Multiconnectivity in Multicellular, Multiuser Systems: A MatchingBased Approach

This article discusses the feasibility of various multiconnectivity approaches and proposes new solutions to achieve reliability requirements of ultrareliable and low-latency communication.

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ABSTRACT | Wireless communication systems have been evolving since the first generation. With the fifth generation of wireless systems, not only the evolutionary aspect of increased data rates is tackled but also the revolutionary aspect. Here, emerging use cases such as massive machine-type communication and ultrareliable low-latency communication will play a crucial role. Within this context, applications with stringent latency and reliability requirements are emerging. Wireless reliability is understood as successfully transmitting the desired amount of data within a given time. Diversity techniques, such as multiconnectivity, are potential solutions to achieve stringent reliability requirements. However, in a multiuser scenario, in which resources are shared, this might not always be possible. In this paper, we discuss the feasibility of various multiconnectivity approaches and propose a matching theory-based algorithm together with a novel scheduler aiming to guarantee the reliability requirements of as many users as possible in a multicellular, multiuser system. System-level simulations demonstrate that the proposed approach achieves 100% reliability for the fifth-percentile users in a highly loaded system. The maximum gain of fifth-percentile user throughput as compared to a static multiconnectivity approach is 150%.

KEYWORDS | Diversity; fifth generation (5G); many-to-many matching; matching theory; multiconnectivity; reliability; wireless systems

I. INTRODUCTION

Cellular technology dominates today's life, and the interest for bandwidth seems to be without foreseeable limits. Wireless systems from the second generation to today's fourth generation have been evolving toward offering the users connectivity at increasingly higher data rates. While this trend is expected to continue in the fifthgeneration (5G) wireless systems, new features such as high reliability and new applications like machinetype communication requesting these features will be part of 5G [1], [2]. Within this context, the International Telecommunications Union (ITU) initiative has defined the three classes of 5G use cases: 1) enhanced mobile broadband; 2) massive machine-type communication (mMTC); and 3) ultrareliable low-latency communication (URLLC) [3]. Fifth-generation systems will support simultaneously various applications/services of these use cases and, therefore, need to span a wide range of requirements [4]–[6]. Hence, there is another frontier to be tackled besides the race for increased data rates in 5G [6].

To achieve the stringent reliability requirements of URLLC services, different techniques can be executed. Due

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to multipath propagation and mobility, the wireless channel is impaired by fading, which can jeopardize the wireless link quality, leading to reduced reliability and impaired service quality and user experience. Other limiting factors in wireless networks are the interference and the scarcity of wireless resources. To compensate for deep fades and to achieve high reliability, it is widely accepted that diversity is key. This is also facilitated by the flexible architecture in 5G supporting multiple radio access technologies (RATs) [7], [8]. Subsequently, three main types of diversity, namely, time, space, and frequency diversity are considered.[1] Time diversity is mainly achieved by retransmissions, e.g., hybrid automatic repeat request (HARQ), which is a combination of retransmissions and forward error correction coding. While the erroneous transmission can be corrected by HARQ, retransmissions lead to significant delays, so that the expected amount of data might not be transmitted within the expected time interval, i.e., reliability might not be achieved. In space diversity, the same information is transmitted from or to different locations, e.g., by transmitting over multiple antennas with spacing of the order of a wavelength leading to uncorrelated small-scale fading. In frequency diversity, the frequencies of multiple signals are separated by at least the coherence bandwidth if transmission is performed within a frequency (sub-)band or multiple carrier frequencies are combined for one transmission. Frequency diversity can also be achieved by coding over multiple carriers [or carrier aggregation (CA)]. Then, the same data observe multiple realizations of an independent fading process (if carriers are separated by more than the coherence bandwidth).

In this paper, the focus is on intrafrequency multiconnectivity, in which multiple base stations (BSs) operating at the same carrier frequency transmit simultaneously to the same user equipment (UE). This leads to the fact that interfering BSs become desired BSs, i.e., an improved signalto-interference-plus-noise ratio (SINR). Given the scarcity of frequency resources, such an approach, however, does not naturally lead to increased reliability. This is because multiple UEs might have to share the resources of one BS leading to reduced data rates and, hence, to unmet reliability requirements. To this end, we first present results of different connectivity approaches for different numbers of BSs and UEs to demonstrate the feasibility of these approaches under various load conditions. We then propose a novel matching theory-based connectivity approach aiming for fairness among UEs to guarantee reliability for a large number of UEs. In this context, fairness is considered to be achieved if the minimum service requirement is guaranteed to as many UEs as possible and if resources are shared equally among UEs.

This paper consists of seven sections, in which we first highlight our motivation and contribution. In Section II,

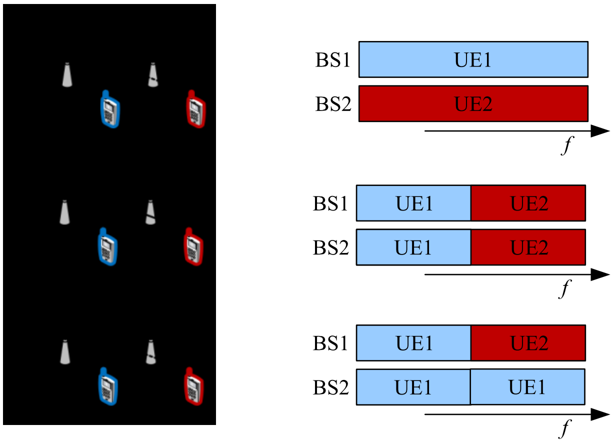

Fig. 1. *Sample connectivity options in two BSs and UEs scenarios. Solid lines: desired links. Dashed lines: nondesired, interfering links.*

different connectivity approaches are introduced together with the matching theory basics and reliability definitions. Existing work related to these topics is also briefly summarized. In Section III, the system model is considered and the problem formulation is presented. Section IV details different connectivity approaches evaluated together with the proposed matching theory-based approach. In Section V, we present the proposed resourcefair scheduler. System-level simulation results are presented and discussed in Section VI. Section VII concludes this paper.

A. Motivation

There are various approaches discussed within the context of reliability for URLLC services. These include (but are not limited to) [9] frame or packet structure for short packet transmission, adaptive modulation and coding for short packet transmission, fast HARQ schemes, wireless caching and edge computing, control channel adaptation, and multiconnectivity. One dominating approach is the latter. However, the simultaneous connection to multiple wireless links might not always lead to increased reliability in case of multiuser systems. The aim of this paper is to demonstrate this for different user densities.

Let us assume a multicellular, multiuser system, in which each UE can be assigned to each BS as long as certain assignment conditions, e.g., received power strength, distance, or geometry-based conditions, are fulfilled. Each UE can also request to be assigned to more than one BS at the same time based on the UE's service requirements. Let us focus on a small example system of two BSs, say BS1 and BS2, operating at the same carrier frequency but providing uncorrelated links, and two UEs, say UE1 and UE2. The following connectivity options (among others) may apply to this scenario, as depicted in Fig. 1.

1) *Connectivity Option 1:* Let UE1 be connected to BS1 and UE2 to BS2, i.e., each UE is connected to one BS. Hence,

[1] Within this context, we disregard the concept of multiuser diversity as it assigns resources to users with good channel conditions, so that users with bad conditions may not receive any resources/data.

the single-connectivity case applies. This way, each UE is allocated the whole bandwidth
but faces full interference from the BS it is not assigned to. Full interference occurs due to full bandwidth assignment of overlapping frequency bands of BS1 and BS2.

2) *Connectivity Option 2:* In the same setup, let each UE be connected simultaneously to both BSs. In this case, the intrafrequency multiconnectivity to two BSs applies for each UE. While the interference might be significantly reduced (zeroed in this case) for both UEs, both UEs are allocated to significantly less bandwidth as compared to Connectivity Option 1. Hence, the SINR values are maximized, so that the probability of these values being smaller than a threshold value is reduced leading to an SINR outage probability reduction [10]. However, a reduction of the SINR outage probability or an increase in the SINR value does not naturally lead to an increased data rate, as the allocated bandwidth is reduced. Consequently, the addition of links in a resource shared multiuser system may not lead to reliability improvement, if the UE is not able to receive the desired amount of data in a given time over a reduced bandwidth.
3) *Connectivity Option 3:* Let UE1 be connected to both BSs, BS1 and BS2, and UE2 be connected to BS2 only. This case might happen if UE1 has more stringent service requirements than UE2. While UE2 is allocated a reduced bandwidth and faces interference from BS1, UE1 is allocated more bandwidth and its SINR value is increased. Such a scenario may or may not lead to reliability improvement, depending on the SINR values obtained and the UEs' service requirements.

Without loss of generality, this scenario illustrates that adding wireless links to the connectivity of a UE may not necessarily lead to an increased SINR value/reduced SINR outage probability. However, this does not lead by implication to an improvement in terms of reliability, if resources are shared, which is usually the case in multiuser systems. Therefore, we present the achievable reliability under different UE load and BS density conditions based on different BS-UE connectivity approaches and propose a matching theory-based connectivity approach, which aims for a balanced link association to guarantee as many UEs as possible their minimum data rate requirements.

B. Contribution

The contributions of this paper are summarized as follows.

1) We consider multicellular, multiuser heterogeneous cellular systems with all UEs having the same stringent reliability requirement.
2) A discussion and comparison of different connectivity approaches, i.e., single connectivity, dual connectivity, and multiconnectivity, under different load conditions and a different number of small cells are provided.
3) We develop a matching theory-based multiconnectivity approach. The proposed approach aims to achieve fairness among the number of links per UE as well as to guarantee a minimum throughput to all UEs assigned to one small cell leading to enhanced reliability performance.
4) A novel multiconnectivity scheduler for the transmission over multiple BSs to a UE is introduced. The proposed scheduler is resource fair and aims to minimize the interference of each UE by considering each UE's instantaneous link connectivity. In addition, it allocates all subbands to all UEs in a resourcefair manner so that no resources remain unused.
5) We demonstrate the achievability and provide a tradeoff analysis of the feasibility of multiconnectivity approaches under different load conditions and different number of available links, i.e., small cells, in a multiuser environment with resource sharing. We demonstrate that the simple approach of adding (uncorrelated) links to a UE's connectivity does not necessarily lead to reliability enhancement in a multiuser system and depends on the load and the number of serving BSs.

II. B ACKGRO UND AND LI TER AT UR E R E V IE W

In this section, we briefly summarize different connectivity approaches and highlight their various solutions proposed in the literature. We then introduce the concept of matching theory and discuss its application within wireless networks. Finally, we present different reliability definitions and discuss first the results presented in research articles on wireless reliability.

