IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received March 11, 2019, accepted March 26, 2019, date of publication March 29, 2019, date of current version April 15, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2908203

Spectrum Sharing in Satellite-Mobile Multisystem Using 3D In-Building Small Cells for High Spectral and Energy Efficiencies in 5G and Beyond Era

RONY KUMER SAHA
Wireless Platform Laboratory, KDDI Research, Inc., Saitama 356-8502, Japan
e-mail: ro-saha@kddi-research.jp

ABSTRACT In this paper, we present a novel technique for sharing satellite spectrum with terrestrial-mobile 3-dimensional (3D) in-building small cells, namely femtocells. Both the space-satellite and the terrestrial-mobile systems (TMSs) operate at their respective licensed spectrums. However, due to the scarcity of the available spectrum, a huge amount of data generated indoors, and a high external wall penetration loss of a 3D building, we propose to reuse the satellite spectrum to small cells deployed only in 3D buildings of the TMS. The proposed spectrum sharing technique is detailed by identifying and addressing the major related issues. The co-channel interference generated because of the co-existence of the satellite user equipments (UEs) in the small-cell coverage is analyzed, and the handover procedures for a satellite UE toward and away from any small cell are discussed. The almost blank subframe (ABS)-based enhanced intercell interference coordination (eICIC) technique is employed to small cells in order to assure the quality-of-service (QoS) between small-cell UEs and satellite UEs. We derive the system-level capacity, spectral efficiency, and energy efficiency performance metrics for the proposed technique by varying the number of buildings over the coverage of a macrocell and deduce the condition for optimality for both the energy efficiency and the spectral efficiency. With an extensive system-level simulation and numerical analysis, we justify the impact of using the ABS-based eICIC technique toward provisioning QoS in terms of radio resource allocation. Furthermore, we show the outperformance of the proposed technique in terms of spectral efficiency and energy efficiency over the ones expected for the fifth generation (5G) network requirements as well as achieved by numerous existing techniques. Finally, we discuss the radio resource scheduler implementation as well as the significance, challenge, and future research perspective of the proposed spectrum sharing technique.

INDEX TERMS 3D, in-building, mobile, satellite, spectrum sharing, small cell, spectral efficiency, energy efficiency, eICIC.

I. INTRODUCTION

A. BACKGROUND

The demand of users for high data rate services has increased by many folds in recent years. Since most data is generated in indoor environments, particularly in urban 3-dimensional (3D) multi-storage buildings, it becomes a major concern of how to address the high data rate demand of users in such multi-storage buildings with the radio spectrum costly and scarcely allocated to the terrestrial-mobile system (TMS). Though spectrum extension is one of the major ways to satisfy the high data rate demand, the spectrum allocated to an operator over time has not been increased proportionately with the data rate demand. Another effective way to address such high data rate services by limited spectrum is to share the spectrum of a primary system with a secondary one so long as the capacity demand of the TMS can be addressed. In such cases, small cells, comprising the secondary system in indoor environments, can play an important role on providing with the high data rate services by sharing spectrum with small cells because of their small coverage that help receive strong signals at the user equipments (UEs) within short distances. In line with so, Federal Communications Commission (FCC) proposed to make available of 100 megahertz of spectrum for sharing between the satellites of the space-satellite system (SPS) and the small

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

cells of the TMS in the 3.5 GHz band [1]. Recently, the third generation partnership project (3GPP) has also initiated a Study Item for the fifth generation (5G) systems to support Non-Terrestrial Networks [2], including an integration of satellite systems to terrestrial-mobile networks or a standalone satellite system [3].

B. RELATED WORK

Researches on spectrum sharing and hence management of co-channel interference generated between the satellite and the small cells particularly in indoor environments are not so apparent. A few works toward this direction have been carried out. For example, in [4], small cells have been considered sharing the same spectrum at 3.5 GHz band as that of the satellite. By sharing the same satellite spectrum with small cells, authors have analyzed the co-channel interference between the fixed-satellite service system and small cells deployed in both outdoor and indoor environments.

Moreover, being complementary systems to each other, an integration of the satellite system and the TMS seems to be promising. This is because of the fact that, in some parts of the TMS, e.g. mountains, sea ships, space aircrafts, and disaster-affected areas, the coverage cannot be provided by mobile systems. In such areas, the satellite integrated with the TMS can be a solution to provide large coverage by establishing communication directly via the satellite. On the other hand, typical satellite systems using line-of-sight communication can also use the TMS in places where the satellite signal is poor, e.g. indoor coverage and blockages created by a large number of buildings to the satellite line-of-sight components in urban areas. That is why, telecommunications regulatory bodies have granted radio station licenses [5] to some satellite networks to add a complementary ground component (CGC) in Europe and ancillary terrestrial component (ATC) in North America to their networks [6]. These integrated networks are called mobile-satellite systems (MSS) with ATC or MSS/ATC networks [6].

Toward this direction, a number of research works such as [7] have proposed solutions on how to realize such integrated satellite-terrestrial mobile systems by presenting techniques for allocating and reusing the satellite spectrum in TMSs. Besides, numerous research efforts have been taken to address interference between fixed-satellite service systems and International Mobile Telecommunications-Advanced (IMT-Advanced) systems (e.g., steering nulls towards the fixed-satellite service systems in [8] and developing protection zones from IMT-Advanced systems to protect the fixed-satellite service systems in [9]). However, such researches have made effort toward addressing interference that is mostly limited to high power base stations, e.g. macrocell base station.

C. PROBLEM STATEMENT

Notably, in order to improve system-level spectral efficiency of a TMS by sharing with it the satellite spectrum, numerous crucial issues need to be resolved in-prior. Existing research workssuch as [4], however, have not considered an obvious and significant co-channel interference issue when sharing the satellite spectrum with indoor small cells caused due to the presence of any satellite UE within their coverage. Such a satellite UE, communicating directly with its satellite station, causes significant co-channel interference with indoor small cell base stations (SBSs) and their UEs based on the mode of operation. Further, the investigation in [4] has been limited to small cells deployed in single-floor buildings for the indoor scenario, the results of which cannot be transported to analyze small cells deployed in 3D multi-storage buildings. This is because of the fact that the 2-dimensional (2D) analysis cannot capture the complex 3D propagation phenomenon (e.g., effects from floors and internal walls of a 3D multi-storage building).

Similarly, even though several research works on integrated satellite-terrestrial mobile systems such as [9] have been carried out, including interference analysis and mitigation technique and frequency reuse mechanism in TMSs, no research works yet have addressed explicitly how to address co-channel interference generated between the satellite system and the terrestrial indoor small cell system to reuse the satellite spectrum in small cells in such integrated satellite-terrestrial mobile systems. Hence, though operating in-building small cells at the same spectrum (e.g., 3.5 GHz band as recommended by FCC) as that of the satellite system can generate significant co-channel interference to satellite system components, particularly in-building satellite UEs, there is no technique proposed so far in the existing literature that can address this mutual co-channel interference between in-building satellite UEs and small cells. This necessitates developing a technique that can address this co-channel interference to share the satellite spectrum with the terrestrial 3D in-building small cells to improve spectral and energy efficiencies of the TMS.

D. CONTRIBUTION AND LIMITATION

Getting motivated by this fact, in this paper, we propose a spectrum sharing technique for a multiple communication system comprising a SPS and a TMS. The proposed spectrum sharing technique considers sharing the whole spectrum allocated solely to the SPS with small cells deployed in each of the 3D multi-storage buildings located within the coverage of a macrocell of a TMS.

Note that, our focus in this paper is to develop a technique to share the satellite spectrum with the terrestrial in-building small cell base stations to improve spectral efficiency and energy efficiency of terrestrial-mobile systems. Hence, we limit evaluating the performance to terrestrial-mobile systems only. The space-satellite system is taken into account in order to share its spectrum to in-building small cells by addressing major relevant *challenges* discussed in the following section under simplistic scenario of space-satellite systems. In other words, our attention is not to evaluate the performance of space-satellite systems but terrestrial-mobile systems when sharing satellite spectrum with terrestrial in-building small cells. Hence, the scenario of space-satellite systems and the analysis of relevant procedures are kept *general* and as *simple* and *ideal* as possible, whereas the scenario of terrestrial-mobile systems and the analysis of relevant procedures are kept *specific* and as *detailed* and *practical* as possible.

More specifically, we provide a detail analysis of terrestrial-mobile systems, model its relevant aspects, and evaluate the outperformance of the proposed technique in the light of terrestrial-mobile systems, e.g. 5G and beyond mobile systems, as compared to other existing techniques available in literature. On the other hand, the space-satellite system is kept generic, in terms of its type (e.g., Geostationary or Geosynchronous Earth Orbit (GEO) or Low Earth Orbit (LEO)), operating frequency bands (e.g., L or S bands), and the analysis of relevant procedures such as handover and co-channel interference of the satellite UE with the small cell base station.

E. ORGANIZATION

The paper is organized as follows. In section II, the system model is first described, followed by explaining the proposed spectrum sharing technique and related issues. Co-channel interference is analyzed for normal and reverse modes of operation of the satellite and small cell systems in section III. We discuss the configuration and the handover procedures for a satellite UE toward and away from an SBS in section IV. In section V, problems of the proposed technique are formulated, including satellite-mobile network model, traffic activity of satellite UEs, and radio resource scheduling and fairness. In section VI, a number of performance metrics such as system-level capacity, spectral efficiency, and energy efficiency for a single building scenario, and the quality-of-service (QoS) provisioning condition between small cell UEs and satellite UEs with almost blank subframe (ABS) based enhanced intercell interference coordination (eICIC) technique are derived. In section VII, we extend the derivation for system-level performance metrics in section VI to multiple buildings as well and deduce the conditions for optimality of energy efficiency and spectral efficiency. In section VIII, we discuss the operation and scheduler implementation of the proposed spectrum sharing technique. In section IX, we evaluate the performance of different metrics derived in sections VI and VII and the impact of ABS based eICIC technique toward QoS provisioning between small cell UEs and satellite UEs and also show the outperformance of the proposed technique over numerous exiting techniques. Finally, the significance, challenge, and future research perspective of the proposed technique are discussed in section X. We conclude the paper in section XI. Note that we use femtocell and small cell interchangeably throughout the paper.

II. SYSTEM MODEL AND SPECTRUM SHARING TECHNIQUE

A. SYSTEM MODEL

Figure 1 shows the system architecture of a satellite and terrestrial-mobile heterogeneous network. The terrestrial heterogeneous mobile network consists of a set of small cells deployed in a number of 3D buildings located within the coverage of a macrocell. A certain percentage of macro UEs is considered indoor, and a number of macro UEs are offloaded by picocells. The rest of the macro UEs is considered outdoor located within the macrocell coverage. Each floor of a building is modeled as a set of regular square-grid apartments; and a small cell is deployed in each apartment (Fig. 2). Each SBS has coverage equal to the area of the apartment, and is placed in the center of ceiling of the apartment. For convenience, SBSs of one building are shown in Fig. 1.

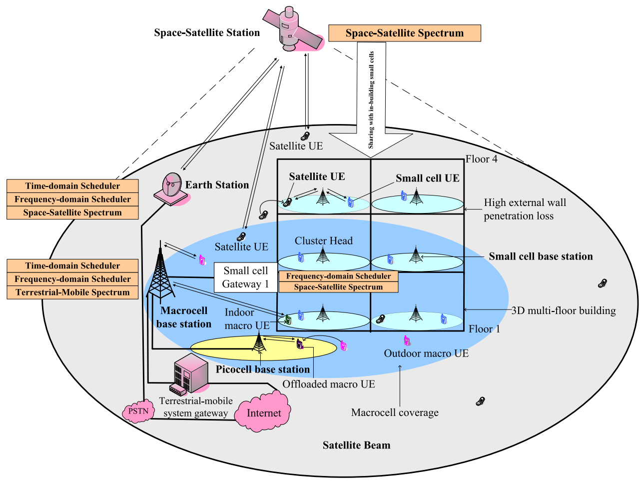

FIGURE 1. A satellite-terrestrial mobile heterogeneous network for sharing the satellite spectrum with small cells deployed only in 3D multi-storage buildings of a terrestrial-mobile network.

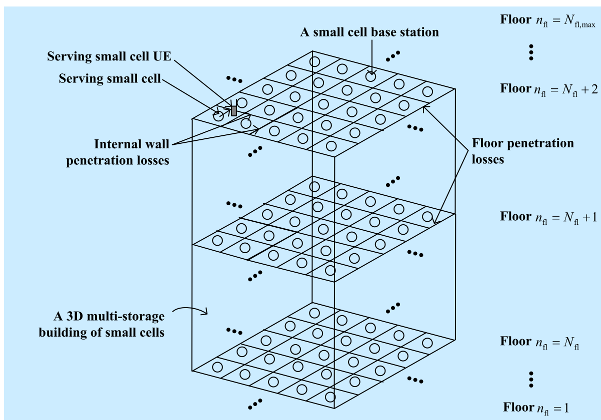

FIGURE 2. A terrestrial 3D in-building small cell system.

The satellite system can be a GEO, Medium Earth Orbit (MEO) and LEO. Since each of these types of satellite system has both pros and cons, for example, large coverage and large delay for GEO satellites [3], whereas small delay and small coverage for LEO satellites, choosing an appropriate satellite system is solely dependent on the requirements of the satellite system service provider. Further, in line with the FCC that has proposed to deploy small cells in the 3.5 GHz satellite band, i.e. 3550 MHz-3650 MHz frequency band used for satellite systems globally [4], we also assume that the space-satellite system in Fig. 1 operates at 3.5 GHz, i.e. S band. It is to be noted that the most suitable segment of microwave spectrum to communicate signals between the space and the terrestrial systems lies between 1 GHz and 4 GHz, i.e., for L band (1 GHz to 2 GHz) and S band (2 GHz to 4 GHz) [10]. Hence, many commercial satellite service providers employ L and S bands to provide MSSs, including Thurya and Immarsat using L band, whereas GlobalStar and Iridium using both L and S bands, to operate dual mode cellular/satellite phones [11].

B. PROPOSED SATELLITE SPECTRUM SHARING TECHNIQUE AND RELATED ISSUES

Both the satellite system and the TMS operate at their respective allocated spectrums. Since the external wall penetration loss of a 3D building is high, the satellite signal in such buildings is poor. Hence, the satellite spectrum can be considered reusing in small cells deployed in such 3D in-buildings because of insignificant co-channel interference effect. In line with so, we propose to reuse the whole satellite spectrum to small cells per building. In return, any satellite UE, whenever exists in any indoor small cell coverage, is handed over or offloaded to the corresponding small cell by adjusting its mode of operation to that of the small cell. In an absence of a satellite UE, any small cell of the corresponding building can transmit in any transmission time interval (TTI).

However, to enable reusing such satellite spectrum in small cells within a building, the following *major challenges* need to be addressed. In the following, we first state each of these challenges one at a time followed by briefly describing the mechanisms and approaches, which are addressed in detail in the following sections, of how each of these challenges is addressed as part of the contribution of this paper.

1) CHALLENGE 01: HOW TO DETERMINE THE EXISTENCE OF A SATELLITE UE WITHIN A 3D BUILDING?

How to address: The UE determines whether or not it has entered a 3D building by monitoring the level of the reference signal transmitted by the satellite. However, if the UE periodically transmits a reference signal to the satellite, the satellite communication ground network, i.e. the earth station, may determine the entry of the UE within a building based on the level of the reference signal from the satellite UE. In this case, the satellite communication ground network instructs the satellite UE to detect an in-building SBS to handover to it.

2) CHALLENGE 02: HOW TO DETERMINE BY THE SATELLITE UE WHETHER THE IN-BUILDING BASE STATION IS OPERATING IN THE NORMAL MODE OR IN THE REVERSE MODE?

How to address: Since it is unknown whether the in-building SBS is operating in the normal mode or in the reverse mode, the satellite UE in each of the frequency band of the downlink signal of the satellite and the frequency of the uplink signal, by determining whether or not the reference signal from the SBS can be received, can assure the existence of the SBS. Upon receiving the reference signal from the SBS in one of the frequency bands, the satellite UE broadcasts the existence of the SBS with the identifier (i.e., the SBS identity (ID)) of the SBS, and the SBS is operating whether in the normal mode or in the reverse mode.

3) CHALLENGE 03: A SATELLITE UE, BECAUSE OF OPERATING AT THE SAME SATELLITE SPECTRUM, WHENEVER EXISTS WITHIN THE COVERAGE OF ANY SBS IN THE BUILDING GENERATES CO-CHANNEL INTERFERENCE EITHER WITH THE SBS OR WITH ITS SMALL CELL UE.

How to address: This interference is avoided by converting the co-channel interference signal into the desired signal by serving the satellite UE through the SBS, i.e. by handing over or offloading to the SBS from the satellite station. This causes the TMS to get benefitted from reusing additional satellite spectrum in indoor small cells, whereas the SPS gets benefitted from improving the indoor signal strength of satellite UEs.

