User Performance in a 5G Multi-connectivity Ultra-Dense Network City Scenario

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***Abstract*—Multi-connectivity and network densification are two solutions intended to improve performance and reliability. These solutions can improve 5G NR's system performance especially when using high-frequency bands. This work focuses on the user equipment (UE) performance using multi-connectivity within an ultra-dense deployment in a city environment. By being connected to more than one access node simultaneously, the UE should benefit from increased reliability and performance. However, this improved performance comes at the expense of a potentially increased power consumption. Simulation results show that multi-connectivity improves performance by up to 46% and 27% in downlink and uplink resp., increases UE energy efficiency by up to 30% and improves reliability for highly mobile users by up to 37%. The price to pay is an increased UE power consumption of up to 25% and 60% for dual-connectivity and tri-connectivity resp. A multi-connectivity scheme is presented to reduce the secondary connection's transmit power.**

***Keywords*—Multi-connectivity, UE, ultra-dense networks, urban, performance, power consumption**

I. Introduction

The minimum technical requirements of the Fifth-Generation of Mobile Communication (5G) defined in [1], target 20 and 10 Gb/s peak data rate for downlink and uplink resp. In order to achieve such data rates, the 3rd-Generation Partnership Project (3GPP) has defined features via the NR specification such as: multiple numerologies, usage of mmWave frequencies, massive MIMO and dual-connectivity (DC), among others [2]. However, all of these new features may also increase UE power consumption. Already now the cellular subsystem is responsible for almost 50% of the UE's power consumption when all of its components are fully-loaded[1]. One of the most significant power consumption contributor on the cellular subsystem is the uplink transmit power. In addition, there's an increasing gap between battery capacity and the energy to power a modern smartphone, which leads to lower user satisfaction [3].

Long Term Evolution (LTE) and New Radio (NR) dual-connectivity (DC), i.e. simultaneous connectivity to both radio access technologies (RATs), represents an important solution for ongoing 5G deployments. DC is the basis of the non-standalone operation of 5G. NR can operate on the mmWave band, specifically from 24.25 GHz - 52.6 GHz known as Frequency Range 2 (FR2) as defined by 3GPP; where radio coverage at such frequencies is a challenge due to high overall path loss, high indoor penetration loss and low diffraction. DC improves coverage and user throughput by leveraging the already existing LTE infrastructure deployed on lower frequency bands [2]. Although the link budget at the FR2 band can be extended by beamforming [4], adverse radio channel conditions are further amplified on urban city scenarios. Since reliability is hampered significantly if only the FR2 band is used in urban environments, heterogeneous networks, i.e. cells with different coverage sizes, containing high-frequency NR small cells overlaid by a LTE-based macro cell layer is relevant for current FR2 band-based 5G NR deployments in urban environments.

Multi-connectivity (MC), the general case for DC, allows the UE to be connected to multiple secondary nodes to further increase user throughput and reliability. Ultra-dense networks (UDNs), a densified small-cell version of heterogeneous networks [5], enables multi-connectivity by allowing users to be connected to a set of access nodes from multiple options from its vicinity. Hence, the UE transmits uplink and receives downlink data across multiple carriers from different RATs which cause further increased UE power consumption assuming there is a separate transmitter per connection. However, higher data rates can be targeted to provide better battery lifetime for the user equipment by minimizing active time and using ultra low power sleep modes [6]. The core of this work is centered on studying the advantages and disadvantages of employing multi-connectivity from the perspective of the UE within a densified deployment in a realistic scenario, and in addition, provide mechanisms to mitigate the latter using mobility management.

In this article, we study UE performance in terms of downlink and uplink throughput, power consumption, energy efficiency and reliability using multi-connectivity within an ultra-dense network deployed in an urban city scenario. To this end, we integrate an urban city scenario that captures the large-scale propagation characteristics of the FR1 and FR2 band into a system-level simulation platform. We extend a context-aware UE power consumption model for uplink and downlink communication using multi-connectivity at the FR2 band. An uplink power control scheme for multi-connectivity together with a secondary cell association scheme to minimize

[1]In normal usage scenarios, the UE's most power consuming component is the display.

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transmit power of the secondary connection are proposed. This paper is organized as follows: Section II provides an overview of the state-of-the-art; Section III describes the system model and proposed solutions; Section IV presents the performance evaluations of the system-level simulations and Section V concludes the work.

II. State of the Art

As per the current 3GPP specification, LTE/NR DC is already standardized for further early deployments employing non-standalone 5G [2]. The key reasons for LTE/NR DC standardization are to use the low-frequency LTE system to improve coverage, and also due to the limitations of carrier aggregation since additional carriers for a user session isn't possible across carriers belonging to different radio access technologies [2]. There are various combinations on how to connect the core network and the radio access network of both RATs. Option 3, as labeled in 3GPP, is the most appropriate for the ongoing 5G NR integration in current networks. In this setup, gNBs connect to the Evolved Packet Core (EPC) via the Xn interface, the eNB itself and the X1 interface; where mobility is handled by the Mobility Management Entity (MME) from LTE [2].

