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A Study of Transmission Point Selection for Multi-Connectivity in Multi-Band Wireless Networks

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Abstract: In 5th generation mobile communication networks, the frequency band of the millimeter band of 30–100 GHz is supported to provide a transmission speed of 20 Gbps or higher. Furthermore, a huge transmission capacity, i.e., up to 1 Tbps, is one of the main requirements for the 6th generation mobile communication networks. In order to meet this requirement, the terahertz band is considered a new service band. Hence, we consider multi-band network environments, serving the sub-6Hz band, mmWave band, and additionally sub-terahertz band. Furthermore, we introduce the transmission point selection criteria with multiple connections for efficient multi-connectivity operation in a multi-band network environment, serving and receiving multiple connections from those bands at the same time. We also propose a point selection algorithm based on the selection criteria, e.g., achievable data rate. The proposed point selection algorithm attains lower computational complexity with a 2-approximation of the optimal solution. Our simulation results, applying the channel environment and beamforming in practical environments defined by 3GPP, show that selecting and serving multiple transmission points regardless of frequency band performs better than services through single-connectivity operation.

Keywords: mobile communication networks; multi-band; multi-connectivity; transmission point selection; user association

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1. Introduction

In 5th generation (5G) mobile communication wireless networks [1], a maximum transmission speed of 20 Gbps or more, a user transmission speed of 100 Mbps or more, and a transmission delay of less than 1 ms are provided by adopting a millimeter band (mmWave) of 30–100 GHz in addition to the existing sub-6GHz band. The 6th generation (6G) mobile communication system is expected to be deployed in 2030. A prospective vision of 6G network as well as its key enabling technologies are being studied to support future networks, such as the fully digital and connected world exploiting a new spectrum, the Internet of Everything, and the native artificial intelligence service of mobile broadband applications [2–5]. However, due to support for transmission bandwidth under 20 GHz, it is difficult to support the maximum transmission speed of 1 Tbps or more and the user reduction speed of 10 Gbps or more required in the 6G mobile communication wireless networks [2]. Therefore, the terahertz band is being considered as an additional service band to meet the requirements of the 6th generation mobile communication wireless system [4,5]. It is also necessary to design a multi-band environment with ultra-wide frequency aggregation technology, provide ultra-high-precision massive beam-based multi-access and mobile connectivity, and provide multi-connectivity in a multi-band environment that simultaneously provides sub-6GHz band, mmWave band, and Sub-THz band (hereafter, we identify sub-6GHz band, mmWave band, and Sub-THz band by Frequency-Range 1 (FR1), Frequency-Range 2 (FR2), and Frequency-Range 3 (FR3), unless notified, respectively) [3–5]. In particular, multi-band is required as one of the technologies to overcome unstable radio access in the mmWave band and the Sub-THz band [4,5]; for instance, the UE association algorithm [5] which selects a base station operated in FR2 and FR3, i.e., multi-band mobile communication networks. However, it considers a single connectivity operation in multi-band mobile communication. In contrast to selecting base station in [5], it is necessary to discover radio access technology to improve system performance through collaboration between bands or access nodes and to design a multi-connectivity operation in mobile communication networks that allows mobile stations to access simultaneously at each access node (or base station) via a transmission point.

In addition to this, in order to provide large-capacity transmission wireless access networks, performance analysis considering multi-band radio environments in mobile communication networks should be preceded. Thus, we extend transmission point selection (TPS) problem, also known as user association problem (see [6–15] and references therein). For example, a cell is selected as the service cell for a user according to the expected service rate based on the received signal strength (RSS), i.e., max-RSS-based TPS [8]. For the spectrum efficiency, particularly in multi-tier networks, biased and load balancing, TPS are provided [9,10], e.g., conventionally according to received power-based rule [8]. Also, the TP is selected according to at least one of the widely used metrics: outage/coverage probability [8], fairness [11], spectrum and/or energy efficiency [9], and latency [12]. In general, several user association algorithms have been studied with these metrics.

Meanwhile, some user association algorithms have also been studied recently for AI-embedded wireless networks [13–15]. To minimize the average age of the information of mobile Internet of Things (IoT) nodes by optimizing the selection of the hybrid access point (HAP) or station IoT node, we consider energy consumption of wireless-powered IoT [13]. In [14], a hierarchical double auction model for a collaborative computing-based system is designed to improve the long-term network capacity. In decision-making in stochastic systems with access points (APs) operating on multiple channels, an AP is assigned to each user upon arrival to minimize the long-term total average holding cost [15].

In contrast to those previous studies that do not consider multi-band multi-connectivity in mobile communication networks, we propose a transmission point selection algorithm, which selects one or more connectivities by considering the multi-band radio environment of FR1, FR2, and FR3. We also perform simulations in practical network environments exploiting the channel model and beamforming model identified by the 3rd Generation Partnership Project (3GPP). Our simulation results show that selecting and serving multiple transmission points regardless of frequency band performs better than services through single-band single-connectivity operation. It is clearly helpful for research and development of multi-band multi-connectivity operation technology.

