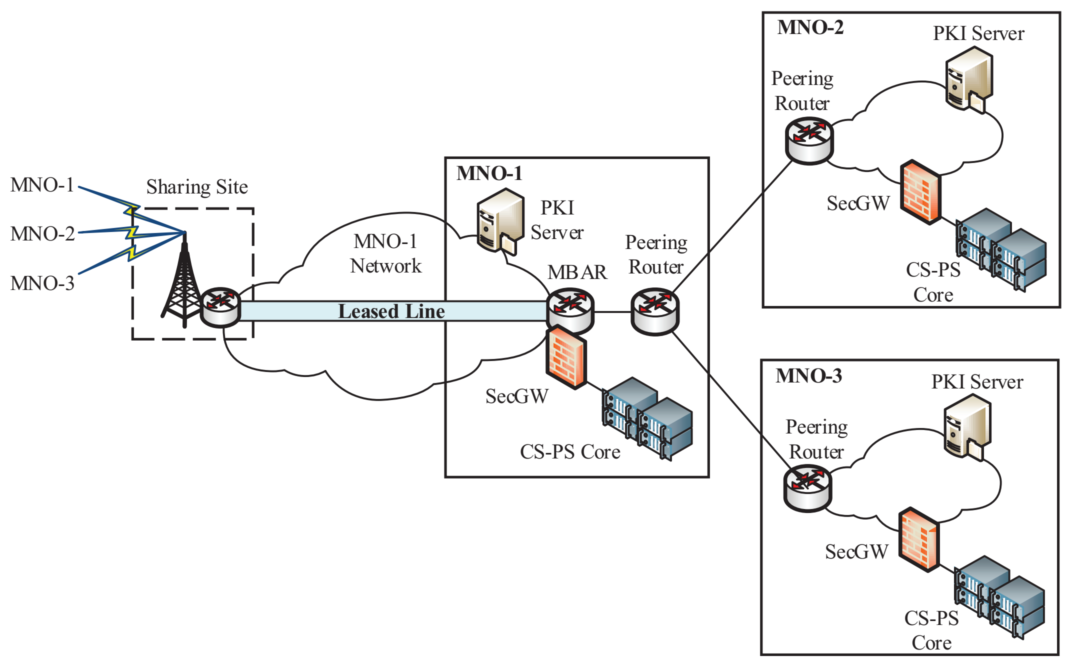

Figure 4. Topology of the target transport network.

4. Experimental results

During our experimental trials, RAN sharing was enabled between 29 October 2018 and 04 November 2018 (7 days) and comparisons are made when no RAN sharing was enabled between 02 January 2018 and 15 January 2018 (14 days) for LTE systems. Our experimentally tested RAN sharing network scenario is MOCN as MORAN for two MNOs as illustrated in Figure 3. Before RAN sharing was enabled, each MNO had 50 sites scattered around the city and the measurement campaign was done for MNO-1. For RAN sharing, 70 newly added sites were selected for experimenting MOCN as MORAN scenario among two MNOs in Turkey. Those sites were selected jointly by two MNOs that were involved in active RAN sharing trial. Investigated KPI values during our experimental trial are radio resource control (RRC) setup success rate, E-UTRAN radio access bearer (E-RAB) setup success rate, service drop rate, intrafrequency HO out success rate, inter-RAT HO out success rate, circuit switched fallback (CSFB) success rate, and user DL and UL average throughput. All related KPIs are calculated by averaging the hourly values of the considered sites.

RRC setup success rate KPI simply measures successful attachment counts of UE into the network during RRC connection request of UE which can be formulated as

$$RRCSetUp_{SR} = \frac{\#\text{ of } RRCSetUpSuccess}{\#\text{ of } RRCSetUpAttempt} \times 100\% \tag{1}$$

where $RRCSetUpSuccess$ is RRC connection establishment's success count and $RRCSetUpAttempt$ is RRC connection establishments attempt count. After successful RRC connection, the network goes from RRC_idle mode to $RRC\_connected$ mode. Some possible practical reasons for observing low RRC setup success rates in a call are related to resource allocation failure (due to UE admission failures) or no response from UE (due to poor coverage or terminal problem).