Multi-connectivity is one potential key technology that will further improve user throughput and reliability to enable ultra-reliable and low latency use cases for 5G and beyond. And, thus, it has been studied extensively in the literature [7]–[9]. In particular, the study in [7], proposes a multi-connectivity scheme that uses ultra-fast selection of serving cells from a set of prepared cells. Multi-connectivity reduces service interruption when users enter challenging coverage areas since a set of serving cells are prepared before any of the connections is broken. Multi-connectivity relies on this principle in order to reduce radio-link failure (RLF) rate for highly mobile users. Moreover, architectural solutions for next-gen radio resource management (RRM) have also been proposed in the literature, e.g. in [10] and [11]. In [10], among other contributions, was one of the first studies to propose Packet-Data Converge Protocol (PDCP) layer as common for LTE/NR, which was subsequently standardized. In [11], proposes an architecture for UDNs together with a dynamic traffic steering framework to increase capacity, reliability and energy efficiency.

Various mechanisms to reduce UE power consumption with network-related procedures are specified in 3GPP standards and, in addition, mobility management schemes for this purpose are also proposed in the literature. Discontinuous reception (DRX), a mechanism in which the UE periodically switches to active mode to check if it's scheduled, has been studied extensively in the literature. The study in [12] shows that energy savings due to extended DRX cycles range from 10-20% when the device is transmitting frequently. Currently, NR employs various energy saving mechanisms for the user equipment such as receiver-bandwidth adaptation and ultra-lean design principles detailed in [2]. In the context of mobility management, in [13], an energy-centric handover decision scheme that minimizes UE power consumption by adopting an adaptive hysteresis margin that favors a neighboring cell with good propagation characteristics and low interference is proposed. The latter shows gains in energy efficiency by up to 88% compared to a strongest cell handover scheme. The study in [14] establishes that carrier aggregation has a positive effect in UE power consumption as long as it boosts the downlink data rate by at least 25%. In [15], the effects of decoupling uplink and downlink communication are studied, where the users associate with a different base station on both communication directions. Path loss as an uplink handover criteria, in order to offload traffic from macro cells to the much closer small cells yields a reduced uplink transmit power and improves uplink signal-to-interference-plus-noise ratio (SINR). The survey in [16] investigates a plethora of mobility management schemes for heterogeneous networks to tackle different performance metrics including UE energy efficiency and reliability. The study in [17] studies multi-connectivity from the perspective of the radio access network and it proposes various multi-connectivity schemes showing via system-level simulations that multi-connectivity decreases RLF rate by up to 37% with dual-connectivity and 52% with tri-connectivity for high-speed users in a generic environment. Our study follows the system-level simulation approach from the previous work and builds upon it by studying multi-connectivity from the user's perspective within an ultra-dense network urban environment using a multi-RAT LTE/NR UE power consumption model with realistic uplink power control for multi-connectivity and a mechanism to manage its transmit power with mobility management.

III. System Model

Subsections A, B and C describe the models concerning the UDN city environment and its large-scale propagation properties for the FR1 and FR2 band. Subsections C, D and E concern the UE power consumption model, uplink power control scheme for multi-connectivity and a secondary cell association multi-connectivity scheme resp.

A. Urban Environment

The reason we have selected an Ultra-Dense Network urban environment is that it is a challenging environment, where the signal can fade quickly when the user moves behind a building. In such an environment there is typically a relatively high probability for radio link failures due to missing handover or coverage holes. This is something we want to investigate in this paper. The 5G mmWave (FR2) deployments are primarily expected to take place in dense urban environments. Thus, to evaluate the performance of such network deployments, there's an increasing need to (at least) capture the large-scale properties of signal propagation in the mmWave band within realistic city environments. In [18], the Mobile and wireless communications Enablers for Twenty-twenty Information Society (METIS) defined simulation guidelines for evaluation of such systems and it recommended three main approaches to model a dense urban city scenario: stochastic, hybrid and map-based. In this study we use a METIS- and map-based

