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3-Sector Cell vs. Omnicell: Cell Sectorization Impact on the Performance of Side-by-Side Unlicensed LTE and 802.11ac Air Interfaces

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ABSTRACT Due to the benefits of networks coexistence, it is common nowadays to equip mobile phones with two types of network interfaces: LTE and 802.11ac. However, using the same 5GHz bandwidth by 802.11ac and LTE in unlicensed spectrum, along with the structural differences of the two networks, result in multiple coexistence limitations and implementation issues. Considering the potential benefits of cell sectorization over the conventional omnicells for improving the performance of LTE users, can they achieve similar improvements in coexisting networks. Moreover, can LTE signals interfere and affect the performance of 802.11ac users coexisting with LTE. In this case, which LTE cell deployment, either omnicell or sectorized cell, has the most impact. Toward addressing these issues, this work proposes a link-level and physical-level model. The model consists of two distinct LTE sites: a conventional omnicell site (360 degrees) and a three-sector site (3 × 120 degrees). In addition, the model contains two similar 802.11ac networks, one for each site, to coexist 802.11ac Wi-Fi stations with LTE users. The model is further optimized to include a pure 802.11ac network, dedicated as the baseline. Subsequently, the model is verified in NS3 through various simulation scenarios by means of measuring and quantifying the three-sector, omnicell, and pure 802.11ac networks performances to facilitate resolving any doubt of mobile operators and developers regarding the cell sectorization and coexistence issues. The simulation results indicate that in coexisting networks, LTE users in omnicell sites attain better performance than users in 3-sector sites, while the performance of 802.11ac users varies when different features are combined.

INDEX TERMS 3-sector cell, 802.11ac, cell sectoring, LTE, omnicell.

I. INTRODUCTION

The long term evolution (LTE) is a wireless standard used by mobile devices to transfer data via a radio access network (RAN) called evolved UTRAN (EUTRAN). The ETURAN includes a component called eNodeB through which the user equipment (UE) are linked to the LTE core network. The core, itself, is composed of two components: serving gateway (SGW) and packet data network gateway (PGW). While the latter handles the connectivity of the SGW with the rest of the world, the former provides the connectivity between eNodeB and PGW. The radio coverage area of an eNodeB is called a cell. Accordingly, the cell site is where the eNodeB radio equipment and its antennas are placed. Based on the antenna type, there can be two types of cell deployments: omnidirectional cell and sectorized cell. The omnidirectional cell also called omnicell, includes an Omni antenna to cover the signals in 360-degree field which practically means in all directions. Figure 1 shows a typical structure of LTE omnicells.

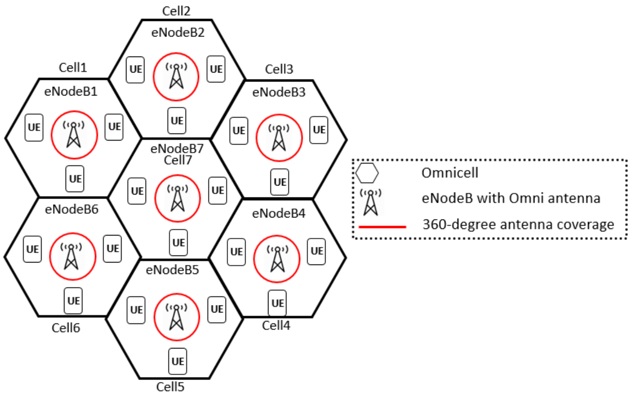

FIGURE 1. Typical structure of LTE omnicells.

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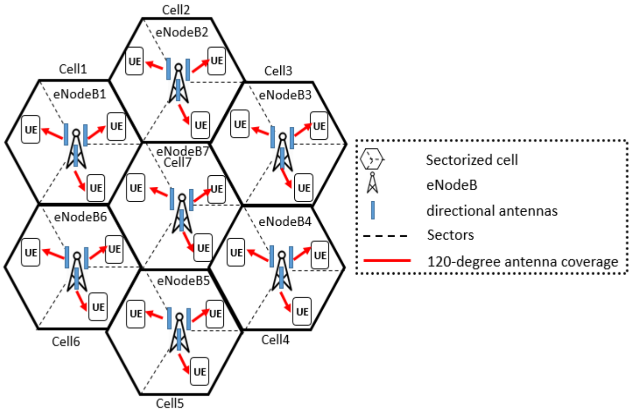

FIGURE 2. **Typical structure of LTE 3-sector cells (each cell includes 3 × 120 degree sectors).**

In contrast to omnicells, the sectorized cells have been designed to enhance the cellular system capacity. The sectorization refers to when cells are divided into different parts called sector. The antenna for eNodeB is replaced with sector antenna owning different order of sectorization, e.g. three, six, or nine with 120, 60, 40 degrees' coverage, respectively [1], where each sector is covered by one of the sector antennas. The importance of cell sectorization is mainly due to improving the transmission capabilities and capacity gain and thereby, it is widely used by mobile communication industries to increase the data rate [2]–[4].

For the purposes of this work, we are primarily concentrating on three-sector sites with 120-degree coverage per each sector. Figure 2 presents a typical structure of LTE 3-sector cells.

On the other hand, because of the success of 802.11ac wireless networks in communication systems, nowadays the mobile phones are commonly equipped with two types of network interfaces as LTE and 802.11ac. This can be used to form coexisting radio networks in which the mobile users are able to alternatively switch among the interfaces for seeking better services. In order to achieve such a coexistence, LTE in unlicensed spectrum was developed to access 5GHz frequency band [5], [6]. We also develop our model based on the unlicensed LTE which for the simplicity it has been referred to as LTE in this work.

The coexisting techniques are quite beneficial in many cases including private LTE, a dedicated network which covers the interior and exterior of buildings, particularly favorable for consumers, businesses, and internet of things (IoT) [5]. However, because the LTE devices are working on 5GHz bandwidth which is already populated by 802.11ac devices, the corresponding interferences caused by LTE signals can impose limitations and unexpected effects on the performance of 802.11ac users in coexisting networks.

The issue of interfering the LTE signals with 802.11ac signals is further increased by considering the LTE cell sectorization alternatives along with the fact that the coexisting can be performed for all types of LTE cell deployments i.e. omnicell and sectorized cell sites.

Addressing these issues requires precise design, measurement, and analysis and this work contributes to this direction as follows:

1) It proposes a link-level and physical-level model to help in improving the overall stability of LTE-802.11ac coexisting networks. The model includes the mobile phones equipped with LTE and 802.11ac air interfaces placed in two distinct sites: omnicell and sectorized cell (3-sector).

2) It determines that despite the potential benefits of cell sectorization for improving the performance of UEs in LTE networks, whether this is still true for UEs in a coexisting environment with 802.11ac devices. It is noticeable to mention that the cell sectorization will add extra cost for the extra required equipment with less number of channels per sector. The cell sectorization also demands precise cell planning in both enterprise markets and consumer markets. Moreover, the performance of users placed in higher order sectorization sites depends on a number of unpredictable factors such as antenna radiation patterns or inter-cell interference [2], so that any non-ideal configuration can significantly affect the performance. Thereby, to achieve all figure of merits of cell sectoring and to overcome the corresponding limitations, extensive deliberations of the benefits and risks must be considered. In this regard, it must be determined that in what extent the UEs in coexisting LTE-802.11ac network and LTE companies can benefit from the cell sectorization compared to conventional omnicells in terms of experiencing better performance and justifying the extra cost and cell planning, respectively.

3) It takes 802.11ac users into account and verifies that whether they achieve better mobile services in the coexisting networks or in pure 802.11ac networks. In case of former, it also determines which site deployment, either higher order sectorization sites or omnicell sites, is more suited for performance enhancement of 802.11ac users.

The rest of this paper is organized as follows. Section 2 discusses the related works. Section 3 introduces the model and the implementation method including the simulation setup and environment, scenarios, and parameters. Section 4 presents the simulation results followed by the evaluation. Finally, the conclusions are made in section 5.

II. RELATED WORKS

The related works have been classified into LTE cell sectorization and coexisting between LTE and Wi-Fi networks. The 802.11n and LTE coexistence are analyzed in [6] by adopting a MATLAB-based simulator called Vienna LTE downlink link level simulator. The LTE link performance is obtained for various channel quality indicator (CQI) values and system bandwidths of 1.4 and 20 MHz to evaluate the relation between block error rate (BLER), throughput, CQI, and bit error rate (BER) and signal-to-interference ratio (SIR). The work evaluates neither 802.11ac nor other important link-level parameters and sectorization.

The coexisting of LTE in unlicensed spectrum (LTE-U) and 802.11ac is evaluated in [7]. They show that it fails to fulfill fair coexisting with 802.11ac and proposes two optimal transmission policies. By varying the number of Wi-Fi wireless nodes, MPDU between 1500B and 15000B, and frame duration, the impact on the throughput is evaluated for both U-LTE and the proposed policies. The work does not take into account the sectorization and other important link layer or physical layer parameters. The LTE Unlicensed is also analyzed in [8]–[15]. In contrast, in [16], [17], the LTE licensed assisted access (LTE-LAA) is explored using the national instrument (NI) and an analytical model. The LTE-LAA is also investigated in [18]–[21].