An E-RAB carries the service data of UE as an access layer bearer. E-RAB setup success rate is related to accessibility and E-RAB counter KPI is utilized after successful RRC connection. The E-RAB success rate depends on successful connections to CN, which can be formulated as

$$ERABSetUp_{SR} = \frac{\#\text{ of } ERABSetUpSuccess}{\#\text{ of } ERABSetUpAttempt} \times 100\% \tag{2}$$

where $ERABSetUpSuccess$ is successful E-RAB establishments and $ERABSetUpAttempt$ is received E-RAB establishment attempts.

A CS-capable device that is registered to LTE needs to fall back to 3G (or even 2G) before a call is terminated/originated. For this reason, many MNOs have integrated the CSFB feature so that voice services can be offered to LTE UE without the support of additional investments (e.g., voice over LTE (VoLTE)). The following formula is used to calculate CSFB success ratio:

$$CSFB_{SR} = \frac{\#\text{ of } CSFBSuccess}{\#\text{ of } CSFBAttempt} \times 100\% \tag{3}$$

where $CSFBSuccess$ is successful CSFB attempts and $CSFBAttempt$ is all CSFB attempt.

Intrafrequency HO out success rate ($IntraFreqHOOut_{SR}$) is defined as the success rate of intrafrequency HOs from local cell to neighboring cells and is calculated as:

$$IntraFreqHOOut_{SR} = \frac{\#\text{ of } IntraFreqHOOutSuccess}{\#\text{ of } IntraFreqHOOutAttempt} \times 100\% \tag{4}$$

Similarly, inter-RAT HO outgoing success rate ($InterRATHOOut_{SR}$) is defined as the success rate of outgoing handovers from 4G cell to other different 3GPP and non-3GPP type cells (e.g., 2G, 3G cells) and is calculated as:

$$InterRATHOOut_{SR} = \frac{\#\text{ of } InterRATHOOutSuccess}{\#\text{ of } InterRATHOOutAttempt} \times 100\% \tag{5}$$

Figure 5 shows the changes in 4G average UL and DL throughput, before and after RAN sharing was enabled in the considered sites. We can observe that both DL and UL average user throughput values increased by 17.8% and 42.85%, respectively, after RAN sharing was enabled in the network. This signifies that the load on the considered MNO increased after the addition of more UE of another MNOs in the experimental region. This indicates that 4G network coverage after enabling RAN sharing increased significantly. Figure 6 shows the change in HO-related KPIs after enabling RAN sharing. This figure shows that inter-RAT HO out success rate and service drop rates decreased by 70.66% and 86.1%, respectively, whereas intrafrequency HO out success rate increased by 358.33% after RAN sharing was enabled in the network. Note that interference levels can have a huge impact on the HO success rate values. A huge increase in intrafrequency HO success rate indicates that the interference level in BSs has diminished significantly and UE with different ranges of speed can successfully perform HOs between cells with much higher success rates. As a matter of fact, observing low values in inter-RAT handovers outgoing success rate in Figure 6a is not a desirable outcome when network optimization and capacity planning are planned by MNOs. One of the major reasons is that the handover between technologies (e.g., from 4G to 3G) is undesired by MNOs as it can cause unpredictable consequences on user's quality-of-experience (QoE). Hence, homogeneous 4G coverage distribution in large geographical regions is preferred. On the other hand, in our shared RAN implementation, one can easily observe that the usage of 4G technology increased due to increased usage of UEs with 4G capability after RAN sharing. However, 3G technology coverage remained constant as no major upgrades were done in terms of 3G coverage expansion during the experimental trial. For this reason, after RAN sharing was enabled between MNOs, the increase in the number of UE due to higher 4G coverage yielded a higher number of inter-RAT handover attempts. As a consequence, inter-RAT handover out success rate decreased.