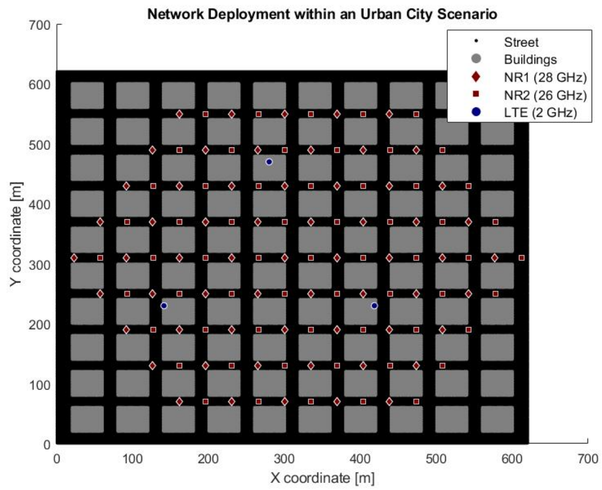

Fig. 1: UDN deployed in the Manhattan Grid

TABLE I: Network Deployment Parameters

RAT	LTE	NR(NR1)	NR(NR2)
Frequency	2 GHz	28 GHz	26 GHz
Carrier Bandwidth	40 MHz	40 MHz	40 MHz
Antenna Height	22 m	10 m	10 m
Antenna Type	Tri-sector	Omni	Omni
Intersite Distance	272.12 m	69.72 m	69.72 m
Carriers per Connection	1	1	1
Number of Sites	9	61	61

Manhattan grid as the city layout comprised by multi-story buildings and streets. The network deployment is comprised by LTE Macro cells located at the rooftops of the buildings, and NR small cells deployed on the streets which mimic antennae deployed on traffic lights, as shown on Fig. 1.

The UDN is comprised by a three-tier deployment. The macro and micro tiers are comprised by LTE and NR resp., with two deployments for the latter. The deployment configuration parameters can be found in Table I.

B. User Models

Users are created randomly on the streets and have an equal chance to move north or south if they are created on a vertical street. Conversely, users have an equal chance to move east or west if they are created on a horizontal street. Users when close to the edge of the deployment bounce on an imaginary circle and head to the opposite direction. An FTP Traffic model with exponentially distributed inter-arrival times and fixed file size is used. The parameters are given in Table III. In our scenario we used a fixed file size FTP Traffic model with an exponentially distributed inter-arrival time. The traffic model is designed so that the number of offered bits is independent of the user throughput. Therefore, the offered bits are the same for a different number of connections. The main objective with our user movement model is to reflect the movement of cars in a city, since that is expected to cause most handovers and put most requirements on the network in terms of reliability. To simplify the evaluations we have selected a relatively simple traffic model and to not include pedestrians and users inside buildings.

TABLE II: Traffic Model Parameters

Parameter	Value
Session Distribution Time	Exponential
Mean Inter-arrival Time	1 s
File Size	5 MB
DL/UL ratio	1

C. Propagation Characteristics

Via field measurements on the FR2 band, METIS-I proposed a modified version of the ITU-R M.2135 propagation model from [19] to adapt it to the FR2 frequency band [18]. In this study, we integrated the aforementioned modified path loss model for Urban micro (UMi) scenarios at 28 and 26 GHz into our simulation setup. Figs. 2 and 3 illustrate the propagation characteristics at 2 GHz and 28 GHz. Evidently, radio propagation characteristics for low frequency and high frequency bands are very distinct. For the former, as the LTE base station is located on rooftops, most of the signal reaches the users via diffraction. For the latter, high path loss, high indoor penetration loss and low diffraction render a tough environment for non-line-of-sight (NLOS) users. The reader can refer to the METIS technical deliverable in [18] for more details on the channel models. figure

D. UE Power Consumption Model

Non-standalone operation requires NR devices to have both LTE and NR modems employing different RF chains, especially if the latter operates in the mmWave band. Conversely, as low-frequency LTE spectrum is gradually migrated into 5G, multiple chipsets may be required for the 5G evolution. In [20] and [14], a context-aware UE power consumption model dependent on the uplink transmit power and carrier aggregation is proposed. Derived empirically, the relationship between the UE power consumption and transmit power is a piece-wise function with two regions that emulate the different power amplifier (PA) stages used to achieve a certain uplink transmit power level. Low- and high-power regions are separated by a device-specific threshold $\gamma_{threshold}$. In this work, based on [20], we extend this model for downlink power consumption. Hence, the total UE power consumption model when the UE is in active mode is divided in two parts: uplink and downlink power consumption referred to as P_{UL} and P_{DL}. Let m_{ACTIVE}, m_{DL}, m_{UL} account for when the user is active, has data to receive on its downlink buffer and has data to transmit from its uplink buffer resp. Similarly, m_{IDLE} accounts for when the user is in idle mode. $\overline{P}_0$ and $\overline{P}_1$ denotes micro sleep and idle average power consumption resp. Thus, the total UE power consumption is given by Eq. (1).

$$P_{T,UE} = m_{ACTIVE} \cdot (m_{UL} \cdot P_{UL} + m_{DL} \cdot P_{DL}) + m_{IDLE} \cdot \overline{P}_{\{0,1\}} \quad (1)$$