The major contributions of this paper are as follows:

- We propose TPS algorithms that select multiple transmission points regardless of frequency band in multi-band radio environments, e.g., with FR1, FR2, and FR3: (a) a general TPS algorithm and (b) a sequential TPS algorithm. The proposed TPS algorithms select TPs with the most allowed number of connections for each user, disregarding other users' situations, e.g., received signal strength.
- The general algorithm first selects the TP with the maximum expected service time among the available TPs. Then, it selects the maximum expected service time among the TPs, excluding the previously selected TP(s), until the number of connections reaches the total number of allowed connections for each user.
- The sequential TPS algorithm selects TPs for each user based on maintaining the candidate set of TPs, by comparing the maximum expected service time in the candidate set with that for prospective TP. In other words, the TP with the maximum expected service time is sequentially eliminated from the TPs in the candidate set, including the prospective TP, until no more TPs are available to compare.

- The computational complexity of the general TPS algorithm, which selects connection by connection, depends on the number of connections and transmission points. In contrast, the sequentially selected algorithm attains low complexity compared to the general TPS algorithm. It is due to the fact that the sequential algorithm for a user maintains the candidate set of TPs, by determining whether a TP is included in the set or not. We also show the computational complexity of the proposed TPS algorithms as well as the performance bounds by proving approximation ratios in terms of service time. In particular, the sequential TPS algorithm is a 2-approximation algorithm and it decreases the computational complexity compared to the general TPS algorithm.
- Via extensive simulation settings with realistic parameters in the UMi-Street Canyon scenario, we have expressly observed the following: *transmission with multiple connections and an increasing number of connections achieve high system performance regarding the rate of received data, compared to transmission with a single connection, relatively.*

The rest of this paper is organized as follows. We begin with the system model in Section 2. Next, we propose a transmission point selection algorithm in a multi-connectivity operation in multi-band networks in Section 3. We evaluate the proposed algorithm via simulations in Section 4. Finally, we conclude this paper in Section 5.

2. System Model

We consider a wireless communication network which consists of N TPs and K users to be served by the network. A set of users and a set of TPs are denoted by $\mathcal{K} = \{1, 2, \ldots, K\}$ and $\mathcal{N} = \{1, 2, \ldots, N\}$, respectively. Here, the set of TPs is re-ordered in order of frequency, i.e., $\mathcal{N} = \mathcal{N}_1 \cup \mathcal{N}_2 \cup \cdots \mathcal{N}_t$, where $\mathcal{N}_t \in FR_t$. In other words, $\mathcal{N} = \{1, 2, \cdots, n_1, n_1 + 1, \cdots, n_1 + n_2, n_1 + n_2 + 1, \cdots, n_1 + n_2 + n_3, \cdots \sum_{\forall t} n_t\}$, where $\mathcal{N}_t = \{1, 2, \ldots, n_t\}$. In addition, a set of users to be served by TP n, where $n \in \mathcal{N}$, is denoted by $\mathcal{K}_n$, i.e., $\mathcal{K} = \mathcal{K}_1 \cup \cdots \cup \mathcal{K}_N$. We also consider that each user is served by at least one TP. We focus on the transmissions from the TP and multiple users, i.e., downlink transmissions, where at least one serving TP for each user is selected in advance at each time. Each user reports the channel quality of TPs (i.e., $\mathcal{K}_n$) to its associated TP. Accordingly, we assume that the channel quality from TP n to user k with the achievable data rate, denoted by r_k^n, is available at each time slot of performing the TPS. Since a user k is served by at least one TP, the achievable data rate from the selected TPs in a given time is given by

$$R_k = \sum_{n \in \mathcal{N}} r_k^n x_k^n, \tag{1}$$

in which x_k^n denotes the service indicator, where $x_k^n = 1$ when the TP n is selected to serve the user k, and $x_k^n = 0$, otherwise. In other words, the number of TPs serving user k, denoted by t_k, is obtained by $t_k = \sum_{n \in \mathcal{N}} x_k$. Note that if single connectivity is allowed, $t_k = 1$. Here, for user k, the achievable data rate [in bps] served by TP n, i.e., r_k^n, can be obtained according to Shannon's capacity formula [16] by

$$r_k^n(p_n) = B \log_2(1 + \gamma_k^n(p_n)), \tag{2}$$

in which B denotes the system bandwidth and $\gamma_k^n(p_n)$ denotes the received SINR of user k from TP n with the given power p_n stated by $\gamma_k^n(p_n) = \frac{g_n^k p_n}{\sum_{m \in \mathcal{N} \setminus n} g_m^k p_m + \sigma_n^k}$, where g_n^k denotes the channel gain from TP n to user k and σ_n^k denotes the thermal noise power on the user k. We also assume that the length of the data packet for user k served by TP n in a given time is denoted by d_k^n. Thus, the service time for users served by TP n can be obtained by