The coexistence of LTE-advanced (LTE-A) and traditional LTE is investigated in [22]. The throughput is measured with different radio frequency parameters but the sectorization and 802.11ac are not investigated.

As we can see, the coexistence of Wi-Fi and LTE and the corresponding issues have been discussed widely by many researches. Despite that, there are only a few studies available on the coexistence with respect to cell sectorization. A statistical model to theoretically characterize the performance of sectorization deployments in LTE networks using orthogonal frequency division multiple access (OFDMA) is presented in [2]. The number of sectors is considered as 3, 6, and 12 and the performance is obtained in terms of SIR, outage probability, resource allocation, and throughput. The work considers neither 802.11ac networks nor omnicell configuration. The cell average spectral efficiency and SINR of the UEs in the case of three sectors are evaluated for LTE-A in [3]. Moreover, the quasi-dynamic multi-cell system level simulator has been used to evaluate 6-sector-site performance against 3-sector-site deployment in the downlink LTE by the authors in [23]. The cell throughput, cumulative distribution function of the user goodput, and geometry factor (G-factor) are used as the performance metrics. The authors in [24] compare the energy efficiency of 3-sector and 6-sector LTE cells. The results show that although sectorization can improve cell capacity, it also consumes more energy. They conclude that having a higher number of sectors is less energy-efficient than having less. In [25], Omni, 3-sector, and 6-sector LTE cells are compared. The Monte Carlo simulation is used for varying the cell radius and measuring the average uplink area spectral efficiency.

A deeper look at the previous studies reveals a number of shortcomings. To the best of our knowledge, no previous study has investigated the LTE and 802.11ac coexisting issues with respect to the order of sectorization, to measure and evaluate any possible performance gain or loss incurred in this regard, which are the main contributions of this work.

III. IMPLEMENTATION METHOD

This section provides the implementation details of the proposed model along with the cell planning and sectorization scheme, simulation scenarios, simulation parameters, and the performance metrics used to evaluate the model using NS3 tool.

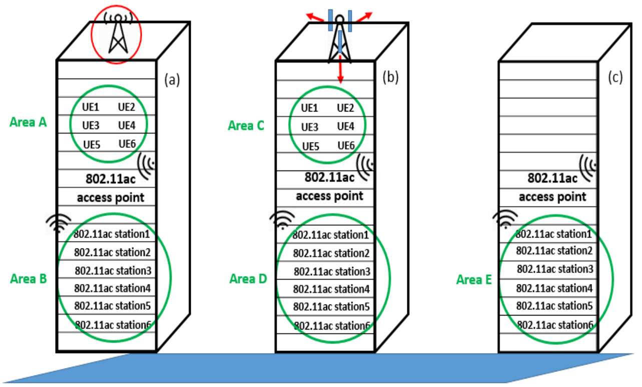

FIGURE 3. The cell planning and areas in different floors of the buildings.

A. CELL PLANNING AND SIMULATION SETUP

As mentioned, the LTE and 802.11ac coexisting issues with respect to the order of sectorization are the main focus of this work. Therefore, this work introduces a link-level and physical-level model. The cell planning, a process by which the model will identify several areas of relevance and achieve its objectives, is summarized as follows:

- Two types of LTE cells are designed: one omnicell and one 3-sector cell, in which a number of UEs are placed.
- Two similar 802.11ac networks, one for each cell, are designed to coexist the UEs with 802.11ac users. This provides two distinct coexisting networks.
- A pure 802.11ac network, as the baseline, is designed and placed where there is no LTE cell around.
- The performance of UEs in 3-sector cell and omnicell are measured and compared against each other. This comparison enables us to evaluate the impact of cell sectorization and verify whether the benefits of cell sectorization are also provided for LTE users in coexisting networks.
- The performance of 802.1ac users in both coexisting networks (under interference caused by omnicell and 3-sector cells) are measured.
- The results are compared against the performance of 802.11ac users when there are no LTE interferences around (the baseline network). This comparison provides evidence to determine whether LTE signals interfere and affect the performance of 802.11ac users in coexisting networks. It is further required to asses which LTE cell deployment, either omnicell or sectorized cell, has the most impact.

Figure 3 shows the three distinct networks required for the cell planning of the model.

The model sets up three different residential buildings (*SetBuildingType* is Residential). All the buildings are characterized so that the type of walls is concrete (*SetExtWallsType* is *ConcreteWithWindows*) and the number of floors is 16 (*SetNFloors* is 16) while there are two rooms in each x and y axis's (*SetNRoomsX* is 2 and *SetNRoomsY* is 2), providing 4 rooms in each floor.

In the first building (a), an eNodeB with conventional Omni antenna on the roof is simulated. Six LTE radio interfaces are placed on different floors so that UE1 and UE2 are on the 3rd floor, UE3 and UE4 are on the 4th floor, and UE5 and UE6 are on the 5th floor. Since there are four rooms in each floor, the position of each UE in its corresponding floor is chosen randomly to replicate substantial aspects of the real world. The Omni antenna of eNodeB on the roof provides 360-degree signal coverage for all UEs around, forming Area A.

Moreover, in the same building but lower floors, six Wi-Fi radio interfaces are attached to an 802.11ac access point, creating Area B. In this area, 802.11ac station1 to station6 are on the 10th to 15th floor, respectively. The physical position of each station in its corresponding floor is chosen randomly to be similar to the real world examples.

In the second building (b), on the other hand, an eNodeB with a 3-sector antenna is placed on the roof of the building to provide services for the UEs in Area C. The antenna orientation is measured in degrees from the X axis so that each sector antenna covers 120 degrees as follows:

1) First sector:

SetEnbAntennaModelAttribute (“Orientation”, DoubleValue (0))

2) Second sector:

SetEnbAntennaModelAttribute (“Orientation”, DoubleValue (360/3)

3) Third sector:

SetEnbAntennaModelAttribute (“Orientation”, DoubleValue (2∗360/3))

Here, the physical position of the UEs is so that UE1 and UE2 are on the 3rd floor under the coverage of first sector, UE3 and UE4 are on the 4th floor under the coverage of second sector, and UE5 and UE6 are on the 5th floor under the coverage of third sector. Like before, the position of each UE in its corresponding floor is chosen randomly to be similar to the real world examples. Moreover, six 802.11ac users are placed in the lower floors, creating Area D. The physical position of 802.11ac stations in Area D is done in the same way as those stations in Area B.

In the third building (c), there is no LTE presence, and there are only six 802.11ac users connected to the access point. The physical position of 802.11ac stations in Area E is similar to those stations in Area B and Area D. This topology is used as a baseline to evaluate the possible effects of LTE signals interference on the performance of 802.11ac users.

Taken together, there are five different areas that require performance evaluation and comparison.

The direction of traffic transmitted in all three buildings is downlink for which more components are required to be added to the simulation areas. Thus, an UDP-based server application is set up to transmit similar packets in the three buildings. Moreover, an SGW/PGW device is set up through which the packets are delivered to the UEs in LTE networks (Area A and Area c). Likewise, an 802.11ac access point is placed to deliver the packets to 802.11ac users in their corresponding areas (Area B, Area D, and Area E). The details regarding the topology of the five areas are presented in Figure 4.

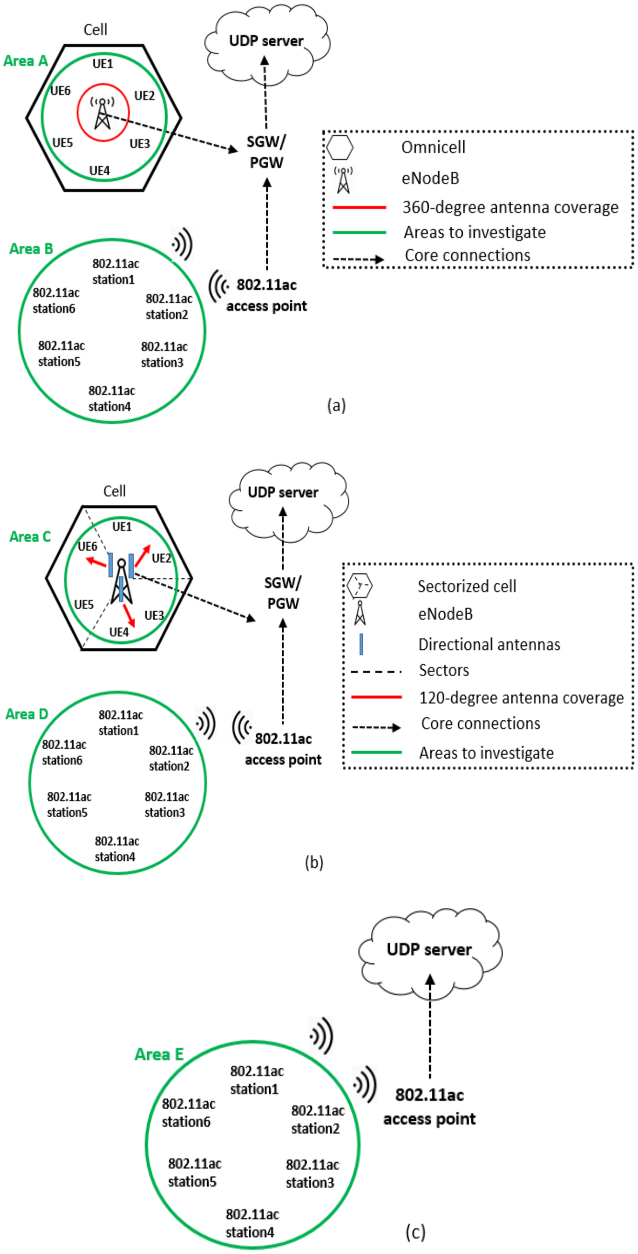

FIGURE 4. Topology of the five areas.