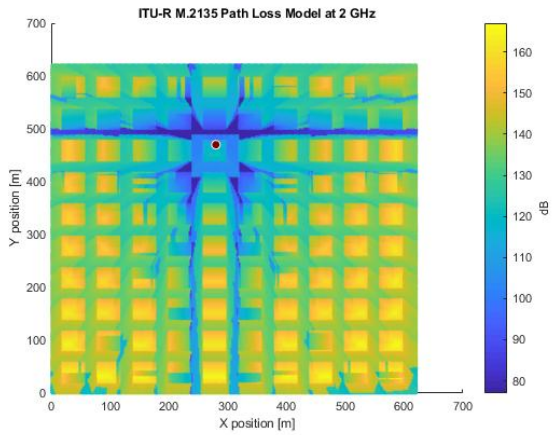

Fig. 2: Path Loss Map for a LTE macro base station

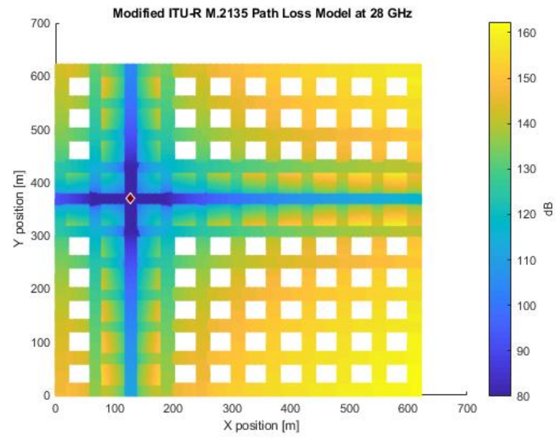

Fig. 3: Path Loss Map for a NR micro base station

UE power consumption due to uplink communication is mainly dependent on the transmit power level on each carrier to achieve a target received power at the serving base station(s) given by the uplink power control mechanism. Hence, when employing multi-connectivity, each link may experience different channel conditions. The transmit power regions per transmit carrier are further subdivided into Low, High and Max average UE power consumption levels denoted as $\overline{P}_2$, $\overline{P}_3$ and $\overline{P}_4$ resp. Independent RF chains for LTE and NR are assumed and the latter increases Low and High power consumption levels by 10%. Their respective UE power consumption parameters due to uplink communication for both RATs is given in Table IV. Let N_{conn} denote the number of serving base stations for a particular user and N_c the number of carriers per serving base station. In addition, let AS and i_{BTS} denote the active set of serving base station(s) and their corresponding index resp. Thus, the Eq. 2 describes the UE power consumption due to uplink communication.

$$P_{UL} = \sum_{i_{BTS} \subseteq AS}^{N_{conn}} N_{c,i} \cdot \overline{P}_{\{2,3,4\},i_{BTS}} \qquad (2)$$

In this way, UE power consumption is context-aware of the channel condition at each connection and the RAT employed. Furthermore, based on guidelines from the study in [14], the model was extended for UE power consumption due to downlink communication which is mainly dominated by the number of allocated resources and number of active RF chains as described in Eq. 3. Let M, μ and δ denote the number of allocated downlink resource blocks, UE power consumption per resource block and power consumption to activate an additional RF chain resp.

$$P_{DL} = N_{conn} \cdot N_c \cdot (\mu \cdot M + \delta) \qquad (3)$$

E. Uplink Power Control for Multi-connectivity

The reason for uplink power control are twofold. Firstly, the transmit power per uplink carrier is limited by the device's power class. Secondly, there's a maximum total transmit power across all carriers due to regulatory reasons. To this end, in this study, we integrate into our system model an uplink power control mechanism for multi-connectivity based on recommendations from the NR specification [2]. The uplink power control procedure is open-loop with fractional path loss compensation as described in Eq. 4 which is the model used by LTE and NR, see [21]. Let $P_{tx,c}$, $P_{C_{max}}$, α and P_0 be the uplink transmit power per carrier, maximum transmit power per uplink carrier, path loss compensation factor and target received power at the base station resp. In Algorithm 1, UE's available transmit power P_T is first allocated to the LTE carriers and subsequently allocated to the NR carriers with the purpose of increasing the robustness of the links by allocating the necessary power to the more robust low-frequency connections, i.e LTE connections.

$$P_{tx,c} = min\{P_{CMAX}, P_0 + \alpha PL + 10\ log_{10}(M)\} \qquad (4)$$

TABLE III: Parameters for UE Power Consumption due to Downlink

Parameter	Value
μ [mW/RB]	0.8
δ [mW/active carrier]	323

TABLE IV: Parameters for UE Power Consumption due to Uplink [14]

RAT	LTE(2 GHz)	NR(28 & 26 GHz)
$\overline{P}_0$ (Micro Sleep)[mW]	25	25
$\overline{P}_1$ (Idle)[mW]	97	97
$\overline{P}_2$ (Low)[mW]	860	946
$\overline{P}_3$ (High)[mW]	1578	1736
$\overline{P}_4$ (Max)[mW]	2450	2450
$P_{c,max}$[W]	0.25	0.125
$\gamma_{threshold}$[dBm]	10	10