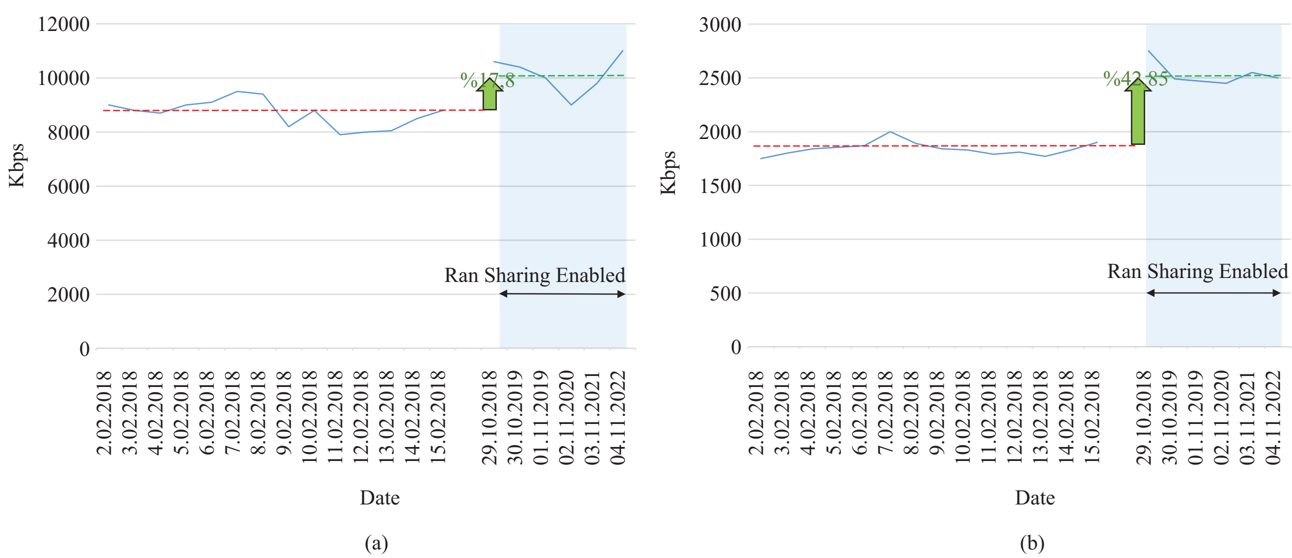

Figure 5. 4G average throughput KPIs. (a) User DL average throughput, (b) user UL average throughput.