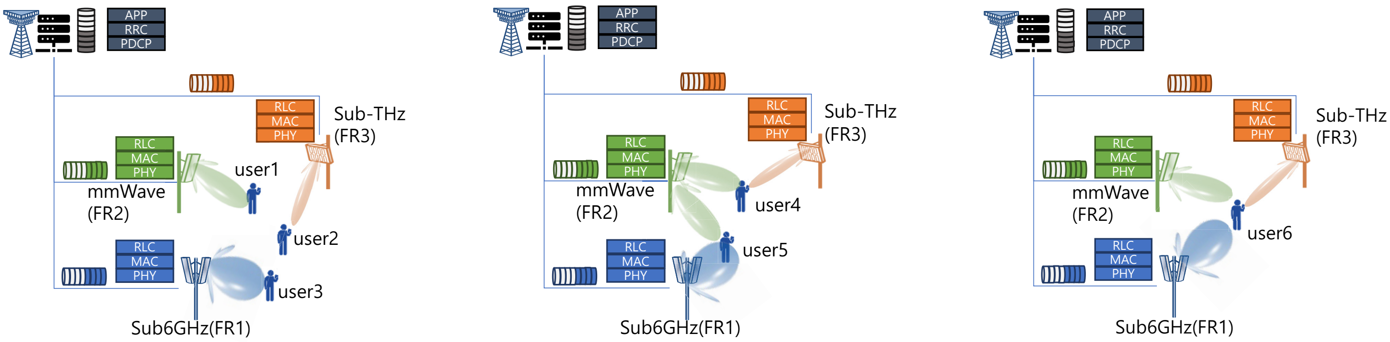
$$T_n = \sum_{k \in \mathcal{K}_n} t_k^n, \tag{3}$$

where t_k^n denotes the service time for a user k served by TP n, i.e., $t_k^n = d_k^n / r_k^n$. Note that we assume all packets are the same length for all users, for simplicity.

3. Transmission Point Selection in Multi-Band Multi-Connectivity Operation

3.1. Multi-Band Multi-Connectivity Operation in Mobile Networks

Figure 1 shows examples of multi-band multi-connectivity operation in mobile networks, where PHY, MAC, RLC, PDCP, and RRC are components of the radio protocol stack defined in 3GPP TS 38.300 [17]. In the figure, one band is selected and a single connectivity with the selected band is only available for the data transmission to a user, e.g., user 1 with FR1, in (a); two bands are selected and a multi-connectivity with the selected two bands is available for the data transmission to a user, e.g., user 4 with FR2 and FR3, in (b); and three bands are selected and a multi-connectivity with the selected three bands is available for the data transmission to a user, e.g., user 6 with FR1, FR2, and FR3, in (c). It is true that according to the terminal's capabilities and settings and the network environment supporting FR1, FR2, and FR3, the user can be served from one, two, and three transmission point(s) (or base station(s)) operating FR1, FR2, and FR3. In other words, a user can receive data via at least one connectivity as a result of the TPS algorithm.



(**a**) single connectivity (**b**) Two connectivities (**c**) Three connectivities

Figure 1. Examples of multi-band multi-connectivity operation in mobile communication networks: (**a**) data transmission with a connectivity from single band (e.g., user 1 with FR2, user 2 with FR3, and user 3 with FR1), (**b**) data transmissions with two connectivities from two bands (e.g., user 4 with FR2 and FR3 and user 5 with FR1 and FR2), and (**c**) data transmissions with three connectivities from three bands (e.g., user 6 with FR1, FR2, and FR3).

3.2. Problem Statement

Our objective is to select transmission points (or base stations), providing maximizing the system performance. In other words, our problem (i.e., transmission point selection) can be formulated as minimizing the total amount service time, denoted by T, which is dependent on the achievable data rate r_k^n if it is served by TP n. Thus, we can write the solution as follows:

$$\min T = \min\left\{\sum_{n\in\mathcal{N}} T_n\right\} = \min\left\{\sum_{n\in\mathcal{N}}\sum_{k\in\mathcal{K}_n} t_k^n x_k^n\right\}, \tag{4}$$

$$\text{subject to } \sum_{n\in\mathcal{N}} x_k^n \leq C, \forall k \in \mathcal{K}, \tag{5}$$

$$x_k^n \in \{0,1\}, \forall n \in \mathcal{N}, \forall k \in \mathcal{K}, \tag{6}$$

$$x_k^n = 0, \forall n \in \mathcal{N}, \forall k \notin \mathcal{K}_n, \tag{7}$$

where $C(1 \leq C \leq N)$ is the allowed number of connections for user k. In addition, $\mathcal{K}_n := \mathcal{K}_n \cup \{k\}$ and $x_k^n = 1$ when TP n is selected and $x_k^n = 0$, otherwise. For instance, if $C = 1$, only one connection is allowed, i.e., the network operates with a single connectivity.

3.3. Transmission Point Selection Algorithm

Algorithm 1 shows the proposed transmission point selection algorithm, where TPs are selected at most C according to the minimum value in Equation (4), i.e., $v_k^n = t_k^n$ (see line 5 in Algorithm 1). In contrast to finding the minimum value (e.g., interference, service latency [12], etc.), TPs can be selected based on the maximum value (e.g., achievable data rate in Equation (1)) sequentially, i.e., line 5 in Algorithm 1 is replaced by the following:

$$n \leftarrow \underset{n \in \mathcal{N}}{\operatorname{argmax}}\, v_k^n. \tag{8}$$