TABLE V: Uplink Power Control Parameters

Type	Fractional
α	0.8
M	55
P_T[W]	2.5
P_0[dBm]	-112

Algorithm 1 Fractional Path Loss Compensation for Multi-connectivity and Baseline Power Sharing for each UE

Input: $Available\ P_T$
Output: $P_{tx,c},\ Remaining\ P_T$
Initialization: $Remaining\ P_T\ := Available\ P_T$
for $LTE\ Carriers$ **do**
  $P_{tx,c}\ =\ Power\ Control\ (4)$
  $Remaining\ P_T = Remaining\ P_T - P_{tx,c}$
end for
for $NR\ Carriers$ **do**
  $From\ Remaining\ P_T$:
  $P_{tx,c}\ =\ Power\ Control\ (4)$
  $Remaining\ P_T = Remaining\ P_T - P_{tx,c}$
end for
return $P_{tx,c}$, $Remaining\ P_T$

F. Mobility Management and Multi-connectivity

Multi-connectivity entails the usage of multiple serving base stations, i.e. master and secondary cells. The study in [17] defined a multi-connectivity scheme labeled as BEST SINR, among others. It is based on adding target secondary cells if their downlink SINR is above a predefined threshold. This threshold is dependent on the experienced downlink SINR from the master cell. Similarly, a disconnection threshold is used to disconnect secondary cells. In this work, this scheme is used as a baseline to show the multi-connectivity gains compared to single-connectivity. The reader can refer to this work for further details. Moreover, the handover procedure, i.e. master cell to master cell, uses downlink SINR as target metric based on event A3 [22]. The reader can also refer to this 3GPP document for more details on the handover procedure. In order to reduce UE uplink transmit power, we propose the multi-connectivity scheme Low UE Power State depicted in Alg. 2 to exploit the ultra-dense deployment. The main goal is to add secondary links with a transmit power per uplink carrier that produces low UE power states, i.e. below the device-specific $\gamma_{threshold}$. The $\phi_{threshold}$ is derived by evaluating the upper bound uplink transmit power given by the $\gamma_{threshold}$ together with a 1 dB margin and solving for the pathgain in (4). In addition, to avoid inter-cell interference incurred when using intra-frequency or intra-RAT multi-connectivity on the same resources blocks, secondary connections are only added when they belong to a different RAT or deployment tier.

TABLE VI: Low UE Power State Scheme Parameters

Parameter	Value
$\phi\ _{threshold}[dB]$	92

Algorithm 2 Interference Avoidance and Low UE Power State Scheme

Input: $\phi\ _{threshold},\ Pathgain\ _{\forall BS},\ candidate\ BSs\ _{\forall UE},\ AS\ _{\forall UE}$
Output: $new\ AS\ _{\forall UE}$
Initialization : $candidate\ BSs = \emptyset$
if $\min(Pathgain\ _{\forall BS}) \leq\ \phi\ _{threshold}$ **then**
  $candidate\ BSs\ _{\forall UE} =\ \min(Pathgain\ _{\forall BS})$
  for $ue\ \in UE$ **do**
    $\{candidate\ BSs\} = \{RAT(candidate\ BSs)\} \setminus \{RAT(AS)\}$
  end for
end if
$AS\ _{\forall UE} =\ candidate\ BSs\ _{\forall UE}$
return $new\ AS\ _{\forall UE}$

IV. Performance Evaluation

A MATLAB-based proprietary network simulator is used to assess UE performance using multi-connectivity within an UDN city scenario with two main setups. Setup A is designed to study UE performance in terms of downlink and uplink throughput [Mbits/s], energy efficiency [Bits/J] and power consumption [mW]. Setup B is designed to study reliability in terms of mobility by measuring RLF rate [%]. In Setup A, simulation runs are performed increasing the load in terms of number of users. Table VII shows simulation parameters for Setup A, where in Setup A.1 we employ the proposed Low UE Power State multi-connectivity scheme. In Setup B, shown in Table VIII, simulation runs are performed varying the speed of users using a Full Buffer Traffic Model to guarantee the users are always in ACTIVE mode, and, in addition, a sparse deployment is employed to recreate instances of adverse channel conditions. Moreover, gains in reliability using multi-connecitivity in an urban environment are compared with a generic random movement mobility scenario.