4) CHALLENGE 04: FURTHER, TO OFFLOAD OR HANDOVER A SATELLITE UE TO AN SBS, IT IS NECESSARY THAT BOTH THE SBS AND THE SATELLITE UE DO OPERATE AT THE SAME UPLINK AND DOWNLINK FREQUENCIES. NOTE THAT SBSS CAN OPERATE IN THE NORMAL MODE AS WELL AS THE REVERSE MODE WITH RESPECT TO THE SATELLITE SYSTEM.

How to address: When operating in the normal mode, there is no need for the satellite UE to change its existing mode of operation since both the satellite UE and the SBS operate at the same satellite uplink and downlink frequencies. However, if the indoor SBS operates in the reverse mode with respect to the satellite system, when moving from the outside into the building, the satellite UE changes its existing mode of operation. So, irrespective of the modes of operation, whenever a satellite UE is in a building, it gets always served by the SBS instead of its satellite station.

5) CHALLENGE 05: SINCE, IN GENERAL, THE NUMBER OF SATELLITE UES AS COMPARED TO THE SMALL CELL UES IS LOW ENOUGH DURING ANY GIVEN INTERVAL OF TIME, THE FAIRNESS IN RESOURCE ALLOCATION BETWEEN THE SATELLITE UES AND THE SMALL CELL UES CANNOT BE GUARANTEED.

How to address: In such cases, in order to ensure the QoS with a fair allocation of radio resources between the small cell UEs and the satellite UEs within a building, we propose to employ the time-domain ABS based eICIC technique with SBSs in a building such that the satellite UEs are served during ABSs, whereas the small cell UEs are served during non-ABSs by in-building SBSs (Fig. 3).

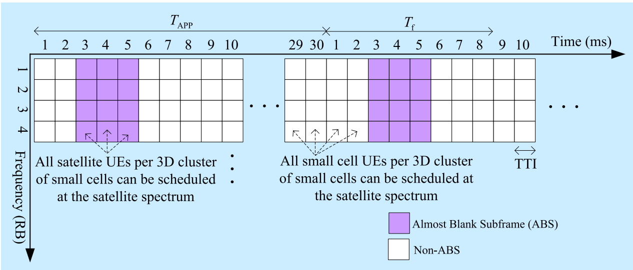

FIGURE 3. Application of the ABS based eICIC technique to ensure QoS for both satellite UEs and small cell UEs per 3D in-building small cells.

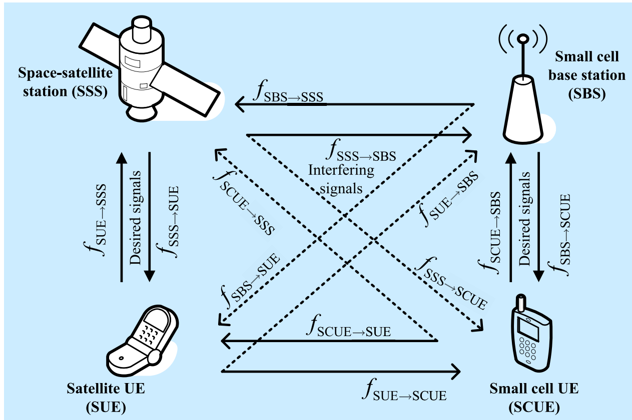

FIGURE 4. Interference scenario in a typical satellite-and terrestrial-mobile system where SCUE and SUE define respectively small cell UE and satellite UE.

6) CHALLENGE 06: WHEN ENFORCING THE ABS BASED EICIC TECHNIQUE TO IN-BUILDING UES, THE NUMBER OF TTIS OVER AN ABS PATTERN PERIOD (APP) BECOMES FIXED FOR ANY UE CATEGORY SUCH THAT THE CAPACITY OF ALL SMALL CELL UES AND THE CAPACITY OF ALL SATELLITE UES BECOME INDEPENDENT OF THE NUMBER OF EITHER THE SATELLITE UES OR THE SMALL CELL UES. THIS CAUSES THE AVERAGE THROUGHPUT PER UE OF ANY CATEGORY OF UES TO DECREASE WITH AN INCREASE IN THE NUMBER OF UES OF THE CORRESPONDING CATEGORY OVER TIME T.

How to address: We consider finding an optimum value of the number of ABSs in percentage of the APP based on the ratio of the average number of satellite UEs to the average number of small cell UEs arrived to get access to the SBSs per building over certain duration of time *T*.

Note that the ABS based eICIC, developed for 3GPP Release 10, is a time-domain eICIC technique. In the ABSs, no control and data signals are transmitted except the reference signals such that victim UEs are scheduled only in the ABSs to mitigate interference from other nodes [12].

III. MODES OF OPERATION AND INTERFERENCE ANALYSIS

For the analysis of co-channel interference generated due to reusing the satellite spectrum in in-building small cells, we consider a simplified architecture of the system shown in Fig. 1. The simplified system consists of the satellite components system, including a space-satellite station (SSS) and a satellite UE, and a terrestrial components system, including a SBS and a small cell UE shown in Fig. 4. Both satellite and terrestrial in-building small cell components of the satellite-and terrestrial-mobile system operate at the same satellite spectrum. Since each node of a component system acts as a transceiver, a node of one component system can generate co-channel interference to both nodes of the other. Hence, in general, for both component systems, the maximum of eight possible co-channel interferences can be generated in a satellite-and terrestrial-mobile system (Fig. 4) when both component systems operate simultaneously at the same satellite spectrum [13]. In general, whether or not all these eight interferences may exist in the system depends on several factors such as modes of operation. With an omnidirectional terrestrial antenna pattern, if uplink and downlink of both component systems operate at the same frequency, the systems are referred to as operating in normal mode.

Figure 5 shows the interference scenario when the satellite and terrestrial components systems operate at the same frequency in normal mode, i.e. $f_{\text{SUE}\to\text{SSS}} = f_{\text{SCUE}\to\text{SBS}}$ and $f_{\text{SSS}\to\text{SUE}} = f_{\text{SBS}\to\text{SCUE}}$.

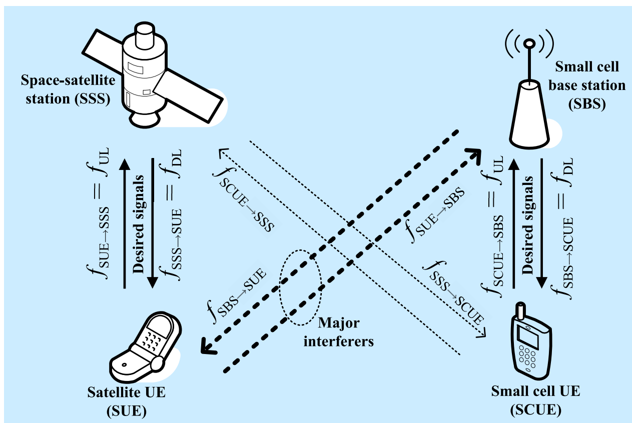

FIGURE 5. Interference scenario when a space-satellite system and a terrestrial-mobile system operate simultaneously at the same satellite spectrum in normal mode.

In normal mode of operation, the co-channel interference between the SBS and the SSS, as well as the interference between the small cell UE and the satellite UE are completely eliminated because of using different uplink and downlink frequencies in both cases. Hence, four types of interferences, between the SBS and the small cell UE, and between the satellite UE and the SSS, exist in normal mode of operation shown in Fig. 5 as follows.

- From the satellite UE to the SBS,
- From the SBS to the satellite UE,
- From the SSS to the small cell UE, and
- From the small cell UE to the SSS.

However, due to internal wall and inter-floor penetration losses of a building, we do not need to consider the interference effect from neighboring small cells at the satellite cell UE within the building. Hence, for simplicity we consider only the interference effect of the serving small cell where the satellite UE is located.

In normal mode of operation, because of a small set of SBSs and hence small cell UEs within a building, the aggregate uplink interference at the satellite station is not significant because of a long distance between the SPS and the small cell UEs as well as the external wall penetration loss of the building. Hence, the interference effect to and from the SPS and the small cell UEs of the TMS can be considered negligible. However, the major interference effects in normal mode occurs between the SBS and the satellite UE due to a short distance between them and high transmit powers of both the SBS and the satellite UE (Fig. 5). This interference can be avoided by auto-switching the satellite UE onto the SBS whenever the satellite UE moves into a 3D building and exists within the coverage of the SBS such that the interference signal from the SBS becomes the desired signal for the satellite UE.

On the other hand, if the terrestrial in-building small cell network operates in reverse mode with respect to the satellite system, uplink and downlink transmissions' frequencies of the terrestrial components system are used respectively for the downlink and uplink transmissions of the satellite components system, i.e. $f_{SUE\rightarrow SSS} = f_{SBS\rightarrow SCUE}$ and $f_{SSS\rightarrow SUE} = f_{SCUE\rightarrow SBS}$ in Fig. 1. Reversing the use of frequency bands in link-level of one system with respect to the other changes the interference scenario such that the overall system-level interference can be minimized or eliminated. Figure 6 shows the overall interference scenario when both satellite and terrestrial component systems operate simultaneously in reverse mode. As shown in Fig. 6, when operating in reverse mode, no interference between a UE of one system and the serving station of another system exists.

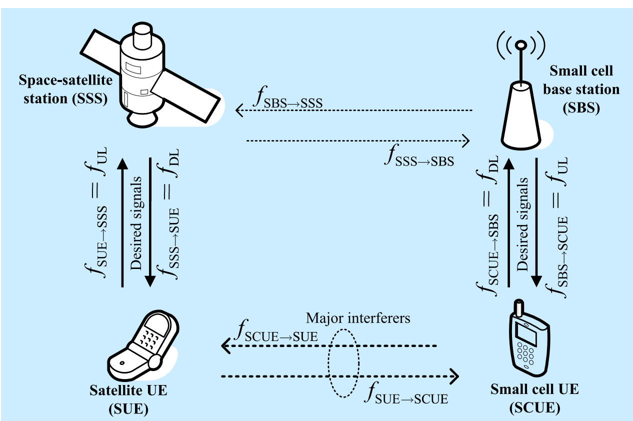

FIGURE 6. Interference scenario when a space-satellite system and a terrestrial-mobile system operate simultaneously at the same satellite spectrum in reverse mode.

More specifically, in reverse mode of operation, the co-channel interferences between the satellite station and the small cell UE as well as between the SBS and the satellite UE are eliminated completely because of using different uplink and downlink frequencies in both cases. Hence, four potential interference scenarios exist in the reverse mode shown in Fig. 6 as follows.

- From the SSS to the SBS,
- From the SBS to the SSS,
- From the small cell UE to the satellite UE, and
- From the satellite UE the small cell UE.

In summary, the terrestrial small cell UE and the space satellite UE as well as the SSS and the SBS interfere with each other as shown in Fig. 6 in reverse mode. However, due to a large distance and an external wall penetration loss of the building, interference between the satellite station and the SBS is considered negligible, and the interference between the small cell UE and the satellite UE is mainly significant in reverse mode of operation. This interference can be avoided by employing a method that whenever a satellite UE exists within the coverage of an in-building SBS, it first changes its mode of operation to the reverse mode, the same as that of the in-building SBS, from the normal mode and handed over or offloaded to the corresponding SBS to get served by it instead of the satellite station. Since both the satellite UE and the small cell UE now operate at the same mode, like normal mode of operation in Fig. 5, the co-channel interference between them is eliminated.

IV. SATELLITE UE CONFIGURATION AND HANDOVER PROCEDURE

A. SATELLITE UE CONFIGURATION

Figure 7 shows a configuration diagram of the satellite UE. The transmission unit performs a process of transmitting a signal to the satellite or the base station. The receiving unit performs a process of receiving a signal from the satellite or the base station. The UE configures a transmission band and a reception band according to the detected mode of the base station. That is, if the base station is in the normal mode, the UE keeps the transmission band and the reception band

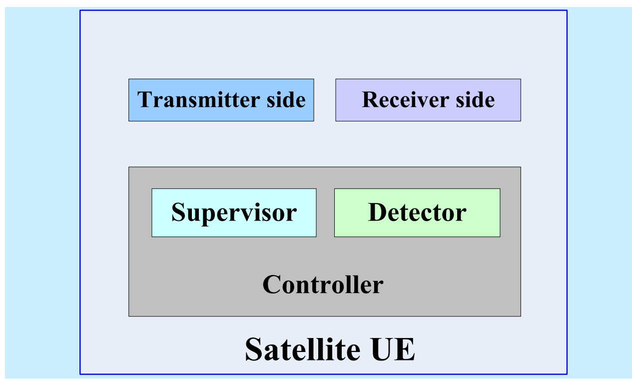

FIGURE 7. A configuration diagram of the satellite UE.

the same as during the communication via the satellite. On the other hand, if the base station is in the reverse mode, the transmission band and the reception band are reversed from those at the time of communication via the satellite. However, since it is unknown whether the in-building base station is operating in the normal mode or in the reverse mode in prior, the UE, in each of the frequency band of the downlink signal of the satellite and the frequency band of the uplink signal, by determining whether or not the reference signal from the base station can be received, the base station can be assured to exist. Upon receiving the reference signal from the base station in one of the frequency bands, the UE broadcasts the existence of the base station with the identifier (base station ID) of the base station, and whether the base station is in the normal mode or the reverse mode.

In communication with the satellite, it is assumed that the frequency band used by the transmitting unit is the first frequency band (i.e., uplink frequency) and the frequency band used by the receiving unit is the second frequency band (i.e., downlink frequency). Hence, when the base station is in the normal mode, the transmission unit is configured to transmit a signal with a frequency of the first frequency band, and is configured to receive a signal at a frequency in the second frequency band to perform communication via the base station. On the other hand, when the base station is in the reverse mode, the transmission unit is configured to transmit a signal at the frequency of the second frequency band, and the reception unit is configured to receive a signal at a frequency in a first frequency band.

Note that when the UE moves from the outdoors into the building (indoors), the UE repeatedly monitors the level of the reference signal transmitted by the satellite. Specifically, the UE repeatedly compares the level of the reference signal with a predetermined threshold value. When the level of the reference signal becomes equal to or less than the predetermined threshold, the UE determines that the user entered the room indoors. The monitoring unit of the control unit monitors the reference signal level from the satellite. When the monitoring unit determines that the reference signal level from the satellite is less than or equal to the threshold value, the detecting unit determines whether the reference signal can be detected from the base station. At this time, since the receiving unit is configured to receive the signal of the second frequency band, firstly, the detecting unit determines whether the reference signal can be detected from the base station in this state. If the reference signal from the base station cannot be detected, the control unit configures the reception unit to receive the signal of the first frequency band, and the detection unit sets the reference signal from the base station in this state. When the detection unit detects the reference signal from the base station, the control unit transmits and controls the transmitting unit to transmit a switching request signal including the detected base station ID of the base station to the satellite communication ground network, i.e. earth station, via the satellite. Further, when receiving the reference signal from the base station in the first frequency band, the control unit transmits the signal of the second frequency band after the transmission of the switching request signal.

It is to be noted that, the UE is executed by one or more processors of a user device capable of communicating via a satellite and a base station device of a mobile communication network. These computer programs are stored in a computer readable storage medium or can be distributed via a network. Finally, when the UE moves outdoors during communication via the base station, the level of the reference signal transmitted by the satellite becomes higher than the predetermined threshold value, and the UE determines that it is moving outdoors. If it is determined that the mobile terminal is moving outdoors, the UE transmits a switching request signal to the base station, and the base station transmits the switching request signal to the satellite communication network. As a result, the satellite communication system and the mobile communication system collaborate to perform a handover of the channel used by the UE for communication. A detail description of the satellite UE handover procedure is given in the following section.

B. SATELLITE UE HANDOVER PROCEDURE

Figure 8 shows the handover procedure for a satellite UE from the satellite network to the terrestrial small cell network and the interaction among network components while carrying out the procedure. Following Media Independent Handover function of IEEE 802.21 [14], which is applicable for inter-working of communication systems [15], the handover procedure of a satellite UE from a satellite network to a small cell network and vice versa can be explained. We present in the following a *generic* handover procedure for a satellite UE between the satellite station and the in-building small cell base station irrespective of the type of satellite stations. An ideal scenario for the handover procedure is considered such that there is no impact of the type of satellite spot-beam cells, e.g. geostationary for a GEO satellite or mobile (i.e., non-geostationary) for a LEO satellite, on the handover procedure of a satellite UE between the small cell base station and the satellite station.

A satellite UE in the downlink measures the radio link quality (e.g., reference signal strength) using for example the channel state information (CSI) signal in every certain number of TTIs. When a satellite UE moves into a building from outside, the strength of the satellite received reference signal at the satellite UE drops suddenly due to a high external wall penetration loss of the building (e.g., 10 dB to 20 dB) as shown in Fig. 9, which causes the satellite UE to initiate a handover request to a SBS with the best reference signal strength (Fig. 8).

