Broadcasting Services over 5G NR Enabled Multi-Beam Non-Terrestrial Networks

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***Abstract*—The era of the fifth-generation (5G) New Radio (NR) technology has just begun, and its promises to substantially improve the system performance have turned into reality. The 5G NR enabled Non-Terrestrial Network (NTN) is almost upon us and will represent an effective solution to provide services anytime, anywhere, and over wider coverage areas. In this context, high throughput satellite systems with advanced multi-beam transmissions have gained significant attention owing to their ability to boost the system capacity through beam frequency re-use, increased user data rates, and system spectral efficiency. In this paper, we propose a novel radio resource management scheme, named Single-Frequency Multi-Beam Transmission (SF-MBT), for efficient delivery of the enhanced Mobile Broadband (eMBB) services over the 5G NR multi-beam NTN systems. The main thinking is to group beams into the dedicated Beam Areas, wherein a certain content flow is delivered via simultaneous multi-beam transmissions over the same radio resources without causing inter-beam interference. A simulation campaign is conducted under different scenarios to assess the effectiveness of the proposed SF-MBT algorithm as compared to the current schemes based on frequency reuse. System-wide performance is evaluated in terms of the aggregate data rate, mean throughput, and system spectral efficiency.**

***Index Terms*—Non-Terrestrial Networks, Satellite Communication, 5G New Radio, Broadcast, Multicast, MBSFN, eMBB.**

I. INTRODUCTION

THE growing interest in Non-Terrestrial Network (NTN) technology [1] by both telecom operators and the broader research community has been fueled by the rapid evolution of telecommunication technologies, the continuous demand for new services, and the increasing number of smart devices. NTN is expected to become an effective solution to support terrestrial networks in service provisioning by satisfying the stringent performance requirements and ensuring high Quality of Service (QoS) expectations for all users even when traveling on cruises, trains, and airplanes. Indeed, NTN extends terrestrial coverage to under-served zones to achieve anytime and anywhere connectivity, which is a key feature for next-generation telecommunication systems.

In the past few years, the demand for certain types of service has increased dramatically and it is expected to grow further in the coming years. In particular, the Ericsson Mobility Report [2] forecasts that mobile traffic will grow by 30% annually between 2018 and 2024, and most of this increase will come from video services. This uphill trend is mainly driven by the volume of embedded video in online applications, the growth of Video-on-Demand (VoD) streaming services, the adoption of higher screen resolutions, and the large number of smart devices being connected to the mobile network.

In this context, handling numerous devices that require different broadcast services [3] could be challenging in terms of both capacity and radio spectrum management. To boost the system capacity and to efficiently exploit the spectrum, the traditional Fixed Satellite System (FSS) based on single-beam transmissions has evolved into High Throughput Satellite (HTS) technology, featured by multi-beam deployments, wherein the radio frequency is re-used across multiple beams to avoid inter-beam interference. Today, the multi-beam NTN systems mostly exploit the four-color frequency re-use scheme where four different frequencies are shared by the beams [4].

In this paper, we propose a new Single-Frequency Multi-Beam Transmission (SF-MBT) scheme as a promising radio resource management (RRM) approach for efficient exploitation of the radio spectrum when delivering the enhanced Mobile Broadband (eMBB) services in multi-beam NTN systems based on the emerging 5G New Radio (NR) technology. The designed SF-MBT algorithm groups the beams into areas according to the NTN terminal interests and performs efficient multi-content radio resource allocation by avoiding interference among the beams belonging to more areas. The key objective of our SF-MBT scheme is to improve the multi-beam NTN performance in terms of Aggregate Data Rate (ADR) as compared to the current frequency re-use approaches.

To facilitate the understanding of terminology, Table I lists the main acronyms and abbreviations used in this work. The remainder of this paper is organized as follows. In Section II, we introduce the state of the art, including the motivation behind this work, the main related literature on multi-beam satellite systems, and our contributions. In Section III, we outline the reference system model and detail both the 5G NR multi-beam NTN and the channel models. Our proposed RRM scheme and its computational complexity are discussed in Section IV. An extensive analysis of the performance results is provided in Section V. Finally, conclusions are drawn in Section VI.

TABLE I: Abbreviations and acronyms

NTN	Non-Terrestrial Network
5GC	5G Core Network
RRM	Radio Resource Management
GEO-sat	GEO satellite with transparent payload
GEO-gNB	GEO-sat component on the ground
SF-MBT	Single-Frequency Multi-Beam Transmission
CSI	Channel State Information
MCS	Modulation and Coding Scheme
RB	Resource Block
ADR	Aggregate Data Rate
eMBMS	evolved-Multimedia Broadcast/Multicast Service
MBSFN	eMBMS over Single Frequency Network
eMBB	enhanced Mobile Broadband
RTD	Round Trip Delay
NR	New Radio
μ	numerology
ρ	frequency re-use factor
SCS	Sub-Carrier Spacing
OFDM	Orthogonal Frequency-Division Multiplexing
CP-OFDM	Cyclic Prefix – OFDM
DFT-s-OFDM	Discrete Fourier Transform – spread – OFDM
LMS	Land-Mobile Satellite
LoS	Line-of-Sight
SBA	Synchronized Beam Area
MBA	MBSFN Beam Area
CMS	Conventional Multicast Scheme
MLA	Multicast Link Adaptation
MS	Multicast Subgrouping
MS-MSI	Multicast Subgrouping – Maximum Satisfaction Index
ALJC	Application Layer-Joint Coding

II. STATE-OF-THE-ART REVIEW

A. Motivation

Improvements in satellite manufacturing technology coupled with the growing demand for anytime and anywhere services draw the attention of telecom operators and research organizations to NTN solutions that will integrate with the 5G NR systems. 5G NTN [5] is required to offer wider area coverage, improve service continuity for both massive Machine Type Communication (mMTC) devices and human users traveling on-board moving platforms, and help enhance service availability in mission-critical use cases (such as natural disasters, failure recovery, and public safety). Furthermore, the 5G NTN may increase network scalability by delivering multicast/broadcast services, i.e., evolved-Multimedia Broadcast/Multicast Service (eMBMS) [6], to groups of NTN terminals through Point-to-Multipoint (PtM) connections.