TABLE VII: Simulation Parameters for Setup A

Parameter	Value
Number of Seeds	10
Simulation Time	30 s
Simulation Type	Varying Load
User Speed	5 km/h
Deployment Type	3-Tier UDN
Deployment Configuration	9LTE+61NR1+61NR2
Multi-connectivity Scheme	BEST SINR
Environment	Manhattan City
Mobility Model	Street Movement
Propagation Model	ITU-R M.2135 and METIS version
Setup A.1	
Multi-connectivity Scheme	Low UE Power State

TABLE VIII: Simulation Parameters for Setup B

Parameter	Value
Number of Seeds	10
Simulation Time	10 s
Simulation Type	Varying Speed
Number of Users	30
Traffic Model	Full Buffer
Deployment Type	3-Tier UDN
Deployment Configuration	9LTE+27NR1+27NR2
Intersite Distance	{500, 120, 120} m
Multi-connectivity Scheme	BEST SINR
Environment	Manhattan City
Mobility Model	Street Movement
Propagation Model	ITU-R M.2135 and METIS version
Setup B.1	
Environment	No Scattering Objects
Deployment Configuration	9LTE+21NR1+27NR2
Mobility Model	Users Bounce inside Imaginary Circle
Propagation Model	COST-HATA

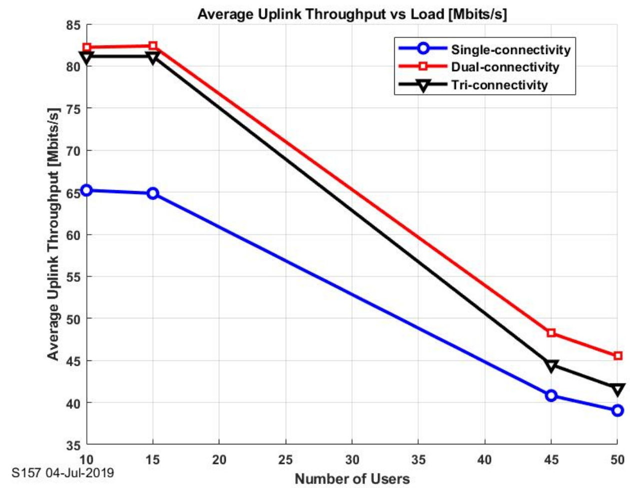

Fig. 5: Average Uplink Throughput vs Load [Mbits/s]

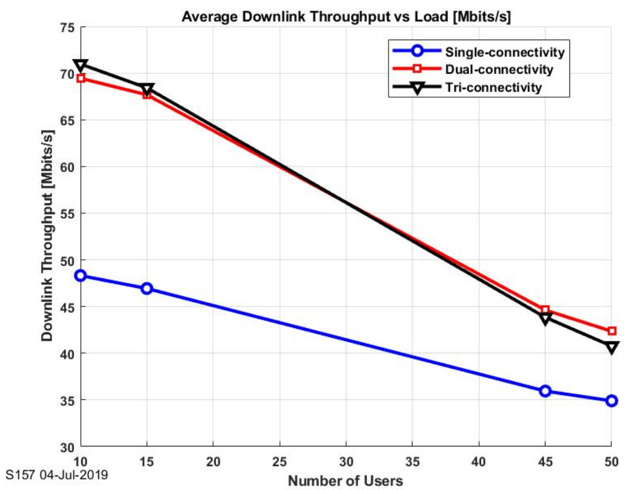

Fig. 4: Average Downlink Throughput vs Load [Mbits/s]

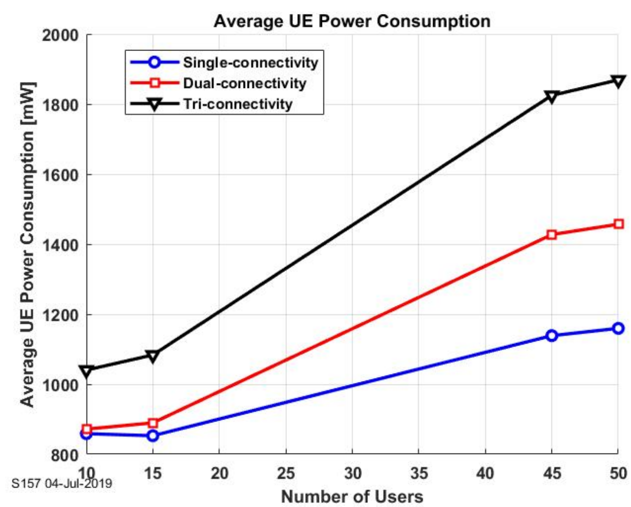

Fig. 6: Average UE Power Consumption vs Load [mW]