The satellite UE scans and estimates the received signal power levels of all the small cells around it within the building and determines the physical cell identity (PCI) and the mode of operation of the small cell with the best received signal strength. Note that, because the satellite UE is dual-mode, it can measure the terrestrial received signal power of small cells with the corresponding transceiver operating at the

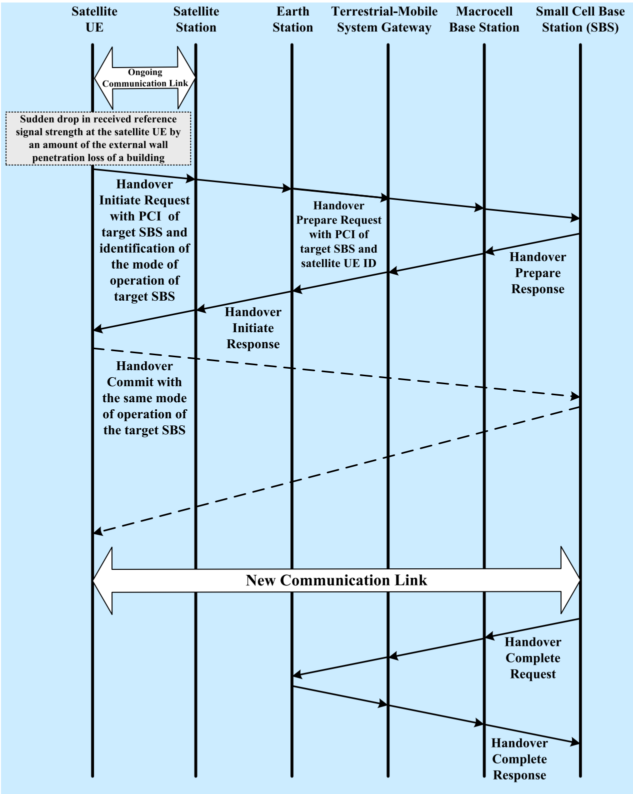

FIGURE 8. Relationship among network components during the handover procedure for a satellite UE from the satellite network to the terrestrial small cell network.

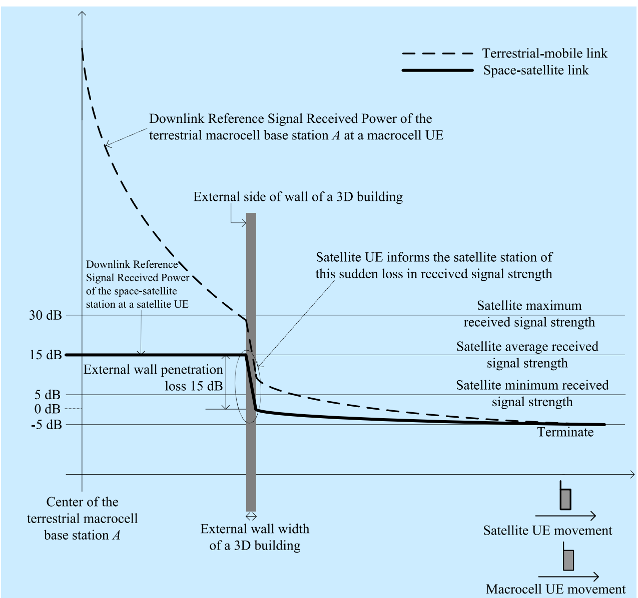

FIGURE 9. Estimation of the reference signal received power by a satellite UE to identify its existence within a 3D building.

terrestrial frequency band. The satellite UE sends a Handover Initiate Request accompanied with the PCI of the target small cell to the earth station via the satellite station. The earth station then sends Handover Prepare Request with PCI of the target small cell base station and the ID of the satellite UE to the terrestrial macrocell base station via the TMS gateway. Since the macrocell base station knows the PCIs of all the small cells deployed within it coverage, and there is no direct connection (or interface such as X2) between the macrocell and any small cell, the macrocell base station informs the target small cell with the satellite UE ID to get prepared for the satellite UE's handover onto it over S1 interface via the terrestrial-mobile core network. The small cell then sends Handover Prepare Response message via the macrocell base station to the earth station. The earth station then sends Handover Initiate Response message of the target SBS to the satellite UE via the satellite station. The satellite UE then checks its current mode of operation with the satellite station. If the current mode of operation of the satellite UE is the same as that of the target SBS, the satellite UE then commits handover to the target small cell. Otherwise, the satellite UE changes its current mode of operation to that of the target SBS and commits handover to it.

For establishing the handover connection with the target SBS, the satellite UE can follow either the forward handover procedure or the backward handover procedure. If considering the backward handover procedure, all handover signaling messages exchange via the ongoing connection with the satellite components. However, if forward handover procedure is considered, the satellite UE quickly reestablish a new signaling channel with the target small cell first so that the handover related signaling can be exchanged via the new channel with the small cell. After authenticating with the small cell, the stored information in the satellite UE about the ongoing connection is used to transfer the connection from the satellite station to the target SBS. The traffic channel is then restored. The satellite UE then informs in the uplink the satellite station to release radio and network resources allocated to the ongoing connection. The satellite UE is now handed over from the satellite network to the terrestrial small cell network, and a new communication link between the satellite UE and the target SBS is established. The SBS then sends Handover Complete Request message via the macrocell base station to the earth station. The earth station finally, replies with a handover Complete Response message to the target SBS via the macrocell base station.

Since small cells are connected to the terrestrial-mobile core network via fixed lines, e.g. DSL cable, fiber-optic or twisted-pair telephone lines, using S1 interface to communicate user data with the internet or external networks, the data is now communicated via the SBS [16] using the new connection (new control and traffic bearers) instead of the ongoing connection. In similar way, the handover procedure of a satellite UE from the terrestrial small cell network to the satellite network can be explained as shown in Fig. 10.

V. PROBLEM FORMULATION

A. MODELING SATELLITE-MOBILE NETWORK

Consider that there are N macro UEs in the TMS, and W satellite UEs in the SPS. Let S_P denote the number of

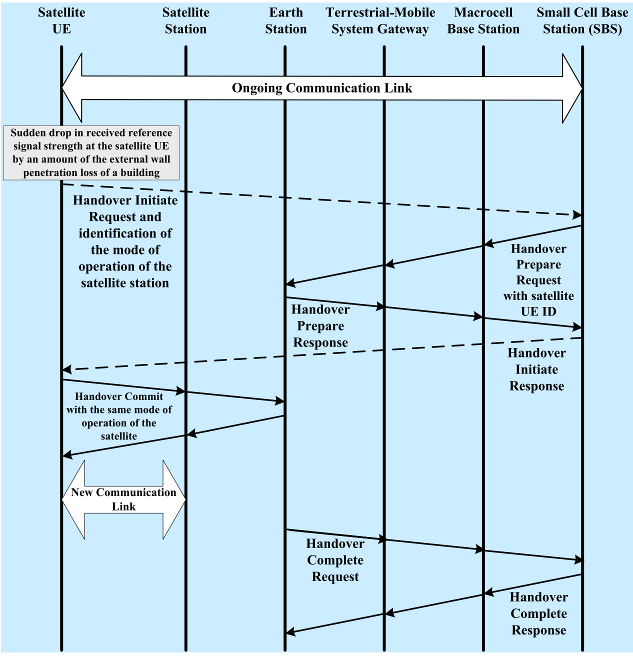

FIGURE 10. Relationship among network components during the handover procedure for a satellite UE from the terrestrial small cell network to the satellite network.

picocells in the macrocell coverage. Consider that the number of offloaded macro UEs of TMS to the picocells is uniformly distributed in the interval $[1, U_{\mathrm{OFL}}]$ where U_{OFL} denotes the total number of offloaded macro UEs. If all picocells have an equal number of offloaded macro UEs U_{P}, i.e. $\forall q\, U_{\mathrm{P}}^{q} = U_{\mathrm{P}}$, then $U_{\mathrm{OFL}} = S_{\mathrm{P}} \times \mathrm{U_P}$. However, in general, U_{P}^{q} is a random variable, which varies from one picocell to another and the realization of U_{P}^{q} for a picocell is mutually independent from the others. If μ_{MI} denotes the ratio of the number of indoor macro UEs, then the total number of indoor macro UEs is $U_{\mathrm{MI}} = \mu_{\mathrm{MI}} \times N$, outdoor macro UEs served by the macrocell is $U_{\mathrm{MO}} = N - U_{\mathrm{OFL}} - U_{\mathrm{MI}}$, the total outdoor macro UEs served by the macrocell and picocells is $U_{\mathrm{MP}} = U_{\mathrm{MO}} + U_{\mathrm{OFL}}$, and the total macro UEs served by the macrocell is $U_{\mathrm{M}} = U_{\mathrm{MO}} + U_{\mathrm{MI}}$.

Let $\boldsymbol{N}_{\mathbf{M}}$ denote the set of indices of all macro UEs of TMS such that $\boldsymbol{N}_{\mathbf{M}} = \{1, 2, 3, \ldots, N\}$. Denote $\boldsymbol{N}_{\mathbf{MO}}$, $\boldsymbol{N}_{\mathbf{P}}$, and $\boldsymbol{N}_{\mathbf{MI}}$ respectively the set of indices of all outdoor macro UEs, offloaded macro UEs, and indoor macro UEs. Note that $\boldsymbol{N}_{\mathbf{M}}$ is partitioned randomly into three disjoint subsets $\boldsymbol{N}_{\mathbf{MO}}$, $\boldsymbol{N}_{\mathbf{P}}$, and $\boldsymbol{N}_{\mathbf{MI}}$. Also, the realization of macro UEs served by the macrocell and picocells are not mutually independent since macro UEs served by picocells are macro UEs offloaded from the macrocell, and the schedulers have a complete knowledge when a macro UE is offloaded. The indoor macro UEs are distributed randomly and non-uniformly within buildings.

Let L denote the maximum number of buildings in the macrocell coverage of TMS, and S_{F} denote the number of active femtocells, i.e. small cells, in each building. Assuming that S_{F} is the same for all buildings, the total number of active femtocells in TMS is $S_{\mathrm{FS}} = L \times S_{\mathrm{F}}$. Consider that the number of femto UEs and satellite UEs in buildings is independent and uniformly distributed in the interval $[1, U_{\mathrm{F}}]$ and $[1, U_{\mathrm{W}}]$ respectively where U_{F} and U_{W} denote respectively the total number of femto UEs and the total number of satellite UEs in any building. In general, U_{F} and U_{W} are random variables that vary from one building to another, and the realization of U_{F} and U_{W} for a building is mutually independent from the others where a realization is defined as a simulation run time. Recall that we use the terms femtocell and small cell as well as femto UE and small cell UE interchangeably.

Let U_{F}^{w} and U_{W}^{w} denote respectively the number of femto UEs and satellite UEs served by a femtocell S_{F}^{w} in a building such that $\forall w\, U_{\mathrm{F}}^{w} \in \left[0,\ U_{\mathrm{F,max}}^{w}\right]$ and $\forall w\, U_{\mathrm{W}}^{w} \in \left[0,\ U_{\mathrm{W,max}}^{w}\right]$ where $U_{\mathrm{F,max}}^{w}$ and $U_{\mathrm{W,max}}^{w}$ denote respectively the maximum number of femto UEs and the maximum number of satellite UEs served by the femtocell S_{F}^{w}. If all femtocells have an equal number of femto UEs U_{FU}, i.e. $\forall w\, U_{\mathrm{F}}^{w} = U_{\mathrm{FU}}$ and an equal number of satellite UEs U_{SU}, i.e. $\forall w\, U_{\mathrm{W}}^{w} = U_{\mathrm{SU}}$, then the total number of femto UEs and the total number of satellite UEs in any building are respectively given by, $U_{\mathrm{F}} = S_{\mathrm{F}} \times \mathrm{U_{FU}}$ and $U_{\mathrm{W}} = S_{\mathrm{F}} \times \mathrm{U_{SU}}$. However, in general, U_{F}^{w} and U_{W}^{w} are random variables that vary from one femtocell to another, and the realization of U_{F}^{w} and U_{W}^{w} for a femtocell is mutually independent from the others. If each femtocell in a building serves exactly one femto UE and one satellite UE at a time, i.e. $U_{\mathrm{FU}} = 1$ and $U_{\mathrm{SU}} = 1$, the total number of femto UEs and the total number of satellite UEs in a building are respectively given by $U_{\mathrm{F}} = S_{\mathrm{F}}$ and $U_{\mathrm{W}} = S_{\mathrm{F}}$ and in the TMS is given by $U_{\mathrm{FS}} = L \times \mathrm{U_F}$.

Let $\boldsymbol{N}_{\mathbf{F}}$ and $\boldsymbol{N}_{\mathbf{W}}$ denote respectively the set of all femto UE indices and the set of all satellite UE indices in a building such that $\boldsymbol{N}_{\mathbf{F}} = \{1, 2, 3, \ldots, U_{\mathrm{F}}\}$ and $\boldsymbol{N}_{\mathbf{W}} = \{1, 2, 3, \ldots, U_{\mathrm{W}}\}$. Let $\boldsymbol{T}$ denote simulation run time with the maximum time of Q (in time step each lasting 1 ms) such that $\boldsymbol{T} = \{1, 2, 3, \ldots, Q\}$. Let $\boldsymbol{T}_{\mathbf{ABS}}$ denote the number of ABSs in every APP of 8 subframes such that $T_{\mathrm{ABS}} \subseteq T$ and $\boldsymbol{T}_{\mathbf{ABS}} = \{t : t = 8v + z; v = 0, 1, 2, \ldots, Q/8; z = 1, \ldots, T_{\mathrm{ABS}}\}$ where $T_{\mathrm{ABS}} = 1, 2, \ldots, 8$ corresponds to ABS patterns $\varphi = 1/8, 2/8, \ldots, 8/8$ respectively. Let t_{ABS} and $t_{\mathrm{non-ABS}}$ denote respectively an ABS and a non-ABS such that $t_{\mathrm{ABS}} \in T_{\mathrm{ABS}}$ and $t_{\mathrm{non-ABS}} \in \boldsymbol{T} \backslash \boldsymbol{T}_{\mathrm{ABS}}$.

B. MODELING TRAFFIC ACTIVITY OF IN-BUILDING SATELLITE UES

Given that an SBS serves traffic in-progress of a satellite UE, we are interested in finding the probability of any possible number of satellite UEs $U_{\mathrm{SU,3D}} \in \boldsymbol{U}_{\mathbf{SU,3D}}$ where $\boldsymbol{U}_{\mathbf{SU,3D}} = \left\{0,\ 1,\ 2, \ldots, U_{\mathrm{W,3D}}\right\}$. Since we assume that a small cell can serve the maximum of one satellite UE at any time t, the maximum number of satellite UEs per 3D building $U_{\mathrm{W,3D}} = U_{\mathrm{W}}$. According to [17], [18], sessions or call arrivals can be modeled as a Poisson process. Hence, the traffic activity of a satellite UE served by an in-building SBS can be modeled as exponentially distributed continuous time Poisson process. Since given the present state, the future state is independent of the past state, the traffic activity of a satellite UE can be modeled as two-state Markov chain such that the off-state traffic activity to on-state traffic activity transition rate of a satellite UE is denoted by λ, whereas the on-state traffic activity to off-state traffic activity transition rate is denoted by μ.

Let $p\,(0)\,,\;\; p\,(1)\,,\;\; p\,(2)\,,\cdots,\;\; p\,(U_{\mathrm{W}})$ denote on-state probabilities of the SBSs, corresponding to the number of active satellite UEs $U_{\mathrm{SU,3D}} \in \{0,\,1,\,2,\ldots,U_{\mathrm{W}}\}$ per 3D building. The values of these probabilities can be found following the Birth-Death process as given below [17]. Consider that there is U_{W} maximum number of satellite UEs per 3D building of which $U_{\mathrm{SU,3D}}$ satellite UEs are active to communicate with the SBSs at any time t as shown in Fig. 11.

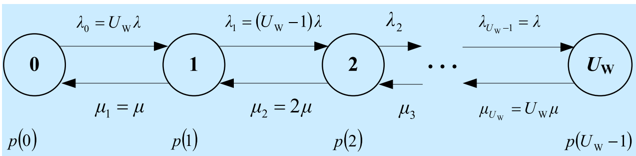

FIGURE 11. Occupancy (i.e., traffic in-progress) state diagram for satellite UEs per 3D building.