A. Connectivity Approaches

Multipoint concepts, also known as multiconnectivity approaches, have been studied intensely during the past two decades, especially in the light of third generation partnership project (3GPP) standardization efforts. One distinguishes between intrafrequency concepts, in which multiple BSs send signals over the same frequency band, and interfrequency concepts, in which BSs send signals over distinct frequency bands. Among the intrafrequency approaches, coherent and noncoherent demodulations of signals are possible. From a conceptual point of view, multiple data streams are split either at the lower layers, such as the medium access control (MAC) layer, or the higher layers, which is the packet data convergence protocol (PDCP) layer in most cases. In a certain sense, the data flow split also relates to the purpose of multipoint transmission: data duplication at lower or higher layers can be carried out for increased reliability exploiting redundant data transmission.

1) (Dynamic) Single-Frequency Networks: A popular intrafrequency multipoint concept with noncolocated same-type BSs is one of the single-frequency networks (SFNs). SFN relies on the macrodiversity capability [of orthogonal frequency-division multiplexing (OFDM)], on the coordination among BSs in creating the signals, and on tight time synchronization across the cooperating BSs. The multiple signals, sent from a group of BSs within the so-called SFN area, are treated as multipath propagation eventually enhancing the SINR at the UE's receiver yielding a lower SINR outage probability.

There is a large number of research articles available in the literature with a focus on applying SFN to optimize the S(I)NR and its outage probability (see [11]) and (see [12]), improving the system performance (see [13]), achieving mobility robustness optimization (see [14]), and on how to select the set of BSs forming an SFN (see [15]). In [11], it has been presented that SFN leads to the sum of powers of desired and nondesired links in the SINR calculation as SFN essentially constitutes an over-the-air combination of the same signals. In addition, an algorithm has been proposed to dynamically design the set of BSs in an SFN based on which a significant performance enhancement in terms of fairly shared spectrum efficiency has been achieved as compared to a scheduling approach with a dynamic channel assignment. In [12], it has been shown that SFN can significantly improve the SNR. However, it has been also demonstrated that resources are extremely wasted if the set of BSs in SFNs overlap. The authors propose an algorithm to reduce this waste of resources. The research in [14] and in [15] focuses on SFN-based multiconnectivity approaches in a mobile 5G network. The authors present solutions for the selection of the set of BSs in an SFN and for achieving mobility robustness in 5G networks.

2) Coordinated Multipoint: Coordinated multipoint (CoMP) is considered for long term evolution (LTE)Advanced as a tool to improve the coverage of high data rates, the cell-edge throughput, and/or to increase the system throughput in both highly loaded and low loaded scenarios [16]. CoMP is an intrafrequency multiconnectivity concept, where several colocated or noncolocated BSs cooperate in the data transmission process to multiple users [17]–[19]. Generally, CoMP builds on powerful backhaul connections, widely distributed antenna technology, and shrinking cell sizes, to combat severe intercell interference at the cell edge [20]. Basic CoMP transmission/reception functionality has been standardized in 3GPP Rel. 11. The most prominent CoMP variants are the following: in coordinated scheduling/coordinated beamforming (CS/CB), beamforming vectors and transmit powers are adjusted on the basis of channel state information (CSI) reported by multiple UEs; in joint transmission (JT), multiple signals, which are formed according to the CSI feedback, are combined at the receiver. In CS/CB, user data are available at the cooperating serving BS, while data duplication is employed for JT making user data available at all cooperating BSs [21]. Noncoherent JT can use SFN to target at diversity gains [22]. Coherent JT is essentially realized as multicell multiuser multiple input multiple output (MIMO), in which a BS cooperation cluster serves a group of UEs. Here, UEs belonging to a UE cooperation cluster are served by a BS simultaneously [20]. It is based on spatial CSI feedback, necessitating fast backhauling and fast CSI feedback in the uplink [22].

A large number of research articles are available in the literature discussing and applying CoMP techniques. We highlight only a few of these, detailed surveys are provided in [23]–[25]. A majority of articles focuses on CoMP-based performance enhancement and propose optimization solutions on enhanced intercell interference coordination in heterogeneous networks (HetNets) [26] and interference alignment techniques [27], on fair resource sharing in LTE-Advanced networks [28], [29], performance enhancement based on advanced MIMO techniques [30], or on joint energy and spectral efficiency optimization [31].

CoMP is also discussed within the context of 5G. In [32] and [24], CoMP is applied to ultradense networks to maximize the per area spectral efficiency and to improve the system throughput by mitigating intercell interference, respectively. In [33], CA (see Section II-A3) and CoMPbased techniques are proposed to achieve high availability in HetNets. The presented gain is mainly obtained by multi-CA, which is an expected gain of this approach as multiple noninterfering carrier frequencies are added to a UE's connection.

3) Carrier Aggregation: CA is an interfrequency technique to combine multiple contiguous or noncontiguous frequency bands or component carriers (CCs) of the same or different BSs to employ scheduling and interference management across these CCs for the goal of system capacity enhancement (no data duplication). CA is realized through a lower layer data flow split. In particular, a common radio link control (RLC) layer feeds multiple MAC instances of the participating BSs [34]. Therefore, similar to CoMP, CA over noncolocated BSs requires high-speed, low-latency, fiber-based backhaul and centralized scheduling [35]. CA has been widely applied in LTE HetNets to coordinate intercell interference. Simsek *etal.* [36] propose a reinforcement learning-based CA approach, in which macrocell and small cell jointly optimize the UE throughput and overall system performance.

4) LTE Dual Connectivity: LTE dual connectivity (DC) as specified by 3GPP as small cell enhancements in LTE Rel. 12 [37] is an interfrequency multipoint technique with two noncolocated BSs, of which one is a small cell. Because the data flow split is carried out at the PDCP layer, DC extends CA and CoMP to noncolocated BSs with nonideal backhaul connections, as the higher layer split does not require SFN synchronization. DC facilitates a controland user-plane separation, where control-plane functionality is transmitted over the macro-BS, or master eNodeB (MeNB), and user-plane traffic is transmitted over the small cell, or secondary eNodeB (SeNB) [38]. Therefore, a UE maintains its radio resource control connection only with the MeNB reducing signaling complexity and increasing mobility robustness through less frequent handovers. Conceptually, the MeNB decides which SeNB is added as an additional connection based on the UE measurements reported to the MeNB. The benefits of LTE DC are increased (cell-edge) UE throughput, mobility robustness, reduced signaling toward the core network [35], load balancing between MeNBs and SeNBs, and enhanced network energy efficiency through longer small cell sleep periods (see [39]–[44]). Furthermore, a comparison between CoMP and DC has been studied in [45]. The authors conclude that, with an increasing number of small cells, DC yields better throughput performance than CoMP.

In some very recent research articles, DC has been applied to 5G networks. Polese *et al.* [46] apply DC to improve the handover performance in 5G millimeter wave (mmWave) networks and show that DC with mmWave and LTE frequencies improves the end-to-end network performance. Han *etal.* [47] apply DC to boost the network throughput by formulating a small cell selection problem. The proposed solution is based on many-to-one matching, in which multiple UEs can be assigned to one small cell.

5) Fifth-Generation Multi-RAT Dual Connectivity: 3GPP has recently generalized LTE DC to multi-RAT DC (MRDC) [48] in [49]. In MR-DC, UEs can utilize connections to two BSs, where one BS provides LTE connectivity and the other one provides new radio wireless access. Similar to LTE DC, both BSs can be connected via nonideal backhaul as the data flow split is carried out at the PDCP layer. One of the BSs is the master node (MN) and the other one is the secondary node (SN),[2] where the MN decides about how many and which SNs to add as additional connections for a UE and at least the MN is connected to the core network.

6) Fifth-Generation Multiconnectivity: Research into 5G multiconnectivity (5G-MC), where a UE is connected to more than two BSs out of the same or different frequencies, i.e., intrafrequency and interfrequency multiconnectivity, is gaining momentum currently. Within the context of 5G-MC, different architectural solutions and concepts have been proposed in [48] and [50]–[52]. Two main research trends can be observed: offering extremely high data rates by utilizing mmWave frequencies provided by multiple 5G SNs (see [53] and [54]) and facilitating highly available transmission by combining multiple links, for example, in [55] and [56]. The softwarization of network function components in the form of network function virtualization and cloud-radio access networks (C-RAN) leads to a conceptual shift in the realization of 5G-MC from X2-based MC to fronthaul split-based MC [34], where access points do not need to be classified as MNs or SNs and where control-plane functionality resides in the C-RAN along with the PDPC layer. Here, 5G BSs exhibit only RLC, MAC, and PHY functionality, and high reliability is achieved by some kind of data multicasting from the cloud-based PDCP to the BSs [34]. A similar cloud-based architecture, in which RRHs and lower layer data split are employed, would be an SFN-like alternative, which has been shown to provide increased mobility robustness and reduced signaling overhead in ultradense small cell networks [15], [57]. Although data duplication at the PDCP layer is less complex, especially if carried out in the cloud close to the wireless edge, a shared MAC layer would still be beneficial for mmWave frequencies as it allows for faster link switching in the case of abrupt blocking of a link [51]. To the best of our knowledge, there is no existing work in the literature with a focus on achieving high reliability in multiuser systems by applying 5G-MC.

The described connectivity approaches demonstrate an evolution in terms of the amount of information exchange required, number of frequency bands/layers (and RATs) supported, and target key performance indicator (KPI) enhancement. The focus was initially on interference reduction and/or data rate enhancement with extreme coordination requirements on synchronization (SFN) or information exchange via the backhaul (CoMP and CA). Relieved requirements are considered for LTE DC and 5G MR-DC in terms of backhaul connections. While LTE DC focuses on similar KPIs as the previous approaches, 5G MR-DC supports also high-reliability targets. The 5G-MC approach evolves from a mix of the other approaches and supports the connection to multiple links in various ways with a target on different KPIs. Similarly, the focus in this paper is on a mix of various approaches. We consider the case of CA-based connectivity between a macrocell and a small cell and of 5G-MC as an extension of DC, in which a UE is assigned to one macrocell at an adjacent carrier frequency and multiple small cells operating at the same carrier frequency. All BSs perform the data transmission in a CoMP-JT-based approach while it is assumed that the set of small cells assigned to a UE form an SFN.

B. Basics of Matching Theory

Matchings occur in our everyday life. When there are nondivisible goods and entities, which have different interests in these goods, there is a corresponding matching market. There are one-sided or two-sided markets depending on each preference for potential goods of the other side. Matchings can have different properties (Pareto optimality, maximum rank, and stability), which are of different importance in different applications. Often, the matching or assignment problems on these matchings markets can be formulated as generalized assignment problems [58, Ch. 7].