1) Downlink and Uplink Performance: System-level simulations for Setup A to study average downlink and uplink user throughput, UE power consumption and energy efficiency are depicted in Figures 4, 5, 6 and 7 resp. Figures 4 and 5 show that the usage of multi-connectivity within an ultra-dense network increases average downlink user throughput by up to 46% and increases average uplink user throughput by up to 27%. In downlink, tri-connectivity increases average downlink throughput by 2% with respect to dual-connectivity, whereas the latter increases it by 44% compared to single-connectivity. As one of the key limitations in an ultra-dense deployment is inter-cell interference, performance degrades substantially as load increases. Added to this, the usage of multi-connectivity accentuates this limitation even further. When using multi-connectivity, the number of data transmissions per UE increases inter-cell interference on neighboring non-serving cells and moreover; when using intra-frequency multi-connectivity, independent schedulers may cause the UE to use same resource blocks on its connections and thus a user's serving cells could interfere each other. This effect is captured in the steeper curves for UE performance vs load using multi-connectivity compared to single-connectivity, shown in Figures 4 and 5. In uplink, dual-connectivity increases performance by 27% at low load (15 users) and reduces to 18% at (45 users) mid load. One of the possible explanations that tri-connectivity decreases performance compared to dual-connectivity is attributed to how the BEST SINR multi-connectivity scheme chooses secondary cells since it only takes into account the downlink SINR.

2) Power Consumption and Energy Efficiency: The increase in performance comes at a cost, dual-connectivity and tri-connectivity increase UE power consumption by 4-25% and 27-60% resp. at low and mid load as seen in Fig. 6. As load increases, inter-cell interference, caused by both an increasing number of users and the usage of multi-connectivity, degrades uplink and downlink performance and thus UEs spend more time in ACTIVE RRC state in order to send and receive data

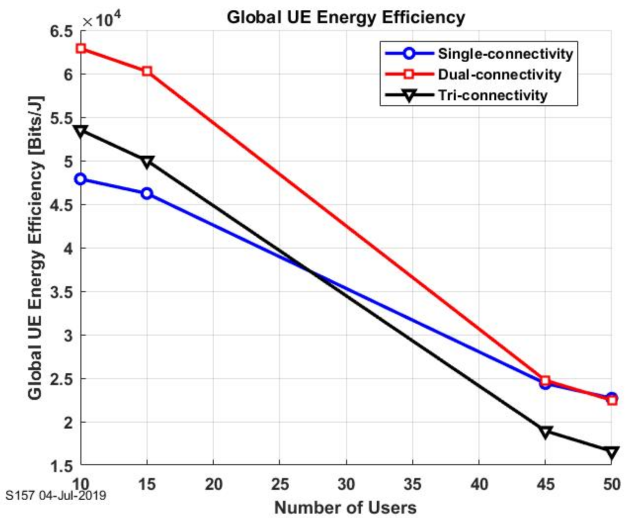

Fig. 7: Global UE Energy Efficiency vs Load [Bits/J]

causing a substantial increase in UE power consumption. UE power consumption is inversely correlated with the time the UE spends in IDLE RRC state.

In terms of UE energy efficiency, the significant increase in downlink and uplink performance at low loads employing dual-connectivity combined with a low UE power consumption cost causes a 30% increase in energy efficiency compared to single-connectivity. Even though tri-connectivity increases performance, it causes a significant increase in UE power consumption and thus, it is the least energy efficient configuration at mid load.

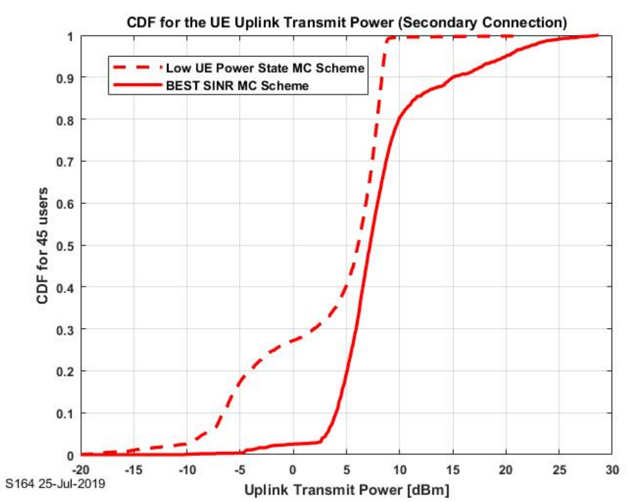

Fig. 8: CDF for the UE Uplink Transmit Power (Secondary Connection) [dBm]

3) Uplink Transmit Power Reduction: Taking advantage of the ultra-dense deployment, the Low UE Power State multi-connectivity scheme reduces uplink transmit power of the secondary connection compared to the baseline BEST SINR multi-connectivity scheme as seen in Fig. 8. Algorithm 2 maintains a low UE power state on the secondary connection as its transmit power is kept below 10 dBm. With the BEST SINR multi-connectivity scheme, a 10 dBm uplink transmit power on the secondary connection corresponds to the 80th percentile. In addition, UE performance gains using dual-connectivity with the Low UE Power State scheme are 35% and 32% in downlink and uplink resp. at low load. At mid-load the performance gain is 8% in downlink and, in uplink, performance reduces by 6% below single-connectivity. With this scheme, tri-connectivity seldom occurs.