In recent years, the telecommunication research community has been specifically interested in investigating multi-beam NTNs (i.e, HTSs) [7]. In such systems, frequencies are re-used among beams and the available frequency bands depend on the frequency re-use factor that determines how many and which frequency sets are re-used across the beams. The frequency re-use factors of one (i.e., full frequency re-use scheme), two (i.e., four-color frequency re-use scheme), or three (i.e., three-color frequency re-use scheme) are the available 3GPP options [1].

Over the following years, multi-beam NTNs are expected to play a crucial role in the eMBMS provisioning due to their ability to achieve higher data rates. Moreover, eMBMS will also be provided in the Single Frequency mode (MBSFN [8]) with prior network synchronization. Multi-beam NTN and MBSFN demonstrate important benefits by revolutionizing the traditional cellular networks and the conventional Point-to-Point (PtP) transmission mode, respectively. Indeed, NTN takes advantage of wider area coverage as compared to the terrestrial network, whereas MBSFN benefits from more efficient radio spectrum usage since the same content is sent to multiple users only once over the same radio resources, thus limiting the interference.

It is essential to note that multicast/broadcast transmissions are not yet supported in the present 3GPP Release 15 [9]. The work on Release 16 is currently ongoing and eMBMS will be introduced for the 5G NR access technology in Release 17 [10]. Furthermore, NR over NTN is being specified in Release 17, following the outcome of the preceding study items [11]. Hence, this paper aims to stimulate future investigations by the research community on multicast/broadcast transmissions in the single-frequency mode over multi-beam NTN systems.

B. Related Work

One of the most explored issues in multicast transmissions is the support for Adaptive Modulation and Coding (AMC), which is the link adaptation procedure for setting transmission parameters on a per-group basis (i.e., the content is delivered with the most robust modulation supported by all of the target users). In the literature, multiple AMC approaches were proposed for single-beam satellite networks. For instance, the conservative approach or Conventional Multicast Scheme (CMS) [12] adapts the transmission to users with the worst channel quality by guaranteeing fairness but suffers from low spectral efficiency.

With the opportunistic approach or Multicast Link Adaptation (MLA) [13], part of the multicast group is being served in a time slot to optimize a given cost function (i.e., throughput maximization). Multicast Subgrouping (MS) [14] aims to split the multicast group into subgroups, wherein users are combined according to the channel similarity and served in each time slot. In [15], a new MS policy is proposed for the maximization of the Multicast Subgrouping-Maximum Satisfaction Index (MS-MSI) to achieve the trade-off between throughput and fairness, whereas an RRM scheme that combines the MS approach with the Application-Layer Joint Coding (ALJC) technique [16] is offered in [17] aiming to improve the quality of multicast transmissions over the satellite eMBMS networks.

Satellite systems based on multi-beam transmissions represent an evolution of the single beam-based satellites (i.e., FSS) to increase the system capacity and improve the radio resource utilization. Multi-beam transmissions are based on the principle of frequency re-use; hence, the nearby beams exploit different bandwidths to avoid inter-beam interference. The latter occurs when the same frequency is used by all of the beams, thus limiting the HTS system performance. Therefore, satellite operators allocate dissimilar frequency bands to the adjacent beams according to a given frequency re-use scheme. To limit inter-beam interference, several solutions were considered in past literature.

Appropriate RRM approaches are one of the options to mitigate the inter-beam interference. In [18], a scheme for resource allocation (i.e., transmit power, bandwidth, and modulation parameters) that takes into account the user locations and, therefore, different radio propagation conditions, is proposed for multi-beam satellite systems. To compensate for the impact of varying channel on the performance degradation in multi-beam satellite communications, a channel estimation method and a detection technique are developed in [19]. An adaptive bandwidth adjustment is performed in [20], where a dynamic bandwidth allocation scheme is proposed for multi-beam satellite systems by assuming uniform signal attenuation across each beam to achieve a trade-off between the maximum capacity and the fairness among beams under different traffic demands.

In [21], the authors propose a dynamic channel allocation algorithm and formulate an optimization problem based on deep reinforcement learning techniques to minimize the service blocking probability in multi-beam satellite networks. In [22], a genetic algorithm is designed for the allocation of both power and bandwidth by considering the propagation effects, interference among beams, and atmospheric attenuation. A mathematical model is constructed in [23] aiming at characterizing the trade-off between the transmit power and the beam directivity to increase the flexibility in handling traffic demands; further, a novel power allocation scheme is also derived.

Pre-coding is another technique to mitigate the interference among users located at the beam edges due to the existence of side lobes in beam radiation patterns. In [24], the authors provide an optimal solution to the linear pre-coding problem by proposing a generic iterative algorithm that optimizes both pre-coding vectors and power allocation. In [25], an overview of multicast multigroup pre-coding techniques and user clustering methods is provided for multi-beam satellite communications. Multicast multigroup pre-coding and user scheduling remain the main topics in [26] and [27]. In [26], the authors formulate an optimization frame-based pre-coding problem that aims at maximizing the throughput of a satellite system under given power constraints and at proposing a multicast-aware user scheduling policy.

In [27], the authors investigate the problem of multicast multigroup transmission in frame-based multi-beam satellite systems by proposing a low complexity pre-coder for minimizing the robust power by considering – differently from [26] – the Channel State Information at the Transmitter (CSIT) for user clustering. To overcome the effect of imperfect CSIT due to long propagation delays, a low complexity two-stage pre-coding scheme is delivered by [28] to limit the interference among beams. Grouping users within a cluster to serve them simultaneously in the same frame is the aim of [4], where two k-means based clustering approaches are employed according to two similarity metrics based on the Euclidean distance and the channel coefficients.

In [29], the problem of user clustering is addressed by introducing a novel mathematical framework suitable for maximizing the overall throughput for the two designed clustering algorithms (i.e., those for fixed-size and variable-size clusters). Differently from past research, which is focused on the design of multicast multigroup pre-coding or user clustering algorithms, the work in [30] analyzes the impact of the system scheduler on multicast pre-coding and develops a geographical scheduling scheme to improve the performance of multicast and unicast pre-coding in terms of the average spectral efficiency with respect to the random scheduling approach.