In addition, $\mathcal{K}_n \leftarrow \mathcal{K}_n \cup \{k\}$ and $x_k^n \leftarrow 1$ (see lines 6–7 in Algorithm 1) when the TP n is selected to serve the user k as a result of Equation (8). We have defined the following lemmas, extended from [9,12], on the optimal solution of the service time, denoted by T^*, where the optimal solution T^* for the given optimal allocation $\mathcal{K}_n^*$ for TP n is as follows:

$$T^* = \max_n \sum_{k \in \mathcal{K}_n^*} t_k^n. \tag{9}$$

For optimality analysis, we also define the following:

$$\hat{t}_k = \min_{n \in \mathcal{N}} t_k^n. \tag{10}$$

Algorithm 1 Transmission Point Selection Algorithm

Require: $\mathcal{K} = \{1, 2, \ldots, K\}, \mathcal{N} = \{1, 2, \ldots, N\}, C (1 \leq C \leq N)$
1: Initialise $\mathcal{K}_n \leftarrow \emptyset, \forall n \in \mathcal{N}$, $x_k^n \leftarrow 0, \forall n \in \mathcal{N}, \forall k \in \mathcal{K}$
2: **while** $\mathcal{K} \neq \emptyset$ **do**
3: Choose any user $k \in \mathcal{K}$
4: **for** $i \leftarrow 0$ to $C - 1$ **do**
5: Find TP having the minimum value v_k^n in $\mathcal{N}$ for user k:

$$n \leftarrow \underset{n \in \mathcal{N}}{\operatorname{argmin}}\, v_k^n$$

6: Set $\mathcal{K}_n \leftarrow \mathcal{K}_n \cup \{k\}$
7: Set $x_k^n \leftarrow 1$
8: Remove n from $\mathcal{N}$: $\mathcal{N} \leftarrow \mathcal{N} \backslash \{n\}$
9: $i \leftarrow i + 1$
10: **end for**
11: Remove k from $\mathcal{K}$: $\mathcal{K} \leftarrow \mathcal{K} \backslash \{k\}$
12: **end while**
13: **return** $\mathcal{N}, \mathcal{K}_n, x_k^n, \forall n, k$

Lemma 1. *The optimal solution, denoted by T^*, is bounded by*

$$T^* \geq \frac{1}{N} \sum_{k \in \mathcal{K}} \hat{t}_k, \tag{11}$$

where $\hat{t}_k = \min_{n \in \mathcal{N}} t_k^n$.

Proof. Optimal solution is T^* for the given optimal allocation $\mathcal{K}_n^*$ for TP n. Thus,

$$T^* \geq \frac{1}{N} \sum_{n \in \mathcal{N}} \sum_{k \in \mathcal{K}_n^*} \hat{t}_k = \frac{1}{N} \sum_{k \in \mathcal{K}_n} \hat{t}_k. \tag{12}$$

It is true that the value of T^* is always greater than the mean of the minimum values by the definition of $\hat{t}_k$ in (10). In addition, the sum of the network-wide service time is the same as the sum of service time of the set of all users in the network. □

Lemma 2. *The optimal solution, denoted by T^*, is bounded by*

$$T^* \geq \max \hat{t}_k, \tag{13}$$

where $\hat{t}_k = \min_{n \in \mathcal{N}} t_k^n$.

Proof. By (9), it is clear that

$$T^* = \max_n \sum_{k \in \mathcal{K}_n^*} t_k^n \geq \max_n \sum_{k \in \mathcal{K}_n^*} \hat{t}_k^n. \tag{14}$$

It is also clear that the service time is at least the maximum service time of any one user, i.e., served by any TP in the network. □

Proposition 1. *The computational complexity of the transmission point selection in Algorithm 1 is $\mathcal{O}(CNK)$, where C, N and K denotes the total number of connections for each user, the total number of TPs operating in all frequency bands over the network, and the number of users, respectively.*

Proof. The TPS algorithm selects the C number of TPs having the highest, the second highest, ..., the C-th highest value of v_k sequentially, without considering the other users' value $v_j (j \neq k)$, i.e., $\mathcal{O}(C \times N)$. In accordance with this algorithm, a single TP can be selected by multiple users. It is due to the fact that multiple users can have the maximum value (e.g., SINR) from an identical TP. It is also true that a TP is selected by a user after looking up the TPs disregarding other users' channel status. Thus, the complexity of the transmission point selection depends on the number of allowed connections as well as the total number of users and the total number of TPs, i.e., $\mathcal{O}(C \times N \times K)$. □

3.4. Sequential Transmission Point Selection Algorithm

Because a single TP may be selected by multiple users according to Algorithm 1 in Section 3.3, the latency to be selected may increase. It is also due to the fact that the number of connections to be allowed may further degrade the computational complexity. In other words, after TP having the $c-1$-th highest value of v_k, the TP having the c-th highest value of v_k is selected among the TPs that were not selected, from the first to $c-1$-th highest value of v_k. In contrast, we suggest a transmission point selection for each user in sequential order. The corresponding problem, hence, can be expressed as

$$\min T = \sum_{n \in \mathcal{N}} \sum_{k \in \mathcal{K}_n} t_k^n x_k^n, \tag{15}$$

$$\text{subject to } (5) - (7), \tag{16}$$

where $\mathcal{K}_n := \mathcal{K}_n \cup \{k\}$ and $x_k^n = 1$ if TP n is selected and $x_k^n = 0$, otherwise.