One of the most popular matching problems is the stable marriage problem, in which a set of men and a set of women decide on who to get married with; that is the marriage matching market. This is usually a two-sided one-to-one matching problem. Both sides have different preference lists. In the marriage market, these preferences are built on phenotypic properties, e.g., hair color, weight, or face features. Since society as well as the couples themselves have interest in enduring marriages, the notion of stability is important here [59]. The first who studied stable matchings and showed that there always exists at least one stable matching by a constructive algorithm—the deferred acceptance algorithm—are Gale and Shapley [59]. A simple nonconstructive proof which shows that stable matchings always exist is derived in [60]. In the monograph [61], one-to-one and many-to-one stable matchings, their construction, properties, and applications to the labor market and college admissions are studied. Because of many applications of matching markets and their importance, there is a large body of work on stable matchings in one-to-one and one-to-

[2] Note that the terms "MN" and "SN" are similar to MeNB and SeNB, respectively. The usage of a different terminology implies only that the BSs can be out of a different RAT than LTE.

many matching markets. In [62], the properties of the preference relations of colleges and students are analyzed and equivalence is shown between Pareto efficiency, group strategy proofness, consistency, and acyclicality. An axiomatic framework for deferred acceptance is developed in [63]. An asymptotic analysis of incentive compatibility and stability in (asymptotic) large two-sided matching markets is performed in [64].

In wireless communications, due to the limited resources in time, spectrum, and space, resource allocation problems are extensively studied [65]. The first comprehensive tutorial on the use of matching theory for resource management in wireless networks is developed in [66]. Glisic [67] discusses the use of matching theory for resource management in wireless networks. Bayat *et al.* [68] provide a comprehensive survey of matching theory, its variants, and their significant properties appropriate for the demands of wireless communications and network engineers.

In particular for 5G and beyond, matching approaches are applied to resource allocation and scheduling for a downlink nonorthogonal multiple access (NOMA) network in [69]. Li *et al.* [70] integrate NOMA technology into cognitive OFDM systems, referred to as NOMA-OFDM, and applies matching algorithms for clustering. The user association and mode selection in NOMA wireless cellular networks are modeled as a many-to-one matching problem, whose goal is to associate users to small cell BSs and select a transmission mode (half-/full-duplex and orthogonal/NOMA) [71].

The first application of stable matching in general interference networks is reported in [72]. In [73], the distributed energy-efficient resource allocation in MIMO multicarrier multiple-access channel networks is performed using a merge between the popular Dinkelbach's algorithm with the frameworks of distributed auction theory and stable matching.

In cognitive and multiple antenna radio systems, the matching theory is well suited to model the distributed assignment of cognitive links to spatial, temporal, or spectral resources. In [74], a stable matching algorithm is implemented for secondary channel assignments. In [75], the spatial properties of MIMO channels are applied to develop a stable matching algorithm. The user assignment and precoding and beamforming are coupled programming problems. In [76], distributed joint user association and beamforming in multicell MIMO systems is performed.

In underlay device-to-device (D2D) resource allocation, stable matching algorithms can be applied to assign D2D links to resource blocks [77]. Relay-aided D2D with uncertainty is considered in [78] and a centralized as well as distributed resource allocation strategy based on stable matchings is developed. A many-to-many stable matching framework is applied in [79] to develop a distributed and efficient resource allocation for underlay D2D. An energyefficient stable matching approach for resource allocation in energy-harvesting D2D communications is considered in [80].

In HetNets, the assignment of users to their corresponding serving BSs can also be modeled as a matching market. Shao *etal.* [81] formulate the user-cell association problem as a distributed transfer-matching game between small cell BSs and users to address the sum-quality of experience maximization problem. In [82], the many-to-one stable matching framework is applied to the nonorthogonal spectrum assignment with the goal of maximizing the social welfare of the network.

In summary, matching-based approaches have been studied within the context of wireless communications networks mainly in forms of one-to-one or one-to-many matching games. The focus of our contribution is on distributed and fair stable many-to-many matchings because we consider multiconnectivity in HetNets in order to improve the reliability in these wireless networks.

C. Reliability in Wireless Networks

In a maintained system, where failures appear and repairs are made, uptime and downtime occur. Uptimes and downtimes can be specified by the interconnected terms such as reliability, survivability, and availability [83]–[85].

According to [86] and (similarly in [87]), reliability is defined as the probability that a system that is in an operative state will perform the required function for a specified period, i.e., reliability characterizes the uptime of a system. Survivability, on the other hand, specifies the process of recovering from a failure and, hence, describes the downtime of a system [88]. According to [87], an item is available, if it is in a state to perform a required function at a given instant of time or at any instant of time within a given time interval, assuming that the external resources, if required, are provided. Hence, availability combines the information about a system's uptimes and downtimes [84].

Within the context of 5G, reliability is defined by ITU as "the capability of transmitting a given amount of traffic within a predetermined time duration with high success probability" [3]. This definition has been slightly modified by 3GPP as "reliability is the amount of sent network layer packets successfully delivered to a given node within the time constraint required by the targeted service, divided by the total number of sent network layer packets" [6].

Other definitions in the literature focus on the packet drops and introduce the reliability as "the probability that the latency does not exceed a predescribed deadline" under the convention that dropped packets have infinite latency [89]. A different attempt to introduce the reliability definition is provided in [90] and [91]. The focus is on the reliability theory, which has been introduced as a tool to analyze the life cycles and failures of technical systems. Here, reliability is defined as the probability that an item can perform a required function under stated conditions for a given time interval assuming that the considered item is operational at time $t = 0$. An item in wireless communications systems can be interpreted, e.g., as a component of a system, a system itself, a service or a wireless channel. In addition, the term interval reliability is considered, which is the probability that the considered item is operating at a specified time t and will continue to operate for an interval of duration t.

Although the terms reliability and availability are not the same, they are used interchangeably in the literature. However, this is only possible if the system status, especially the wireless channel, does not change during a period that is longer than the time constraint associated with reliability. In this case, the availability level describes directly the reliability performance. Since URLLC applications have very stringent latency requirements, it is likely that the communication channel remains approximately constant during the available transmission time. For this reason, the reliability requirements of URLLC applications can also be expressed as availability requirements, as done in some research articles (see [55], [56], and [92]–[94]).

There exists only a few research articles on achieving reliability in wireless networks in the literature. Most of these research articles (see [94]–[96]) focus on the requirements and practical implementation challenges of URLLC. Other articles propose system and radio design solutions [97], [98]. Li *et al.* [97] provide a high-level system design for URLLC, which is supported by theoretical queueing analysis and system-level simulation results. The fundamental tradeoff between outage, system bandwidth, and the latency requirement of URLLC is demonstrated. It is shown that wideband resource allocation is required for URLLC to achieve the desired performances. Ashraf *et al.* [98] introduce different radio design concepts and integrate them into a comprehensive framework at link and system levels. Different methods to achieve reliable wireless communication are discussed together with the impact of waveform numerologies and signaling channels placement. It is concluded that it is feasible to meet the strictest URLLC requirements with sufficient coverage given a suitable radio design. Other research articles focus on solutions for different URLLC services (see [99]). Here, an indoor communication environment, i.e., a factory environment, is considered. The authors demonstrate that handling intercell interference can effectively lead to a significant performance improvement in terms of reliability, i.e., block error rate (BLER) without bringing any degradation to the latency performance.

The focus in almost all of the research articles is on the outage probability. In today's wireless systems, a system is not in outage if the SINR and BLER are at least −8 dB and at most 10^{-2}, respectively. Our anticipated goal in this paper, however, is not to propose approaches for improving the SINR/reducing the BLER, but for guaranteeing a minimum throughput leading to the required data rate within a given time interval, which meets the ITU and 3GPP reliability definitions. To this end and inspired from the interval reliability in reliability theory, the term reliability refers to the probability that service is successfully completed within a given time interval in this paper.

III. SYSTEM MODEL

In this section, we describe the deployment scenario together with the parameter definition, the channel model, and the UE assignment procedure in order to present our optimization problem formulation.

A. Deployment Scenario and Parameters

We focus on the downlink transmission of a two-layer HetNet, where layer 1 is modeled as macrocells and layer 2 as small cells. The HetNet consists of a set $\mathcal{M} = \{1,\ldots, M\}$ hexagonal macrocells overlaid by a set $\mathcal{S} = \{M+1,\ldots, M+S\}$ of small cells. It holds that a BS is either a macro-BS or a small cell BS, i.e., $\mathcal{M} \cap \mathcal{S} = \emptyset$. Without loss of generality, we assume adjacent sub-6-GHz frequencies for both, macrocells and small cells, whereby small cells operate at the same carrier frequency. Within each macrocell m, small cells are randomly positioned, so that their coverage areas may overlap. A set $\mathcal{U} = \{1,\ldots,U\}$ of UEs are randomly dropped within the cellular network, whereby a hotspot deployment is considered according to [16], i.e., 2/3 of the UEs are uniformly randomly dropped within a radius of 40 m around the small cells and 1/3 of the UEs are uniformly dropped within the macrocellular area. Note that we do not distinguish between macrocell and small cell UEs since we enable each UE to be simultaneously associated with one or multiple BSs of the different/same transmit power and frequency. We denote a UE assigned to cell k by u_k with $k \in \{m,s\}$ with $m \in \mathcal{M}$ and $s \in \mathcal{S}$ and a cell k serving UE u by k_u, respectively. The considered traffic model is the URLLC traffic model FTP Model 3, which is defined in [100] under system-level simulation assumptions. In this paper, we consider a fixed number of URLLC traffic UEs with a file size of $F = 200$ B and a latency budget of 1 ms. Simulations are performed for a different number of UEs to consider low and highly loaded scenarios.

1) Channel Model: We briefly summarize the main parameters for LTE channels, i.e., the considered sub-6-GHz channel model, which relies on the definitions in [16]. The following parameters are applied:

a) *Path Loss:* The path loss is defined as
Macrocell BS to UE

$$\mathrm{PL}^{\mathrm{LTE}}_{u,m} = 128.1 + 37.6\log_{10}(d/1000)$$

Small cell BS to UE

$$\mathrm{PL}^{\mathrm{LTE}}_{u,s} = 140.7 + 36.7\log_{10}(d/1000)$$

with d being the distance between macrocell m or small cell s and UE u in meters.

b) *Antenna Gain Pattern:* We consider sectorized antennas for macrocell BSs and omnidirectional antennas for small cell BSs with 5-dBi gain.

Macrocell BS: $\mathrm{AG}(\vartheta) = -\min[12(\vartheta/70^\circ)^2, 20]$.

c) *Shadowing:* A shadowing standard deviation of 10 dB with a shadowing correlation of 0.5 for macrocells and 0 for small cells is applied, respectively. The total signal power loss of a macro-BS m to UE u and small cell BS s to UE u in dB, which is defined as the transmit power minus all losses, is represented by $L_{u,m}$ and $L_{u,s}$, respectively.