C. *Our Contributions*

In the existing literature, two key approaches (i.e., RRM and pre-coding techniques) are considered to limit the inter-beam interference at the NTN receivers due to non-null side lobes of the beam radiation patters. In this work, we propose another solution for mitigating the interference between the NTN terminals at the beam edges by exploiting simultaneous MBSFN transmissions among the synchronized beams of the same satellite to deliver the given content over the same radio resources. Therefore, multiple signal waveforms belonging to different beams are considered as a source of constructive interference at the NTN receiver. x To the best of our knowledge, the MBSFN approach has not been considered before for multi-beam satellite communications. In this work, we thus provide the following contributions:

- First, we define the concepts of MBSFN beam transmission, Synchronization Beam Area (SBA), and MBSFN Beam Area (MBA), based on which we design a novel algorithm for MBA formation that aims at increasing the ADR in a multi-beam NTN system. In each MBA, the beams are synchronized in time to deliver the same eMBB flow to several NTN terminals over the same radio resources (i.e., MBSFN transmission[1] is performed by multiple beams).
- Second, we propose a radio resource allocation technique that avoids inter-beam interference when delivering several items of content. We consider the mobility of NTN terminals and thus channel quality variations over time. The channel status reports of NTN terminals are essential for setting the transmission parameters, i.e., modulation and coding scheme. The latter is determined by considering the propagation delay.
- Finally, since none of the proposals in past literature are ready for the 5G NR systems, we tailor our system model to account for the 5G NR technology. With an extensive simulation campaign, we evaluate and compare the system performance of our proposed approach against two alternative frequency re-use schemes.

III. SYSTEM MODEL

As demonstrated in Fig. 1, we refer to a multi-beam NTN radio access architecture supporting multicast transmissions

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[1] The MBSFN transmission or the transmission in the MBSFN mode has been specified in [31] for cellular broadcasting as a simulcast transmission technique where identical waveforms are transmitted at the same time from multiple cells.

where the NTN platform communicates with the NTN terminals via the NR-Uu radio interface and is connected to the 5G Core Network (5GC) through the NTN Gateway.

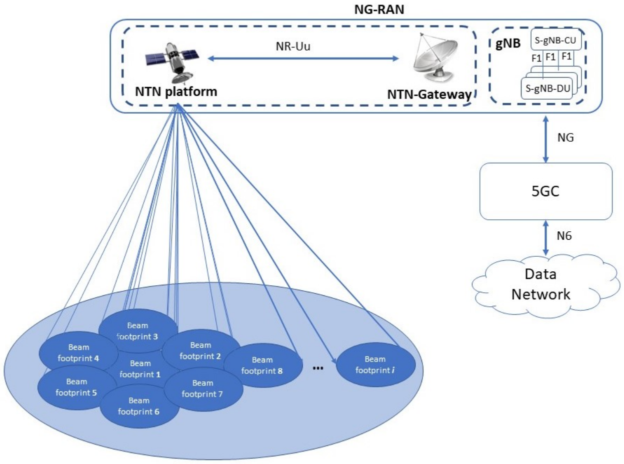

Fig. 1: Reference architecture for multi-beam transmission in single-frequency mode.

A. 5G NR Multi-Beam NTN Model

We consider a GEO satellite (GEO-sat) equipped with a transparent payload [1] operating in the S-band frequency (i.e., 2 GHz) as a reference NTN platform. The ground component of the GEO-sat is the GEO-gNB that is responsible for the link adaptation procedures. In particular, GEO-sat collects and forwards all the Channel State Information (CSI) feedback from the NTN terminals to the GEO-gNB, which selects the appropriate Modulation and Coding Scheme (MCS) for the delivery of a given eMBB content to multiple destinations.

The CSI feedback of the NTN terminals is transmitted via the feeder link, which is denoted as the link from the NTN terminals to the GEO-gNB. The eMBB data are transmitted via the service link, which is denoted as the link from the NTN-gNB to the NTN terminals. The Round Trip Delay (RTD) is the time required for a signal to travel from the NTN-terminal to the NTN-gateway and back (or vice versa). For a transparent payload-based satellite, the RTD is typically equal to 541.46 ms [1].

The considered multi-beam NTN system is based on the 5G NR technology that supports multiple scalable Orthogonal Frequency Division Multiplexing (OFDM) numerologies ($\mu = 0$ to 4), each characterized by a different Sub-Carrier Spacing ($SCS = 15kHz$ to $240kHz$) according to the following equation [5]:

$$SCS = 15kHz \times 2^{\mu}, \tag{1}$$

where μ is the numerology index.

The NR transmission is based on the OFDM with Cyclic Prefix (CP-OFDM) in the downlink, whereas both CP-OFDM and Discrete Fourier Transform-spread-OFDM (DFT-s-OFDM) with CP are supported in the uplink. The NR downlink and uplink transmissions are arranged in frames, each consisting of 1 ms subframes. Every subframe has a different number of slots according to the selected numerology. The radio spectrum is managed in terms of Resource Blocks (RBs), each of which consists of 12 consecutive and equally spaced sub-carriers. In this work, we refer to the NTN terminals interested in eMBB services; hence, we choose the numerology $\mu = 0$ with $SCS = 15kHz$, which is the most suitable for eMBB applications delivered over eMBMS.

Let $\mathcal{I}$ be the set of beams to cover a given area on Earth. We define the *Synchronization Beam Area (SBA)* as a GEO-sat coverage area where one or more MBAs could be formed. We define the *MBSFN Beam Area (MBA)* as an area corresponding to two or more adjacent beam footprints where the respective beams are synchronized in time to deliver the same content flow over the same radio resources to multiple destinations, by performing an MBSFN Beam transmission[2]. We denote $\mathcal{M}$ as the set of all MBAs included within an SBA, and $\mathcal{E}$ is the set of all eMBB content items requested in the SBA.

Let $\mathcal{T}$ be the set of all NTN terminals, which are interested in the broadcasted eMBB contents to be served:

$$\mid \mathcal{T} \mid = \sum_{m \in \mathcal{M}} \mid \mathcal{T}_m \mid, \tag{2}$$

where $\mathcal{T}_m$ is the set of NTN terminals belonging to the m-th MBA.