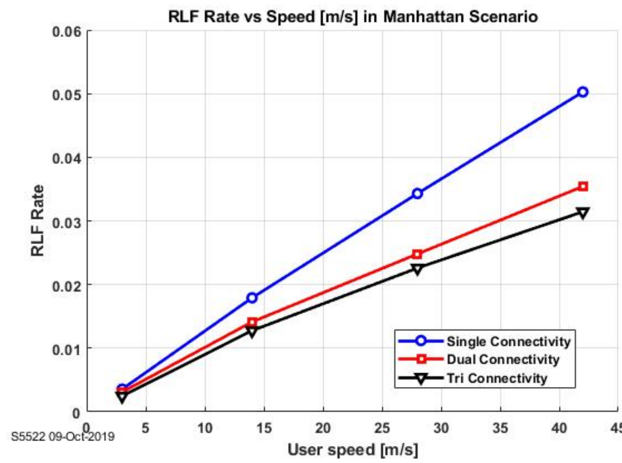

Fig. 9: RLF Rate vs Speed [m/s] in Manhattan Scenario

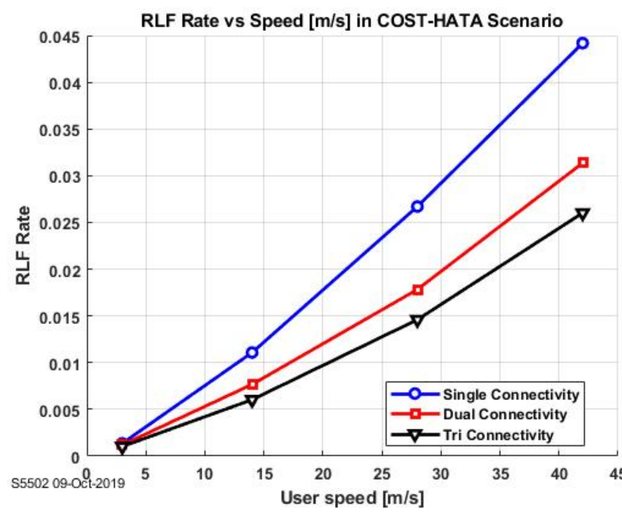

Fig. 10: RLF Rate vs Speed [m/s] in COST-HATA Scenario

4) Reliability: System-level simulations using Setup B and Setup B.1 are conveyed in Fig. 9 and Fig. 10 resp. In the Manhattan scenario, RLF rate is reduced for high-speed users by up to 29% and 37% for high-speed users using dual-connectivity and tri-connectivity resp. as shown in Fig. 9. In the Cost-Hata scenario, RLF rate is reduced for high-speed users by up to 29% and 41% using dual-connectivity and tri-connectivity resp. as shown in Fig. 10. Multi-connectivity is able to reduce RLF rate significantly even in the Manhattan Scenario. In Cost-Hata scenario, higher reliability gains using tri-connectivity compared to the Manhattan Scenario are achieved.

V. Discussion and Conclusions

In this study, we present a realistic urban city scenario that captures the large-scale propagation characteristics of the 2 GHz and the high mmWave frequency bands of NR. We extend a current UE power consumption model that is context-aware of the channel experienced at each connection. In addition, an uplink power control scheme for multi-connectivity to share the available transmit power of the user equipment for uplink transmissions is presented. Furthermore, the proposed multi-connectivity scheme reduces uplink transmit power of the secondary connection and also avoids intra-frequency multi-connectivity. We perform system-level simulations to study performance of the user equipment. The usage of multi-connectivity provides a significant increase in UE performance both in downlink and uplink, increases UE energy efficiency at low load, and also reduces RLF rate for highly mobile users within an urban environment at the cost of a nontrivial rise in UE power consumption. In low load, dual-connectivity due to its high performance and minimal increase in power consumption is the best operating mode. In mid load scenarios, single-connectivity is the most feasible configuration in order to save battery life. In highly mobile and adverse channel scenarios, having three connections is the most beneficial for ultra-reliable service continuity. When user equipment has enough battery capacity dual-connectivity outperforms all other configurations by providing a balanced trade-off between performance, reliability and UE power consumption. Ultimately, the optimal number of connections will also depend on application requirements and on battery capabilities of the user equipment. To scale the multi-connectivity solution, the network can adapt to the behavior, induced load and capabilities of each user. For example, the ratio of highly mobile connected users with ultra-reliable application requirements can have three connections while the rest can employ one or two connections depending on their battery capabilities. To further scale the solution, improve reliability and performance, multi-connectivity-aware radio resource management solutions that avoid interference due to intra-frequency multi-connectivity are crucial for 5G and beyond. To finalize, further studies need to be done with empirically-driven parameters for multiple commercial 5G user equipment in order to obtain fully generalizable results as our parameters are extended from the model of the device-under-test used in [14].

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