B. SIMULATION SCENARIOS

In order to achieve the objectives, the following five different scenarios are included in the model:

1) Scenario A measures the impact of eNodeB interferences caused by an omnicell site on 802.11ac users in Area B. The aim of this scenario is to quantify the performance of 802.11ac users in a coexisting environment when there is a nearby omnicell site around the Wi-Fi users. The results are used to be compared with the baseline results measured

TABLE 1. Main LTE parameters applied in Area A and Area C.

Name	Value
Channel bandwidth	20 MHz
Number of UEs	A) 6 in omnicell B) 6 in 3-sector cell (two in each sector)
Number of subcarriers	12
Number of PRBs	100
Antenna type	A) Omni (360 degree) B) 3-sector (each 120 degree)

in Scenario C to determine any possible capacity gain or loss caused by interferences of the LTE omnicell site on the 802.11ac users.

2) Scenario B considers the interferences imposed by the 3-sector site and measures the possible effects on the performance of 802.11ac users in Area D. The results are first compared with the results of Scenario C as the baseline, to indicate whether or not LTE 3-sector cell sites can affect the performance of 802.11ac users. Then, the results are compared against Scenario A to determine which site, either omnicell or a higher order sectorized cell, has more effect on the performance variations of the 802.11ac users in a coexisting environment.

3) Scenario C is responsible to evaluate the performance of 802.11ac users in the absence of LTE cells in Area E. The results, as the baseline, are utilized by Scenario A and Scenario B.

4) Scenario D will determine the performance of UEs in the presence of conventional omnicell site in Area A. The results are measured for two primary purposes. First, as mentioned, it is common nowadays to equip the mobile phones with two types of air interfaces as LTE and 802.11ac, to alternatively provide connectivity to cellular and Wi-Fi networks, respectively. Having this in mind, the results of this scenario are compared against Scenario A and Scenario B to determine that being in coverage area of both LTE and 802.11ac networks, which network performs better to switch to it. Second, the obtained results are compared against Scenario E to address the uncertainty of whether an omnicell or a higher order sectorization can provide better services for the UEs in LTE networks.

5) Scenario E measures the performance of UEs in the presence of 3-sector cell site in Area C. The results are used in conjunction with Scenarios D to determine whether the deployment of higher order sectorization sites are better options than conventional omnicell sites to meet the growing demand of mobile data usage.

C. SIMULATION PARAMETERS

As mentioned above, the proposed model includes two types of radio networks as LTE and 802.11ac. Accordingly, there are some parameters specific to LTE, some specific to 802.11ac, and some common to both networks which are presented in Table I, Table II, and Table III, respectively.

In addition to the LTE-related parameters shown in Table I, the downlink and uplink carrier frequencies are also specified for LTE network. The carrier frequency of LTE is designated by EUTRAN absolute radio frequency channel number (EARFCN). It is a number ranging between 0-65535 which maps to a corresponding frequency. Here, we set downlink and uplink EARFCN in Area A with Omni antenna as follows:

TABLE 2. Main 802.11ac parameters applied in Area B, Area D, and Area E.

Name	Value
Channel bandwidth	20 MHz
Channel number	36
Number of 802.11ac users	6
Guard interval	Short
Data mode	VhtMcs7
Standard	802.11ac

TABLE 3. Common parameters applied in all five Areas.

Name	Value
Traffic type	UDP
Packet size	1448 bytes
Simulation Time	10s
Mobility Model	ConstantPositionMobilityModel
Initial Energy	20 joule
MTU size	1500

1) Omni cell:

SetEnbDeviceAttribute (“DlEarfcn”, UintegerValue (255444))

which maps to 5180 MHz in band 252.

In contrast, assigning the carrier frequency is different for Area C with 3-sector antennas. All three sectors must operate in different frequency otherwise the interference would be huge. Here, we set EARFCN of each sector as follows:

1) First sector:

SetEnbDeviceAttribute (“DlEarfcn”, UintegerValue (255844))

which maps to 5220 MHz in band 252.

2) Second sector:

SetEnbDeviceAttribute (“DlEarfcn”, UintegerValue (255644))

which maps to 5200 MHz in band 252.

3) Third sector:

SetEnbDeviceAttribute (“DlEarfcn”, UintegerValue (255444))

which maps to 5180 MHz in band 252.

D. SELECTION OF THE PERFORMANCE METRICS

Since the assessment of the model is done on the basis of both physical-level and link-level considerations, this section identifies them for clarification purposes.

1) PHYSICAL-LEVEL PARAMETERS

Six physical-level metrics are measured in the model which include the average of RSRP, RSRQ, RSSI, SNR, energy consumption, and power consumption of users. In this subsection the aspects of these metrics plus the details of the measurements process are described.

a: LTE FRAME TRANSMISSION CONSIDERATIONS

In LTE networks, data is carried between UE and eNodeB in form of radio frames. Each frame contains 10 subframes. The frame duration is 10ms, thus, the subframe duration is 1ms. Depending on the specified channel bandwidth, each subframe includes a different number of physical resource block (PRB). Each PRB, in turn, contains two resource blocks (RB). In our model, the channel bandwidth is set to 20MHz, hence, there are 100 PRBs per subframe (50 RBs per slot) [26]. Each sub-frame is further divided into two slots, each 0.5ms. Each slot is a time-frequency resource grid as follow:

- In the frequency domain (vertical axis), the slot contains 12 consecutive subcarriers each 15KHz. This provides 12×15 kHz = 180KHz width for an RB.
- In the time domain (horizontal axis), the slot contains either six or seven OFDM symbols, depending on the cyclic prefix (CP) length:
  - If the normal CP is used, the slot contains seven symbols (which we employ in the model).
  - If the extended CP is used, the slot contains six symbols.

A single subcarrier for one symbol is called a resource element (RE) which contains one symbol carrying two, four, or six bits of data depending on the modulation scheme. Having all these, LTE systems use PRB as the smallest unit of scheduling assigned to UEs by eNodeB scheduler for data transmission compared to RB which is the smallest unit of resource allocation among UEs.

A PRB consists of 12 consecutive subcarriers in the frequency domain and 14 OFDM symbols in the time domain. In each PRB, some REs are used to carry data (from higher layer), and some specific REs are used to carry reference signals (RS). Reference signals are replaced in specific and pre-determined slots to be used by UE to determine channel conditions and quality. These parameters, used in the proposed model, are presented in Figure 5.

b: PHYSICAL-LEVEL EVALUATION PARAMETERS

The proposed model is able to measure the average of energy and power consumed by the users in downlink direction. Moreover, it is able to evaluate the channel conditions and quality by measuring several channel indicators derived from reference signals [27]. The measuring processes are described as follows.

1) Reference signal received power (RSRP) is an LTE specific metric. The UE measures the power of the signal that it receives from its serving eNodeB and calculates RSRP as the average power of all REs that carry RS. The RSRP is calculated for the useful part of OFDMA symbol and will not consider cyclic prefix. Based on the value of RSRP, the signal strength of the serving eNodeB and its distance to UE is determined.