We denote $\mathcal{RB}$ to be the set of available radio resources (i.e., in terms of RBs). Let $\mathcal{RB}_m$ be the number of RBs assigned to the beams of the m-th MBA. The overall number of RBs to be allocated to the m-th MBA shall not exceed the number of available RBs:

$$\mid \mathcal{RB}_m \mid \leq \mid \mathcal{RB} \mid, \quad \forall m \in \mathcal{M}. \tag{3}$$

If one or more beam footprints belong to more MBAs, the sum of the RBs assigned to the beams of those MBAs shall not exceed the number of available RBs in order to avoid inter-beam interference:

$$\sum_{m \in \mathcal{M}} \mid \mathcal{RB}_m \mid \leq \mid \mathcal{RB} \mid . \tag{4}$$

The aim of the proposed RRM scheme is to increase the overall ADR of the multi-beam NTN system by meeting the above constraints when performing link adaptation with a dynamic selection of the MCS level for the MBSFN Beam transmission according to the CSI feedback information sent by all the NTN terminals to the GEO-sat. By referring to an SBA as the set $\mathcal{M}$ of MBAs, the ADR is given by:

$$\mathcal{ADR} = \sum_{m \in \mathcal{M}} \mathcal{ADR}_m, \tag{5}$$

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[2] In this paper, we define the MBSFN Beam transmission or multi-beam transmission in the MBSFN mode as a simulcast transmission technique realized by the transmission of identical NTN waveforms at the same time from multiple beams of the same NTN-platform. An MBSFN Beam Transmission from multiple beams within the MBSFN Beam Area is regarded as a single transmission by the NTN terminal.

TABLE II: Loo distribution parameters for each modeled environment at an elevation angle of 40°.

Environment	State 1: LoS			State 2: Moderate Shadowing			State 3: Deep Shadowing		
	α (dB)	Ψ (dB)	MP (dB)	α (dB)	Ψ (dB)	MP (dB)	α (dB)	Ψ (dB)	MP (dB)
Open	0.1	0.37	-22.0	-1.0	0.5	-22.0	-2.25	0.13	-21.2
Suburban	-1.0	0.5	-13.0	-3.7	0.98	-12.2	-15.0	5.9	-13.0
Urban	-0.3	0.73	-15.9	-8.0	4.5	-19.2	-24.4	4.5	-19.0
Intermediate Tree Shadowed	-0.4	1.5	-13.2	-8.2	3.9	-12.7	-17.0	3.14	-10.0
Heavy Tree Shadowed	-	-	-	-10.1	2.25	-10.0	-19.0	4.0	-10.0

TABLE III: Markov Chain Matrices $\mathbf{P}$ and state probability vectors $\mathbf{w}$ for each modeled environment at an elevation angle of 40° (University of Bradford experimental campaign).

Environment	w	P		
Open	0.5	0.9530	0.0431	0.0039
	0.375	0.0515	0.9347	0.0138
	0.125	0.0334	0.0238	0.9428
Suburban	0.4545	0.8177	0.1715	0.0108
	0.4545	0.1544	0.7997	0.0459
	0.091	0.1400	0.1433	0.7167
Urban	0.4	0.8628	0.0737	0.0635
	0.2667	0.1247	0.8214	0.0539
	0.3333	0.0648	0.0546	0.8806
Intermediate Tree Shadowed	0.3929	0.7193	0.1865	0.0942
	0.3571	0.1848	0.7269	0.0883
	0.25	0.1771	0.0971	0.7258
Heavy Tree Shadowed	0.0	0.7792	0.0452	0.1756
	0.5	0	0.9259	0.0741
	0.5	0	0.0741	0.9259

where the ADR of the NTN terminals receiving the content in the m-th MBA through the MBSFN Beam transmission is represented as:

$$\mathcal{ADR}_m = \sum_{t \in \mathcal{T}_m} Rate(t) \times \mid \mathcal{RB}_m \mid, \forall m \in \mathcal{M}, \tag{6}$$

where $Rate(t)$ is the minimum data rate per RB related to the t-th NTN terminal with the lowest MCS out of all NTN terminals in the m-th MBA. The proposed RRM scheme targets to solve, via a heuristic approach, the following problem:

$$\arg\max_{\mathcal{RB}} \mathcal{ADR}, \tag{7}$$

subject to (2) – (6).

B. Channel Model

In this work, we consider the Land-Mobile Satellite (LMS) channel represented according to the Pèrez-Fontán model [32]. A three-state first-order Markov chain describes three propagation conditions that are LoS, moderate shadowing, and deep shadowing. The Markov chain is defined by the transition probability matrix $\mathbf{P}$ and the state probability vector $\mathbf{w}$. In each state, signal amplitude variations due to shadowing and multipath phenomena follow three different parameters (i.e., α, Ψ, MP) of the Loo probability density function [33].

Further, this model captures the satellite channel at more elevation angles and in other environments. In this work, we consider an elevation angle of 40°, while five environment types (i.e. Open, Suburban, Urban, Intermediate Tree Shadowed, and Heavy Tree Shadowed) are modeled each by a dedicated Markov matrix, a specific state probability vector, and a particular set of Loo distribution parameters. Below, we consider the Loo distribution parameters collected in Table II; the Markov matrix and the probability vector are demonstrated in Table III.

IV. PROPOSED SF-MBT SCHEME

A. General Description

The proposed SF-MBT scheme aims to efficiently allocate the radio resources in order to provide higher ADR in a multi-beam NTN system with respect to the frequency re-use schemes. To achieve this goal, our SF-MBT algorithm exploits the concept of MBSFN among the beams of the same GEO-satellite by synchronizing (in time) the transmission over the beams when delivering the same eMBB service by exploiting the same set of RBs. The parameters of the MBSFN beam transmission are set according to the lowest MCS (i.e., the most robust modulation) supported by all of the NTN terminals interested in a given eMBB content. Fig. 2 introduces the SF-MBT algorithm in question by means of a flowchart.