Algorithm 2 shows a sequential transmission point selection for each user. First, we find the C number of TPs in $\mathcal{N}$ and add them into a candidate set of TPs, $\mathcal{N}'$ (see lines 4–8 in Algorithm 2). Second, we find the TP with the maximum value of v_k in the set $\mathcal{N}'$ and compare it to any TP in $\mathcal{N}$ excluding those previously selected or compared to in $\mathcal{N}'$. In other words, the TP with the maximum value of v_k in the union set of $\mathcal{N}'$ and the newly selected TP $\mathcal{N}$ are not in $\mathcal{N}'$ (see lines 10–19 in Algorithm 2). Technically, the final set of $\mathcal{N}'$ is the final selected C number of TPs, which has the first to $c-1$-th lowest value of v_k. The rationale behind reducing the number of instances of comparing TPs to $C-1$ is that the newly compared TP j is selected as the candidate set of TPs only in case where the maximum value of v_k in the current candidate set $\mathcal{N}'$ is higher than that of the compared TP j. Note that our proposed TPS is equivalent to the TPS in Algorithm 1. However, the computational complexity of sequential TPS in Algorithm 2 is not higher than that of the TPS in Algorithm 1. It is due to the fact that sequential TPS only depends on the number of TPs and the number of users regardless of the allowed number of connections of a user.

Algorithm 2 Sequential Transmission Point Selection Algorithm

Require: $\mathcal{K} = \{1, 2, \ldots, K\}, \mathcal{N} = \{1, 2, \ldots, N\}, C(1 \le C \le N)$
Initialise $\mathcal{K}_n \leftarrow \emptyset, \forall n \in \mathcal{N}$, $x_k^n \leftarrow 1, \forall n \in \mathcal{N}, \forall k \in \mathcal{K}$
while $\mathcal{K} \neq \emptyset$ **do**
  Choose any user $k \in \mathcal{K}$
  for $i \leftarrow 0$ to $C - 1$ **do**
    $\mathcal{N}' \leftarrow \mathcal{N}' \cup \{i\}$
    Set $\mathcal{K}_i \leftarrow \mathcal{K}_i \cup \{k\}$
    $i \leftarrow i + 1$
  end for
  $\mathcal{N} \leftarrow \mathcal{N} \backslash \mathcal{N}'$
  while $\mathcal{N} \neq \emptyset$ **do**
    Choose any TP $j \in \mathcal{N}$
    Add j to $\mathcal{N}'$: $\mathcal{N}' \leftarrow \mathcal{N}' \cup \{j\}$
    Remove j from $\mathcal{N}$: $\mathcal{N} \leftarrow \mathcal{N} \backslash \{j\}$
    Set $\mathcal{K}_j \leftarrow \mathcal{K}_j \cup \{k\}$
    Find the maximum v_k^n in $\mathcal{N}'$ for user k:

$$n \leftarrow \underset{n \in \mathcal{N}'}{\operatorname{argmax}}\, v_k^n$$

    Set $x_k^n \leftarrow 0$
    Remove n from $\mathcal{N}'$: $\mathcal{N}' \leftarrow \mathcal{N}' \backslash \{n\}$
    Remove k from $\mathcal{K}_n$
  end while
  Remove k from $\mathcal{K}$: $\mathcal{K} \leftarrow \mathcal{K} \backslash \{k\}$
end while
return $\mathcal{N}', \mathcal{K}_n, x_k^n, \forall n, k$

Proposition 2. *The computational complexity of the sequential transmission point selection in Algorithm 2 is $\mathcal{O}(NK)$, where N denotes the total number of TPs operating in all frequency bands over the network and K denotes the number of users in the network.*

Proof. The TPS algorithm selects the C number of TPs for a user sequentially, by looking up the TPs without considering the other users' value $v_j (j \neq k)$, i.e., $\mathcal{O}(C)$. In addition, remaining TPs are determined according to whether they are serving TP or not, by comparing each TP to a TP with a maximum value of v_j in the set of candidate TPs, i.e., $\mathcal{O}(N - C)$. In other words, the complexity of the transmission point selection only depends on the number of users and the total number of TPs, i.e., $\mathcal{O}(N) = \mathcal{O}(C) + \mathcal{O}(N - C)$. □

Lemma 3. *The sequential TPS algorithm solution, denoted by T, is bounded by*

$$T \le \frac{1}{N} \sum_{n=1}^{N} \hat{t}_k + T^*. \tag{17}$$

Proof. Prior to the iteration for the l-th user, TP n has the value of v_k between the first to C-th lowest one. In other words, T^{l-1} is lower than the mean value of the minimum service time (i.e., $\hat{t}_k$) for all TPs in the network. Thus, we can obtain T^{l-1} as follows:

$$T^{l-1} \le \frac{1}{N} \sum_{n=1}^{N} \sum_{k \in \mathcal{K}_n^{l-1}} \hat{t}_k \le \frac{1}{N} \sum_{n=1}^{N} \sum_{k \in \mathcal{K}_n^{l-1}} t_k = \frac{1}{N} \sum_{n=1}^{N} T_n^{l-1}, \tag{18}$$