To measure RSRP by the model, we define I as the number of REs in a single PRB that carry RSs and P_{RS} as the power received from a single RS. Hence, the formula for calculating the average RSRP of a PRB ($RSRP_{PRB}$) is:

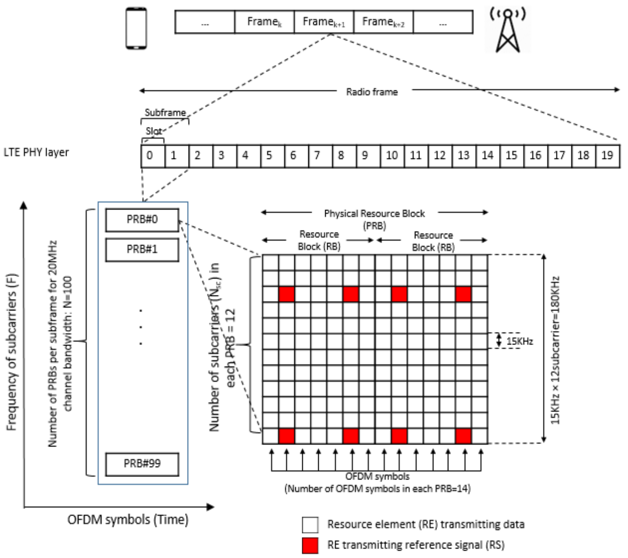

FIGURE 5. 100 PRBs and 7 OFDM symbols used in the proposed model.

$$RSRP_{PRB} = \frac{1}{I}\sum_{i=1}^{i=I} P_{RS,i}$$

$$\textit{where } I \textit{ is number of RSs in a single PRB} \qquad (1)$$

Now, in order to calculate the average value of RSRP over the entire bandwidth, we need the total number of RPBs which we call it N. The value of N depends on the available bandwidth. Here, we set downlink channel bandwidth in terms of number of PRB (N):

Config::SetDefault("ns3::LteEnbNetDevice::DlBandwidth",UintegerValue(100))

By assiging N to 100, the LTE downlink channel bandwidth is set to 20MHz (wideband). The 20MHz channel is used for LTE to provide fair enough conditions for LTE and 802.11ac comparison. Now, the formula for calculating average RSRP over the entire LTE bandwidth ($RSRP_{tot}$) is:

$$RSRP_{tot} = \frac{1}{N \times I}\sum_{n=1}^{n=N}\sum_{i=1}^{i=I}(P_{RS,i})_n \quad \textit{where } N = 100 \qquad (2)$$

2) Reference signal received quality (RSRQ) is another LTE specific metric. As mentioned, RSRP is just an indicator of how strong UE receives signal from its eNodeB while it is not able to indicate how good this signal is. If UE is far away from eNodeB, the RSRP is low, and if UE is close enough to it, the RSRP is high even when there are other neighbor eNodeBs around. In this case, due to all the noises and interferences incurred by the neighbor eNodeBs, the quality of the signal will decrease and can be very low while still, RSRP shows a good high value. Since RSRP does not give any indication on the quality of the received signal, the RSRQ measurement is performed. The RSRQ takes into account noise and interferences to indicate the quality of the received signal. The calculation of RSRQ is on the basis of another parameter called receive signal strength indicator (RSSI).

The measured RSRQ is reported to eNodeB to identify the signal quality and troubleshooting problems within the network.

$$RSRQ_{tot} = N \times \frac{RSRP_{tot}}{RSSI_{tot}} \quad where\ N = 100 \tag{3}$$

3) Receive signal strength indicator (RSSI) is only calculated to assist measuring RSRQ, thus, it is not reported by UE back to eNodeB. While RSRP calculation only includes the REs that carry RS, the RSSI takes into account the total received power of the entire OFDM symbols that carry RS (it means power of all REs and RSs in an OFDM symbol that has RS). It also considers all kinds of noise, existing around the serving cell, such as interference from adjacent channels or other nearby cells. The measured RSSI is used by UE to calculate RSRQ. This way, RSSI can also simply be computed reversibly by eNodeB from RSRQ and RSRP that are reported by UE.

To measure RSSI, we define S as the number of OFDM symbols in a single PRB that carry RSs, $P^{Serving\_cell}_{Symbol,j}$ as the power received from RSs of j^{th} symbol in eNodeB to which UE is connected to, $P^{Neighbor\_cells}_{Symbol,j}$ as the power received from RSs of j^{th} symbol of all nearby eNodeBs (if any), and P_{Noise} as the power of all other types of existing noise in the environment affecting the serving cell performance. Hence, the formula for calculating the average RSSI of a single PRB ($RSSI_{PRB}$) is:

$$RSSI_{PRB} = \frac{1}{S}\sum_{j=1}^{j=S}\left(P^{Serving\_cell}_{Symbol,j} + P^{Neighbor\_cells}_{Symbol,j}\right) + P_{Noise} \tag{4}$$

Similarly, the formula to calculate the average value of RSSI over the entire bandwidth ($RSSI_{tot}$) is:

$$RSSI_{tot} = \frac{1}{N \times S}\sum_{n=1}^{n=N}\sum_{j=1}^{j=S}\left(\left(P^{Serving\_cell}_{Symbol,j} + P^{Neighbor\_cells}_{Symbol,j}\right)\right)_n + P_{Noise} \quad where\ N = 100 \tag{5}$$

4) Signal to noise ratio (SNR) is another indicator of signal quality which can replace RSRQ. UE calculates SNR, which in turn is converted to CQI and reported back to eNodeB where it is used to select the most suitable MCS for user data transmission in the given RB [28]. Since MCS directly affect the data rate, SNR is crucial item to measure. SNR is measured as the ratio of signal power to noise power.

The RSRP and RSRQ metrics are LTE-specific parameters which are measured by the model in Area A and Area B. The RSSI and SNR, on the other hand, are the standard parameters between both LTE and 802.11ac networks, hence, they are measured by the model in all five areas i.e. Area A to Area E.

5) Two other physical-related parameters measured by the model are the average of energy and power consumed by 802.11ac users. In order to measure these parameters, the users are equipped with *BasicEnergySourceHelper* as their energy source. Initially, 20-joule energy is assigned to the users and then their energy consumption due to data processing and transmission is calculated during the entire simulation time. Moreover, the power consumption is measured in mW, as the average of consumed energy over the particular given time of using energy.

2) LINK-LEVEL PARAMETERS

We extend the assessment of the model by measuring the average of link-level parameters, including downlink throughput (both users and networks), packet loss ratio, packet latency, and jitter.

IV. SIMULATION RESULTS

In this section, the results from implementation of the model are provided to accomplish the objectives by following two parallel methodologies. The first methodology involves the scenarios to measure and evaluate how severe LTE signals can interfere and affect the performance of 802.11ac users in a coexisting environment. To determine the level of affection, the results are compared with the performance of 802.11ac users that are not nearby the interferences of LTE network.

The measurements clear cell planning uncertainties about the interference management capabilities of the 802.11ac standard. The second methodology involves scenarios to measure and evaluate in what extent a higher order sectorization, particularly 3-sector site, can affect the performance of UEs in LTE networks compared to conventional omnicells. The measurements are intended to provide an economical viewpoint for mobile operators and developers to justify the extra costs incurred by the additional equipment required to deploy 3-sector sites in coexisting environments.

A. ENERGY AND POWER CONSUMPTION LEVEL OF 802.11AC USERS

The issue investigated by this scenario is to determine whether coexisting with LTE network can affect the energy and power consumption of 802.11ac users. If so, which cell deployment, either omnicell or 3-sector cell, is more energy and power efficient. For this purpose, the average of energy and power consumed by 802.11ac users, required for reception and processing of the packets are modeled in radio interfaces and the results are presented in Figure 6 and Figure 7, respectively.

The data obtained from the implementation of this scenario provide evidence that the average of energy consumed by 802.11ac users when there is no LTE interference in their nearby, is about 4.15J which is very close to when 3-sector cell is around (4.12J). In this context, the consumption of the initial 20 Joule energy increases similarly at a uniform level. On the contrary, placing omnicell site around the 802.11ac users leads to increasing the average of consumed energy to about 4.58J for packet processing as the time moves forward. In this situation, for the first half of the simulation time, the energy consumption level remains the same as the 3-sector cell. However, as time passes by, particularly from the second half, the 802.11ac users demand more energy to

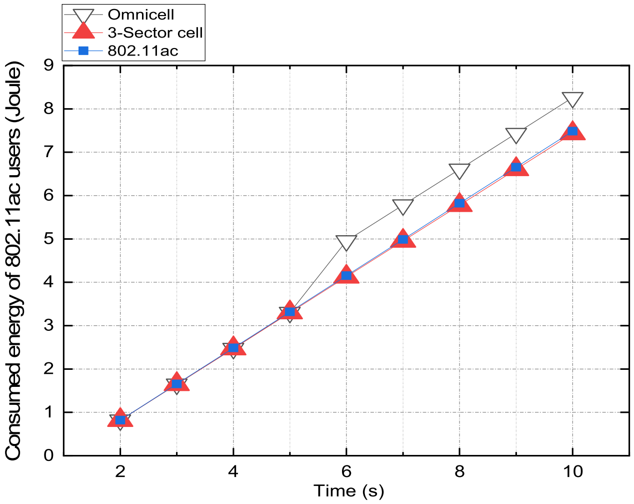

FIGURE 6. Energy consumption level of 802.11ac users.