2) Parameter Definition: The SINR of UE u, which is connected to a macrocell m, is given by

$$\gamma_{u,m} = \frac{p_m g_{u,m}}{\sum_{m' \in \mathcal{M}, m' \neq m} p_{m'} g_{u,m'} + \sigma^2} \quad (1)$$

where p_m is the transmit power of macrocell m, $g_{u,m}$ is the propagation gain between UE u and macrocell m, and σ^2 is the noise power. The SINR of UE u, which is connected to one small cell s, is defined as

$$\gamma^{\text{single}}_{u,s} = \frac{p_s g_{u,s}}{\sum_{s' \in \mathcal{S}, s' \neq s} p_{s'} g_{u,s'} + \sigma^2} \quad (2)$$

with p_s being the transmit power of small cell s. The propagation gain between UE u and small cell BS s is given by $g_{u,s}$. The propagation gains on a linear scale are defined by $g_{u,m} = 10^{-L_{u,m}/10}$ and $g_{u,s} = 10^{-L_{u,s}/10}$, respectively.

In case, a UE u is assigned to more than one small cell, we denote its assigned small cell indices by the set $\hat{\mathcal{S}}_u \subseteq \mathcal{S}$. We assume that the data/control signals are transmitted simultaneously from all small cells in $\hat{\mathcal{S}}_u$ on the same subband. This coordination scheme is termed as SFN, see Section II. The signal components of the small cells are assumed to fall within the cyclic prefix, so that the resulting multiconnectivity SINR of UE u is defined as

$$\gamma^{\text{multi}}_{u,\hat{\mathcal{S}}_u} =$$ [redacted] $$\sum_{s \in \hat{\mathcal{S}}_u} p_s g_{u,s} + \; \ldots \sum_{s \in \mathcal{S} \setminus \hat{\mathcal{S}}_u} p_s g_{u,s} \;\; \sigma \quad (3)$$

UE u's throughput assigned to cell $k \in \{m,s\}$ is defined by

$$r_{u,k} = B_{u,k} \log(1 + \gamma_{u,k}) \quad (4)$$

with $B_{u,k}$ being the bandwidth assigned to UE u by cell k.

UE u's throughput assigned to multiple small cells $\hat{\mathcal{S}}_u$ is defined by

$$r_{u,\hat{\mathcal{S}}_u} = B_{u,\hat{\mathcal{S}}_u} \log\left(1 + \gamma^{\text{multi}}_{u,\hat{\mathcal{S}}_u}\right) \quad (5)$$

with $B_{u,\hat{\mathcal{S}}_u}$ being the bandwidth allocated to UE u by small cells in $\hat{\mathcal{S}}_u$.

If a UE u is assigned to a macrocell m and multiple small cells $\hat{\mathcal{S}}_u$ simultaneously, its throughput is given by

$$r_{u,m,\hat{\mathcal{S}}_u} = r_{u,m} + r_{u,\hat{\mathcal{S}}_u}. \quad (6)$$

It is important to note that the rate gain due to multiconnectivity to macrocells and small cells grows linearly while the rate gain due to multiconnectivity to multiple small cells grows only logarithmically.

3) UE Assignment Procedure: According to the 3GPP standard, a UE performs reference signal receive power (RSRP) measurements. The cell providing the largest RSRP (plus a margin) becomes its serving cell. Based on a predefined timing structure, the UE sends these RSRP measurements to inform its serving cell about its set of potential BSs $\mathcal{K}^{\text{pot}}_u$. This set of potential BSs contains IDs of BSs in a ranked order according to the RSRP values. Hence, the UE assignment is decided based on

$$k_u^* = k_{u,1}^{\text{pot}} \quad (7)$$

with $k_{u,1}^{\text{pot}}$ reflecting the first element of $\mathcal{K}^{\text{pot}}_u$.

In case of dual connectivity, the cell providing the largest RSRP becomes UE u's MeNB $k_u^* := v_u \in \mathcal{V}$ with $\mathcal{V}$ being the set of all MeNBs.[3] The MeNB v_u sends, then, access requests to the second cell out of the UE's potential BSs list $\mathcal{K}^{\text{pot}}_u$. If this cell accepts the request, it serves UE u as its SeNB w_u. Otherwise, the MeNB continues to request access from the next potential BSs. This is repeated until an SeNB w_u is found or all BSs in the set $\mathcal{K}^{\text{pot}}_u$ have been asked.

For the case that a UE u is served by more than two BSs, i.e., in the case of multiconnectivity, we extend the concept of dual connectivity. A UE u's MeNB v_u sends access requests to L SeNBs(/links), so that a UE's SeNBs are denoted by the set $\mathcal{W}_u \subseteq \mathcal{S}$.

[3] Note that we introduce here a new parameter to distinguish the MeNBs from macrocell and small cell BSs, because the MeNB can be out of any frequency and transmit powers, so that a BS serving a UE as a MeNB can simultaneously serve another UE as an SeNB.

B. Problem Formulation

In this section, we describe the optimization problem formulation for the proposed matching-based multiconnectivity approach. Once a UE u is activated in a wireless network, it performs RSRP measurements and selects the BS providing the maximum RSRP as its MeNB v_u. The UE u sends its MeNB and its potential BSs set $\mathcal{K}^{\text{pot}}_u$ with $\{v_u\} \cup \mathcal{W}_u \subseteq \mathcal{K}^{\text{pot}}_u$. Based on this potential BSs list, each UE's MeNB optimizes the number of links to be requested for each of its UEs,[4] i.e., the set $\mathcal{W}_u$. Each SeNB, in turn, accepts as many requests as possible until it can guarantee its own UEs' service requirements. Hence, while each MeNB aims to maximize all of its UEs' throughput by requesting as many links as possible for each of them and without any knowledge about the SeNBs' load conditions, each SeNB aims to guarantee a minimum throughput to each of its UEs by controlling the number of UEs it serves. Here, we assume that the MeNB and the SeNB communicate the UE's service requirement. Knowing each UE's assignment based on the accepted requests and collaborating with the SeNBs on each UE's throughput information, the optimization problem is formulated as follows:

$$\max_{\mathcal{W}_u \forall u \in \mathcal{U}} \sum_{u \in \mathcal{U}} \Bigg(\underbrace{r_{u,v_u}}_{\text{MeNB throughput of UE } u} + \underbrace{r_{u,\mathcal{W}_u}}_{\text{SeNB throughput of UE } u} \Bigg) \quad \text{(8a)}$$

s.t.: p_k [redacted] (8b)

$$r_{u,w_u} \geq r^{\min}_{w_u} \quad \forall u \in \mathcal{U} \quad \text{(8c)}$$

$$\mathcal{W}_u \subseteq \mathcal{K}^{\text{pot}}_u \quad \forall u \in \mathcal{U}. \quad \text{(8d)}$$

Condition (8b) implies that the transmit power of cell k should not exceed the maximum transmit power $p_k^{\max}$. In condition (8c), each SeNB ensures each of its assigned UE's minimum throughput requirement $r_{w_u}^{\min}$. Finally, condition (8d) guarantees that the UE u's SeNBs $\mathcal{W}_u$ are selected out of its potential BSs set.

To solve this optimization problem, we consider the 5G-MC as a potential class of solutions for the formulated problem of achieving each UE's service requirements by finding the best set of SeNBs $\mathcal{W}_u$ for each UE u. In this regard, we extend the concept of DC and incorporate matching approaches, motivated by our prior work [72], [75], [79], [101] and as detailed in Section IV-D. Thus, SeNBs are assumed to obtain control information via the MeNBs about the UE's service requirements. This can be extended to cases of changing service requirements, such that the dynamic resource allocation has to be updated regularly.

IV. x-CONNECTIVITY APPROACHES

In this section, the reference connectivity approaches considered and the proposed matching theory-based multiconnectivity algorithm are described.

A. Single Connectivity

This is the simplest connectivity approach, in which each UE u is assigned to the BS $k \in \{m,s\}$ with the largest RSRP. We consider the single-connectivity scenario, in which BS k can either be a small cell s or a macrocell m. We assume that a UE is always assigned to one BS disregarding any RSRP threshold.

B. Dual Connectivity

In the case of dual connectivity, the cell providing the largest RSRP becomes UE u's MeNB v_u. In this paper, we consider that a UE selects its MeNB based on the strongest macrocell received power, i.e., $\mathcal{V} = \mathcal{M}$.

We assume that the macrocell BS provides full coverage. The MeNB v_u sends access requests to the strongest small cell out of UE u's potential BSs list $\mathcal{K}^{\text{pot}}_u$. We assume that the set of SeNBs $\mathcal{W}$ is equal to the set of small cells $\mathcal{S}$. A small cell accepts to serve a UE u as an SeNB w_u if its RSRP is larger than a predefined threshold. This is to ensure that very weak links are not added to a UE's connectivity. Given the fact that we assume adjacent channels for macrocell and small cells and that a UE's MeNB and SeNB are operating at different carrier frequencies, this connectivity approach may lead to the best data rate performance, especially in systems with low load.

C. Fixed Multiconnectivity

Similar to the dual-connectivity case, a UE u's MeNB v_u is assumed to be the macrocell providing the largest RSRP. In addition, each UE u is assigned to its L strongest small cells serving as its SeNBs $\mathcal{W}_u$ with the cardinality of $\mathcal{W}_u$ being equal to L for all UEs as long as the RSRP values of these L small cells are larger than a predefined threshold. This reference multiconnectivity approach, which is not adaptive, aims for demonstrating that assigning an arbitrary number of links to each UE may lead to significant performance degradation under different load conditions. The additional links lead to the fact that nondesired links serve as desired links and, hence, improve significantly the SINR value of each UE. However, by enforcing the connectivity to multiple small cells, more UEs have to be served by each small cell leading to high loads in the small cells.

D. Matching-Based Multiconnectivity

Similar to the fixed multiconnectivity case, it is assumed that once a UE u has selected its MeNB v_u, which is assumed to be the macrocell providing the largest RSRP, it sends its potential BSs list $\mathcal{K}^{\text{pot}}_u$ to the MeNB v_u. Each UE sends via its MeNB access requests to the BSs in the UEs potential BSs set to serve the UE as

[4] Note that a BS can serve simultaneously as the MeNB of multiple UEs.

an SeNB. The number of BSs to be asked for access is determined for each UE separately based on the proposed matchingbased approach. Each requested (potential) SeNB, in turn, accepts or rejects this request based on its own instantaneous load. The number of accepted requests/UEs depends on the quality of service requirements of the SeNB's assigned UEs and is also determined based on the proposed matching-based approach.

Hence, we formulate the described multiconnectivity framework as a many-to-many matching game, in which UEs request access to more links to satisfy their QoS requirement with the awareness of other UEs being in the system, and SeNBs prefer to accept only additional UEs, if their own already accepted UEs' performance can be guaranteed. The resulting UE assignment is given by the UE's MeNB v_u and the set of SeNBs W^{pot}_u assigned to UE u, with $\{v_u\} \cup \mathsf{W}_u \subseteq \mathsf{K}_u$ being the set of all BSs assigned to UE u. This resulting assignment is called many-to-many matching.