where $\mathcal{K}_n^{l-1}$ denotes the set of users who have been allocated to TP n at the $(l-1)$-th iteration. Let k^* be the last user who selects the TP n^* at l-th iteration. We know that the TP n^* has the minimum service time among all TPs according to the sequential TPS algorithm. Thus, by Lemmas 1 and 2

$$T_{n^*}^l (= T) = T_{n^*}^{l-1} + t_{k^*}^{n^*} \tag{19}$$

$$\leq \frac{1}{N} \sum_{n=1}^{N} T_n^{l-1} + t_{k^*}^{n^*} \tag{20}$$

$$\leq \frac{1}{N} \sum_{n=1}^{N} T_n^{l} + t_{k^*}^{n^*} \tag{21}$$

$$\leq \frac{1}{N} (\sum_{n=1}^{N} \hat{t}_k - t_{k^*}^{n^*}) + t_{k^*}^{n^*} \tag{22}$$

$$= \frac{1}{N} \sum_{n=1}^{N} \hat{t}_k + (1 - \frac{1}{N}) t_{k^*}^{n^*} \tag{23}$$

$$\leq \frac{1}{N} \sum_{n=1}^{N} \hat{t}_k + (1 - \frac{1}{N}) \hat{t}_k \tag{24}$$

$$\leq \frac{1}{N} \sum_{n=1}^{N} \hat{t}_k + T^* \tag{25}$$

□

Theorem 1. *Sequential transmission point selection algorithm is a 2-approximation of optimal solution.*

Proof. According to Lemmas 1–3, it is true that

$$T^* \leq T \leq (2 - \frac{1}{N}) T^* \leq 2T^*, \tag{26}$$

where T^* and T denote the optimal solution and the approximation algorithm solution. Here, N denotes the number of TPs in the network and is assumed to be large. Therefore, the sequential transmission point selection algorithm is a 2-approximation algorithm. □

4. Performance Evaluation

4.1. Simulation Setup

In order to evaluate the performance, we make use of the MATLAB tool 9.14.0 [18] adopting the UMi-Street Canyon scenario in [19–21], including system parameters and channel models mainly recommended for FR1, FR2, and FR3 therein. In detail, loss of noise figure is set to 7 dB and thermal noise power spectral density is set to -174 dBm/Hz. Total fading margin and cable and implementation losses are also set to be 20 dB. The main system parameters, which are used in our performance evaluation, are summarized in Table 1.

Figure 2 shows an example of deployment with TPs in UMi-Street Canyon environment, where four TPs operating in FR1, six TPs operating in FR2, and eight TPs operating in FR3 are considered at 3 m height. We also consider 16 and 32 service beams operating in FR2 and FR3, respectively. Each beam for TPs operating in FR2 and FR3 is generated by 16 and 32 antenna elements and the half power beamwidth of each beam is set to be 4.0625° and 2.0312°, respectively (derived from [22]). Boresights of serving beams are evenly distributed in accordance with the number of concurrent serving beams within ±30°. The number of scheduled users is served at most one TP operating in FR1 or a single beam of TP operating in FR2 or FR3, in other words, the TP or the TP's beam with the maximum value of SINR of user k. We also consider only one TP regardless of the number of serving beams that is selected for simplicity. In the network, users are deployed in the random position at 1.5 m height within each TP (or cell) coverage for FR1 or TP's beam coverage for FR2 and FR3. Each user selects the TPs according to the Algorithm 1. In addition, each user moves randomly in the possible area with the velocity $v = 5$ m/s.

Table 1. Key system parameters of the simulation.

System Parameter	Values
Channel model	UMi-Street Canyon
Carrier frequency (FR1, FR2, FR3)	(4, 28, 32) GHz
Bandwidth (FR1, FR2, FR3)	(20, 200, 3200) MHz
TP transmit power (FR1, FR2, FR3)	(44, 44, 44) dBm
Number of TPs (FR1, FR2, FR3)	(4, 16, 32) TPs at 3 m height, see Figure 2
User distribution	100% randomly deployed at 1.5 m height
Traffic model	FTP Model 3
Network Layout	270 m × 50 m
Simulation time	10,000 slots

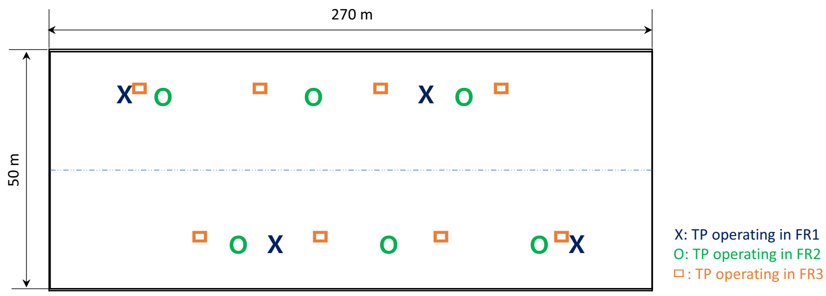


Figure 2. An example of deployment with TPs (X: TP operating in FR1; O: TP operating in FR2; and □: TP operating in FR3) in UMi-Street Canyon environment, where 4 TPs operating in FR1, 6 TPs operating in FR2, and 8 TPs operating in FR3 are assumed to be deployed at 3m height.