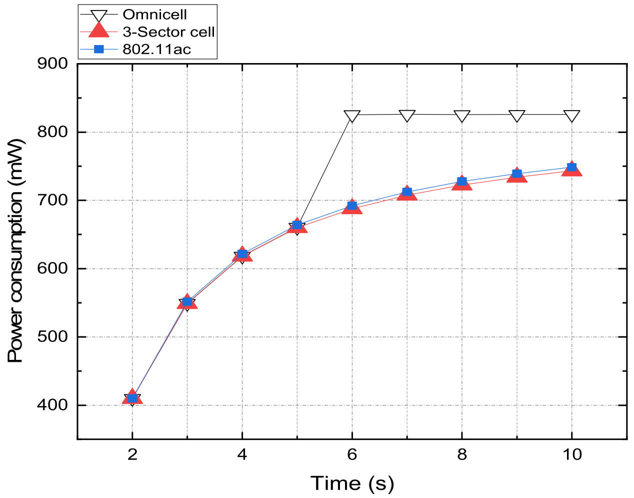

FIGURE 7. Power consumption level of 802.11ac users.

process the packets. Likewise, Figure 7 shows similar results as the power consumed by 802.11ac users under interferences of omnicells is higher than 3-sector cell.

These happen because 802.11ac stations suffer an almost constant interference from LTE omnicell. In contrast, due to different angles of antenna orientation in 3-sector cells, not all 802.11ac stations are under constant interference of LTE. In this case, only Wi-Fi stations that are in the coverage of a particular sector are affected by the LTE interferences. The interferences result in collisions and hence more re-transmissions, for which more energy and power is demanded.

As a result, when the coexisting of 802.11ac and LTE networks is required, from the viewpoint of energy and power consumptions, the higher order sectorized sites are more efficient than omnicell sites deployment.

B. RSRP EVALUATION OF UES

The present scenario is prepared to fulfill two main objectives. Initially, we measure the influence of omnicell site on RSRP of LTE users. Subsequently, in a 3-sector site deployment, we determine the relationship between the orientation of each antenna in the given sector and the RSRP of the corresponding UEs. The results obtained from the implementation of this scenario are reported in Figure 8.

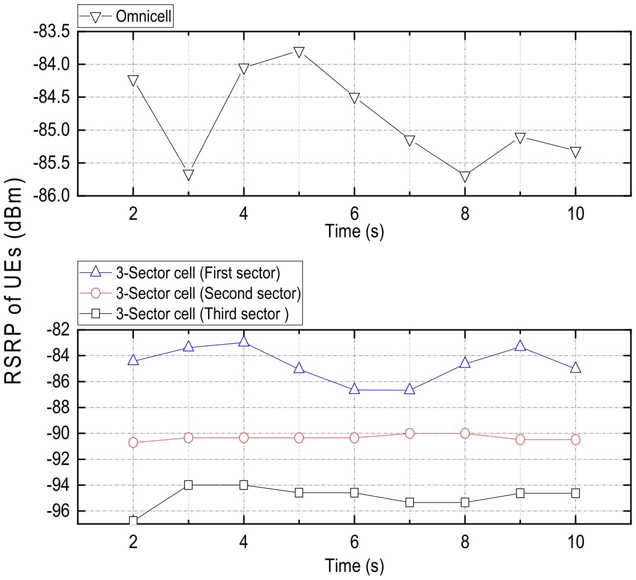

FIGURE 8. RSRP evaluation of UEs.

Based on the results, in omnicell deployment, the RSRP values of UEs are in the range of −82 dBm to −86 dBm which according to mobile signal strength recommendations [26], indicate that the UEs are receiving not excellent but good signal strength. The small fluctuation of RSRPs in the obtained results is because the UEs are separated in different floors of the building in Area A, thus their distance from their attached eNodeB is different. Additionally, other factors that degrade the radio signals between the UEs and eNodeB are building material (concrete in all five simulated areas) and also the existence of various obstacles in different floors of the buildings. These, accordingly, result in experiencing different RSRP values by the UEs.

In this context, a closer look at the 3-sector cell results indicates significant RSRP differences from sector to sector. The UEs in the first sector with the antenna orientation between 0 to 120 degree, can achieve the highest signal strength among the other two sectors. Given this orientation, the average RSRP of −85 dBm shows good signal strength for the UE1 and UE2. Then, the UEs in the second sector with the antenna positioned between 120 to 240 degrees, have an average RSRP of about −90 dBm which is lower than the first sector but still means a fair signal strength for UE3 and UE4. In the third sector, with antenna orientation between 240 to 360 degree, the average RSRP is about −95 dBm which is lower than the other two sectors and practically means the corresponding UEs in this sector (UE5 and UE6) are experiencing fair to weak signal strength from the eNodeB. Thereby, the results lead to the conclusion that, in term of RSRP, the UEs in omnicell site will experience better signal strength than UEs that are placed in a 3-sector site.

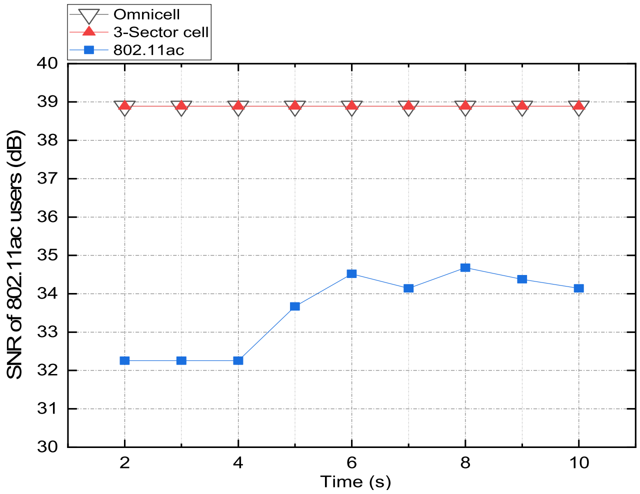

FIGURE 9. SNR evaluation of 802.11ac users.

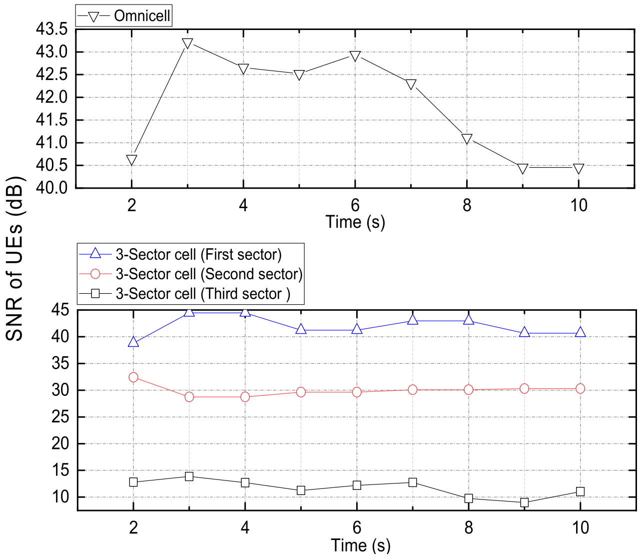

FIGURE 10. SNR evaluation of UEs.

C. SNR EVALUATION OF USERS

The SNR parameter as a critical factor is measured in this scenario. The measurement is essential due to the direct relation of SNR values and data rate of the networks. With this in mind, this scenario provides a basis to answer two questions. First, how SNR of the radio signals received by the 802.11ac users get affected by the interferences caused from omnicell and 3-sector cell sites (Area B and Area D, respectively) compared to when there is no LTE cell deployment around the Wi-Fi users (Area E). Second, which cell deployment, either omnicell or 3-sector cell, provides higher SNR value for the UEs in LTE networks. The data generated by this scenario are reported in Figure 9 and Figure 10 in response to the first and second question, respectively.

Based on the obtained results, no evidence for SNR degradation of 802.11ac stations by LTE signal interferences was found. The SNR measured by the Wi-Fi users that are in the coverage area of either omnicell or 3-sector sites show no difference. In both cases, the SNR remains steady at 39 dB. It is given that, SNR values in Wi-Fi networks are distinguished into five categories: 0-10 dB (low to no signal), 10-15 dB (ok quality), 12-25 dB (good quality), 25-40 dB (very good quality), and higher than 40 dB (excellent quality) [29]. Thereby, here, 39 dB measured SNR indicates a very good signal received by 802.11ac users from their access point in the presence of LTE signals.

Furthermore, we measured the SNR of 802.11ac users in Area E in the pure 802.11ac network without the presence of LTE signals. The average SNR value is about 33 dB which still indicates a very good signal reception from the access point. In this case, the SNR is 6 dB lower than when the 802.11ac users are positioned in coexisting environment with LTE equipment (Area B and Area D). The connection of the 802.11ac access point to the PGW (Figure 4 (a) and (b)) could be the factor responsible for this result. The results imply that LTE signals, either from omnicell site or 3-sector site, do not degrade the SNR of 802.11ac users in coexisting networks.

Next, the SNR measurements performed over UEs in Area A and Area C show an average of 42 dB in the omnicell site which according to [27], is found to be an excellent signal. The results appear consistent with the first and second sector in 3-sector site arrangement indicating an excellent SNR. On the contrary, they are inconsistent with the SNR in the third sector in which the average value of 12dB indicates fair to poor signal strength. A lower SNR value indicates that the signal strength is weaker than the noise levels around. This, in turn, results in a reduction of data rate and consequently increases data corruption and hence retransmissions. Thereby, the UEs in the third sector suffer a lower data rate.