The working principle of the proposed scheme is to group the beams belonging to the GEO-satellite SBA in several MBAs on a per-content basis, thus taking into account the interests of NTN terminals. When a beam belongs exclusively to one MBA or an *independent MBA*, all the NTN terminals within the coverage of that beam are interested in the same content, whereas when a beam belongs to two or more MBAs, it shall deliver two or more items of content. For the latter context, we define the *overlapping MBAs* as two or more MBAs sharing at least one beam. In the case of overlapping MBAs, the SF-MBT scheme performs radio resource allocation across the involved MBAs to avoid inter-beam interference. Further, the SF-MBT scheme improves the system ADR by meeting the constraint to serve all of the interested NTN terminals.

B. Step-by-Step Implementation

Algorithm 1 reports the pseudo-code that describes the working logic of the proposed SF-MBT scheme. Table IV lists the main notation employed by the pseudo-code. The algorithm begins by receiving at the input the set $\mathcal{E}$ of all the eMBB content items, the set $\mathcal{I}$ of GEO-satellite beams, and the set $\mathcal{T}$ of all the NTN terminals interested in at least one eMBB content item (line 1). The first step is to verify, for each GEO-satellite beam i, if there is at least one NTN terminal interested in the e-th content item in order to be considered a

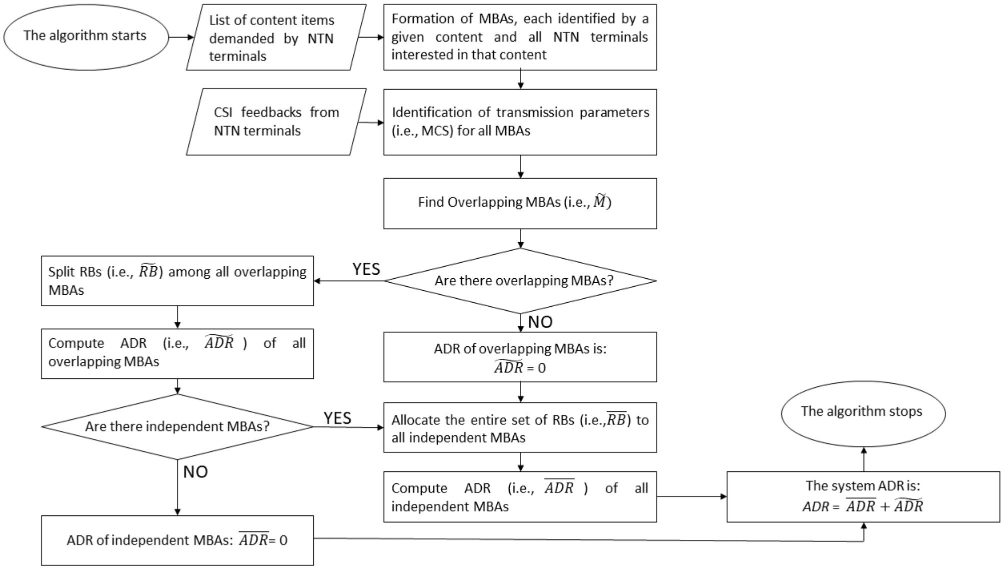

Fig. 2: Flowchart of our SF-MBT algorithm.

part of the same set $\mathcal{I}^*$ of beams, which could join the same MBA after satisfying the adjacency constraint (lines 2–15).

Once the set $\mathcal{M}$ of all the MBAs delivering different eMBB content items is defined, the algorithm proceeds by identifying all of the overlapping MBAs where shared beams shall broadcast more eMBB services (lines 16–19). This step is essential to initiate an efficient radio resource allocation procedure for avoiding inter-beam interference. Indeed, if there are only independent MBAs (line 20) and, hence, no beam is shared among the MBAs, all the available radio resources are re-used in each MBA (line 21) without entailing any kind of interference among the MBAs. The related ADR is then computed (line 22).

Otherwise, in the case of overlapping MBAs (line 23), the available radio resources are split among the overlapping MBAs to avoid inter-beam (among the beams belonging to the overlapping MBAs) and intra-beam (within the beam where more than one content item is delivered) interference due to the transmission of different content flows (line 28). The related ADR is then computed (line 29). Further, the algorithm verifies whether – among all the MBAs – there are also independent MBAs that deliver only one content item (lines 24–27).

If such independent MBAs exist (line 30), all the radio resources are re-used among all the independent MBAs for the eMBB provisioning (line 31) and the related ADR is computed (line 32). In this case, the final set of RBs and the overall system ADR are, respectively, the union of the sets of RBs and the sum of the two ADR components related to the overlapping MBAs and the independent MBAs (lines 33–34). Otherwise, if no independent MBAs are identified (line 35), the final set of RBs and the system ADR are, respectively, the set of RBs and the ADR related to the overlapping MBAs only (lines 36–37). Finally, the algorithm terminates by providing at the output the set $\mathcal{M}$ of all MBAs, the set $\mathcal{RB}$ of the allocated RBs, and the system $\mathcal{ADR}$ (line 40).