Let $\lambda_{U_{\mathrm{SU,3D}}}$ and $\mu_{U_{\mathrm{SU,3D}}}$ denote respectively the birth rate and death rate. Then, according to [19], [20], the followings hold.

$$\lambda_{U_{\mathrm{SU,3D}}} = \begin{cases} \left(U_W - U_{\mathrm{SU,3D}}\right)\lambda, & 0 \le U_{\mathrm{SU,3D}} \le U_W \\ 0, & \text{otherwise} \end{cases}$$

$$\mu_{U_{\mathrm{SU,3D}}} = U_{\mathrm{SU,3D}} \times \mu$$

Hence, the probability of any $U_{\mathrm{SU,3D}}$ can be given by,

$$p\left(U_{\mathrm{SU,3D}}\right) = p\,(0)\;\;(\lambda/\mu)^{U_{\mathrm{SU,3D}}} \begin{pmatrix} U_{\mathrm{W}} \\ U_{\mathrm{SU,3D}} \end{pmatrix} \tag{1}$$

$$\text{But, } \sum\nolimits_{U_{\mathrm{SU,3D}}=0}^{U_{\mathrm{W}}} p\left(U_{\mathrm{SU,3D}}\right) = 1 \tag{2}$$

Using (1) and (2), the following can be obtained.

$$p\,(0) = 1/(1+(\lambda/\mu))^{U_{\mathrm{W}}}$$

Let $\lambda/\mu = \varepsilon$ such that (1) can be rewritten as follows. In other words, the probability that $U_{\mathrm{SU,3D}}$ number of satellite UEs is present within a 3D building and being served by the SBSs in it is given by,

$$p\,\left(U_{\mathrm{SU,3D}}\right) = \frac{U_{\mathrm{W}}!}{U_{\mathrm{SU,3D}}!\left(U_{\mathrm{W}} - U_{\mathrm{SU,3D}}\right)!} \times \varepsilon^{U_{\mathrm{SU,3D}}} \times \frac{1}{(1+\varepsilon)^{U_{\mathrm{W}}}} \tag{3}$$

The Expected value of the number of satellite UEs within the building is then given by,

$$E\left[U_{\mathrm{SU,3D}}\right] = \sum\nolimits_{U_{\mathrm{SU,3D}}=0}^{U_{\mathrm{SU,3D}}=U_{\mathrm{W}}} \left(U_{\mathrm{SU,3D}} \times p\,\left(U_{\mathrm{SU,3D}}\right)\right) \tag{4}$$

Since each SBS can serve the maximum of one satellite UE, the number of SBSs is equal to the number of satellite UEs. This in turn implies that the probability given by $p\,\left(U_{\mathrm{SU,3D}}\right)$ is also the probability that $U_{\mathrm{SU,3D}}$ number of SBSs serve satellite UEs simultaneously during any time period. Note that, since the rate of arrival of satellite UEs to SBSs is relatively lower than that of small cell UEs, the value of $U_{\mathrm{SU,3D}}$ is small in Poisson distribution of satellite UEs. In other words, smaller values of $U_{\mathrm{SU,3D}}$ are more probable than the larger ones such that the distribution of satellite UEs lies mostly toward the left of curve.

C. MODELING RADIO RESOURCE SCHEDULING AND FAIRNESS

Let B_{SSS} and B_{TMS} denote bandwidths allocated to SPS and TMS respectively. We consider Proportional Fair (PF) scheduler to schedule radio resources among UEs to provide an optimal trade-off between fairness and throughput performances. Based on the current and past average throughputs of a UE, a PF scheduler schedules a UE $x_i\,(t)$ in TTI t at resource block (RB) i with the maximum performance metric given by [21],

$$x_i\,(t) = \arg\max_{x}\;\left(\sigma_{x,i}\,(t)/\tilde{\sigma}_{x,i}\,(t)\right) \tag{5}$$

where $\sigma_{x,i}\,(t)$ and $\tilde{\sigma}_{x,i}\,(t)$ represent respectively the current and past average throughputs of UE x at RB i in TTI t. The past average throughput $\tilde{\sigma}_{x,i}\,(t)$ at RB i is updated in every TTI as follows [22] where t_{c} denotes adjustable time constant.

$$\tilde{\sigma}_{x,i}\,(t+1) = \left\{ \begin{array}{ll} \tilde{\sigma}_{x,\,i}\,(t)\;\,(1-1/t_{\mathrm{c}}) + 1/t_{\mathrm{c}}\;\sigma_{x,\,i}\,(t)\;, & x = x_i\,(t) \\ \tilde{\sigma}_{x,\,i}\,(t)\;\,(1-1/t_{\mathrm{c}})\;, & x \ne x_i\,(t) \end{array} \right\} \tag{6}$$

Further, Jain's fairness index is used to evaluate fairness performance of users served by SBSs and can be expressed as follows for small cell UEs, for example [22].

$$F_{\mathrm{J}} = \left(\sum_{x=1}^{U_{\mathrm{F}}} X_x\right)^2 \Bigg/ \left(U_{\mathrm{F}} \times \sum_{x=1}^{U_{\mathrm{F}}} X_x^2\right) \tag{7}$$

where X_x represents the total number of RBs allocated to user x over the simulation runtime.

VI. PERFORMANCE METRICS ESTIMATION FOR A SINGLE BUILDING AND QOS PROVISION

A. SYSTEM LEVEL CAPACITY, SPECTRAL EFFICIENCY AND ENERGY EFFICIENCY ESTIMATION FOR A SINGLE BUILDING

Let d_{MU}, d_{PC}, and d_{FCL} denote respectively the distances of any macro UEs, picocells, and buildings from the macrocell base station, and d_{SC} and d_{SU} denote respectively the distances of a small cell UE and satellite UE from an SBS. The distances of all UEs of each category in a realization are generated following the respective distribution functions as mentioned earlier.

The received signal-to-interference-plus-noise ratio for a UE at RB $= i$ in TTI $= t$ can be expressed as

$$\rho_{t,i} = \left(P_{t,i}/(N^{s}_{t,i} + I_{t,i})\right) \cdot H_{t,i} \quad (8)$$

where $P_{t,i}$ is the transmit power, $N^{s}_{t,i}$ is the noise power, $I_{t,i}$ is the total interference signal power, and $H_{t,i}$ is the link loss for a link between a UE and a base station at RB $= i$ in TTI $= t$.

$H_{t,i}$ can be expressed in dB as

$$H_{t,i}\,(\mathrm{dB}) = (G_{\mathrm{t}} + G_{\mathrm{r}}) - (L_{\mathrm{F}} + PL_{t,i}) + (LS_{t,i} + SS_{t,i}) \quad (9)$$

where $(G_{\mathrm{t}} + G_{\mathrm{r}})$ and L_{F} are respectively the total antenna gain and connector loss. $LS_{t,i}$, $SS_{t,i}$, and $PL_{t,i}$ respectively denote large scale shadowing effect, small scale Rayleigh or Rician fading, and distance dependent path loss between a base station and a UE at RB $= i$ in TTI $= t$.

Using Shannon's capacity formula, a link throughput at RB $= i$ in TTI $= t$ in bps per Hz is given by [23], [24],

$$\sigma_{t,i}\left(\rho_{t,i}\right) = \begin{cases} 0, & \rho_{t,i} < 10\,\mathrm{dB} \\ \beta \log_2\left(1 + 10^{(\rho_{t,i}(\mathrm{dB})/10)}\right), & 10\,\mathrm{dB} \le \rho_{t,i} \le 22\,\mathrm{dB} \\ 4.4, & \rho_{t,i} > 22\,\mathrm{dB} \end{cases} \quad (10)$$

where β is considered as the implementation loss factor.

1) MACROCELL UEs AT TMS SPECTRUM

Let M_{TMS} denote the number of RBs in TMS spectrum bandwidth where an RB is equal to 180 kHz such that in the following expressions, an arbitrary number of RBs must be multiplied by 180 kHz (not shown explicitly) to estimate the capacity in bps. The aggregate capacity of all macro UEs for M_{TMS} RBs and Q TTIs, i.e. the aggregate capacity of TMS, can be expressed as

$$\sigma_{\mathrm{TMS}} = \sum_{t=1}^{Q} \sum_{i=1}^{M_{\mathrm{TMS}}} \sigma_{t,i}\left(\rho_{t,i}\right) \quad (11)$$

where σ and ρ are responses over M_{TMS} RBs of all macro UEs in $t \in \boldsymbol{T}$.

The average system level spectral efficiency of TMS in bps/Hz is given by,

$$\sigma^{\mathrm{SE}}_{\mathrm{TMS}} = \sigma_{\mathrm{TMS}}/(M_{\mathrm{TMS}} \times Q) \quad (12)$$

Recall that S_{F}, S_{P}, and S_{M} denote respectively the number of small cells per building, the number of picocells per macrocell, and the number of macrocells in the system. The energy efficiency is defined as the amount of energy required to transmit a bit [25], [26]. Hence, the average system level energy efficiency of TMS in joules/bit (J/b) is given by,

$$\sigma^{\mathrm{EE}}_{\mathrm{TMS}} = ((S_{\mathrm{P}} \times P_{\mathrm{PC}}) + (S_{\mathrm{M}} \times P_{\mathrm{MC}}))/(\sigma_{\mathrm{TMS}}/Q) \quad (13)$$

2) SMALL CELL UEs AT SPS SPECTRUM

Let M_{SSS} denote the number of RBs in the spectrum bandwidth of SPS. For small cell UEs, the aggregate capacity served by the SBSs per 3D building can be given in general as follows. Recall that there are S_{F} SBSs such that $s \in \{1, 2, \ldots, S_{\mathrm{F}}\}$ per 3D building, and each SBS can serve the maximum of $U_{\mathrm{F,max}}$ small cell UEs such that $u \in \{1, 2, \ldots, U_{\mathrm{F,max}}\}$.

In general, for any number of small cell UEs $u \in \{1, 2, \ldots, U_{\mathrm{F,max}}\}$ over M_{SSS} RBs, the aggregate capacity of the small cell UEs for any SBS, i.e. $\sigma_s : s \in \{1, 2, \ldots, S_{\mathrm{F}}\}$, over Q TTIs is given by,

$$\sigma_{\mathrm{s}} = \sum_{t=1}^{Q} \sum_{i=1}^{M_{\mathrm{SSS}}} \sum_{u=1}^{U_{\mathrm{F,max}}} \sigma_{t,i,u}\left(\rho_{t,i,u}\right) \quad (14)$$

where σ and ρ are responses over M_{SSS} RBs of $u \in \{1, 2, \ldots, U_{\mathrm{F,max}}\}$ small cell UEs for any SBS in $t \in \boldsymbol{T}=\{1,2,\ldots Q\}$.

If each SBS serve the maximum of one small cell UE such that $U_{\mathrm{FU,max}} = 1$, and then (14) can be expressed as follows over Q TTIs.

$$\sigma_{\mathrm{s},1} = \sum_{t=1}^{Q} \sum_{i=1}^{M_{\mathrm{SSS}}} \sigma_{t,i}\left(\rho_{t,i}\right)$$

Now, consider a case where each SBS has exactly one small cell UE, and all SBSs per 3D building are serving simultaneously for Q TTIs. The aggregate capacity per 3D building is then given by,

$$\sigma_{\mathrm{cl,sc}} = \sum_{s=1}^{S_{\mathrm{F}}} \sigma_{\mathrm{s},1} \quad (15)$$

3) SATELLITE UEs AT SPS SPECTRUM

For satellite UEs, the aggregate capacity served by SBSs per 3D building can be given as follows. Recall that there are the maximum of U_W satellite UEs per 3D building such that $U_{\mathrm{SU,3D}} \in \{1, 2, \ldots, U_{\mathrm{W}}\}$ where each SBS can serve the maximum of one satellite UE at any time $t \in \boldsymbol{T}$. Hence, the number of SBSs serving satellite UEs in any time t simultaneously is equal to the number of satellite UEs $U_{\mathrm{SU,3D}}$ offloaded to them from the satellite station.

Now consider a case where we assume that, unlike small cell UEs as above, an SBS may not have a satellite UE over Q TTIs. Recall that the set of all satellite UE indices in a building is given by $\boldsymbol{N}_{\mathbf{W}} = \{1, 2, 3, \ldots, U_{\mathrm{W}}\}$ such that $N_{\mathrm{W}} \in \boldsymbol{N}_{\mathbf{W}}$. Hence, in such cases, the aggregate capacity of all satellite UEs within a 3D building over Q TTIs is given by,

$$\sigma_{\mathrm{cl,su}} = \sum_{t=1}^{Q} \sum_{i=1}^{M_{\mathrm{SSS}}} \sum_{N_{\mathrm{W}}=1}^{U_{\mathrm{W}}} 1_{U_{N_{\mathrm{W}}}}\left(N_{\mathrm{W}}\right) \times \sigma_{t,i,N_{\mathrm{W}}}\left(\rho_{t,i,N_{\mathrm{W}}}\right) \quad (16)$$

where $U_{N_{\mathrm{W}}} \in \{1, 2, \ldots, U_{\mathrm{W}}\}$, and $1(\cdot)$ defines that $1(\cdot) = 1$ if N_{W} exists in the set $U_{N_{\mathrm{W}}}$; otherwise, $1(\cdot) = 0$.

Remark 1: Equation (16) can be interpreted as follows. For any $N_W \in \boldsymbol{N_W}$,

$$\forall t \forall i \ \sigma_{t,i}\left(\rho_{t,i}\right) \in \boldsymbol{\sigma_{t,i}}\left(\boldsymbol{\rho_{t,i}}\right) : \boldsymbol{\sigma_{t,i}}\left(\boldsymbol{\rho_{t,i}}\right) = \begin{cases} \sigma_{1,1} & \cdots & \sigma_{1,M_{\text{SSS}}} \\ \cdots & \cdots & \cdots \\ \sigma_{Q,1} & \cdots & \sigma_{Q,M_{\text{SSS}}} \end{cases} \quad (17)$$

holds, such that $\boldsymbol{\sigma_{t,i}}\left(\boldsymbol{\rho_{t,i}}\right)$ for any satellite UE N_W is non-zero in (16) only when the corresponding satellite UE N_W exists within the coverage of any SBS and is scheduled for at least an RB i in any TTI t such that $\sigma_{t,i}\left(\rho_{t,i}\right) \neq 0$ for the corresponding $\{t,i\}$. Otherwise, $\boldsymbol{\sigma_{t,i}}\left(\boldsymbol{\rho_{t,i}}\right)$ is zero for the satellite UE N_W since it neither exists nor is scheduled for any RB i at any time t for Q TTIs. We use the special cases in (15) and (16) later to evaluate the performance of the proposed technique.

Remark 2: Since the total number of satellite RBs M_{SPS} assigned to SBSs is fixed, an increase in U_W causes to decrease in aggregate capacity of small cell UEs $\sigma_{\text{cl,sc}}$ and increase in aggregate capacity of satellite UEs $\sigma_{\text{cl,su}}$ per building since more RB resources need to be allocated to satellite UEs. Because indoor environments do not vary significantly, irrespective of the types of UEs, the combined capacity of the small cell system however do not vary significantly. Note also that, since more satellite UEs are served within short distances by SBSs instead of the satellite station, an increase in presence of satellite UEs within a building however increases the aggregate throughput of the satellite system.

4) MACROCELL UEs AT TMS SPECTRUM AND SMALL CELL UEs AND SATELLITE UEs AT SPS SPECTRUM

Using (13), (15) and (17), the effective aggregate capacity of TMS because of sharing the whole satellite spectrum with its SBSs per building is given by,

$$\sigma_{\text{TMS}}^{\text{all}} = \sigma_{\text{TMS}} + \sigma_{\text{cl,sc}} + \sigma_{\text{cl,su}} \quad (18)$$

It is to be noted that the satellite spectrum is not licensed by the TMS operator; rather it is shared with TMS and is licensed by the satellite operator. Hence, in estimating spectral efficiency, the capacity that is achieved by the satellite spectrum for TMS can be interpreted as the capacity achieved because of reusing the same satellite spectrum in TMS such that the satellite spectrum needs to be considered for estimating spectral efficiency of the satellite system. Hence, the effective spectrum of TMS is its licensed TMS spectrum only such that the average system level spectral efficiency of TMS after sharing the satellite spectrum with its SBSs to serve small cell UEs and satellite UEs per building in bps/Hz is given by,

$$\sigma_{\text{TMS}}^{\text{SE,all}} = \sigma_{\text{TMS}}^{\text{all}} / (M_{\text{TMS}} \times Q) \quad (19)$$

The average system level energy efficiency of TMS after sharing satellite spectrum with its SBSs per building in joules/bit (J/b) is given by,

$$\sigma_{\text{TMS}}^{\text{EE,all}} = \left(\begin{array}{l} (S_{\text{F}} \times P_{\text{FC}}) + (S_{\text{P}} \times P_{\text{PC}}) + \\ (S_{\text{M}} \times P_{\text{MC}}) \end{array} \right) / \left(\sigma_{\text{TMS}}^{\text{all}} / Q \right) \quad (20)$$

Remark 3: Note that in the above performance metrics estimation, only the terrestrial-mobile channel link models are considered, and no satellite channel link models are introduced. Hence, the performance evaluation and analysis based on these performance metrics are completely independent of the satellite channel link models such that the performance evaluation results presented later are not affected by the satellite channel link models.

B. ENSURING QoS USING ABS BASED eICIC TECHNIQUE

Typically, the average number of satellite UEs is relatively lower than that of small cell UEs over certain duration of time within a building. This causes the satellite UEs to get deprived of scheduling sufficient radio resources to them as compared to small cell UEs by in-building SBSs. Hence, to overcome the effect of an uneven distribution of satellite UEs and small cell UEs within in-building environments in order to ensure QoS between these two categories of UEs per building, we propose to employ the ABS based eICIC technique as shown in Fig. 3. To do so, we consider operating satellite UEs only during ABSs, whereas small cell UEs only during non-ABSs in both normal and reverse modes of operation.