In conclusion of this scenario, based on the results, LTE signals do not affect the SNR of 802.11ac users. Additionally, while all UEs in omnicell site experience excellent SNR, it is not always true in a 3-sector cell, and it depends on the angle of antenna orientation.

D. RSRQ EVALUATION OF UES

While the prior scenarios mainly inspect the power of the received signals, this scenario takes into account the quality of the received signals. Therefore, the RSRQ of the received signals by UEs in Area A and Area C are measured which are shown in Figure 11.

The results point out the consistency with the results reported in the previous scenarios. According to [30], the RSRQ levels range between −3 to −5 dBm, −6 to −8 dBm, −9 to −15 dBm, and −16 to −20 dBm to represent very good, good, average, and poor quality of signals, respectively. Here, an average RSRQ of -3 dBm is measured by UEs in omnicell site which indicates that the quality of the signal received by the UEs is excellent. Likewise, in 3-sector cell site arrangement, the UEs in all three sectors are experiencing excellent signal quality, in spite of a slight difference in the third sector. Hence, the results did not find any evidence for a noticeable difference in term of RSRQ between the higher order sectorization and omnicell sites.

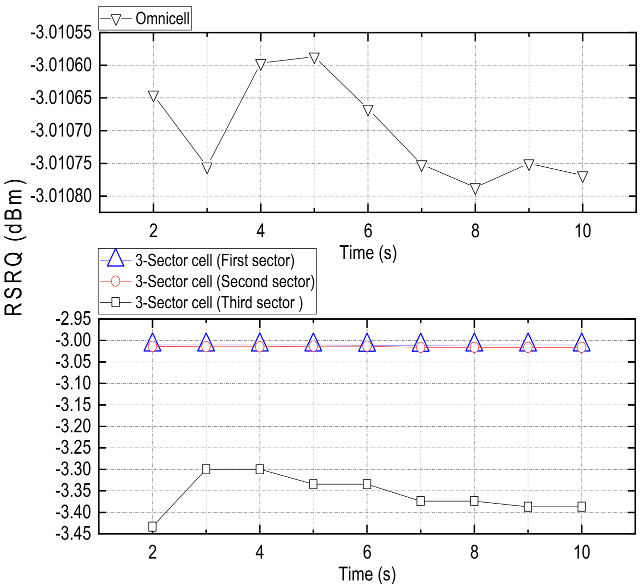

FIGURE 11. RSRQ evaluation of UEs.

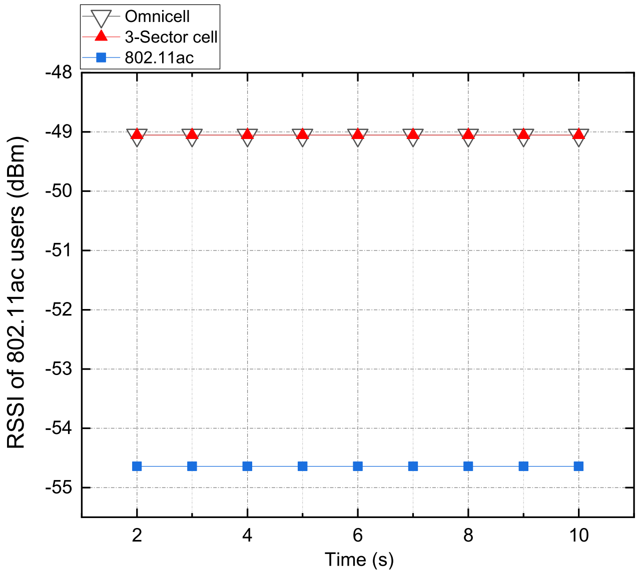

FIGURE 12. RSSI evaluation of 802.11ac users.

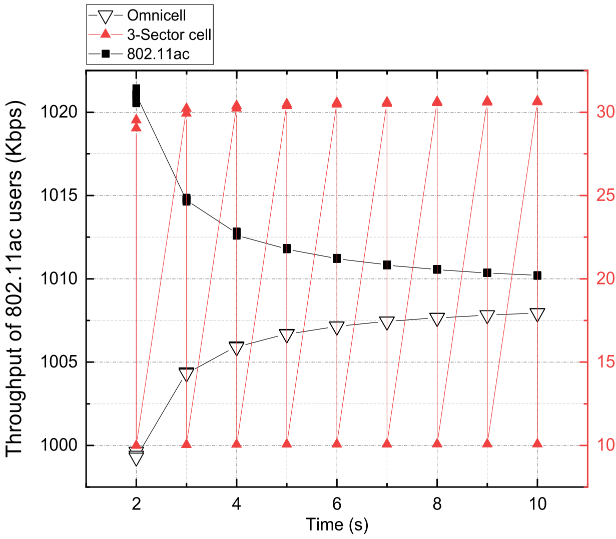

FIGURE 13. Throughput evaluation of 802.11ac users.

E. RSSI EVALUATION OF 802.11AC USERS

The main issue addressed in this scenario is to calculate RSSI value of 802.11ac users to imply how well they can hear signals from their corresponding access point when the interference caused by LTE signals is around them. The effect is verified in both omnicell and 3-sector cell sites (Area B and Area C, respectively) and validated by comparing against the 802.11ac devices that are not under influence of any form of LTE signals (Area E). The RSSI results obtained from the implementation of this scenario is demonstrated in Figure 12.

It is generally given that excellent and poor RSSI values fall between −20 dBm and 100 dBm, respectively. On this basis, the average of −49 dBm RSSI value measured for the 802.11ac users implies two facts. First, a similar influence of omnicell and 3-sector cell on RSSI of 802.11ac users is confirmed. Second, the value signifies an excellent hearing of the access point by the users positioned in the area of both types of LTE sites, which in turn reveals the lack of influence of LTE signals on 802.11ac users in term of RSSI. Furthermore, comparing this value against −54.5 dBm RSSI for users of the pure 802.11ac network indicates that in spite of the slight difference, the RSSI of the users remains in the range of excellent value. Hence, in line with the findings, it can be concluded that the RSSI levels of the 802.11ac users are not degraded due to the interference caused by coexisting with omnicell and 3-sector cell sites.

F. THROUGHPUT EVALUATION OF USERS AND NETWORK

In the preceding scenarios, we have devised a methodology on the basis of physical-level parameters. In this context, several questions regarding the link-level parameters remain to be addressed. To answer these questions and provide further comprehensive evidence, link-level scenarios included in the model, are implemented.

In this subsection, the average of downlink throughput of 802.11ac users is determined. The aims are twofold. First, to quantify the impact of LTE signal interferences on the throughput of 802.11ac users and to investigate in what extent the omnicell and 3-sector cell signals can possibly affect their throughput. The results are obtained and further compared against the throughput of 802.11ac users that are not in a coexisting environment. Second, to assess 3-sector cell site deployment under special consideration of throughput optimization compared to traditional omnicell sites in coexisting networks. The results in line with the first and second aims are presented in Figure 13 and Figure 14, respectively.

As shown in Figure 13, the results are in good consistency with the aforementioned results. In a coexisting environment,

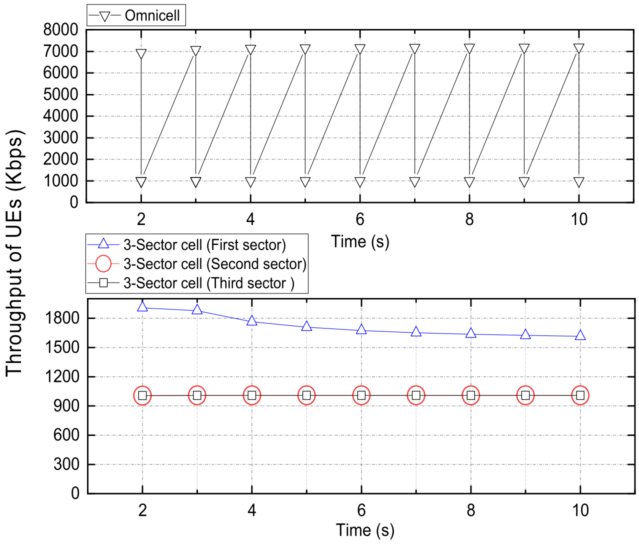

FIGURE 14. Throughput evaluation of UEs.

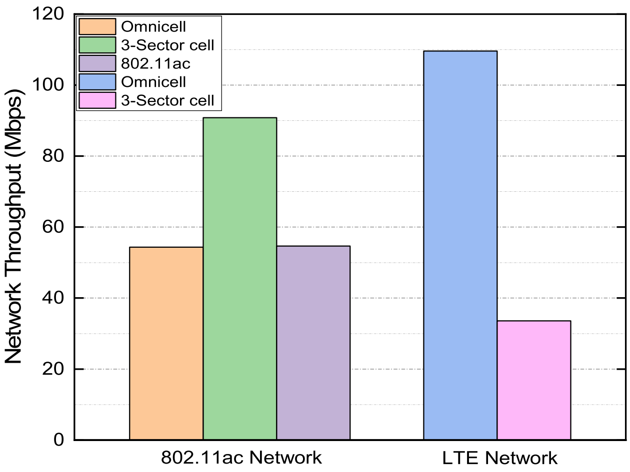

FIGURE 15. Network throughput evaluation of LTE and 802.11ac networks.