Algorithm 1 Single-Frequency Multi-Beam Transmission

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 1: Input: $\mathcal{E}$, $\mathcal{I}$, $\mathcal{T}$
 2: $\mathcal{M} = \emptyset$;
 3: for $e \in \mathcal{E}$ do
 4:     $\mathcal{I}^* = \emptyset$;   ▷ set of beams transmitting $e$-th content
 5:     $\mathcal{M}^* = \emptyset$;   ▷ set of MBAs where delivering $e$-th content
 6:     for $i \in \mathcal{I}$ do
 7:         if (count NTN terminals interested in $e$-th content) $\geq 1$ then
 8:             add $i$ in $\mathcal{I}^*$;
 9:         end if
10:     end for
11:     $\mathcal{M}^* = FindAdjacentBeams(\mathcal{I}^*)$;
12:     for $m^* \in \mathcal{M}^*$ do
13:         add $m^*$ in $\mathcal{M}$;
14:     end for
15: end for
16: $\tilde{\mathcal{M}} = \emptyset$;   ▷ set of MBAs having one or more beams in common
17: $\tilde{\mathcal{RB}} = \emptyset$;   ▷ set of RBs allocated to MBA in $\tilde{\mathcal{M}}$
18: $\tilde{\mathcal{ADR}} = 0$;   ▷ ADR related to $\tilde{\mathcal{M}}$
19: $\tilde{\mathcal{M}} = FindOverlappingMBA(\mathcal{I}, \mathcal{M})$;
20: if IsEmpty($\tilde{\mathcal{M}}$)==TRUE then
21:     $\mathcal{RB} = AllocateAllRB(\mathcal{M})$;
22:     $\mathcal{ADR} = ComputeADR(\mathcal{M}, \mathcal{RB})$;
23: else if IsEmpty($\tilde{\mathcal{M}}$)==FALSE then
24:     $\bar{\mathcal{M}} = \emptyset$;   ▷ set of MBAs with no beam in common
25:     $\bar{\mathcal{RB}} = \emptyset$;   ▷ set of RBs allocated to MBA in $\bar{\mathcal{M}}$
26:     $\bar{\mathcal{ADR}} = 0$;   ▷ ADR related to $\bar{\mathcal{M}}$
27:     $\bar{\mathcal{M}} = \mathcal{M} \cap \tilde{\mathcal{M}}$;
28:     $\tilde{\mathcal{RB}} = SplitRB(\tilde{\mathcal{M}})$;
29:     $\tilde{\mathcal{ADR}} = ComputeADR(\tilde{\mathcal{M}}, \tilde{\mathcal{RB}})$;
30:     if isEmpty($\bar{\mathcal{M}}$)==FALSE then
31:         $\bar{\mathcal{RB}} = AllocateAllRB(\bar{\mathcal{M}})$;
32:         $\bar{\mathcal{ADR}} = ComputeADR(\bar{\mathcal{M}}, \bar{\mathcal{RB}})$;
33:         $\mathcal{RB} = \bar{\mathcal{RB}} \cup \tilde{\mathcal{RB}}$;
34:         $\mathcal{ADR} = \bar{\mathcal{ADR}} + \tilde{\mathcal{ADR}}$;
35:     else if isEmpty($\bar{\mathcal{M}}$)==TRUE then
36:         $\mathcal{RB} = \tilde{\mathcal{RB}}$;
37:         $\mathcal{ADR} = \tilde{\mathcal{ADR}}$;
38:     end if
39: end if
40: Output: $\mathcal{M}$, $\mathcal{RB}$, $\mathcal{ADR}$
```

C. Complexity Analysis

A detailed complexity analysis of the proposed SF-MBT scheme is provided below.

TABLE IV: Notation in Use

$\mathcal{I}$	set of all beams of a GEO-sat
$\mathcal{M}$	set of all MBAs
$\mathcal{T}$	set of NTN terminals requiring broadcast service
$\mathcal{E}$	set of all eMBB content items requested in the SBA
$\mathcal{I}^*$	set of beams transmitting a given content *e*
$\mathcal{M}^*$	set of MBAs where delivering a given content *e*
$\tilde{\mathcal{M}}$	set of MBAs having one or more beams in common
$\bar{\mathcal{M}}$	set of MBAs with no beams in common
$\mathcal{RB}$	set of available radio resources
$\tilde{\mathcal{RB}}$	set of RBs for MBAs with beams in common
$\bar{\mathcal{RB}}$	set of RBs for MBAs without common beams
$\mathcal{ADR}$	ADR of the multi-beam NTN system
$\mathcal{A}\tilde{\mathcal{D}}\mathcal{R}$	ADR of MBAs with at least one common beam
$\mathcal{A}\bar{\mathcal{D}}\mathcal{R}$	ADR of all MBAs without common beams
$\mid \cdot \mid$	cardinality of a set

In lines 1–15, the complexity is:

$$O\Big(\mid \mathcal{E} \mid \cdot (\mid \mathcal{I} \mid \cdot \mid \mathcal{T} \mid + \mid \mathcal{I} \mid^2 + \mid \mathcal{M} \mid)\Big),$$

where:

- $O(\mid \mathcal{E} \mid)$ is the complexity due to the "for" cycle over the eMBB content items (line 3);
- $O(\mid \mathcal{I} \mid \cdot \mid \mathcal{T} \mid)$ is the complexity of verifying (for all beams) how many NTN terminals are interested in a given service (lines 6–10);
- $O(\mid \mathcal{I} \mid^2)$ is the complexity due to the verification of the adjacency constraint among the beams (line 11);