Note that when enforcing the ABS based eICIC technique to in-building UEs, the number of TTIs over an APP becomes fixed for any UE category such that the capacity of all small cell UEs and the capacity of all satellite UEs become independent of the number of either satellite UEs or small cell UEs. This causes UEs of any category to be scheduled only on the fixed allocated TTIs irrespective of the number of UEs of the corresponding category active over an APP. Hence, the average throughput per UE of any category decreases with an increase in the number of UEs of that category over time T. This results in resolving the variation in aggregate capacity of each UE category with the variation of the number of UEs of the corresponding category.

Consider that satellite UEs are scheduled only during ABSs T_{ABS}, whereas small cell UEs are scheduled only during non-ABSs T_{nABS} over an APP T_{APP} such that the summation of T_{ABS} and T_{nABS} gives T_{APP}. We assume a fair allocation of time resources to each category of UEs such that the more the number of UEs of a category, the more the number of TTIs allocated to that category of UEs. Hence, the allocation of T_{ABS} and T_{nABS} over T_{APP} is defined in proportionate with the average number of satellite UEs and the average number of small cell UEs respectively over time T. Further, we assume that if there exists at least a UE of any category, the number of TTIs allocated to that category must be non-zero to ensure continuity of services.

Like satellite UEs, we assume that the arrival process of small cell UEs follows Poisson process with mean λ_{SC}. Hence, following the above assumption, an optimum value of the number of ABSs over T_{APP} reflecting the QoS is derived in percentage of the APP based on the ratio of the average number of satellite UEs λ_{SU} to the average number of small cell UEs λ_{SC} arrived to get access to the SBSs per building over certain duration of time T by solving the following optimization problem.

$$\begin{aligned}
&\min T_{ABS}\\
&\text{subject to } (a)\ \frac{\lambda_{SC}}{\lambda_{SU}} = \frac{T_{nABS}}{T_{ABS}}\\
&(b)\ T_{ABS} + T_{nABS} = T_{APP}\\
&(c)\ \exists U_{FU} \in \boldsymbol{U}_{\mathbf{FU}}, T_{nABS} > 0\\
&(d)\ \exists U_{SU} \in \boldsymbol{U}_{\mathbf{SU}}, T_{ABS} > 0\\
&(e)\ T_{nABS} = \mathbb{N} \le T_{APP}\\
&(f)\ T_{ABS} = \mathbb{N} \le T_{APP}\\
&(g)\ P_{T,\,FC} \le P_{T_{max},\,FC}
\end{aligned} \tag{21}$$

The optimal solution of the above optimization problem in favor of satellite UEs is given by,

$$T^*_{ABS} = \lceil \lambda_{SU}/(\lambda_{SU} + \lambda_{SC}) \rceil \times T_{APP} \tag{22}$$

such that $T^*_{nABS} = \lfloor \lambda_{SC}/(\lambda_{SU} + \lambda_{SC}) \rfloor \times T_{APP}$

Proof: Using constraints 21(a)-21(b),

$$\begin{aligned}
\lambda_{SC}/\lambda_{SU} &= T_{nABS}/T_{ABS}\\
\lambda_{SC}/\lambda_{SU} &= (T_{APP} - T_{ABS})/T_{ABS}\\
(\lambda_{SC}/\lambda_{SU}) \times T_{ABS} &= (T_{APP} - T_{ABS})\\
(\lambda_{SC}/\lambda_{SU} + 1) \times T_{ABS} &= T_{APP}\\
T_{ABS} &= [1/(\lambda_{SC}/\lambda_{SU} + 1)] \times T_{APP}
\end{aligned}$$

Since T_{ABS} and T_{nABS} are strictly integers, then by satisfying constraints 21(b), 21(e), and 21(f) and allowing a favor to the satellite UEs, the optimal value of T_{ABS} can be given by,

$$T^*_{ABS} = \lceil \lambda_{SU}/(\lambda_{SU} + \lambda_{SC}) \rceil \times T_{APP} \tag{23}$$

Hence,

$$\begin{aligned}
T_{nABS} &= T_{APP} - [\lambda_{SU}/(\lambda_{SU} + \lambda_{SC})] \times T_{APP}\\
T^*_{nABS} &= \lfloor \lambda_{SC}/(\lambda_{SU} + \lambda_{SC}) \rfloor \times T_{APP}
\end{aligned}$$

VII. PERFORMANCE METRICS ESTIMATION FOR DENSE SMALL CELL DEPLOYMENT

A. CAPACITY, SPECTRAL EFFICIENCY, AND ENERGY EFFICIENCY FOR MULTIPLE BUILDINGS OVER MACROCELL COVERAGE

Consider that there is more than one building (i.e., $L > 1$) of small cells located within the coverage of the macrocell. We assume that the indoor propagation characteristics and the distances of UEs from their respective SBSs in each of the L buildings do not deviate significantly from one another because of the small coverage of a SBS such that by linear approximation, the average aggregate capacity of TMS because of sharing the satellite spectrum with small cells of each of the L buildings is then roughly given by,

$$\sigma^{all}_{TMS,L} = \sigma_{TMS} + L \times \left(\sigma_{cl,sc} + \sigma_{cl,su}\right) \tag{24}$$

where σ_{TMS}, $\sigma_{cl,sc}$ and $\sigma_{cl,su}$ are given by (11), (15), and (16). When L is large enough such that $L \times \left(\sigma_{cl,sc} + \sigma_{cl,su}\right) \gg \sigma_{TMS}$, (24) can be approximated as follows.

$$\sigma^{all}_{TMS,L} \cong L \times \left(\sigma_{cl,sc} + \sigma_{cl,su}\right) \tag{25}$$

Using the aforementioned assumptions since $\left(\sigma_{cl,sc} + \sigma_{cl,su}\right)$ can be considered to be the same for all the L buildings, in such cases, (25) can be approximated further as follows.

$$\sigma^{all}_{TMS,L} \propto L \tag{26}$$

Following (24), the spectral efficiency for L buildings is given by,

$$\sigma^{SE,all}_{TMS,L} = \sigma^{all}_{TMS,L} \big/ (M_{TMS} \times Q) \tag{27}$$

Given M_{TMS} and Q, using (26), (27) can be expressed as follows.

$$\sigma^{SE,all}_{TMS,L} \propto L \tag{28}$$

Hence, for $L > 1$, the system level spectral efficiency is directly proportional to the number of buildings L within the macrocell coverage, i.e. the number of times the satellite spectrum can be reused spatially in small cells deployed in L buildings within the macrocell coverage. In other words, by increasing the value of L, the system level spectral efficiency can be improved to meet the requirements of 5G and beyond mobile networks.

Now, the energy efficiency for L buildings is given by,

$$\sigma^{EE,all}_{TMS,L} = \begin{pmatrix} (L \times S_F \times P_{FC}) + \\ (S_P \times P_{PC}) + \\ (S_M \times P_{MC}) \end{pmatrix} \Big/ \left(\sigma^{all}_{TMS,L}/Q\right) \tag{29}$$

However, the impact of $(L \times S_F \times P_{FC})$ is small enough as compared to $[(S_P \times P_{PC}) + (S_M \times P_{MC})]$ for low values of L.For example, if $L \le 3$ then $(L \times S_F \times P_{FC}) = (3 \times 0.1 \times 18 = 5.4W)$, which is very much less than $[(S_P \times P_{PC}) + (S_M \times P_{MC})] \cong 50W$. Hence, in such cases, (29) can be approximated as

$$\sigma^{EE,all}_{TMS,L} \cong ((S_P \times P_{PC}) + (S_M \times P_{MC})) \Big/ \left(\sigma^{all}_{TMS,L}/Q\right) \tag{30}$$

Since S_P and S_M are fixed over the observation interval T, using (26), (30) can be expressed as follows.

$$\sigma^{EE,all}_{TMS,L} \cong k/L \tag{31}$$

where $k = ((S_P \times P_{PC}) + (S_M \times P_{MC})) \times Q$ is a constant.

Hence, for low values of L, the energy required per bit transmission is inversely related to L such that the energy efficiency per bit transmission improves by the factor L. However, for large values of L,the impact of $(L \times S_F \times P_{FC})$ becomes comparable to $[(S_P \times P_{PC}) + (S_M \times P_{MC})]$ such that the energy efficiency improves following (29).

B. MODELING ENERGY EFFICIENCY AND CONDITION FOR OPTIMALITY AND MAXIMALITY

1) MODELING ENERGY EFFICIENCY

Recall that from (29), the energy efficiency is given by,

$$\sigma^{EE,all}_{TMS,L}(L) = \begin{pmatrix} (L \times (S_F \times P_{FC})) + \\ (S_P \times P_{PC}) + \\ (S_M \times P_{MC}) \end{pmatrix} \Bigg/ \left(\begin{matrix} \sigma_{TMS} + \\ L \times \begin{pmatrix} \sigma_{cl,sc} + \\ \sigma_{cl,su} \end{pmatrix} \end{matrix} \Big/ Q \right)$$

$$\sigma_{\mathrm{TMS},L}^{\mathrm{EE,all}}(L) = \left(\begin{array}{c} (L \times (S_\mathrm{F} \times P_\mathrm{FC})) + \\ \left(\begin{array}{c} (S_\mathrm{P} \times P_\mathrm{PC}) + \\ (S_\mathrm{M} \times P_\mathrm{MC}) \end{array} \right) \end{array} \right) \Bigg/ \left(\begin{array}{c} \sigma_\mathrm{TMS}/Q + \\ L \times \left(\begin{array}{c} \sigma_\mathrm{cl,sc} + \\ \sigma_\mathrm{cl,su} \end{array} \right)/Q \end{array} \right) \tag{32}$$

For simplicity in analysis, $\sigma_{\mathrm{TMS},L}^{\mathrm{EE,all}}(L)$ is expressed as follows.

$$\sigma_{\mathrm{TMS},L}^{\mathrm{EE,all}}(L) = (a_\mathrm{P} + (L \times b_\mathrm{P}))/(c_\sigma + (L \times d_\sigma)) \tag{33}$$

where $a_\mathrm{P} = ((S_\mathrm{P} \times P_\mathrm{PC}) + (S_\mathrm{M} \times P_\mathrm{MC}))$

$$\begin{aligned} b_\mathrm{P} &= (S_\mathrm{F} \times P_\mathrm{FC}) \\ c_\sigma &= \sigma_\mathrm{TMS}/Q \\ d_\sigma &= (\sigma_\mathrm{cl,sc} + \sigma_\mathrm{cl,su})/Q \end{aligned}$$

Putting the values of transmit powers and achievable capacities of all base stations in (33), it can be found that $(a_\mathrm{P} \times d_\sigma) > (b_\mathrm{P} \times c_\sigma)$ results in the energy required per bit transmission decays with L. In other words, energy efficiency can be modeled by (33) given that the following condition strictly satisfies in (33) for any value of L. Otherwise, the energy required per bit transmission increases with L.

$$(a_\mathrm{P} \times d_\sigma) > (b_\mathrm{P} \times c_\sigma)$$

Note that, when $L >> 1$ in (33), the following proposition holds for energy efficiency.

Proposition 1: Energy efficiency from reusing satellite spectrum in in-building small cells of TMS $\sigma_{\mathrm{TMS},L}^{\mathrm{EE,all}}(L)$ *is non-zero irrespective of the value of L, i.e. the density of small cells within the macrocell coverage.*

Proof: When $L >> 1$, in (33), $(a_\mathrm{P} + (L \times b_\mathrm{P})) \cong (L \times b_\mathrm{P})$ and $(c_\sigma + (L \times d_\sigma)) \cong (L \times d_\sigma)$ such that $\sigma_{\mathrm{TMS},L}^{\mathrm{EE,all}}(L)$ can be approximated as

$$\begin{aligned} \sigma_{\mathrm{TMS},L}^{\mathrm{EE,all}}(L) &\cong (L \times b_\mathrm{P})/(L \times d_\sigma) \\ \sigma_{\mathrm{TMS},L}^{\mathrm{EE,all}}(L) &\cong b_\mathrm{P}/d_\sigma \\ \sigma_{\mathrm{TMS},L}^{\mathrm{EE,all}}(L) &\cong (S_\mathrm{F} P_\mathrm{FC}) \times Q/(\sigma_\mathrm{cl,sc} + \sigma_\mathrm{cl,su}) \\ &\neq 0 \end{aligned}$$

Hence, as $L \rightarrow \propto$, energy efficiency gets fixed to b_P/d_σ, i.e. $\sigma_{\mathrm{TMS},L}^{\mathrm{EE,all}}(L) \rightarrow b_\mathrm{P}/d_\sigma$.

It is to be noted that, from (33), because $\sigma_{\mathrm{TMS},L}^{\mathrm{EE,all}}(L)$ improves with L, then by employing Proposition 1, the maximum value of energy efficiency is obtained when $L \rightarrow \propto$. Hence, the maximum value energy efficiency is given by,

$$\begin{aligned} \sigma_{\mathrm{TMS},L_\mathrm{max}}^{\mathrm{EE,\,all}}(L) &= b_\mathrm{P}/d_\mathrm{q} \\ \sigma_{\mathrm{TMS},L_\mathrm{max}}^{\mathrm{EE,all}}(L) &= (S_\mathrm{F} P_\mathrm{FC}) \times Q/(\sigma_\mathrm{cl,sc} + \sigma_\mathrm{cl,su}) \end{aligned}$$

2) CONDITION FOR OPTIMALITY

To find an optimal value of energy efficiency and L, taking the derivative on (33), we can find the following.

$$\frac{d\left(\sigma_{\mathrm{TMS},L}^{\mathrm{EE,all}}(L)\right)}{dL} = \begin{array}{c} ((c_\sigma + d_\sigma L) \times b_\mathrm{P}) - \\ ((a_\mathrm{P} + b_\mathrm{P} L) \times d_\sigma) \end{array} \Bigg/ \left(\begin{array}{c} c_\sigma + \\ (L \times d_\sigma) \end{array} \right)^2$$

$$\frac{d\left(\sigma_{\mathrm{TMS},L}^{\mathrm{EE,all}}(L)\right)}{dL} = (b_\mathrm{P} c_\sigma - a_\mathrm{P} d_\sigma)/(c_\sigma + (L \times d_\sigma))^2 \tag{34}$$

Note that from (34), $\frac{d\left(\sigma_{\mathrm{TMS},L}^{\mathrm{EE,all}}(L)\right)}{dL}$ varies with L as follows.

$$\frac{d\left(\sigma_{\mathrm{TMS},L}^{\mathrm{EE,all}}(L)\right)}{dL} = \begin{cases} (b_\mathrm{P} c_\sigma - a_\mathrm{P} d_\sigma)/c_\sigma, & \text{for } L = 0 \\ \Delta, & \text{for } 0 < L < \propto \\ 0, & \text{for } L = \propto \end{cases} \tag{35}$$

where Δ is any non-zero value of $\frac{d\left(\sigma_{\mathrm{TMS},L}^{\mathrm{EE,all}}(L)\right)}{dL}$. Note that Δ is a design parameter that trade-offs both spectral efficiency and energy efficiency requirements set by an operator. Hence, using (35), we can find an optimal value of L that corresponds to the slope $\frac{d\left(\sigma_{\mathrm{TMS},L}^{\mathrm{EE,all}}(L)\right)}{dL} = \Delta$ as follows.