We also consider the time to change TP within FR and across FR as well as the time to change the serving beam according to the time defined in [23,24]. The time to change TP within FR and the time to change TP across FR are set to 7 in a unit of TTI and 37 in a unit of TTI, respectively, where TTI is assumed to be 0.5 ms in the simulation. In addition, we also set the time to change the serving beam within the same TP to 1 in unit of TTI.

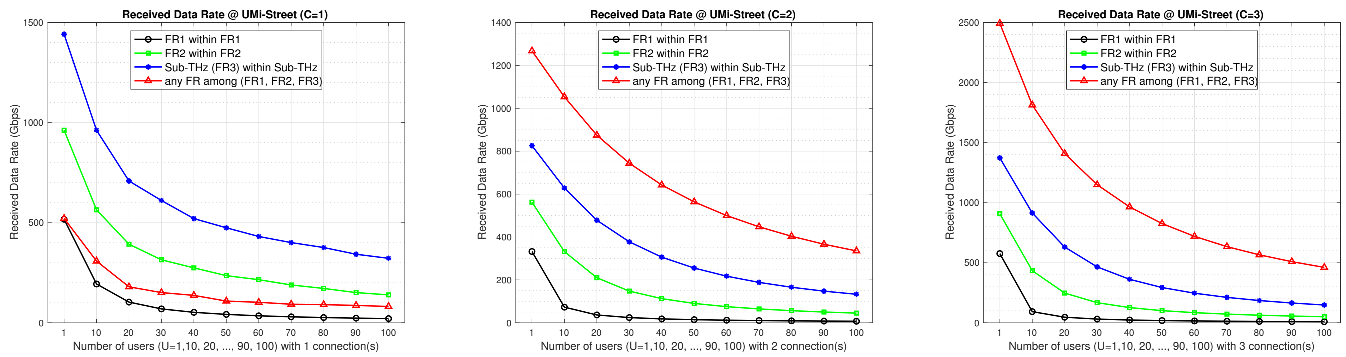
4.2. Simulation Results

The considered simulation results are (i) the received data rate and (ii) the TP change rate with different number of users, i.e., 1, 10, 20, . . . , 90, 100. In order to focus on the channel condition and to avoid selecting TP considering the system bandwidth, we choose the SINR as the TPS criterion. We average the results of 10 performances in the same network environment.

4.2.1. Received Data Rate

Figure 3 shows the average received data rate with different number of users (i.e., U = 1, 10, 20, 30, . . . , 100 users), where a data packet with 4000 bytes is transmitted by the selected TP for each serving user. Note that "FR1 within FR1", "FR2 within FR2", and "Sub-THz (FR3) within Sub-THz" denote the connection (i.e., TP) is selected in FR1, FR2, and FR3 may change within the initially selected FR1, FR2, and FR3, respectively. These are equivalent to max-SINR rule-based TPS with single connectivity in single-band wireless networks, e.g., [8,12]. "any FR among (FR1, FR2, FR3)" also denotes that the connection can be changed within FR as well as across FR (e.g., from FR1 to FR3), which is equivalent to

TPS with single connectivity in multi-band wireless networks, e.g., [5]. Here, Figure 3a–c show the average received data rate in the case of allowing only a single connection for a user, in the case of allowing two connections for a user, and in the case of allowing three connections for a user, respectively. (i) The result in Figure 3a shows that the average data rate of users served by TP operating in FR3 is higher than the others. This is due to the fact that we allocate the wider system bandwidth to FR3, compared to that in FR1 and FR2. Also, only TP within the FR, which is selected initially, can be selected and changed. Interestingly the average data rate of users served by any FR is not the highest. This is because the TP operating in FR3 is not often selected to serve users. It also implies that the channel gain in FR3 is lower than that in FR1 and FR2. (ii) In contrast to the case of allowing only single connection, the average data rate of users by selecting TP operating any FR having the highest SINR is higher than the others in case of allowing multiple connections for users as shown in Figure 3b,c. We infer that multi-connection operation across multiple bands is beneficial for the system performance in terms of received data rate for users, compared to the multi-connection operation with a single band. (iii) In addition, as the number of connections increases, the average received data rate also increases. We also infer that multiple connections and increasing the number of connections for a user lead to the better data rate.