- $O(\mid \mathcal{M} \mid)$ is the complexity due to the insertion of all the MBAs wherein a given eMBB service is delivered to the final set of MBAs (line 12–14).

In line 19, the complexity to find all the overlapping MBAs is $O\big(\mid \mathcal{I} \mid \cdot \mid \mathcal{M} \mid\big)$. It depends on the search of common beams in all the created MBAs. In lines 20–39, the complexity is $O\big(\mid \mathcal{M} \mid\big)$ due to the allocation of radio resources and the computation of the ADR, which is because the check as to whether the overlapping MBAs exist (lines 20 and 23) and the check as to whether at least one independent MBA exists (lines 30 and 33) have constant complexity.

The implementation of the SF-MBT algorithm has the following polynomial complexity:

$$O\big(\mid \mathcal{E} \mid \cdot \mid \mathcal{I} \mid \cdot \mid \mathcal{T} \mid + \mid \mathcal{E} \mid \cdot \mid \mathcal{I} \mid^2 + \mid \mathcal{E} \mid \cdot \mid \mathcal{M} \mid + \mid \mathcal{I} \mid \cdot \mid \mathcal{M} \mid\big).$$

The proposed SF-MBT algorithm is, however, more complex than the current re-use based schemes, whose complexity is:

$$O(\mid \mathcal{I} \mid \cdot \mid \mathcal{E} \mid \cdot \mid \mathcal{T} \mid).$$

However, the SF-MBT complexity is reasonable for realistic scenarios in a multi-beam NTN system. Indeed, the proposed algorithm is executable in feasible runtime owing to the high performing GEO-gNB of the next-generation technology. Further, to support the SF-MBT in 5G NR multi-beam NTN systems, the 5G NR technology may require certain adaptations. First, multi-beam transmission synchronization at the network side and signal combination at the receiver should be configured by choosing the appropriate cyclic prefix to compensate for the delay spread.

Therefore, signals belonging to different beams are regarded as multi-path components of the same signal and are constructively combined at the NTN terminal. Second, an air interface should be designed to support non-terrestrial broadcasting/multicasting in multi-beam NTN systems based on the 5G NR technology. Finally, additional features, modifications, and solutions to support 5G NR applications for NTN are planned to be defined in the subsequent 3GPP Release 17.

V. PERFORMANCE EVALUATION

A. Simulation Model

A simulation campaign has been conducted by using a dedicated simulator specifically developed, through the MATLAB tool, for the SF-MBT over 5G NR multi-beam NTN systems. Further, it has been calibrated by following the guidelines of the 3GPP technical report [1]. Each simulation run has been repeated multiple times to attain 95% confidence intervals.

The proposed RRM scheme comprises of two-way communications using multi-beam transmissions operating in the single frequency mode. We assume that two eMBB flows are requested by the NTN terminals. Since the overlapping MBAs (i.e., MBAs that share at least one beam where delivering both content items) may be formed, the radio resources are split to avoid inter-beam interference and are allocated according to a fair policy (i.e., the volume of available radio resources is equally divided between the two content flows).

We consider the simulation time of 1000 ms, which corresponds to 100 frames. We further assume that the channel conditions of the NTN terminals vary every Transmission Time Interval (TTI) and that the GEO-gNB schedules the transmissions towards the NTN terminals during every subframe that lasts 1 ms. We also consider $\mathcal{I} = 71$ to be the number of beams required to cover Europe [4]. More information about the modeling parameters is available in Table V.

We assess the following five environment types: Heavy Tree Shadowed, Intermediate Tree Shadowed, Open, Suburban, and Urban. For all of them, we study the performance in two different modeling cases:

- **Case A**, where the channel bandwidth is fixed to 30 MHz[3] (i.e., 160 RBs are available [34]), and the number of NTN terminals per beam varies from 100 to 1000;