3-sector cell site deployment can provide higher throughput for the 802.11ac users compared to omnicell. However, the results signify apparent differences between different areas. In Area D, for the first and second Wi-Fi stations, which are closer to their access point, a significant rise in throughput is observed. By comparison, the Wi-Fi stations in Area B and Area E show some similarity and some differences in term of throughput. Their overall throughput is the same, however, while the throughput in Area B gradually rises over time, it declines in Area E.

With this in mind, the throughput analysis is further extended to UEs. The UEs that are attached to eNodeB in omnicell can achieve much higher throughput than the UEs connected to 3-sector cell. In this regard, the first sector provides slightly higher throughput for the UEs than the second and third sectors.

In addition to users' throughput, in this respect, the networks' throughput also measured and shown in Figure 15.

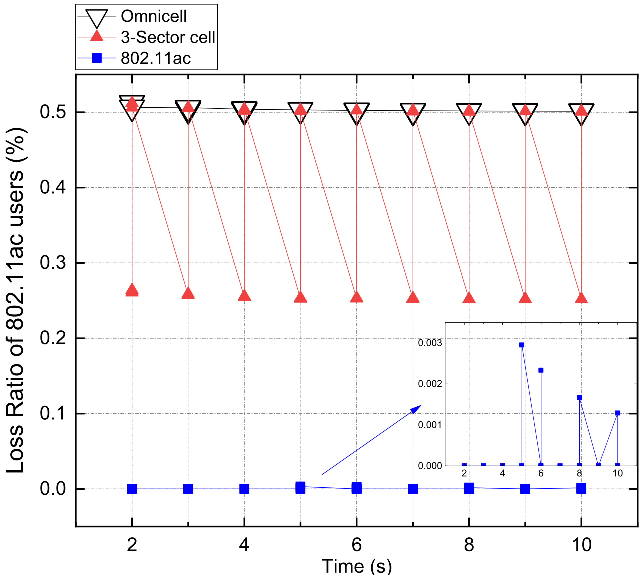

FIGURE 16. Packet loss ratio evaluation of 80211ac users.

The results suggest that the overall throughput in 802.11ac network that is positioned side-by-side with omnicell LTE network (Area B), is about 54Mbps compared to 90Mbps network throughput when 802.11ac network coexists with 3-sector LTE network (Area D). Further analysis of the results reveals the same overall throughput for 802.11ac network in Area B and Area E (Wi-Fi users in omnicell coexisting environment and Wi-Fi users with no LTE network around, respectively). These results have led us to conclude that, in term of network throughput, while the coexisting of 802.11ac with LTE will improve the overall performance of Wi-Fi network compared to when no LTE coexistence is around, a 3-sector cell site has more benefits than omnicell site. However, this is the opposite for the LTE network as an omnicell site provides higher network throughput than a 3-sector cell site.

G. PACKET LOSS RATIO EVALUATION OF USERS

Further tests are carried out in this scenario to achieve two objectives. First, to verify whether the coexisting of 802.11ac network with LTE network and the corresponding interferences can affect the packet loss ratio of the Wi-Fi users. Comparing the results with the results of pure 802.11ac network without interferences of the LTE signals will further quantify the degree of affection. Second, to verify that in order to reduce the packet loss ratio, which site deployment is more efficient, omnicell or 3-sector. The average of loss ratio results for 802.11ac users and UEs are demonstrated in Figure 16 and Figure 17, respectively.

The results provide evidence that, in term of the number of lost packets, coexisting of 802.11ac network with any type of LTE network, either 3-sector or omnicell, will decrease the overall performance of the 802.11ac users. In this regard, establishing an omnicell site is even worse than 3-sector as it highly increases the number of dropped packets for

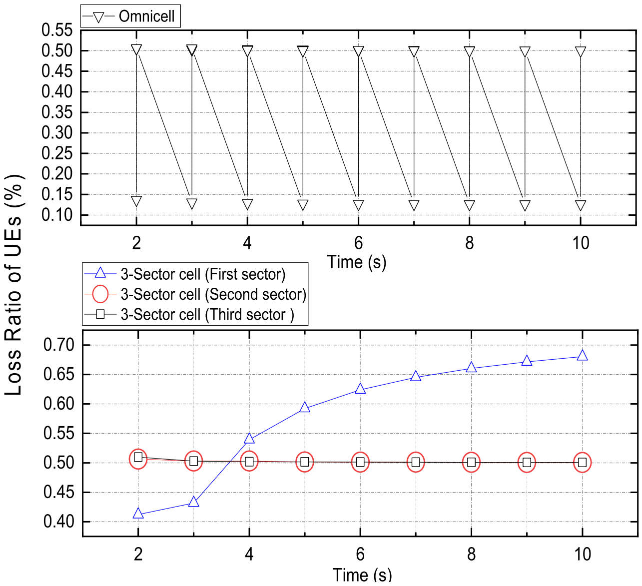

FIGURE 17. Packet loss ratio evaluation of UEs.

802.11ac users. A closer look at the results reveals that the optimal performance of 802.11ac users is provided when 802.11ac network is set up alone with no presence of LTE signal interferences. In this case, the loss ratio remains steady and close to zero, neglecting the minimal variations. Thereby, LTE signal interferences can substantially degrade the performance of sensitive applications in 802.11ac networks that do not handle packet loss.

The scenario, correspondingly, takes UEs into account and denotes that despite the fluctuations, the average loss ratio in omnicell and 3-sector cell sites are close (0.439953% and 0.529447%, respectively). The UEs in omnicell experience more loss ratio fluctuation than the UEs in a higher order sectorization site. In 3-sector cell, the first sector initially has a lower loss ratio. However, as time passes by, the ratio reaches a peak of 0.65%. In contrast, the other two sectors provide an equal and constant loss ratio of 0.50% for their corresponding UEs. This proves the importance of properly assigning the angle of antenna orientation in sectorized cells.

In conclusion, the evidence points towards the idea that when the number of dropped packets for 802.11ac networks is a matter of importance, they should not coexist with LTE networks. Moreover, before establishing 3-sector cell sites, examining the angle of antenna orientation, to peak the best suitable one which matched with the position of the UEs, is highly essential.

H. TRANSMISSION DELAY EVALUATION OF USERS

This scenario initially attempts to clarify the impact of LTE signal interferences on the average end-to-end delay of the packets received by 802.11ac users in a coexisting network with LTE omnicell and LTE 3-sector cells. In order to validate the results, they are compared against the results measured without the presence of any form of LTE interferences. In addition to investigating the performance of 802.11ac users, the scenario also measures the average delay of the packets received by UEs in both omnicell and 3-sector cell to determine which network provides better performance in terms of lower delay values. The results are provided in Figure 18 and Figure 19, respectively.

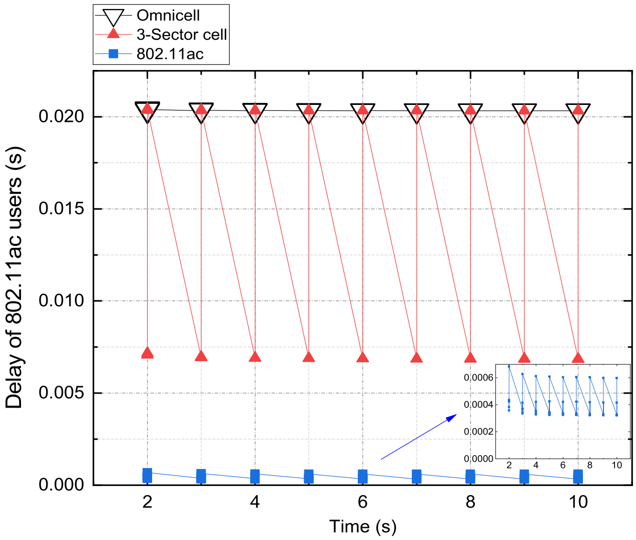

FIGURE 18. Transmission delay evaluation of 802.11ac users.