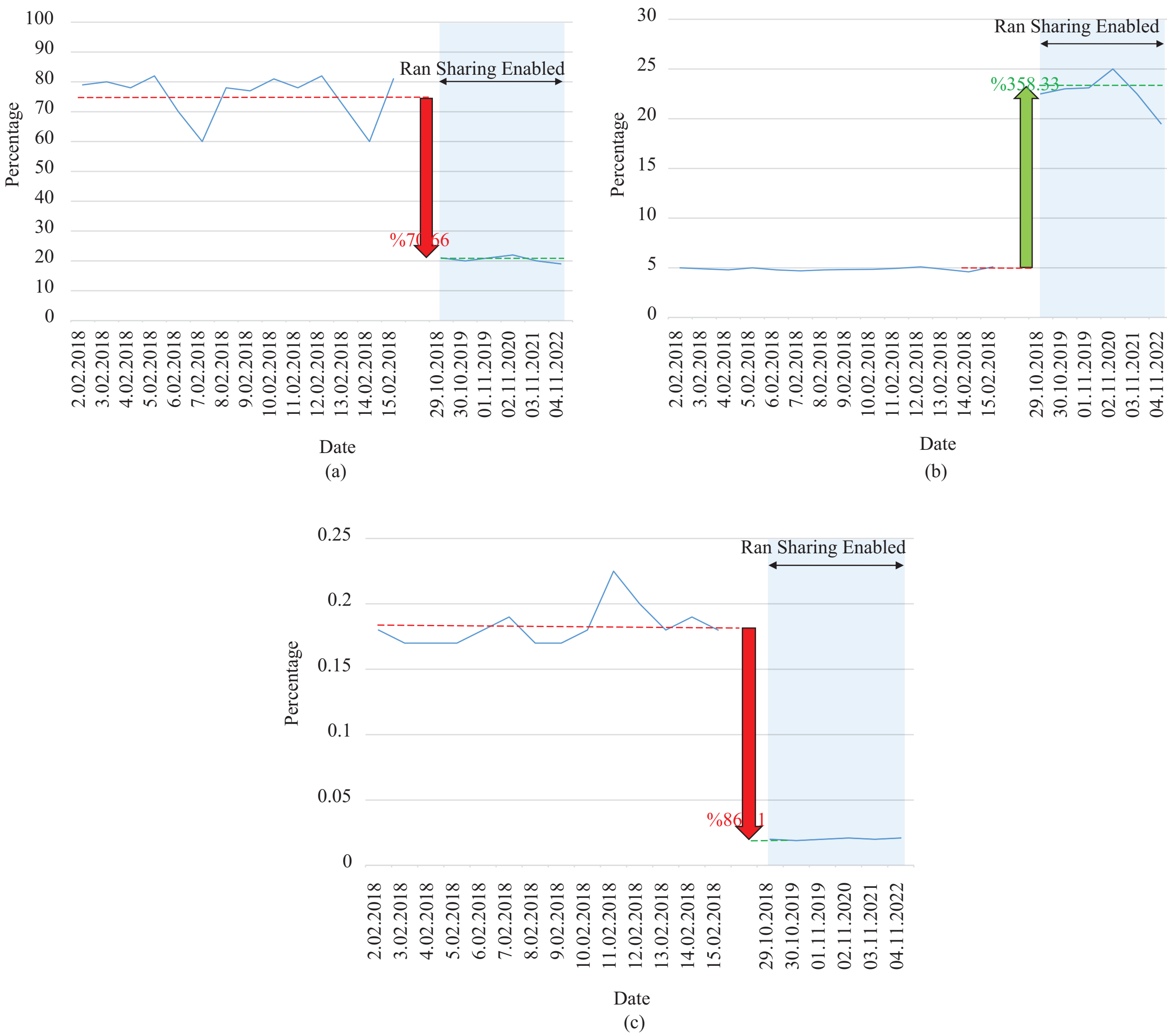

Figure 6. 4G handover KPIs. (a) Inter-RAT handover outgoing success rate, (b) intrafrequency handover outgoing success rate, (c) service drop rate.

Figure 7 shows the changes in connection-related KPIs after enabling RAN sharing. From Figure 7, it is seen that the RRC setup success rate, E-RAB setup success rate, and CSFB success rate increased very slightly by 0.01%, 0.04%, and 0.7%, respectively, after RAN sharing was enabled. Therefore, we can say that RRC and E-RAB setup success rates were relatively stable. CSFB success rate values are also observed to be higher after enabling the RAN sharing feature. This is in fact related to 4G coverage expansion outcome of the RAN sharing. On the other hand, we can also observe that CSFB success values did not increase substantially. This can be related to low percentage of UE utilizing VoLTE services in comparison with the total increasing number of UEs utilizing LTE network.