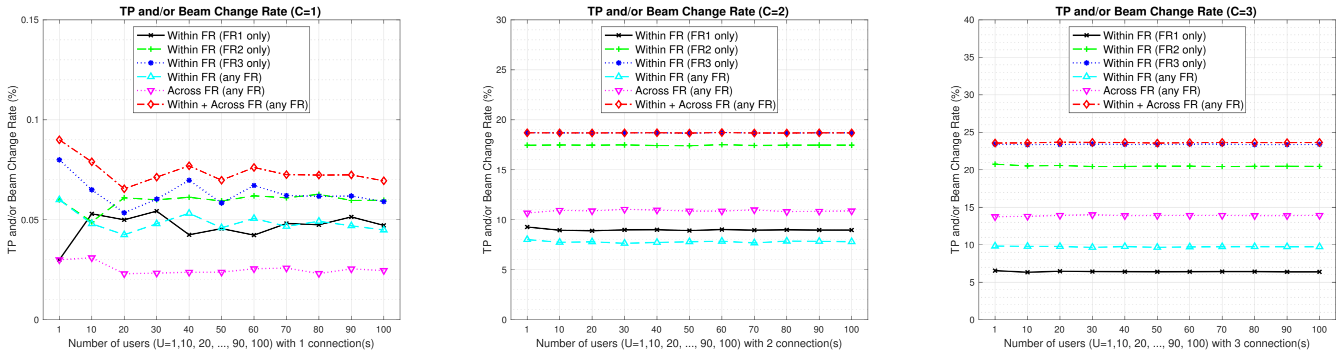


(**a**) Number of connections (C = 1) (**b**) Number of connections (C = 2) (**c**) Number of connections (C = 3)

Figure 3. The average received data rate with different number of users (U = 1, 10, 20, . . . , 100) in case of that (**a**) only one connection is allowed for a user (C = 1), (**b**) two connections are allowed for a user (C = 2), and (**c**) three connections are allowed for a user (C = 3).

4.2.2. Transmission Point Change Rate

Figure 4 shows the average transmission point change rate as a result of the transmission point selection at each time slot with different number of users (i.e., U = 1, 10, 20, 30, . . . , 100 users) during the simulation time, where a data packet with 4000 bytes is transmitted by the selected TP for each serving user. In particular, TP change includes from one TP to another TP, and from one serving beam to another serving beam, since we consider beamforming for FR2 and FR, as described in Section 4.1. "Within FR (FR1 only)", "Within FR (FR3 only)", and "Within FR (FR3 only)" denote the connection (i.e., TP and/or beam) selected in FR1, FR2, and FR3 may change within the initially selected FR1, FR2, and FR3, respectively, which are equivalent to TPS with single-connectivity in single-band wireless networks, e.g., [8,12]. "Any FR among (FR1, FR2, FR3)" also denotes that the connection can be changed within FR as well as across FR (e.g., from FR1 to FR3), which is equivalent to TPS with single-connectivity in multi-band wireless networks, e.g., [5]. "Within FR (any FR)", "Across FR (any FR)", and "Within + Across FR (any FR)" denote the connection (i.e., TP and/or beam) changes within the same FR, the connection (i.e., TP) changes across the FR, and any change within the same and across the FR, respectively. Note that the serving beam may change within TP or across TP and within/across FR. (i) The average TP change rates within FR2 and within FR3 are higher than that within FR1 for all cases. This is because beamforming covers narrow coverage in an angular domain and the channel of mmWave and Sub-THz are unstable, which leads to (re-)selecting the TP and serving beams frequently. (ii) The average TP change rate across FR is higher than that within FR. We infer that multiple connections increase the time complexity to compare transmission points, but that multi-connection operation across multiple bands is beneficial for the system performance in terms of the received data rate for users, compared to the multi-connection operation with a single band, as explained in Section 4.2.1.



(**a**) Number of connections (C = 1) (**b**) Number of connections (C = 2) (**c**) Number of connections (C = 3)

Figure 4. TP and/or serving beam change rate with different users (U = 1, 10, . . . , 100) in the case where (**a**) only one connection is allowed (C = 1), (**b**) two connections are allowed (C = 2), and (**c**) three connections are allowed (C = 3).

5. Conclusions

In this paper, we present a multiple-connectivity operation in wireless networks operating in three bands (i.e., the sub-6GHz band, mmWave band, sub-THz band) simultaneously. In addition, we propose a transmission point selection algorithm, which is suitable for both single connectivity and multi-connectivities. The proposed algorithm finds the allowed transmission point sequentially and adds it into a candidate set of selected transmission sets in the network without considering other users' situations, e.g., channel status, service time. To maintain the candidate set of selected transmission sets, we compare the TP with the minimum service rate to the temporally selected TP's service rate. Then, the TP with the lower service rate is eliminated from the candidate set until no more TPs are available to compare. We also derive the performance bounds and the approximation ratios of the proposed algorithm, which is a 2-approximation of optimal solution. Our simulation results show that selecting and serving multiple transmission points regardless of frequency band performs better than services through single-band single-connectivity operation. The study presented in this paper, and its further extension, taking into account multi-band multi-connectivity operation technology, can be employed extensively in several network environments such as multi-layer networks, IoT networks, AI-embedded networks, etc.

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Abbreviations

The following abbreviations are used in this manuscript:

3GPP	3rd Generation Partnership Project
5G	5th Generation
6G	6th Generation
AI	Artificial Intelligence
AP	Access Points
APP	Application
BS	Base Station
FR	Frequency-Range
FTP	File Transfer Protocol
HAP	Hybrid Access Point
IoT	Internet of Things
MAC	Medium Access Control
mmWave	millimeter Wave
PDCP	Packet Data Convergence Protocol
PHY	Physical
RLC	Radio Link Control
RRC	Radio Resource Control
SINR	Signal to Interference plus Noise Ratio
TP	Transmission Pointer
TPS	Transmission Pointer Selection
TTI	Transmit Time Interval
UMi	Urban Micro

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