From (34),

$$\begin{aligned} \frac{d\left(\sigma_{\mathrm{TMS},L}^{\mathrm{EE,all}}(L)\right)}{dL} &= (b_\mathrm{P} c_\sigma - a_\mathrm{P} d_\sigma)/(c_\sigma + (L \times d_\sigma))^2 \\ &\Rightarrow (b_\mathrm{P} c_\sigma - a_\mathrm{P} d_\sigma)/(c_\sigma + (L \times d_\sigma))^2 = \Delta \\ &\Rightarrow c_\sigma + (L \times d_\sigma) = \sqrt{(b_\mathrm{P} c_\sigma - a_\mathrm{P} d_\sigma)/\Delta} \end{aligned} \tag{36}$$

Note that Δ is always negative since energy efficiency improves with L such that the angle of the slope on the curve energy efficiency versus L, $\theta > 90^0$. Since $(a_\mathrm{P} \times d_\sigma) > (b_\mathrm{P} \times c_\sigma)$, then $(b_\mathrm{P} \times c_\sigma) - (a_\mathrm{P} \times d_\sigma)$ is also negative such that in the above equation both negatives in the numerator and denominator cancel each other. Hence, from (36), an optimal value of L, subject to $(a_\mathrm{P} \times d_\sigma) > (b_\mathrm{P} \times c_\sigma)$, is given by,

$$L^* = \left(-c_\sigma + \sqrt{(b_\mathrm{P} c_\sigma - a_\mathrm{P} d_\sigma)/\Delta}\right)/d_\sigma \tag{37}$$

Since all other parameters are constant, knowing Δ, the value of L can be determined using (37). Now using (37), the optimal value of energy efficiency corresponding to L^* is then given by,

$$\sigma_{\mathrm{TMS},L}^{\mathrm{EE,all}^*}(L) = \left(\begin{array}{c} (L^* \times (S_\mathrm{F} \times P_\mathrm{FC})) + \\ (S_\mathrm{P} \times P_\mathrm{PC}) + \\ (S_\mathrm{M} \times P_\mathrm{MC}) \end{array} \right) \Bigg/ \left(\begin{array}{c} \sigma_\mathrm{TMS} + \\ L^* \times \left(\begin{array}{c} \sigma_\mathrm{cl,sc} + \\ \sigma_\mathrm{cl,su} \end{array} \right)/Q \end{array} \right)$$

VIII. OPERATION AND SCHEDULER IMPLEMENTATION OF THE PROPOSED SPECTRUM SHARING TECHNIQUE

A. PRINCIPLE OF OPERATION OF THE PROPOSED TECHNIQUE

The flowchart in Fig. 12 describes the operation of the proposed spectrum sharing technique. As detailed in section V.A, the number of macro UEs N is first disjointed into three macro UE groups randomly, namely indoor macro UEs, outdoor macro UEs and offloaded macro UEs. The channel conditions of each category of macro UEs are updated in each TTI. The throughput of each UE on each RB of TMS

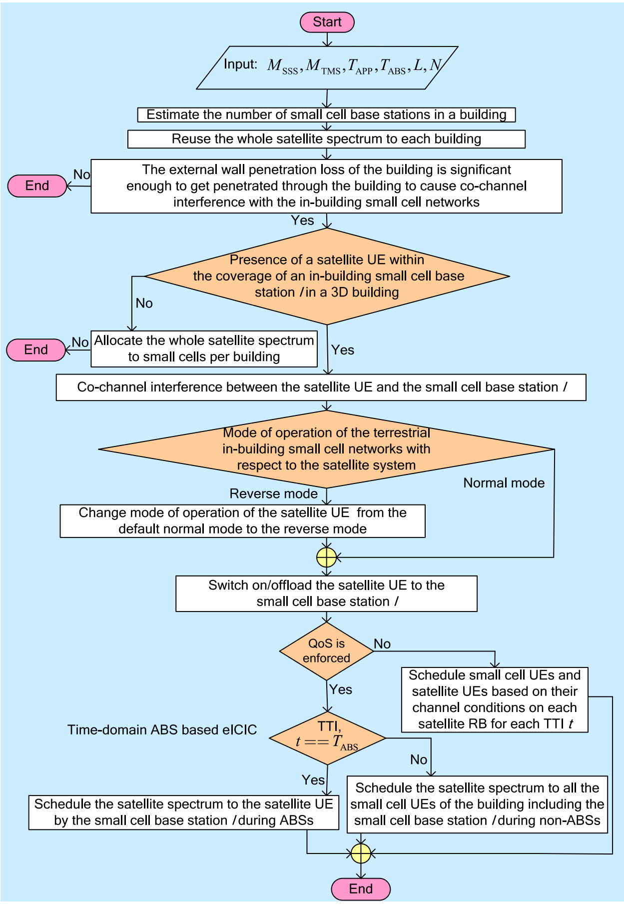

FIGURE 12. **Flowchart of operation of the proposed spectrum sharing technique.**

spectrum is estimated and the UE with the maximum performance metric following PF scheduling principle is scheduled. The same process repeats for all macro UEs on all TMS RBs. For small cells, the same procedure as described for TMS spectrum is followed and RBs of satellite spectrum is allocated to small cell UEs and satellite UEs based on the presence of satellite UEs in a building. The aggregate capacity achieved by the macro UEs, small cell UEs and satellite UEs are then added up to estimate overall system level spectral efficiency and energy efficiency.

B. SCHEDULER IMPLEMENTATION OF THE PROPOSED TECHNIQUE

In TMS, the time-domain scheduling functionality and the frequency-domain scheduling functionality are separated for in-building small cells to address the latency constraint. As shown in Fig. 1, we consider one frequency-domain scheduler for all UEs within a building, which is located at the cluster head. A cluster head is basically any SBS within a building with frequency-domain scheduling functionality that schedules RBs of the satellite spectrum to all UEs within the corresponding building.

The time-domain scheduler of all UEs of TMS, including macro UEs and in-building small cell UEs of the TMS and in-building satellite UEs of the SPS, is located at the macrocell base station. The function of the time-domain scheduler is to inform the frequency-domain scheduler at the cluster head to allocate the satellite spectrum to the satellite UEs during ABSs and small cell UEs during non-ABSs when QoS is enforced in the negotiation. However, if the QoS not is enforced, the frequency-domain scheduler at the cluster head can schedule a satellite RB to either a small cell UE or a satellite UE based on their respective performance matrices for the corresponding satellite RB in each TTI without concerning with any update from the time-domain scheduler regarding time allocation to UEs. Note that, unlike terrestrial-mobile in-building small cells, both time-domain and frequency-domain schedulers for the terrestrial-mobile spectrum are located at the macrocell base station that allocates mobile spectrum to terrestrial macro UEs only. However, on the other hand, both time-domain and frequency-domain schedulers for all outdoor satellite UEs are resided at the earth station that schedules mainly outdoor satellite UEs. Below is an example operation of these schedulers for easy of understanding.

The small cell, within which a satellite UE exists, detects the presence of the satellite UE and informs the cluster head where the frequency-domain scheduler of the building*is*located such that the frequency-domain scheduler at the cluster head can initiate enforcing the ABS based eICIC within small cells if QoS is provided. The offloading process of radio bearers of the satellite UE is initiated by measuring the RSRP of the satellite UE such that there is a sudden drop in received power loss when moving from the outside to the inside of the building due to a high external wall penetration loss. The satellite UE can detect its presence within a building by knowing the fall of its received signal strength so that it can inform the satellite in the uplink with the physical cell identity of the small cell to start initiating the auto-switching mechanism from the satellite to the SBS by transferring all its radio bearers to the small cell.

IX. PERFORMANCE EVALUATION

A. EVALUATION SCENARIO

All default parameters and assumptions for the performance evaluation are given in Table 1. Recall that, for the performance evaluation, we limit evaluating the performance to TMSs only. Since to evaluate the performance of the TMS, we do not need to take into consideration of the satellite channel link model, the satellite channel link model is not given in Table 1. Only the terrestrial channel link models are given in Table 1 depending on the type of base stations (e.g., macrocell base station, picocell base station, or femtocell base station) and environmental profiles (e.g., indoor or outdoor). For the TMS, we consider an evaluation scenario where small cells operate at the same spectrum of the SPS, i.e. the whole satellite bandwidth is reused to small cells per 3D building such that the satellite UEs are served by the small cells at the satellite spectrum along with the small cell UEs. When a satellite UE is offloaded to a SBS, the satellite UE is served by the SBS. If there is any ongoing serving UE of the SBS, the SBS then serves both categories of UEs following PF scheduling principle.

For performance evaluation, we assume that each SBS can accommodate the maximum of one satellite UE at any instance of time. An arrival of more than one satellite UEs are assumed to be served by other neighboring small cells. In ideal case, we assume that the satellite strength is sufficient enough such that the control signaling connection for any satellite UE persists with the satellite station until a new connection with any SBS within a building is established. Moreover, we assume that an SBS can serve one small cell UE at any time t. More specifically, the evaluation is carried out under the scenario that each SBS has one small cell UE, whereas a satellite UE within a SBS may or may not exist over any particular duration of time T. Since the TMS and satellite carrier frequencies as given in Table 1 do not deviate significantly, for simplicity, we assume that the in-building propagation characteristics at both bands are the same. Hence, the path loss and other assumptions considered for TMS are also equally applicable to SBSs operating at the satellite spectrum.

B. PERFORMANCE EVALAUTION

1) SYSTEM LEVEL CAPACITY PERFORMANCE

Figure 13 shows the capacity responses when small cells of a single building operate at the satellite spectrum and macro UEs operate at the TMS spectrum. A slight increase in small cell capacity is obtained due to the shorter distance and better channel condition between any SBS and its small cell UE than that between the macrocell base station and its macro UEs. Since the overall capacity is directly proportional to the bandwidth, sharing satellite spectrum with small cells improves the capacity by about twice as compared to when no sharing is considered. In other words, if small cells were to operate at the TMS spectrum, a certain portion of the spectrum would need to be assigned for small cells causing a reduction in the overall capacity of TMS.

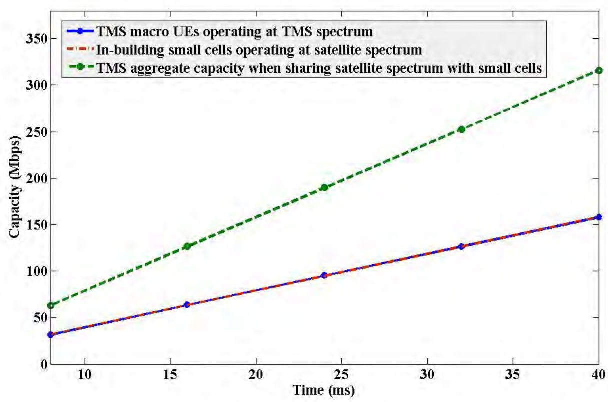

FIGURE 13. Capacity improvement of TMS by sharing the satellite spectrum with small cells within a building in the absence of satellite UEs.

TABLE 1. Default simulation parameters and assumptions.

Parameters and Assumptions			Value
E-UTRA simulation case[1]			3GPP case 3
Satellite type and operating frequency band			GEO or LEO, S band
Effect of mobility of satellite spot-beam cells on the satellite UE handover			None
Cellular layout[2] and Inter-site distance (ISD)[1,2]			Hexagonal grid, dense urban, 3 sectors per macrocell site and 1732 m
Carrier frequency[2,3] and transmit direction			2 GHz (mobile system), 3.5 GHz (satellite system) and downlink
System bandwidth			5 MHz (for both 2 GHz and 3.5 GHz)
Considered system for performance evaluation			TMSs only
Number of cells			1 macrocell, 2 picocells, and 18 femtocells per building
Total base station transmit power[1] (dBm)			46 for macrocell[1,4], 37 for picocell[1], 20 for femtocell[1,3,4]
Co-channel fading model[1]			Frequency selective Rayleigh for macrocell and picocell and Rician for femtocell
Indoor propagation characteristics at both bands			Same
External wall penetration loss[1] (L_{ow})			20 dB
Path loss	Macrocell base station and a UE[1]	Indoor macro UE	PL(dB)=15.3 + 37.6$\log_{10}R$, R is in m
		Outdoor macro UE	PL(dB)=15.3 + 37.6$\log_{10}R$ + L_{ow}, R is in m
	Picocell base station and a UE[1]		PL(dB)=140.7+36.7$\log_{10}R$, R is in km
	Femtocell base station and a UE[1,2,3]		PL(dB)=127+30$\log_{10}(R/1000)$, R is in m
Lognormal shadowing standard deviation (dB)			8 for macrocell base station[2], 10 for picocell base station[1], 10 for femtocell base station[2,3]
Antenna configuration			Single-input single-output for all terrestrial mobile base stations and UEs
Antenna pattern (horizontal)			Directional (120^0) for macrocell[1] and omnidirectional for picocell[1] and femtocell[1]
Antenna gain plus connector loss (dBi)			14 for macrocell base station[2], 5 for picocell base station[1], 5 for femtocell base station[1,3]
UE antenna gain[2,3]			0 dBi
UE noise figure[2] and UE speed[1]			9 dB, 3 km/hr
Total number of macro UEs			30
Maximum number of satellite UEs served simultaneously by an SBS			1
Picocell coverage and macro UEs offloaded to all picocells[1]			40 m (radius), 2/15
Indoor macro UEs[1]			35%
3D multi-storage building and SBS models (regular square-grid)	Number of buildings		L
	Number of floors per building		2
	Number of apartments per floor		9
	Number of SBSs per apartment		1
	SBS activation ratio		100%
	SBS deployment ratio		1
	Total number of SBSs per building		18
	Area of an apartment		$10\times10\,m^2$
	Location of a SBS in an apartment		center
Scheduler and traffic model[2]			Proportional Fair and full buffer
Type of small cells			Closed subscriber group
Channel state information			Ideal
TTI[1] and scheduler time constant (t_c)			1 ms and 100 ms
Total simulation run time			8 ms

taken[1]from [27] , [2]from [28], [3]from [29], [4]from [30].

Further, when no satellite UE is present within a building, the maximum sharing of satellite spectrum with small cell UEs can be achieved since all the RBs of satellite spectrum can be allocated to only small cell UEs within a building. Similarly, the minimum sharing with small cell UEs is achieved when each SBS has a satellite UE. Note that we assume for simplicity that an SBS can serve the maximum of one satellite UE at a time. However, in general, there can be more than one satellite UE that can be served by an SBS.

From Fig. 14, it can be found that as the number of satellite UEs within any building increases, there is a corresponding increase in their achievable capacity due to more resources of the satellite spectrum allocated to satellite UEs. This can be found reflected in Fig. 14 in the response of capacity for satellite UEs that increases with an increase in the number of satellite UEs for a given number of small cell UEs. Because the satellite spectrum is fixed, an increase in the number of satellite UEs causes to help increase the probability of getting scheduled more satellite UEs to satellite RBs than that of a given number of small cell UEs. This in turn increases the capacity of satellite UEs with a corresponding decrease in capacity of small cell UEs as shown in Fig. 14. As the number of satellite UEs approaches to that of small cell UEs, the difference in achievable capacity between them gets smaller. Since both small cells and satellite UEs are generated randomly there is a possibility that the aggregate throughput of satellite UEs would increase than that of small cell UEs.

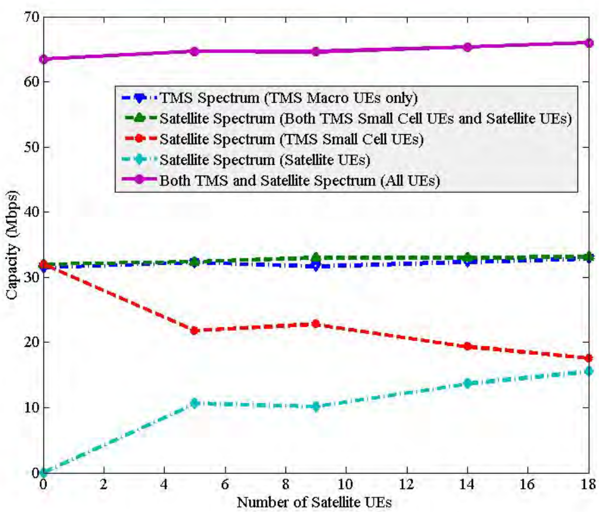

FIGURE 14. Capacity versus the number of satellite UEs over time *T* (i.e., λ_{SU}) when no QoS is enforced and the satellite spectrum is shared with an in-building small cells.

In general, the number of satellite UEs would be lower than that of small cell UEs. Hence from Fig. 14, for the lower values of satellite UEs, the aggregate throughputs of all small cells are higher than that of satellite UEs. This can be overcome by enforcing a condition that can maximize the total throughput of satellite and small cell UEs. In such cases, the ABS based eICIC technique can be employed. Note that, if the satellite UEs are not offloaded to small cells, in indoor environment, the satellite signal becomes very weak resulting lower satellite aggregate throughput.

Based on whether or not the QoS is enforced for small cell UEs and satellite UEs, we propose two techniques to offload and serve satellite UEs along with small cell UEs by SBSs as follows. This is because of the fact that the number of UEs in both SBS of TMS and the satellite UEs are not fixed. However, the total number of satellite RBs is fixed. That's why an increase in one category of UEs causes to reduce allocation of RBs to another category of UEs as shown in Fig. 14.

- *Method 1- If QoS is enforced*: This method applies if either TMS or the satellite operators would like to limit certain QoS in terms of, e.g. the throughput limit, in such cases, the ABS based eICIC technique can be applied. The condition for optimality can be set based on the ratio of the number of active small cell UEs to the number of satellite UEs such that the APP will be distributed in proportionate to the ratio.
- *Method 2 - If no QoS is enforced*: In this method, no QoS is enforced such that an offloaded satellite UEs can be considered as new UEs in addition to ongoing both satellite and small cell UEs. The scheduler allocates RBs based on their channel conditions following the PF scheduling principle, irrespective of the number of satellite UEs or small cell UEs as shown in Fig. 14.

2) SYSTEM LEVEL SPECTRAL EFFICIENCY AND ENERGY EFFICIENCY PERFORMANCES

a: FOR L= 1

To analyze the spectral efficiency and energy efficiency performances, we consider two major cases, namely only macro UEs operating at the TMS spectrum, and all UEs where macro UEs operating on the TMS spectrum and satellite/small cell UEs operating at the satellite spectrum. Since typically outdoor macro UEs are sparsely located within macrocell coverage at a relatively longer distance from the MBS in comparison with the small cell UEs or satellite UEs from the SBS, the radio channels of macro UEs are affected more due to the large distance distant-depended path losses and other fading effects. That's why the spectral efficiency of macro UEs at the TMS spectrum (0.89 bps/Hz) is lower than that (1.79 bps/Hz) when satellite spectrum is shared with the in-building SBSs as shown in Fig. 15(a). In other words, spectral efficiency of TMS with satellite spectrum sharing with in-building SBSs increases by almost twice the one when no spectrum sharing is considered.