E-RAB setup request and response are established between eNodeB and core network of MNOs. E-RAB success rate is related to availability of radio resources and RRC connected number of users. No significant changes in E-RAB success rate in Figure 7 indicate that before and after active RAN sharing trial, the UE was able to reach the CN successfully. Hence, no major failures occurred in either radio or core network during E-RAB setup before and after RAN sharing. After RAN sharing was enabled, the number of 4G UEs increased due to LTE coverage extension. However, RRC setup and E-RAN success rates remained relatively constant with no major changes after enabling RAN sharing. In E-RAB connection, the locations of core networks for both MNOs were unchanged after RAN sharing feature was enabled. Hence, while RAN sharing feature was activated during experiments, the core network locations were kept separate for both MNOs in the same city. However, these locations were in a different city from the location where RAN sharing was performed. Therefore, transport network was also shared between MNOs. Each UE traffic belonging to different MNOs was separated by VLANs between the MBAR and the shared BSs. Thus, one leased line was configured with three VLANs. The purpose of transport network sharing was to focus on operational expenditure (OPEX)/capital expenditure (CAPEX) savings. In fact, the transport path to the core network did not become shorter in terms of distance after RAN sharing was enabled. For this reason, the E-RAB success rate remained the same due to no major differences on the length and performance of the transport network path. These results again validates the increase in UE throughput values due to the improvements done in RAN domain due to active RAN sharing feature. The outcomes of the experiments have also demonstrated that the scheduler of eNodeBs was successful in scheduling new arriving UE appropriately since no significant changes occurred during RRC setup. This signifies that the buffer size was not full and there were enough resources to assign to newly arriving UE RRC connection request during experiments.

Note that among the discussed RAN sharing mechanisms explained in Section 2, we have demonstrated scenario #2: MOCN as MORAN in our experiments instead of scenario #7: MOCN. It is known that simple MOCN scheme improves the interference levels in network but suffers from network coverage issues [24]. The main difference compared to MOCN is that high-capacity and costly BBU is needed to be utilized in MOCN as MORAN scenario since the carriers are separated for each MNO. The fact that the processing and computing power of this BBU was higher also improved the QoS provided to UE. Another major advantage of using MOCN as MORAN was the ability of each MNO to utilize their own carriers or frequencies. This gave much flexibility and higher total bandwidth to MNOs compared to shared carrier frequency case of MOCN scenario.

During activation of the RAN sharing feature, new and optimized BS locations were selected by two MNOs jointly. This also improved the utilization of cell towers and hence the coverage significantly, as can be observed from the improvements in both UL and DL user average throughout values in Figure 5. Moreover, careful selection of a joint QoS policy by two MNOs also resulted in higher improvements in throughput values due to lower interference values in coverage areas even though relatively stable values in both RRC and E-RAB setup success rates are observed. On the other hand, RAN sharing activation also had a major impact on the utilization of services provided by MNO during live trial period. UL traffic values increased more than DL traffic values as given in Figure 5. This signifies that UE has started to utilize UL services (e.g., multimedia sharing, image and video uploads) after RAN sharing was enabled in the network. This is also a consequence of lower service drop rates that are observed in Figure 6c after RAN sharing was enabled.

5. Conclusions and future work

In this paper, we have investigated the RAN sharing solutions and their possible deployment scenarios together with their characteristics, advantages, and limitations. In addition, city-wide experimental studies of one of the considered MOCN as MORAN scenarios in RAN sharing were performed on operational LTE networks in