1) Definitions for Matching Games: To model our connectivity approach as a many-to-many matching game, we consider the two sets of UEs U and SeNBs W as two teams of players with $\mathsf{U} \cap \mathsf{W} = \emptyset$. The matching is defined as an assignment of UEs $u \in \mathsf{U}$ to SeNBs $w \in \mathsf{W}$. Since a UE can be assigned to multiple SeNBs and an SeNB can accept/serve multiple UEs, the game proposed is a manyto-many matching game. Here, we assume that each player acts independently, i.e., the matching game is a distributed game. Each UE aims to achieve its service requirements and requests links from SeNBs. At the same time, SeNBs accept new UEs while serving their own UEs and guaranteeing their UEs' service requirements. In a matching game, the number of SeNBs that are required to satisfy a UE u and how many UEs can be associated with an SeNB w are known as quota, q_u and q_w, respectively. The quota of a player describes how many resources, i.e., links or UEs, a player can have at most.

In the matching theory, each player seeks for a matching with his/her most preferred partners. We define our matching game as a pairwise stable matching with the following definitions.

Definition 1: A many-to-many matching μ is a mapping from the set $\mathsf{U} \cup \mathsf{W}$ into the set of all subsets of $\mathsf{U} \cup \mathsf{W}$ such that for each $u \in \mathsf{U}$ and $w \in \mathsf{W}$, the following holds:

1) $\mu(w) \subset \mathsf{U}$ and $\mu(u) \subset \mathsf{W}$;

2) $|\mu(u)| \leq q_u \forall u \in \mathsf{U}$;

3) $|\mu(w)| \leq q_w \forall w \in \mathsf{W}$;

4) $w \in \mu(u)$ if and only if $u \in \mu(w)$; with $\mu(u)$ ($\mu(w)$) being the set of player u's (w's) partners under the matching μ.

Condition 1) describes that players w ($/u$) are matched with players out of the set U ($/\mathsf{W}$). Conditions 2) and 3) guarantee that the number of matched players is at most the same as the players quota. Condition 4) states that if an SeNB w is matched to a UE u, then this UE u is also matched to the same SeNB w, which is naturally given in an UE-BS assignment problem.

Definition 2: A blocking pair is the pair of player $u \in \mathsf{U}$ and player $w \in \mathsf{W}$, who prefer each other to some of their partners in the current matching, i.e., $u \succ_w \tilde{u}$ with $u, \tilde{u} \in \mathsf{U}$ for some $\tilde{u} \in \mu(w)$ and $w \succ_u \tilde{w}$ with $w, \tilde{w} \in \mathsf{W}$ for some $\tilde{w} \in \mu(u)$, respectively. Here, the notation $a \succ_b \tilde{a}$ means that player b prefers player a over player $\tilde{a}$, i.e., b is matched with $\tilde{a}$ but would prefer to be matched with a.

Definition 3 (The Matching Is Pairwise Stable, If There Are No Blocking Pairs): In other words, a matching, where no player perceives any gains from further changing his/her matching(s), is called stable. In many-to-many matching, stability is achieved in terms of pairwise stability, which is accomplished if a matching is not blocked by an individual or pair(s) of players [79]. In general, the preferences are assumed to be responsive, i.e., $\forall A \subseteq B$ with $|A| \leq q$ and $b, b \in B \backslash A$: $A \cup b$ is preferred to $a \cup b$ if and only if b is preferred to b. Furthermore, $A \cup b$ is preferred to A if and only if b is acceptable. Then, it holds[5]: when preferences are responsive, a matching is group stable if and only if it is (pairwise) stable. Therefore, we concentrate on pairwise stability. In the literature, there exist alternative matching concepts, including the maximum weight perfect matching in a bipartite graph. This matching can be computed centrally by the Hungarian method [103] with complexity of order $O(n^4)$, where n is the number of elements in the set. The maximum weight perfect matching is not necessarily stable. In our setup, we are interested in a stable outcome, which can be computed in a distributed efficient way.

In the matching-based multiconnectivity approach, a UE u decides on the SeNBs based on its preferences and an SeNB w can accept access requests of different UEs based on its own preference. Hence, before any assignment request or decision is performed, each player needs to define its preferences over subsets of the opposite set of players based on its optimization goal.

2) Matching-Based Multiconnectivity Algorithm: After formulating the multiconnectivity problem as a many-tomany matching game in which the UEs are requesting access from SeNBs (via their MeNBs), we propose a threephased algorithm.

The first phase is the initialization phase, in which the preference lists l_u^{pref} and l_w^{pref} of both set of players, i.e., UEs u and SeNBs w, are obtained before the matching process starts. Based on instantaneous conditions, the preference lists of each player are defined according to a descending order of receive powers. The UEs' preference list is defined over the set of SeNBs out of the potential BSs list K^{pot}_u, while the SeNBs define their preference list over the set of UEs. Here, it is assumed that SeNBs receive the UEs' receive power levels from their MeNBs.[6]

[5] Proposition 1 in [102].

[6] It can also be assumed that the MeNBs exchange with the SeNBs the channel quality indicator, which is sent by the UEs over the uplink shared channel and indicating the UEs signal strength based on which a similar preference list over the UEs can be obtained.

In the second phase, SeNBs determine how many UEs they can accept to serve additionally, i.e., q_w, based on their instantaneous load. Here, the MeNB and the SeNB coordinate, so that the SeNB is informed about the UE u's link quality and can estimate its expected data rate to be provided by the SeNB.

Algorithm 1: Many-to-Many Matching-Based Multiconnectivity Link Assignment Algorithm

***First Phase:* Preference Lists**

Obtain preference lists of all players l_u^{pref} with $u \in U$ and l_w^{pref} with $w \in W$

***Second Phase:* Quotas**

Determine quotas q_u with $u \in U$ and q_w with $w \in W$

Third Phase:* Proposing and Matching Phase *Initial Phase:

Proposals:

The player UE u sends access requests (via its MeNB v_u) to its q_u most preferred SeNBs. These indices are cleared from the preference list l_u^{pref} of the UE.

Decisions:

The SeNB w accepts at most q_w proposals subject to its preference list l_w^{pref} and rejects proposals when the SeNB quota q_w is reached. ***Iterative Phase:***

while $\exists u \in U : l_u^{pref} \neq \emptyset$ (not yet proposed to all SeNBs $w \in W$) and $|\mu(u)| < q_u$ (quota not achieved) **do** *Proposals:*

UE u sends access requests (via its MeNB v_u) for the index of the next $q_u - |l_u^{pref}|$ preferred SeNBs. These indices are cleared from the preference list l_u^{pref}.

Decisions:

Same as in initial decision phase.

end while

The SeNB's quota is determined according to its instantaneous number of associated UEs given by U_w plus a number of potential UEs U and their estimated per UE throughput, i.e., the total throughput of all UEs divided by the instantaneous load. The SeNB continues to accept UEs while the following inequality holds:

$$q_w = \max\{U + U_w\} \quad \text{such that} \quad \frac{\sum_{i=1}^{U+U_w} r_{i,w_i}}{U + U_w} \geq r_w^{\min}{}_u . \tag{9}$$

The parameter $r_w^{\min}{}_u$ is related to the UE's targeted minimum required data rate $r_u^{\min}$ and is typically chosen to be larger than $r_u^{\min}$. It impacts the matching result by determining the SeNB's quotas q_w. The parameter must be chosen carefully to avoid the following extreme cases.

If the SeNB's quotas q_w are too small, i.e., $r_w^{\min}{}_u < r_u^{\min}$, not every UE might be able to be assigned to at least one SeNB in order to achieve its minimum required data rate. On the other hand, too high quotas, i.e., $r_w^{\min}{}_u \gg r_u^{\min}$, cause too many links to be assigned. This would reduce the bandwidth per link and allow poor links with low SINR values. In addition, this increases the risk of starvation, i.e., UEs that have already reached their minimum data rate are assigned further links instead of weaker UEs.

Note that this quota is determined according to the instantaneous conditions and may change until matching is performed in a dynamic system. In addition to this, we consider the case of a fix quota (fq) q_w in which the maximum number of UEs that an SeNB can accept is given and equal for all SeNBs.

Once the SeNBs' quota is determined, the UE's quota q_u is calculated. Here, our aim is to achieve resource fairness through almost uniform distribution of the links allocated to UEs over many realizations, similar to [79]. The resulting UE quota q_u is as follows:

$$q_u = \frac{\sum_{w=1}^{W} q_w}{U_v} . \tag{10}$$

Here, a UE is informed about all SeNBs within the MeNB coverage and the number of UEs U_v. It considers all available SeNB links and aims for an equal distribution of the links among all the UEs U_v, i.e., the resulting quota is the same for all UEs u in a MeNB v. As mentioned, such a quota determination aims for resource fairness among all players of a team, i.e., all UEs in MeNB v.

In the third phase, each UE u requests access from the q_u SeNBs starting with the most preferred SeNB of UE u's preference list. Then, each requested SeNB w accepts the most preferred UEs from the set of proposed UEs until its quota q_w is reached. This phase is repeated until pairwise-stable matching is achieved, the final set of UEs-SeNBs assignment is reached, i.e., the matchings $\mu(u)$ and $\mu(w)$ are obtained. A pseudocode of the algorithm is given in Algorithm 1 similar to that in [79].

The proposed matching-based multiconnectivity link assignment algorithm has iterations in the third phase. The number of iterations is bounded by n; the number of elements in the accepting side. Therefore, it has linear complexity $O(n)$. Exact numbers are shown later in the numerical simulation results (see Section VI-B). Furthermore, the resulting matching is stable according to [79, Th. 1]. However, the resulting matching has no optimality guarantee in terms of the maximum sum performance [72, Prop. 3]. This refers to the price of stability.

V. PRO POSED MU LTICONNE CTIVITY S CH ED UL E R

In this section, we briefly describe the resource-fair scheduler, which is applied to the single- and dualconnectivity approaches, the modified scheduler for the fixed multiconnectivity approach, and the proposed scheduler for the matching-based multiconnectivity approach.

A. Resource-Fair Scheduler for Single/Dual Connectivity

For the macrocells m and small cells s, a resourcefair scheduler is assumed without loss of generality.

The bandwidth allocation to each UE u_k is performed as follows:

$$B_{uk} = \frac{B_k}{U_k} \tag{11}$$

with B_k being the bandwidth of cell k and U_k being the total number of UEs in cell k. In case of dual connectivity, (11) is applied to both the serving macrocell $k = m$ and small cell $k = s$. Note that the load of each cell k may vary, so that a UE might be assigned to different subband sizes at each of its links.

B. Modified Resource-Fair Scheduler for Fixed Multiconnectivity

In the fixed multiconnectivity approach, the macrocell m utilizes the same scheduler as in (11). Due to the assumed SFN for the set of small cells S, the small cells ensure the allocation of the same subbands to a UE performing multiconnectivity. As described in Section IV-C, each UE is assigned to the same number of links L, as long as the RSRP is larger than a threshold. This condition and the random distribution of the UEs lead to the fact that each small cell may serve a different number of UEs and that each UE might be assigned to a maximum of L links. The modified resource-fair scheduler is, therefore, applied in two steps.