From Fig. 15(b), it can be found that with satellite spectrum sharing, the energy requires per bit transmission is 6.51 μJ, which is about half of the energy 12.68 μJ requires per bit transmission when no satellite spectrum sharing is considered with small cells. Hence, sharing satellite spectrum with small cells improves the energy efficiency of TMS by almost twice. Such an improvement can be clarified by the fact that both

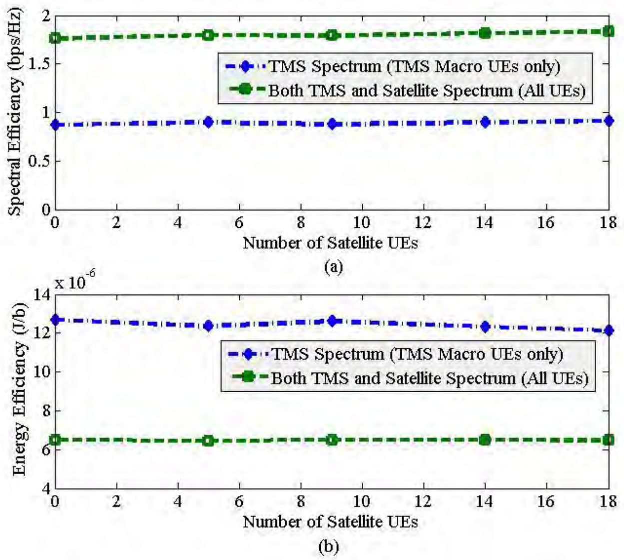

FIGURE 15. System-level spectral efficiency and energy efficiency performances when employing the proposed spectrum sharing technique with the number of satellite UEs over time T (i.e., λ_{SU}) for $L = 1$.

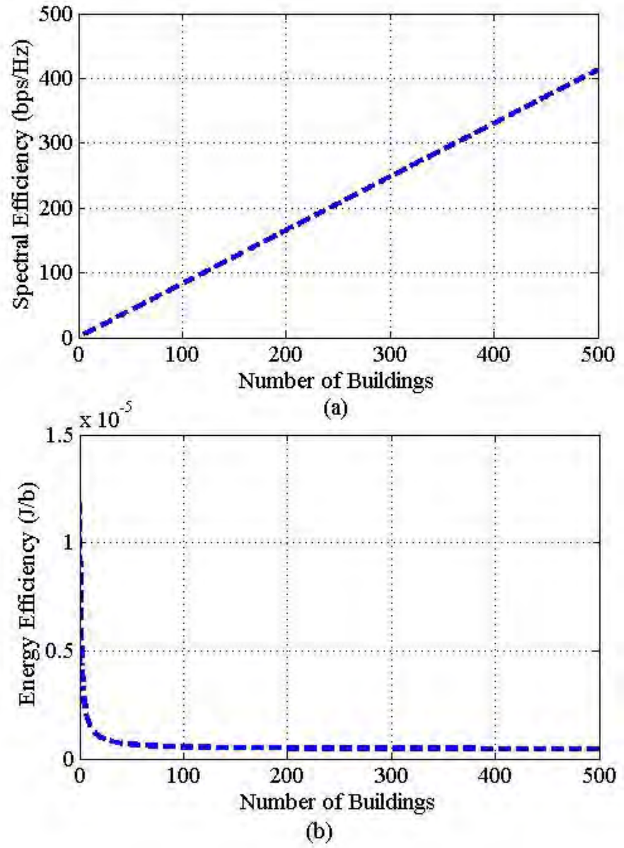

FIGURE 16. System level spectral efficiency and energy efficiency performances when employing the proposed spectrum sharing technique with the number of buildings $L > 1$ over time T.

the MBS and PBSs transmit at high powers, which are respectively about 400 times and 50 times that of a FBS as mentioned in Table 1. Now using Fig. 14, with satellite spectrum sharing the capacity of TMS increases by more than twice to about 64 Mbps from that (i.e., about 31 Mbps) when no spectrum sharing is considered. Such an increase in TMS capacity requires an additional 18 FBSs to transmit for sharing spectrum along with the MBS and 2 PBSs as mentioned in Table 1. These FBSs spend a total of ($18 \times 0.1\text{W} = 1.8\text{W}$) per building. This implies that an increase in total transmit power from ($1 \times 40W + 2 \times 5W = 50W$) with no spectrum sharing to ($1 \times 40W + 2 \times 5W + 18 \times 0.1W = 51.8W$) with spectrum sharing, i.e. ($(51.8W - 50W)/50W = 3.6\%$), is required to increase the TMS capacity by ((64Mbps − 31Mbps)/31Mbps=106%). Hence, in-building small cells, because of their low transmit powers to serve their UEs at short distances; can help boost the energy efficiency of TMS significantly by sharing satellite spectrum with them.

b: FOR $L>1$

For $L>1$, as the value of L increases, the number of times the whole satellite spectrum can be reused in buildings over the macrocell coverage increases. Using (29), the spectral efficiency increases directly in proportional to L as shown in Fig. 16(a) for any values of L. However, from Fig. 16(b) it can be found that the EE improves dramatically for very low values of L (e.g., $1 \leq L \leq 5$ in Fig. 16(b)), and when L gets very large (e.g., $100 \leq L \leq 500$ in Fig. 16(b)), the gain in energy efficiency becomes negligible. This can be clarified by the fact that for low values of L, the effect of the transmit power of small cells in the numerator of (29) is insignificant as compared to the total transmit power of the system so that the energy required per bit transmission decreases steadily with an increase in L in the denominator of (29). As L gets large, the transmit power of small cells gets significant in comparison with the total power in the numerator of (29) such that the effect of increase in L in both the numerator and the denominator of (29) cancels almost each other resulting no significant gain in energy efficiency.

Note that since SE improves linearly with L, it is recommended considering L as large as possible. However, as aforementioned, the case for energy efficiency gain is not straightforward with the minimum gain achieved for $1 \leq L \leq 5$ and the maximum gain for any values of $L \geq 100$. Hence, considering the interval $5 \leq L < 100$, an optimal value of L can be found using (37) by considering a slope Δ as design parameter on the curve for $5 \leq L < 100$ that corresponds to a point on the curve. The value of L corresponding to this point is the optimal value of L.

It is to be noted that, from Fig. 16(b), the angle θ of the slope $\frac{d\left(\sigma_{\text{TMS,L}}^{\text{EE,all}}(L)\right)}{dL}$ is strictly $90^0 < \theta \leq 180^0$, which implies that $\frac{d\left(\sigma_{\text{TMS,L}}^{\text{EE,all}}(L)\right)}{dL}$ is always negative. The corresponding value of L in Fig. 16(b) is given by $0 < L \leq \propto$. Hence, to trade-off spectral efficiency and energy efficiency, a value of L needs to be chosen, which can be found by (37).

In summary using the findings from (32)-(37) and Figs. 16(a)–16(b), the following properties can be concluded for spectral efficiency and energy efficiency with L, i.e. the density of in-building small cells within the macrocell coverage, when reusing satellite spectrum in in-building small cells of TMS.

- Spectral efficiency gain can be achieved almost linearly with an increase in small cell density by reusing the same resources spatially in them. However, energy efficiency gets saturated after a certain level of small cell density, i.e. the value of L, over the macrocell coverage.
- Energy efficiency $\sigma_{\mathrm{TMS,L}}^{\mathrm{EE,all}}(L)$ can be modeled as $\sigma_{\mathrm{TMS,L}}^{\mathrm{EE,all}}(L) = (a_{\mathrm{P}} + (L \times b_{\mathrm{P}}))/(c_\sigma + (L \times d_\sigma))$ subject to $(a_{\mathrm{P}} \times d_\sigma) > (b_{\mathrm{P}} \times c_\sigma)$ when energy efficiency improves with L.
- Energy efficiency $\sigma_{\mathrm{TMS,L}}^{\mathrm{EE,all}}(L)$ is non-zero irrespective of the value of L.
- The slope of energy efficiency is always negative such that the angle corresponds to the slope is given by $90^0 < \theta \leq 180^0$.
- An optimal value of L that satisfies both spectral efficiency and energy efficiency requirements does not lie in the range of values of L which are either too small or too large. Rather, an optimal value of L can be found by choosing an appropriate value of $\frac{d}{dL}\left(\sigma_{\mathrm{TMS,L}}^{\mathrm{EE,all}}\right)$ for $0 < L \leq \propto$.

3) IMPACT OF ABS BASED EICIC TECHNIQUE

From Fig. 17, it can be found that the average throughput per UE for both categories of UEs varies with the variation of the number of satellite UEs. The impact of increase in satellite UEs on the average capacity per satellite UE is more significant for lower values of satellite UEs where satellite UEs are deprived mostly of being scheduled to radio resources. As the number of satellite UEs becomes comparable with the number of small cell UEs, the impact of uneven scheduling of radio resources to satellite UEs is getting lower. To overcome this problem, i.e. to realize a stable average capacity per UE, particularly for the satellite UEs, we consider employing the ABS based eICIC technique to small cells such that satellite UEs can operate only during the ABSs and small cell UEs can operate only during the non-ABSs over an APP.

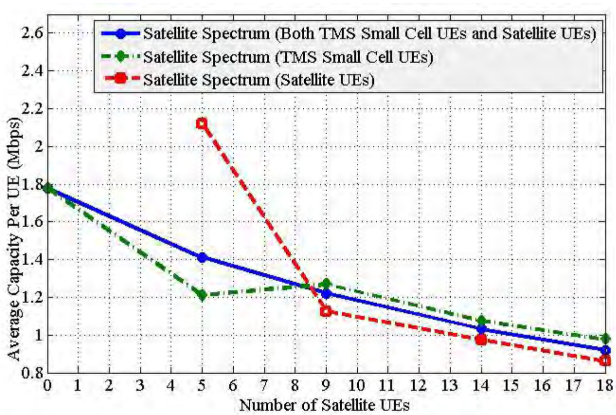

FIGURE 17. Average throughput per UE of both categories of UEs, i.e. satellite UEs and small cell UEs, with the variation of satellite UEs. The number of small cells UEs is kept fixed at 18.

Using (22), an optimal number of ABSs with the variation of the number of satellite UEs is given in Fig. 18. As it should be the case, since the value of T_{ABS} is directly proportional to the number of arrivals of satellite UEs, for a given number of small cell UEs, an increase in satellite UEs causes to increase in the optimal value of T_{ABS} (Fig. 18). Note that since a TTI value cannot be a fraction, we consider rounding any fractional value of T_{ABS} estimated by (22) to its nearest upper integer value as shown in Fig. 18.

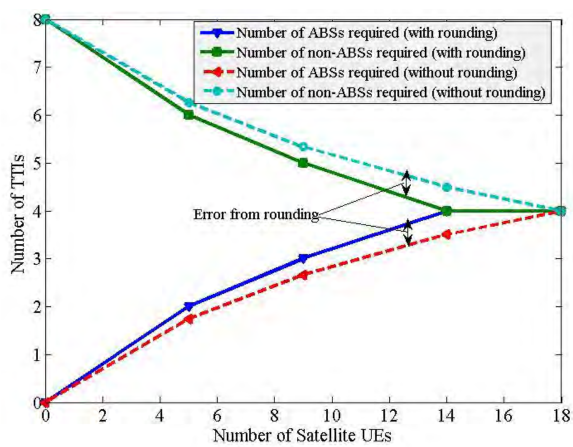

FIGURE 18. An optimal number of ABSs with an error margin from rounding T_{ABS} with the variation in the number of satellite UEs. The number of small cells UEs is kept fixed at 18.

Figure 19 shows the responses of average capacity per UE of both the satellite UEs and the small cell UEs after employing the ABS based eICIC technique to the small cells in a building. Unlike the responses of the average capacity per UE in Fig. 17 with no eICIC technique employed to small cells, the responses of the average capacity per UE in Fig. 19 for both small cell UEs and satellite UEs do not vary significantly with the variation of satellite UEs. Since the summation of

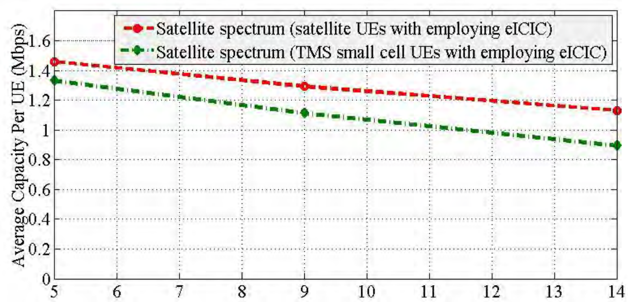

FIGURE 19. Average throughput per UE of both categories of satellite UEs and small cell UEs with employing ABS based eICIC technique in small cell system. The number of small cells UEs is kept fixed at 18.

T_{ABS} and T_{nABS} gives T_{APP}, an increase in T_{ABS} because of rounding causes a corresponding decrease in T_{nABS}. That's why in Fig. 19, the average capacity per UE for satellite UEs is slightly higher than that of small cell UEs. However, ideally, so long as the exact values of T_{ABS} and T_{nABS} can be employed, the average capacity per UE responses of both categories of UEs should be the same. Moreover, since the total amount of time and frequency resources is fixed, with an increase in the number of satellite UEs, the total number of UEs in the small cell system increases, which results in a decrease in the average capacity per UE for both the satellite UEs and the small cell UEs as shown in Fig. 19. Hence, with employing the ABS based eICIC technique to the small cell system, we can achieve an equal amount of average throughput per UE for both the satellite UEs and the small cell UEs to ensure the QoS in terms of user experience irrespective of the type and the number of UEs of any category.

4) PERFORMANCE COMPARISON

a: ENERGY EFFICIENCY PERFORMANCE

According to [31], it is reported that the radio access network (RAN) by 2020 needs to improve energy efficiency to $60\mu J - 100\mu J$, and for a single operator, the achievable energy efficiency of the LTE system is reported about $30\mu J/b$. However, the energy efficiency of 5G networks is expected to improve by 10 times as compared to that of fourth generation (4G) networks [32]. From Fig. 16(b), it can be found that with our proposed spectrum sharing technique, a steady-state energy efficiency of about $1\mu Jb$ can be achieved for $L>45$. Hence, our proposed technique surpasses the energy efficiency requirements of $3\mu Jb$ of 5G networks as well as the RAN by 2020 significantly.

b: SPECTRAL EFFICIENCY PERFORMANCE

According to [33], the average spectral efficiency of 4G networks is 2.4 bps/Hz/cell − 3.7 bps/Hz/cell. However, the spectral efficiency of 5G networks is expected to improve by 10 times as compared to that of 4G networks [32], i.e. 24 bps/Hz/cell − 37 bps/Hz/cell. From Fig. 16(a), it can be found that with our proposed spectrum sharing technique, we can achieve an average spectral efficiency of 40 bps/Hz/macrocell for $L>45$. Hence, our proposed technique can easily meet the spectral efficiency requirements of 5G networks.

c: AVERAGE THROUGHPUT PER UE PERFORMANCE

To estimate an average throughput per UE, we consider an expected value of the number of satellite UEs. Using (18), Fig. 20 shows the probability distribution of satellite UEs for $\varepsilon = 0.2$ such that it is consistent with the assumption that the expected value of the number of satellite UEs is far less than that of small cell UEs during Q TTIs. Then using (4) for $\varepsilon = 0.2$, the expected value of the number of satellite UEs found is $E[U_{\mathrm{W}}] = 3$. The average capacity per UE in

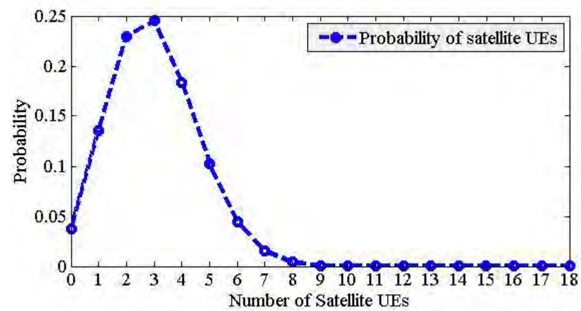

FIGURE 20. **Probability distribution of satellite UEs within a building.**

system-level can be found by,

$$\sigma^{\mathrm{sys}}_{\mathrm{per\ UE}} = \left(\sigma_{\mathrm{TMS}} + \sigma_{\mathrm{cl,sc}} + \sigma_{\mathrm{cl,su}}\right) \Big/ \left(N + U_{\mathrm{F}} + E\ [U_{\mathrm{W}}]\right) \quad (38)$$

From Fig.14 and Fig.17, it can be found that $\sigma_{\mathrm{TMS}} \cong$ 33Mbps, $\sigma_{\mathrm{cl,sc}} + \sigma_{\mathrm{cl,su}} \cong 1.55$ Mbps combinedly for 18 small cell UEs and 3 satellite UEs. Recall that $N = 30$, $U_{\mathrm{F}} = 18$, and $E\ [U_{\mathrm{W}}] = 3$. Putting all these in (38), we can find $\sigma^{\mathrm{sys}}_{\mathrm{per\ UE}} = 1.285$Mbps with our proposed technique, which is higher than that (i.e., less than 1 Mbps of average throughput per UE) reported in [34] as well as in [35] obtained by using both user-centric approach and network-centric approach.