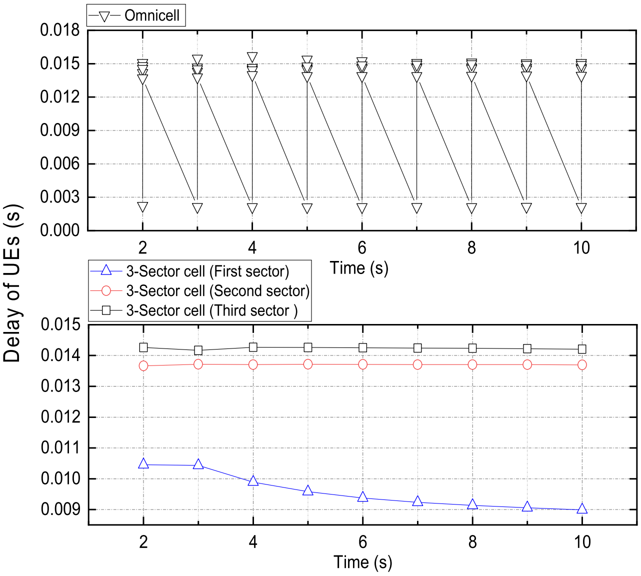

FIGURE 19. Transmission delay evaluation of UEs.

The end-to-end packet delay related to 802.11ac users implies that although the coexistence with LTE networks increases the delay of the received packets, the delay is not significantly high. In Area E, where LTE signals do not interfere with 802.11ac signals, the delay is very low almost close to zero. In contrast, in Area B and Area D, where omnicell signals and 3-sector signals interfere with 802.11ac signals, the corresponding delay values rise. In this respect, the delay caused by omnicell interferences remains constant in contrast to the existing variations in the delay caused by the 3-sector cell.

The average end-to-end delay of the packets for 802.11ac users in the presence of omnicell interferences is about 0.020342s compared to 0.015866s in the case of 3-sector cell interferences. Considering 0.0004s delay for the packets in 802.11ac network without any LTE coexistence, shows that although the differences exist, it is not high enough to degrade the performance of delay-sensitive applications in 802.11ac networks. Thereby, it is concluded that the coexistence of 802.11ac network with LTE network cannot highly increase the amount of delay.

The results further provide a better understanding that either omnicell sites or 3-sector sites are more efficient for UEs in term of packet delay. The results first show that the delay experienced by the UEs in omnicell has more fluctuations than in 3-sector cell. Moreover, the results, once again, prove the importance of setting the angle of orientation. The first sector has the least amount of delay among the other two sectors. Here, the average delay is about 0.009574s in compared to 0.013707s and 0.014234s delay in the second and third sector, respectively. Calculating the average delay of the three sectors show 0.012505s delay which is as high as omnicell delay (0.012532s) mostly due to the higher values in the second and third sectors.

Taken all together, these results conclude that in spite of increasing delay of 802.11ac users from zero to a higher amount in coexisting networks, the grow is not considerable. Moreover, based on the results it is concluded that the UEs in conventional omnicell and 3-sector cells experience a similar amount of delay but with different patterns from which the importance of antenna positioning in the sectors is confirmed.

I. JITTER EVALUATION OF USERS

The present scenario is prepared to complete the evaluation of link-level parameters, in accordance with two objectives. First, it primarily aims at finding a relation between LTE signal interferences and performance of 802.11ac networks surrounded by LTE networks. In order to achieve this, initially, the performance of 802.11acc users in term of average jitter is measured, the results of which are used as the basis comparison. Then, the average jitter of 802.11ac users is measured again, but this time in the cases that they are surrounded by omnicell and 3-sector cell LTE networks. Second, the average jitter of UEs in LTE networks is also measured. The jitter of UEs attached to an omnicell and jitter of UEs attached to a 3-sector cell are obtained and compared against each other to verify which cell deployment provides less jitter. The results are provided in Figure 20 and Figure 21, respectively.

From the results, it is observed that jitter is significantly low (close to zero) in Area E where the 802.11 users are not surrounded by LTE signals. Considering these results as our baseline results, the jitter experienced by 802.11ac users under LTE interferences of omnicell (Area B) is less than delay in 3-sector cell (Area D). To be more precise, the jitter of the baseline results is about 0.000097s compared to 0.000023s in omnicell which surprisingly is even lower than Area E itself. Also, the average of jitter is about 0.004552s in 3-sector cells deployment. These prove that in term of LTE interferences, the influence of 3-sector cell signals on the jitter of the 802.11ac users is more than traditional omnicell in a coexisting environment. However, the jitter values imply that the impact is negligible as they do not effectively render the network unusable.

Furthermore, a closer look at the jitter of UE devices implies that jitter is low in both omnicell and 3-sector

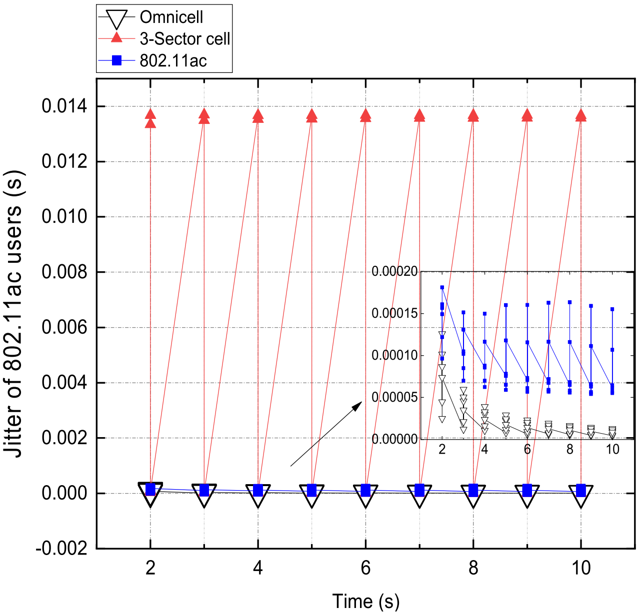

FIGURE 20. Jitter evaluation of 802.11ac users.

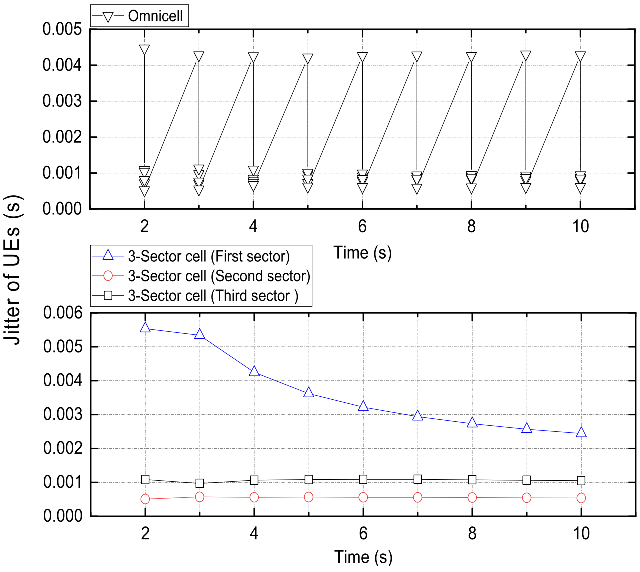

FIGURE 21. Jitter evaluation of UEs.

cell sites. In contrast, the fluctuation of jitter values in Area A is higher than Area C in which almost remains steady. The average jitter of about 0.001404s is obtained for the UEs in omnicell (Area A). This is in comparison with 0.003627s, 0.000549s, and 0.001063 jitter values of UEs in the first, second, and third cells. The average jitter of three cells in Area C is about 0.001746s which is very close to the omnicell average jitter.

Thereby, based on the values of jitter, it is concluded that although LTE networks in any form, either omnicell or 3-sector, will increase the amount of jitter, the performance reduction caused by the interferences is not considerable.

V. CONCLUSION

Mobile users in coexisting networks can achieve a better performance when the associated mobile operators and developers resolve the coexistence challenges and overcome the corresponding issues. In this direction and with respect to the higher order sectorization issues, a physical-level and link-level model was introduced in this work. The model mainly focuses on the coexistence of LTE and 802.11ac networks in two cell deployment methods: omnicell and 3-sector cell. For the analysis, the model verifies that whether interfering the LTE signals has any ill effect on the performance of 802.11ac users. Moreover, the model determines which cell deployment, either conventional omnicell or 3-sector cell, has more impact. In addition to evaluating the performance of 802.11ac users, the model is further extended to take UEs into account. In this regard, it determines which cell deployment can enhance the performance of UEs. The model also establishes three different buildings and includes a variety of scenarios through the implementation of which several link-level and physical-level parameters are measured and evaluated.

The results reveal the better performance of 802.11ac networks, in terms of physical-level parameters, in a coexisting environment compared to when there is no coexisting with LTE networks. On this point, no significant performance differences for the 802.11ac users in omnicell and 3-sector sites were observed. In terms of link-level parameters, the coexistence results in highly increased throughput for 802.11ac users, whereas for the packet loss ratio and delay, the opposite were observed. Hereof, the results indicate a performance degradation due to the coexistence while the worst reduction was observed for the users in the coverage area of LTE omnicells. Moreover, while the coexistence with omnicell does not affect the jitter, 3-sector cells impose high jitter to 802.11ac networks.

In contrast, in coexisting networks, the optimal performance was presented for UEs when no cell sectoring is performed. In terms of both physical-level and link-level parameters, the results reveal the better performance of LTE users in omnicells when coexisting with 802.11ac networks compared to 3-sector cells' users.

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