1) After fixed multiconnectivity is performed, obtain connectivity matrix $\mathbf{A}$, which is a $U \times S$-matrix with binary elements, i.e., $a_{u,s} = 1$ means UE u is assigned to small cell s. Find out the maximum number of UEs a small cell is assigned

U [redacted] $U_* a_{u,s} = \mathbf{A}1.$ (12)

S

$u=1$

Note that the sum in (12) will result in a vector of a number of assigned UEs per small cell s, i.e., of length S. U_* provides the maximum number of all these loads.

2) The bandwidth each UE u is assigned by small cell s is then given as

$$B_{us} = \frac{B_s}{U_*} \tag{13}$$

C. Proposed Resource-Fair Scheduler for Matching-Based Multiconnectivity

In the matching-based multiconnectivity approach, the macrocell m utilizes the same scheduler as in (11). Similar to Section V-B, we consider an SFN for the set of small cells S and ensure that each UE is allocated the same subband(s) over all small cells it is assigned. Therefore, we apply the same two steps as in Section V-B. However, the modified resource-fair scheduler for fixed multiconnectivity may lead to an underutilization of subbands, if loads between small cells vary. This can be illustrated by a simple example: let us assume two small cells s_1 and s_2 and two UEs u_1 and u_2 and an allocation matrix $\mathbf{A} = {}^{1\,1}{}_{0\,1}$, i.e., UE u_1 is assigned to both small cells and UE u_2 is assigned to small cell s_2 only. The maximum number of UEs a small cell is assigned to is in this example $U^* = 2$. Hence, the bandwidth each UE is assigned to is $B_s/2$. Although small cell s_1 is serving only one UE, i.e., UE u_1 is allocated half of its bandwidth. To utilize the resources more efficiently, we proposed the following extension to the scheduler in Section V-B.

1) Apply (12) to determine the maximum number of UEs served by a small cell s.
2) Determine the subbandwidth to be assigned to the UEs u_s by each small cell s according to (13).
3) Assignment of nonutilized subbands.
   a) Check which small cells have nonutilized subbands and collect them in a set S. These cells are the cells with a number of UEs assigned being smaller than U_*.
   b) Find out the numbers U_s of UEs assigned to these small cells for all $s \in$ S.
   c) Determine the nonutilized small cell subband size by

   B [redacted] $B_{s,\text{rest}} U_s$. (14)

   d) Finally, determine the "remaining" nonallocated subband widths of each small cell s to be assigned to UE u_s as follows:

$B_{us} = B^{s,\text{rest}}$ s [redacted] $= B_{*} U_{*} -_{s} U_{s}$

(15)

with U_s being the number of UEs in small cell s. Here, we assume a perfect alignment of the resources allocated to a UE.

VI. SI MU LAT I ON R E SU LTS AN D D IS CUS SI ON

In this section, we briefly describe our simulation parameters and scenario in order to present system-level simulation results.

A. Simulation Scenario and Parameters

In this section, the proposed solutions are validated in a 3GPP-compliant LTE-A system-level simulator based on the assumptions and parameters defined in [16]. We consider a HetNet with a macrocell consisting of $S \in \{1,3,5,10,15,20\}$ small cells per macrosector, uniformly and randomly distributed within the macrocellular environment. Two-third of $U = \{1,5,10,20,30,50,100,150\}$ UEs are randomly and uniformly dropped within 40 m radius of each small cell s. The remaining UEs are uniformly distributed within the macrocellular area.

Table 1 Simulation Parameters

Parameter	Value	Parameter	Value
Cellular layout	Hexagonal grid, 3 sectors per cell	Transmission mode	2×2 MIMO
Carrier frequency	2 GHz	Macro path loss model	$128.1 + 37.6 \log_{10}(R)$ dB (R[km])
Macro cell bandwidth	20 MHz	Small cell path loss model	$140.7 + 36.7 \log_{10}(R)$ dB (R[km])
Small cell bandwidth	20 MHz	Traffic model	FTP Model 1
Subframe duration	1 ms	Scheduling algorithm	Resource-fair
Number of UEs per sector	$\{1; 5; 10; 20; 30; 50; 100; 150\}$	Number of macrocells	1
RSRP threshold	-114 dBm	Min. dist. macro-/small cell BS	75 m
Number of small cells per macrocell m	$\{1;3;5;10;15;20\}$	Min. dist. between small cells	40 m
Max. macro (small cell) BS transmit power	46 dBm (30 dBm)	Min. dist. macro BS-UE	35 m
		Min. dist. small cell-UE	10 m
Number of hotspot UEs U_{hotspot}	$\lceil 2/3U \rceil$	hotspot radius	40 m
Thermal noise density	-174 dBm	Macro (small) cell antenna gain	14 dBi (5 dBi)

The FTP Model 3 traffic is considered for each UE. Each UE has a file size of $F = 200$ B to be downloaded within a latency budget of 1 ms, i.e., the minimum required data rate is $r_u^{\min} = 1.6$ Mb/s. Due to the matching procedure, it is possible that the first items of the preference list are not always assigned. Thus, we estimate an upper bound for the URLLC service requirement by selecting the threshold $r_w{}^{\min}{}_u = 2$ Mb/s > 1.6 Mb/s for matching with adaptive quota (aq). In addition, the results are not bounded by a maximum modulation and coding scheme. The bounding affects extremely high throughputs, which are out of scope for URLLC. Thus, we focus on the Shannon capacity yielding an insightful theoretical bound. Further details about the system-level simulation parameters are provided in Table 1.

B. Simulation Results

In this section, we present our system-level simulation results averaged over 10 000 random realizations. First, we illustrate that different connectivity approaches may lead to different SINR values. Second, we compare various matching-based multiconnectivity solutions and results. Finally, we demonstrate the reliability results obtained by the different connectivity approaches for various UE and small cell numbers to demonstrate the achievability of reliability under different load and connectivity conditions. We conclude this section with results on the number of links per UE and SeNB and the complexity analysis of the proposed matching-based algorithm.

1) SINR Evaluation of x-Connectivity Approaches: In order to present the SINR values of different connectivity approaches out of which the SINR outage probabilities can be concluded, we depict the SINR maps of the connectivity approaches presented in Section IV in Fig. 2. Here, each point reflects a UE's position and the color of each point reflects the UE's SINR value (in decibel reflected in the colorbar) after its BS assignment. We depict the SINR values obtained in all simulation realizations in which 30 UEs per sector are active in one figure, so that 10 000× 30 UEs per sector are depicted. For a fair comparison of the results, we ensure that in all simulation runs, the same UE and small cell positions are randomly selected in all connectivity approaches. Although the number of UEs being active does not play a role in the connectivity approaches in Fig. 2(a)–(d) as they do not consider the load in their assignment decisions, different results are obtained in the matching-based multiconnectivity approach as depicted in Fig. 2(e) and (f). Note that Fig. 2(f) is only depicted to demonstrate this dependency and is not to be compared with Fig. 2(a)–(d).

Fig. 2(a) depicts the single-connectivity approach in which a UE is either connected to a small cell or a macrocell, depending on which layer provides a larger RSRP. As compared to the other cases, fewer UEs are served by the small cells as some UEs are assigned to the macrocell. Given the fact that no RSRP threshold is considered for the single-connectivity case, UEs far away from the macrocell BS and having an RSRP value lower than −114 dBm might be assigned to a small cell. This yields a low throughput performance for these UEs. This case is prohibited in the other connectivity approaches.

In Fig. 2(b)–(d), it is shown that adding a link to UE's connections yields improved SINR values as nondesired links become serving/desired links so that intercell interference is mitigated. Compared to the other connectivity approaches, the matching-based approach yields different SINR values for different loads as its assignment decisions are based on the load conditions. It can be observed that in the case of less load of 30 UEs per sector, more UEs are accepted by the SeNBs so that larger SINR values are obtained. This means that multiple UEs are in many cases connected to $L > 5$ SeNBs, i.e., a larger number of links as compared to the $L = 5$ links case. However, with the increasing number of UEs per sector, matching aims for a balanced link allocation among the UEs, i.e., each UEs' quota is lower, which results in fewer requested links. Based on the depicted results, we can conclude that adding links to a UE's connectivity in a dense HetNet scenario yields improved SINR values as long as the assignment decision does not rely on the system's load.

2) Discussion of Different Matching-Based Connectivity Solutions: To demonstrate the performance of matchingbased multiconnectivity for different loads and different small cell numbers, we present, in this section, the UE throughput obtained after the assignment based on the proposed matching-based approach. Here, the cases of {1;30;100} UEs per sector, i.e., no load, medium load, and high load, and the cases of {3;15} small cells per sector reflecting a low and high small cell density, are evaluated. We depict separately a UE's throughput from its MeNB and its SeNB(s) as a box plot where the bottom and top of the box are the first and third quartiles, and the band inside the box is the median. Outliers are depicted as "+" markers. We present the two different cases of SeNB quota determination as introduced in Section IV-D2, namely, the case of QoS-based quota as in (9) named as aq and the case of fq with $q_w = 30$, respectively.

A pairwise comparison of the results in the top and bottom plots in Fig. 3 shows that the UE throughput performance is in median approximately the same for different small cell densities. This means that irrespective of the number of the SeNBs, the matching approach yields similar results as it does not aim to match as many UEs to SeNBs as possible but to achieve a pairwise stable matching.

In the case of a single UE scenario, it is observed that the MeNB throughput is nearly the same for three and 15 small cells. This is due to the fact that there is only one UE per sector to be served, and depending on the UE's position, there might be slight variations in the UE throughput. Given the fact that the UE quota determination is based on the SeNB quota, the resulting UE quota for the cases "aq" and "fq" varies. The aq case results in a much larger quota than the fq case so that the UE requests links from the neighboring sectors, too. Since the load of the SeNBs is low, they accept this request, although the link is weak. This results in a weaker performance than in the aq case, in which the SeNB accepts requests based on the UE's estimated throughput.