X. SIGNIFICANCE, CHALLENGES AND FUTURE RESEARCH PERSPECTIVES

A. RESEARCH SIGNIFICANCE

The proposed spectrum sharing technique benefits from a number of aspects as follows.

1) OPERATING SMALL CELLS AT SATELLITE SPECTRUM

All indoor small cells operate at the satellite spectrum such that the mobile operator does not need to make a huge investment on licensing costly mobile spectrum to operate small cells. Because small cells do not operate at mobile spectrum, the whole mobile spectrum can be allocated to only macro UEs to boost throughput per macro UE.

2) SERVING IN-BUILDING SATELLITE UEs WITH SMALL CELLS

Since the satellite signal is affected significantly within buildings because of high penetration loss of external walls, instead of serving by the satellite station, any satellite UEs whenever exists within a building can be served by an in-building small cell at a short distance. This in turn helps improve the received signal power and hence the received throughput of satellite UEs.

3) AVOIDING MAJOR CO-CHANNEL INTERFERENCES

In general, the major troublesome interferences in SPS and TMS used to happen between high power nodes and low power nodes, namely between the satellite station and the mobile UEs because of existing a large number of mobile UEs within the coverage of a satellite beam, as well as the terrestrial base station and the satellite UEs because of the short distances between them. However, such interferences, namely between the satellite station and the small cell UEs are avoided because of high external wall penetration loss, whereas between the SBS and the satellite UEs because of converting the interference signal into the desired signal by serving the satellite UEs with in-building SBSs irrespective of the modes of operation.

4) ASSURING QoS BETWEEN SMALL CELL UES AND SATELLITE UEs

The QoS between small cell UEs and satellite UEs within a building is assured by employing the 3GPP recommended and standardized ABS based eICIC technique that helps implement the proposed spectrum sharing technique straightforwardly.

5) APPLICABILITY TO BOTH INTEGRATED AND HYBRID SYSTEMS

Since the spectrum allocation and scheduling functionalities can be integrated into a single system, or made under certain negotiations between the systems, the proposed spectrum sharing technique can be applied to both the integrated and hybrid space-satellite and terrestrial-mobile systems.

6) INITIATING SIMPLE HANDOVER PROCESS

The offloading process of radio bearers of a satellite UE can be initiated by measuring the reference signal received power (RSRP) of the satellite UE at the satellite UE itself such that there is a sudden drop in received power loss when moving from the outside to the inside of the building due to the high external wall penetration loss of the building. The satellite UE can inform the satellite station in the uplink to start initiating the auto-switching mechanism to transfer the ongoing session of the satellite UE to the SBS from the satellite station.

7) APPLICABILITY IN A WIDE RANGE OF SPECTRUMS

Because of inherent high external wall penetration loss of any 3D building, the applicability of the proposed spectrum sharing technique is not restricted to any specific spectrum band. Rather, the technique can be applied to share a wide range of satellite spectrum bands with small cells such as 3.5 GHz low frequency band, 26 GHz or above millimeter wave bands.

B. CHALLENGES AND FUTURE RESEARCH PERSPECTIVES

1) AGREEMENT ON INTERWORKING POLICY

For a hybrid system, i.e. for a separate satellite service provider and a terrestrial mobile system provider, an agreement on interworking policy needs to be done in prior between the systems for seamless communication through their networks. However, for an integrated satellite and terrestrial mobile system, no such agreement is needed since the common satellite/ground interworking policy server (SGIPS) exchanges information and controls resources between the satellite and CGC networks and is responsible for coordinating between the satellite system and TMS.

2) COORDINATION AND BACKHAUL REQUIREMENTS

A tight coordination between the satellite system and the mobile system is needed to perform proper time synchronization, particularly to carryout handover operations. Since the coordination between systems depends largely on the property of the backhaul, ideal backhaul such as optical fiber can be the best choice. However, it costs huge as compared to other non-ideal backhauls such as microwave and millimeter wave backhauls. Unfortunately, non-ideal backhauls suffer from bandwidth and latency constraints. Hence, a rigorous investigation under different deployment scenarios can be carried out to show the trade-off between cost and quality of the backhaul.

3) IN-BUILDING EXISTENCE OF SATELLITE UEs

In practice, because of a long distance between a satellite UE and the satellite station, the distance-depended path loss can be high enough to discontinue the existing link of a satellite UE when it moves into or moves out of the building because of high external wall penetration loss. This may interrupt seamless handover to a small cell from the satellite station and vice versa. This necessitates developing a proper signal detection and maintenance scheme particularly for the satellite UEs to ensure a smooth transition from one system to another.

4) IMPACT OF HIGH FREQUENCY ON SYSTEM MODELING

If the satellite system operates at a high frequency, e.g. millimeter wave frequencies, the propagation characteristics would be different from that when operating at microwave spectrums. Hence, unlike in this paper, an appropriate adjustment in propagation model is crucial. Moreover, loss from external walls and internal walls at higher frequencies is typically higher than that of lower ones. Hence, when operating an integrated terrestrial-mobile and space-satellite system, satellite frequency-specific real time measurement of data for a concerned building would be helpful to avoid unnecessary satellite UE link failure and to model accurately the real setup of the corresponding building.

5) HANDOVER CONTROL MECHANISM

Offloading or handover of a satellite UE to or from an SBS can be performed in a number of ways, namely UE controlled, UE assisted network control, network control, and network assisted UE controlled. Since each method has some pros and cons, though in this paper, UE controlled handover is exposed, other methods than this one can be investigated to see the relative performance improvement of one over another.

6) HYBRID AUTONOMOUS TERRESTRIAL-MOBILE SYSTEM AND INTEGRATED MOBILE-SATELLITE SYSTEM

Integrated MSS has been introduced to overcome bottlenecks faced by the satellite system such as indoor coverage, blockages created by large buildings, etc. by integrating complementary terrestrial base stations along with the MSS. In such systems, complementary terrestrial base stations operate at the same frequency as that of satellite system. When sharing the same satellite spectrum of an integrated MSS with small cells of an autonomous terrestrial-mobile system (aTMS), huge amount co-channel interference occurs between small cells and complementary base stations. Hence, it is crucial to develop a system and spectrum sharing technique for a multiple communication systems comprising MSS and aTMS to improve the spectral efficiency of the overall combined system further.

XI. CONCLUSION

This paper presents a novel technique for sharing satellite spectrum to terrestrial-mobile in-building small cells. By exploring the external wall penetration loss of a building, the proposed satellite spectrum technique has been described along with identifying major relevant issues. The co-channel interference between satellite UEs and SBSs and their UEs has been analyzed for both normal and reverse modes of operation, and a configuration and a handover procedure for the satellite UEs to and from the in-building small cells has been presented by introducing a satellite and terrestrial-mobile system model.

By varying the density of small cells in terms of the number of buildings within which these small cells are deployed, the system level capacity, spectral efficiency, and energy efficiency performance metrics of the proposed technique have been deduced. Moreover, because of relatively smaller in the number of satellite UEs than that of small cell UEs served by small cells, the ABS based eICIC technique has been considered for a fair allocation of radio resources to satellite UEs and small cell UEs.

With numerical and simulation results, it has been shown that though spectral efficiency improves linearly with the number of buildings, the response of energy efficiency is not straightforward. Motivating by this fact, a condition for optimality of the number of buildings over the macrocell coverage has been derived and the corresponding upper limits of both the spectral and energy efficiencies have been deduced. The outperformance of the proposed technique over 5G network requirements and over a number of existing techniques in terms of spectral efficiency and energy efficiency has been shown. Finally, advantages, major research challenges, and future research directions have been discussed.

REFERENCES

[1] FCC. (Dec. 12, 2012). *News 202/418-0500*. [Online]. Available: https://www.fcc.gov/document/fcc-proposes-innovative-small-cell-use-35-ghz-band

[2] *Study on New (NR) to Support Non Terrestrial Networks (Release 15)*, document 3GPP TR 38.811, Jun. 2018.

[3] A. Guidotti *et al.*, "Architectures and key technical challenges for 5G systems incorporating satellites," *IEEE Trans. Veh. Technol.*, to be published.

[4] A. Khawar, I. Ahmad, and A. I. Sulyman, "Spectrum sharing between small cells and satellites: Opportunities and challenges," in *Proc. IEEE ICCW*, London, U.K., Jun. 2015, pp. 1600–1605.

[5] T. Minowa and A. Miura, "On challenges of frequency sharing scheme and its effectiveness," *J. Nat. Inst. Inf. Commun. Technol.*, vol. 62, no. 1, pp. 9–19, 2015.

[6] M. Sadek and S. Aissa, "Personal satellite communication: Technologies and challenges," *IEEE Wireless Commun.*, vol. 19, no. 6, pp. 28–35, Dec. 2012.

[7] W. W. Mayfield, D. C. D. Chang, and J. I. Novak, III, "Communication system employing reuse of satellite spectrum for terrestrial communication," U.S. Patent US 6 735 437 B2, May 11, 2004.

[8] J.-W. Lim, H.-S. Jo, H.-G. Yoon, and J.-G. Yook, "Interference mitigation technique for the sharing between IMT-advanced and fixed satellite service," *J. Commun. Netw.*, vol. 9, no. 2, pp. 159–166, Jun. 2007.

[9] S. Aijaz, "Effects of deploying IMT-advanced systems on fixed satellite services in the 3 400–3 600 MHZ frequency band in Pakistan," in *Proc. 2nd Int. Conf. Adv. Space Technol.*, Islamabad, Pakistan, 2008, pp. 1–5.

[10] B. R. Elbert, *Introduction to Satellite Communication*, 3rd ed. Norwood, MA, USA: Artech House, 2008, pp. 21–24.

[11] N. Panagiotarakis, I. Maglogiannis, and G. Kormentzas, "An overview of major satellite systems," in *Proc. 2nd WSEAS Int. Conf. Multimedia, Internet Video Technol.*, Skiathos, Greece, 2002, pp. 1–6.

[12] D. Lopez-Perez, I. Guvenc, G. de la Roche, M. Kountouris, T. Q. S. Quek, and J. Zhang, "Enhanced intercell interference coordination challenges in heterogeneous networks," *IEEE Wireless Commun.*, vol. 18, no. 3, pp. 22–30, Jun. 2011.

[13] S. K. Sharma, S. Chatzinotas, and B. Ottersten, "Satellite cognitive communications: Interference modeling and techniques selection," in *Proc. 6th Adv. Satell. Multimedia Syst. Conf. (ASMS) 12th Signal Process. Space Commun. Workshop (SPSC)*, Baiona, Spain, 2012, pp. 111–118.

[14] *Draft IEEE Standard for Local and Metropolitan Area Networks: Media Independent Handover Services*, IEEE Standard P802.21/D00.05, Jan. 2006.

[15] T. C. Hong, K. S. Kang, D.-S. Ahn, and H.-J. Lee, "Inter-system handover analysis in integrated terrestrial and GEO satellite communication networks for seamless mobility," in *Proc. ICACT*, Kobe, Japan, Feb. 2007, pp. 717–721.

[16] G. Han and J. M. Harris, "Method for identifying user equipment to a femtocell," U.S. Patent US 8 996 016 B2, Mar. 31, 2015.

[17] H. A. U. Mustafa, M. A. Imran, M. Z. Shakir, A. Imran, and R. Tafazolli, "Separation framework: An enabler for cooperative and D2D communication for future 5G networks," *IEEE Commun. Surveys Tuts.*, vol. 18, no. 1, pp. 419–445, 1st Quart., 2016.

[18] Q. Cui, H. Song, H. Wang, M. Valkama, and A. A. Dowhuszko, "Capacity analysis of joint transmission CoMP with adaptive modulation," *IEEE Trans. Veh. Technol.*, vol. 66, no. 2, pp. 1876–1881, Feb. 2017.

[19] J. D. Chimeh, M. Hakkak, and S. A. Alavian, "Internet traffic and capacity evaluation in UMTS downlink," in *Proc. FGCN*, Dec. 2007, pp. 547–552.

[20] L. Kleinrock, *Queueing Systems: Theory*, vol. 1. Hoboken, NJ, USA: Wiley, 1975.

[21] Y. Wang, K. I. Pedersen, T. B. Sórensen, and P. E. Mogensen, "Carrier load balancing and packet scheduling for multi-carrier systems," *IEEE Trans. Wireless Commun.*, vol. 9, no. 5, pp. 1780–1789, May 2010.

[22] H. J. Bang, T. Ekman, and D. Gesbert, "Channel predictive proportional fair scheduling," *IEEE Trans. Wireless Commun.*, vol. 7, no. 2, pp. 482–487, Feb. 2008.

[23] *Technical Specification Group Radio Access Network; Evolved Universal Terrestrial Radio Access (E-UTRA); FDD Home eNodeB (HeNB) Radio Frequency (RF) Requirements Analysis (Release 9)*, document 3GPP TR 36.921, V.2.0.0, 3rd Generation Partnership Project, Mar. 2010.

[24] J. Ellenbeck, J. Schmidt, U. Korger, and C. Hartmann, "A concept for efficient system-level simulations of OFDMA systems with proportional fair fast scheduling," in *Proc. IEEE GLOBECOM Workshops*, Nov./Dec. 2009, pp. 1–6.

[25] B. Badic, T. O'Farrrell, P. Losket, and J. He, "Energy efficient radio access architectures for Green radio: Large versus small cell size deployment," in *Proc. IEEE 70th Veh. Technol. Conf. (VTC-Fall)*, Sep. 2009, pp. 1–5.

[26] *Energy Aware Radio and Network Technologies (EARTH)*, document EU Funded Res. Project INFSO-ICT-247733, V.1.0, Dec. 2010.

[27] *E-UTRA; Radio Frequency (RF) System Scenarios*, document 3GPP TR 36.942, V.1.2.0, 3rd Generation Partnership Project, Jul. 2007.

[28] *Simulation Assumptions and Parameters for FDD HeNB RF Requirements*, document TSG RAN WG4 (Radio) Meeting #51, R4-092042, 3GPP, May 2009.

[29] S. Geng, J. Kivinen, X. Zhao, and P. Vainikainen, "Millimeter-wave propagation channel characterization for short-range wireless communications," *IEEE Trans. Veh. Technol.*, vol. 58, no. 1, pp. 3–13, Jan. 2009.

[30] R. K. Saha, P. Saengudomlert, and C. Aswakul, "Evolution toward 5G mobile networks—A survey on enabling technologies," *Eng. J.*, vol. 20, no. 1, pp. 87–119, 2016.

[31] G. Auer *et al.*, "How much energy is needed to run a wireless network," in *Green Radio Communication Networks*. Cambridge, U.K.: Cambridge Univ. Press, 2012, ch. 1, p. 20.

[32] C.-X. Wang *et al.*, "Cellular architecture and key technologies for 5G wireless communication networks," *IEEE Commun. Mag.*, vol. 52, no. 2, pp. 122–130, Feb. 2014.

[33] G. Yuan, X. Zhang, W. Wang, and Y. Yang, "Carrier aggregation for LTE-advanced mobile communication systems," *IEEE Commun. Mag.*, vol. 48, no. 2, pp. 88–93, Feb. 2010.

[34] L. You and D. Yuan, "Joint CoMP-cell selection and resource allocation in fronthaul-constrained C-RAN," in *Proc. WiOpt*, Paris, France, May 2017, pp. 1–6.

[35] S. Haddadi and A. Ghasemi, "Coordinated multi-point joint transmission evaluation in heterogenous cloud radio access networks," in *Proc. ICEE*, May 2017, pp. 1938–1943.

RONY KUMER SAHA received the B.Sc. degree in electrical and electronic engineering from the Khulna University of Engineering and Technology (KUET), Bangladesh, in 2004, the M.Eng. degree in information and communications technologies from the Asian Institute of Technology (AIT), Thailand, in 2011, and the Ph.D. degree in electrical engineering from Chulalongkorn University, Thailand, in 2017. He has research experiences on mobile wireless communications in universities and industries for more than ten years. He was a Lecturer and later promoted to an Assistant Professor with American International University-Bangladesh, Bangladesh, from 2005 to 2013. From 2013 to 2014, he was with East West University, Bangladesh. Since 2017, he has been a Research Engineer as part of the Wireless Platform Laboratory, KDDI Research, Inc., Japan. He has authored several peer-reviewed and reputed international journal and conference articles. His current research interests include 5G and beyond ultra-dense HetNets, spectrum sharing, policy, and management in multiple communication systems. He was a member of the Fronthaul Working Group, xRAN Forum, USA. He served as a Reviewer of the IEEE Access journal and a TPC Member of the 2018 IEEE Global Communications Conference Workshops.