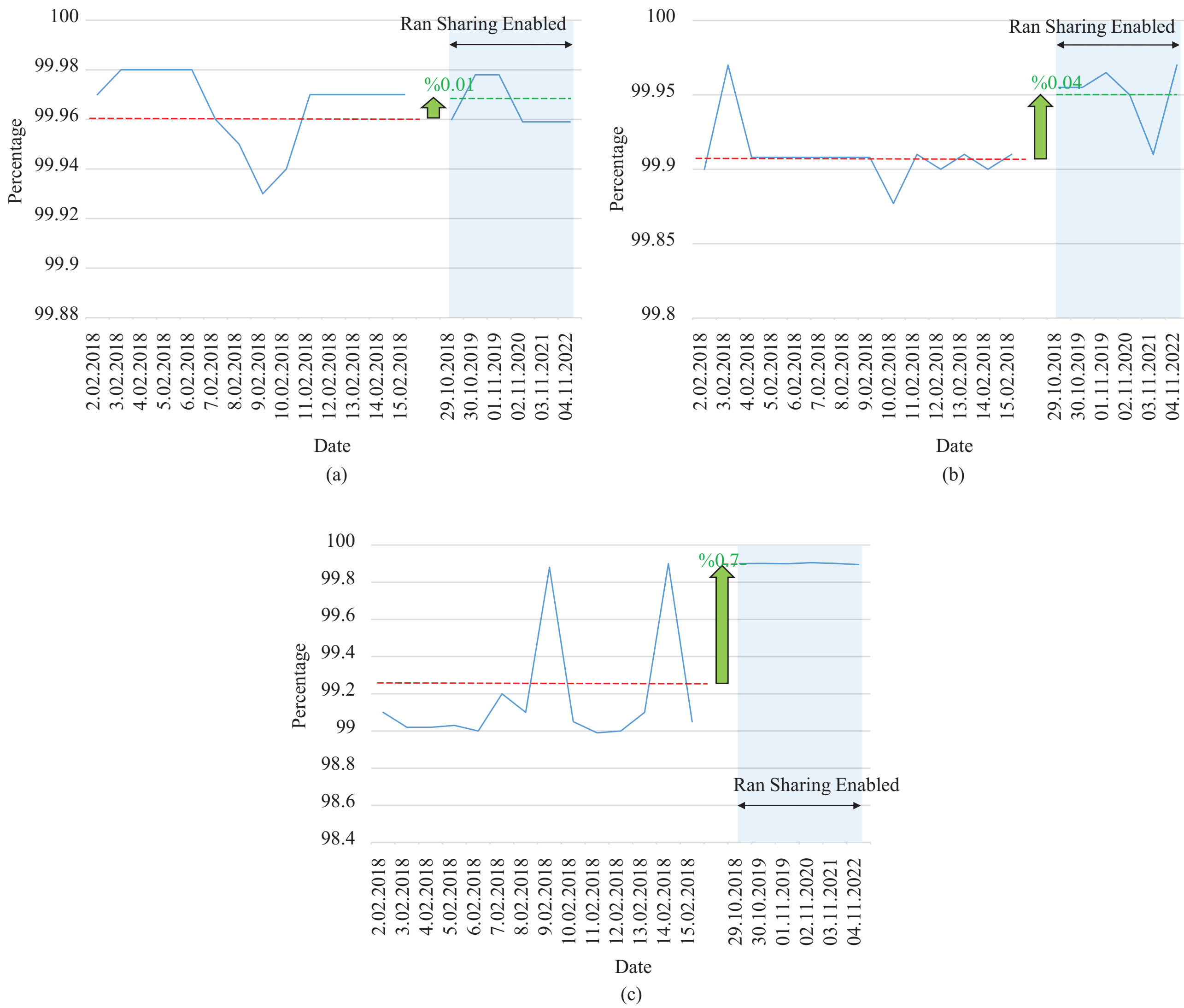

Figure 7. 4G KPIs (a) RRC setup success rate. (b) E-RAB setup success rate. (c) CSFB success rate.

Turkey. Through experimental tests, we showed the overall performance gains of enabling the RAN sharing feature in terms of observing different KPIs that were obtained from shared BSs. In particular, both DL and UL average user throughput values increased by 17.8% and 42.85%, respectively, inter-RAT HO out success rate and service drop rates decreased by 70.66% and 86.1%, respectively, whereas intrafrequency HO out success rate increased by 358.33% after RAN sharing was enabled in the network.

One of the relevant topics that can be studied as a future endeavor is to investigate whether the RAN sharing paradigm can also be applied in a network slicing environment. Although this issue has been solved partly for the shared slicing structure, investigation of the RAN sharing application for the cases where dedicated slicing is used can be considered as a topic for future work. Another important topic of interest is that in cases where there is a cloud RAN structure, details of how to handle RAN sharing can be investigated as well.

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