In the case of the 30 UEs per sector scenario, the aq and fq SeNB throughput performance is very close. This is mainly because the fq is set to $q_w = 30$, which means that an SeNB can be

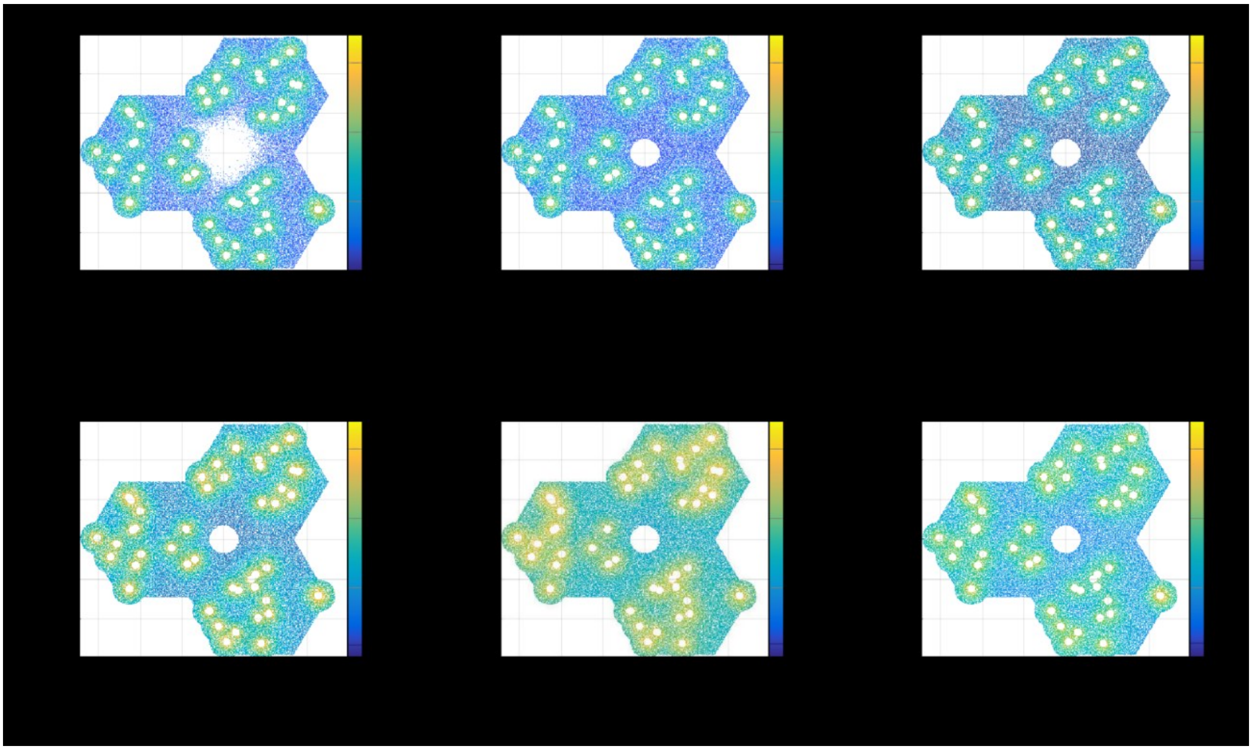

Fig. 2. *SINR maps of different UEs to small cell connectivity approaches for S = 45 small cells, i.e., 15 small cells per sector and U = 90 UEs, i.e., 30 UEs per sector, for (a)–(e) and U = 300, i.e., 100 UEs per sector in (f). (a) Single-connectivity SINR map for small cells only. (b) Dual-connectivity SINR map for small cells only. (c) Fixed multiconnectivity with L = 2 links. (d) Fixed multiconnectivity with L = 5 links. (e) Matching-based multiconnectivity with fixed SeNB quota q_W = 30. (f) Matching-based multiconnectivity with fixed SeNB quota q_W = 30.*

assigned up to 30 UEs. Hence, both quota cases may lead to a maximum of 30 UEs per SeNB yielding to similar results in the same scenario.

This does not hold in the 100 UEs per sector scenario. As depicted, the aq approach achieves in median >1.6 Mb/s for both small cell densities with a small variance. This is because the quota of SeNBs is set to achieve the 2-Mb/s threshold for as many UEs as possible in the matching. In a scenario with more than 30 UEs, here 100 UEs, the fq case can lead to the fact that SeNBs accept many UEs, but UEs do not request too many links due to the fairness consideration in their quota calculation. This leads to SeNBs serving up to 30 UEs and UEs being connected to fewer SeNBs resulting in an SINR value degradation as shown in Fig. 2. However, it also leads to lower load per SeNB yielding better UE throughput. Hence, the fq approach results in better UE performance than the aq approach in highly loaded scenarios.

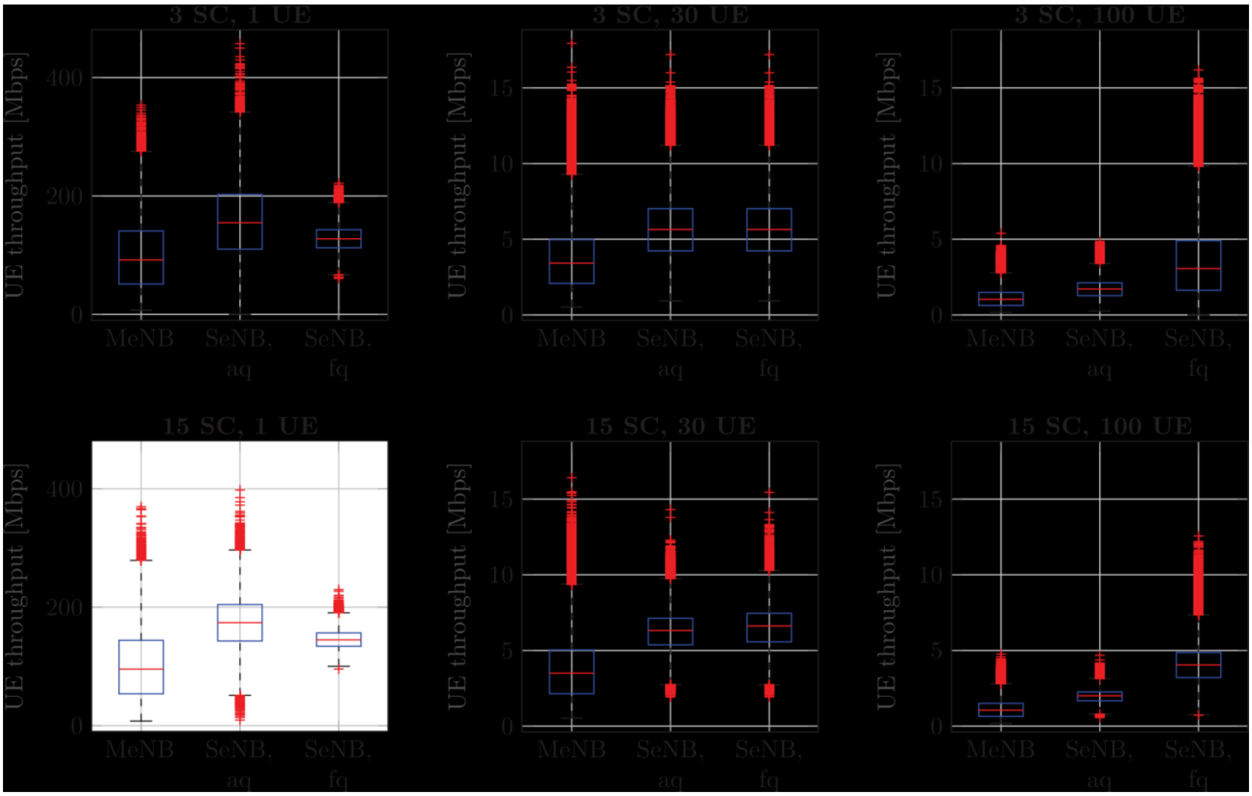

Fig. 3. *UE throughput [Mb/s] from the MeNB and SeNB assignments for different matching-based connectivity scenarios. Top row: 3 small cells per sector and {1; 30; 100} UEs per sector, respectively. Bottom row: 15 small cells per sector and {1; 30; 100} UEs per sector, respectively.*

In summary, it has to be highlighted that the matchingbased approach is sensitive to the quota selection and the number of players per (bidding) team. Based on the presented results, it can be observed that matching-based multiconnectivity does not aim for maximizing the UE throughput. It rather aims for guaranteeing a minimum throughput.

3) Evaluation of Multiconnectivity Approaches: The presented multiconnectivity approaches, i.e., fixed and matching-based multiconnectivity, may yield different performance results. An enhanced SINR value does not necessarily imply an increased UE throughput in a multiuser scenario as it is load dependent. To this end, we present the performance of a long list of various load and small cell density combinations for the multiconnectivity approaches. The goal is to present the dependability of the presented approaches to the load and small cell density and to demonstrate that a simple increase of the number of links may not imply a reliability improvement. We focus on the fifth-percentile UE throughput, namely, the celledge UE throughput. We consider a connectivity to be reliable if all fifth-percentile UEs achieve the minimum required throughput of 1.6 Mb/s, resulting from the service requirement of transmitting 200-B data in a latency budget of 1 ms. Table 2 summarizes the cell-edge UE throughput results for fixed multiconnectivity approach with $L = 2$, $L = 5$, and $L = 20$ links. The matching approaches considered are the fq and aq cases without and with macrocell offloading. In the latter case, the MeNB does not serve a UE if its minimum throughput of 1.6 Mb/s is achieved by its SeNB connection(s).

It can be observed that with the increasing load, the performance is decreased in all cases, as more resources need to be shared by more UEs. In the fixed multiconnectivity case, reliability is not achieved for 150 UEs per sector except for two cases in $L = 2$. This is due to the fact that connectivity is enforced to a fixed number of small cells for a large number of UEs disregarding the small cells load and the UE's achievable throughput. For ten small cells per sector or less, reliability cannot be achieved for a scenario with 100 UEs per sector for L = 5 and L = 10 links, too. For L =

20 in none of the presented densities, reliability is achieved for 100 UEs per sector. Furthermore, comparing the cases L = 5 and L = 20 with a small number of small cells (≤5) and a large number of small cells (≥10), a change in the behavior is observed. There is a significant tradeoff between the number of links a UE is connected to, its link quality, and the load. Given the results presented, it can be concluded that especially for extremely highly loaded systems that are expected for mMTC services, a fixed multiconnectivity approach might not achieve the expected reliability.

In the case of matching-based multiconnectivity, the performance of different options presented varies. A general tendency is that offloading the macrocell from UEs, who have achieved their quality of service requirement, improves the cell-edge UE performance only in very highload scenarios. Furthermore, for small team sizes, i.e., a small number of small cells, the matching approaches are not able to achieve the desired reliability as there are limited available matching combinations. Here, matching stops once pairwise stability is achieved and does not aim to optimize the performance. However, for a large number of players, i.e., high load and density, the proposed fq matching approach is able to achieve the targeted reliability requirement. The aq matching approach does not yield the desired reliability for a large number of UEs as it is based on an estimated UE performance and SeNBs do not coordinate to determine the estimated value. Enabling coordination or information exchange among SeNBs, the proposed aq-based approach can be improved. The estimated performance in case of the fixed quota case with 2 Mb/s estimated per UE throughput

Table 2 Fifth-Percentile UE Throughput of Different Multiconnectivity Approaches in [Mb/s] for Various Number of UEs *U*/ and Small Cells *S*/ per Marcocellular Sector (Gray Cells in the Table Mark the Scenario and Approach Achieving the Reliability Requirement of 1.6 Mb/s)

# { $S/3$; $U/3$}	Fixed MxConn L = 2	Fixed MxConn L = 5	Fixed MxConn L = 20	Matching fq no offloading	Matching aq no offloading	Matching fq offloading	Matching aq offloading
{ 1 ; 1 }	98.43	129.51	129.51	120.55	82.85	67.92	19.60
{ 1 ; 5 }	19.12	24.69	24.69	25.88	19.96	13.53	7.10
{ 1 ; 10 }	9.89	12.56	12.56	13.13	10.51	6.76	4.32
{ 1 ; 20 }	5.06	6.38	6.38	6.84	5.47	3.30	2.90
{ 1 ; 30 }	3.40	4.27	4.27	3.69	3.69	2.56	2.56
{ 1 ; 50 }	2.05	2.57	2.57	0.87	2.24	1.95	2.33
{ 1 ; 100 }	1.03	1.29	1.29	0.37	1.13	0.49	1.39
{ 1 ; 150 }	0.69	0.86	0.86	0.24	0.76	0.28	0.76
{ 3 ; 1 }	111.65	97.47	147.58	138.66	117.82	92.76	58.19
{ 3 ; 5 }	21.33	20.97	28.60	29.51	28.93	18.51	15.18
{ 3 ; 10 }	11.52	11.09	14.50	14.92	14.81	9.24	7.69
{ 3 ; 20 }	6.11	5.77	7.32	7.38	7.49	4.02	3.86
{ 3 ; 30 }	4.18	3.91	4.90	5.01	5.01	2.73	2.58
{ 3 ; 50 }	2.57	2.38	2.96	3.35	3.01	2.35	1.79
{ 3 ; 100 }	1.31	1.21	1.48	0.98	1.51	2.03	1.74
{ 3 ; 150 }	0.88	0.81	0.99	0.30	1.01	0.65	0.99
{ 5 ; 1 }	129.93	99.38	155.53	146.31	126.64	100.04	67.81
{ 5 ; 5 }	22.74	21.27	30.10	30.93	30.94	20.04	17.69
{ 5 ; 10 }	12.44	11.42	15.23	15.62	15.88	10.02	8.96
{ 5 ; 20 }	6.81	6.02	7.69	7.53	8.01	4.30	4.48
{ 5 ; 30 }	4.74	4.10	5.15	5.36	5.36	3.02	2.99
{ 5 ; 50 }	2.98	2.51	3.11	3.57	3.22	2.40	1.81
{ 5 ; 100 }	1.55	1.28	1.56	2.17	1.61	2.18	1.75
{ 5 ; 150 }	1.05	0.86	1.04	1.10	1.07	1.53	1.06
{ 10 ; 1 }	168.99	121.22	112.73	154.83	149.89	114.41	92.56
{ 10 ; 5 }	27.50	26.04	22.70	32.73	32.64	22.87	20.47
{ 10 ; 10 }	14.78	14.55	11.95	16.55	17.46	11.44	10.97
{ 10 ; 20 }	8.23	7.99	6.18	8.10	9.17	4.92	5.72
{ 10 ; 30 }	5.88	5.57	4.18	6.16	6.15	3.82	3.82
{ 10 ; 50 }	3.82	3.49	2.54	4.37	3.70	2.86	2.29
{ 10 ; 100 }	2.07	1.82	1.28	2.62	1.85	2.27	1.63
{ 10 ; 150 }	1.44	1.24	**0.86**	1.86	1.24	**2.15**	1.23
{ 15 ; 1 }	187.78	137.06	101.76	160.00	155.35	120.03	99.38
{ 15 ; 5 }	29.89	27.53	22.68	33.82	31.84	24.04	20.33
{ 15 ; 10 }	15.98	15.39	12.23	17.10	16.88	12.02	10.81
{ 15 ; 20 }	8.80	8.59	6.44	8.37	9.08	5.22	5.80
{ 15 ; 30 }	6.28	6.05	4.39	6.35	6.26	4.05	4.00
{ 15 ; 50 }	4.13	3.85	2.69	4.58	3.81	3.07	2.43
{ 15 ; 100 }	2.30	2.04	1.37	3.00	1.91	2.41	1.53
{ 15 ; 150 }	1.62	1.39	0.92	2.10	1.27	2.19	1.26
{ 20 ; 1 }	193.97	148.42	101.83	165.53	156.60	124.30	101.30
{ 20 ; 5 }	31.97	28.73	24.02	34.79	31.28	24.89	20.20
{ 20 ; 10 }	16.92	15.91	13.22	17.56	16.39	12.44	10.60
{ 20 ; 20 }	9.18	8.99	7.10	8.36	8.79	5.27	5.70
{ 20 ; 30 }	6.53	6.43	4.89	6.45	6.12	4.17	3.95
{ 20 ; 50 }	4.33	4.15	3.03	4.70	3.80	3.18	2.46
{ 20 ; 100 }	2.46	2.25	1.56	3.00	1.94	2.38	1.44
{ 20 ; 150 }	1.75	1.56	1.05	2.25	1.29	2.20	1.28

in a system with 20-MHz bandwidth and 30 UEs (= fixed quota) seems to be a more valid estimate. Hence, with such an estimate and the targeted fairness among UEs, the fixed quotabased matching approach achieves the reliability requirement, especially for highly loaded and dense scenarios,

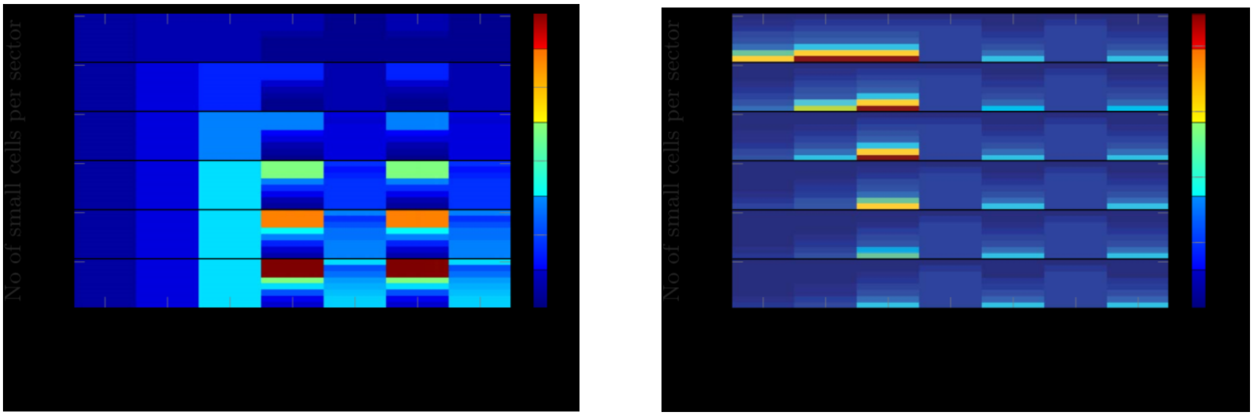

Fig. 4. *Average number of links assigned to a UE or SeNB for each multiconnectivity approach. (a) Average number of links assigned to a UE. (b) Average number of UEs assigned to an SeNB.*

which is not possible with the fixed multiconnectivity approach.

The maximum gain in the results presented in Table 2 is highlighted in bold. Here, the proposed matching-based approach outperforms the static $L = 20$ approach by 150%. In summary, with a good quota estimation/calculation, the matching-based multiconnectivity approach outperforms the fix connectivity approach for highly loaded scenarios, which are more likely in URLLC use cases.

4) Average Number of Links and Complexity: Besides the SINR and throughput/reliability evaluation, we also present the average number of links assigned from the UE and SeNB perspectives, respectively in Fig. 4. Each column represents each column from Table 2, whereas each line reflects the small cell UE numbers, i.e., the lines in Table 2. For the fixed multiconnectivity cases, it is observed that a UE is assigned to L links as long as L small cells are active. In the aq case of the matching-based approach, UEs are assigned to approximately the same number of links irrespective of the number of UEs per small cell number. This reflects the fact that the SeNBs consider a minimum rate to be guaranteed for all UEs when they determine their quota (fairness). If the number of UEs in each sector is up to 10, every UE is matched to every SeNB in the fixed quota case since each SeNB aims to reach the fixed quota $q_w = 30$. Thus, UEs are matched with a large number of links, e.g., 45 or 60, in this case. The maximum number of links per UE is

$$L_{\max} = \min\left(W, \frac{W \cdot q_w}{U}\right). \quad (16)$$

From the SeNB perspective, the SeNB accepts more UEs with the increasing load in the network and with the increasing number of links L. This results in low-reliability performances

of highly loaded scenarios. The fixed quota matching-based approach, leads, as expected, to an almost

Table 3 Average Number of Iterations of the Matching-Based Multiconnectivity Approaches

# UE	# SC	Average # iterations fq	Average # iterations aq
1	1	1.0	1.3
1	20	1.0	16.0
150	1	3.0	3.0
150	20	54.4	26.5

constant number of UEs for different scenarios. In the aq case, tend to accept more UEs in higher loaded scenarios. However, this number is far below the number of UEs they accept in the fixed multiconnectivity approach. This is because they aim to guarantee a minimum performance to all UEs (fairness).

The complexity of the fixed multiconnectivity approaches increases linearly with the number of links L to be assigned. We evaluate the average number of iterations required for the matching decisions. Table 3 presents the cases of the minimum and maximum number of players simulated. It can be observed that the proposed matching-based algorithm does not require a very high number of iterations. Even in the case of 150 UEs and 20 SeNBs, the algorithm requires only a few iterations.

Hence, without being remarkably more complex, the proposed matching-based approach matches more efficiently UEs and SeNB, so that not the SINR values are maximized, but instead, the minimum service requirement is achieved (in most of the scenarios simulated).

VII. CONCLUSION

In this paper, we have presented different connectivity approaches that are available in the literature and have proposed a matching-based multiconnectivity approach together with a multiconnectivity scheduler. We focus on a multiuser, multicellular HetNet in which macrocells operate at an adjacent channel and small cells operate at the same carrier frequency. First, we present that adding additional links to a UE's connectivity may significantly reduce the intercell interference resulting in an increased SINR value and, hence, reduced

SINR outage probability. However, such an increase does not imply achieved reliability requirements in multiuser scenarios with shared resources. This is shown in case of the fixed multiconnectivity approach, in which UEs are enforced to be connected to a fixed number of links. In highly loaded scenarios, the URLLC service requirement of 1.6 Mb/s cannot be achieved with a fix link assignment. The proposed matching-based multiconnectivity approach, however, aims at a fair link matching/distribution among UEs and to guarantee a minimum throughput to as many UEs as possible. This is reflected by the average number of links accepted by an SeNB, particularly in highly loaded scenarios. The results presented demonstrate that with a precise per UE performance estimation (appropriately chosen SeNB quota), the minimum throughput requirement of 1.6 Mb/s can be guaranteed to all cell-edge UEs, especially in highly loaded and dense scenarios.

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