- **Case B**, where the channel bandwidth varies from 5 to 30 MHz (that corresponds to 25, 52, 79, 106, 133, and 160 available RBs [34]), and the number of NTN terminals per beam is set to 1000.

The performance of the proposed SF-MBT scheme has been compared against that for the multi-beam NTN system based on a four-color frequency re-use scheme ($\rho = 2$) [1] and the multi-beam NTN system based on a three-color frequency re-use scheme ($\rho = 3$) [1]. The following metrics of interest have been evaluated:

---

[3] The maximum bandwidth allowed per beam is 30 MHz for S-band [1]

TABLE V: Main Modeling Parameters [1], [5].

PARAMETER	VALUE
NTN architecture option	GEO satellite equipped with transparent payload
GEO altitude	35786 km
GEO EIRP density	53.5 dBW/MHz
GEO Tx max gain	45.5 dBi
Beam footprint size	450 km (diameter)
Beam footprint type	Fixed
Beam footprint layout	Hexagonal
Number of beams	71 to cover all of Europe [4]
NTN terminal type	Handheld
NTN terminal distribution	100% outdoor
NTN terminal speed	3 kmph
NTN terminal antenna type	Omnidirectional with linear polarization
NTN terminal antenna gain	0 dBi
NTN terminal noise figure	9 dB
NTN terminal Tx power	23 dBm
Carrier frequency	S-band (i.e., 2 GHz)
Maximum bandwidth per beam	30 MHz for S-band
Numerology	0
Sub-carrier spacing	15 kHz
Transmission time interval	1 ms
Free-space pathloss	$L = 32.45 + 20\log_{10}(f_c) + 20\log_{10}(d)$ where: f_c is the frequency; d is the distance between the GEO and the NTN terminal

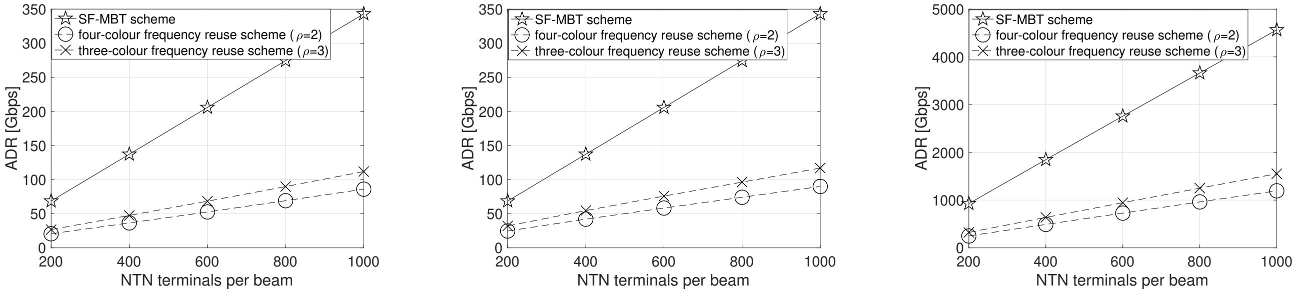
- **Mean Throughput** is the average data rate experienced by the NTN terminals.
- **ADR** is the sum of all the throughputs experienced by the NTN terminals.
- **System Spectral Efficiency** is the ratio between the number of bits received by the NTN terminals and the channel bandwidth of the reference system. This parameter indicates how efficient the radio resource management policy is since it provides information on the amount of system data over the channel bandwidth.

B. Analysis of Results

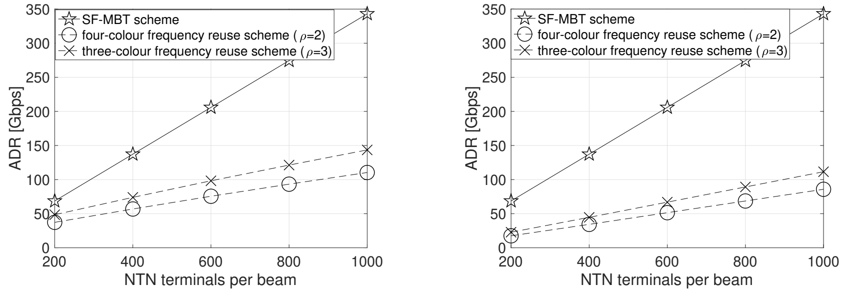
The selected performance results are grouped and analyzed according to the input parameters (i.e., case A and case B). Note that the curve for the SF-MBT scheme has been marked by a solid line with "$\star$", the curve for the four-color frequency reuse scheme has been marked by a dashed line with "o", while the curve for the three-color frequency reuse scheme has been marked by a dashed line with "x".

1) Case A: Fig. 3, 4, and 5 illustrate the ADR, mean throughput, and system spectral efficiency, respectively, for the three schemes in question under a varying number of NTN terminals per beam. It can be noted that – in all five environments – the proposed SF-MBT scheme provides the best system-wide results as compared to both four-color and three-color frequency re-use approaches. In more detail, the ADR follows a growing trend for an increased number of NTN terminals in the system. This behavior is due to the additive nature of the parameter since the ADR is computed as the sum of the data rates for all NTN terminals.

The ADR achieved by the proposed SF-MBT scheme ranges from 68 to 343 Gbps in most environments except for the Open case, where a high-performing multicast link is established; hence, the ADR achieves up to 4560 Gbps in the case of 1000 NTN terminals per beam. When considering a given MBA, it

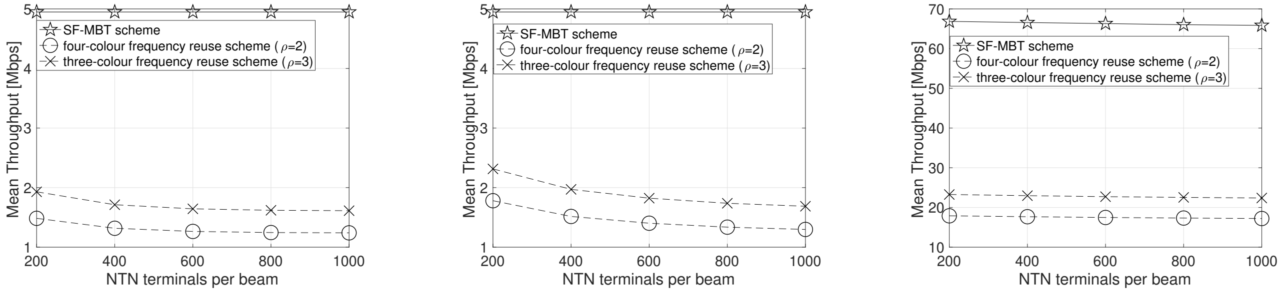


(a) Heavy Tree Shadowed (b) Intermediate Tree Shadowed (c) Open



(d) Suburban (e) Urban

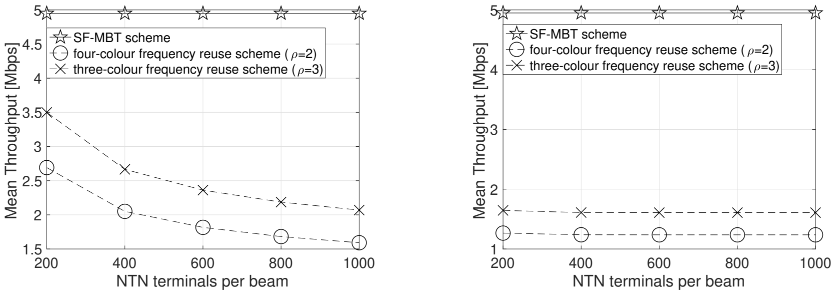
Fig. 3: ADR for SF-MBT, four-color, and three-color frequency re-use schemes with a varying number of NTN terminals per beam.



(a) Heavy Tree Shadowed

(b) Intermediate Tree Shadowed

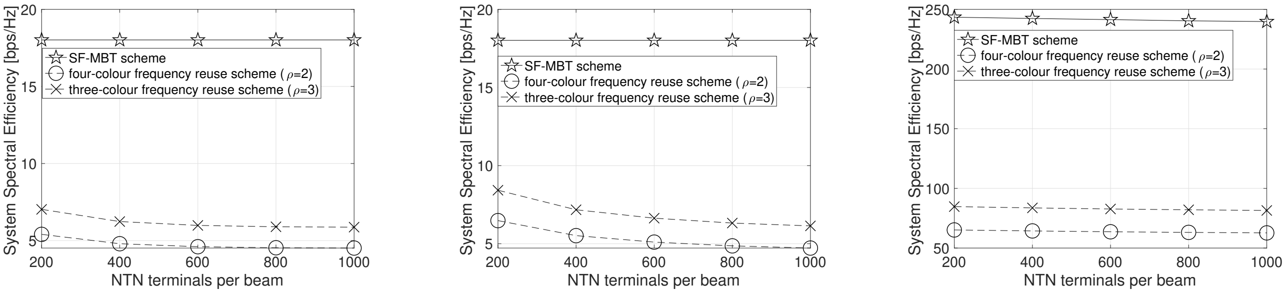
(c) Open



(d) Suburban

(e) Urban

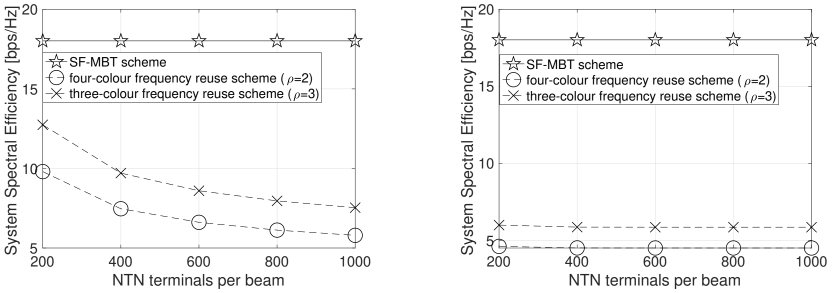
Fig. 4: Mean throughput for SF-MBT, four-color, and three-color frequency re-use schemes with a varying number of NTN terminals per beam.



(a) Heavy Tree Shadowed

(b) Intermediate Tree Shadowed

(c) Open



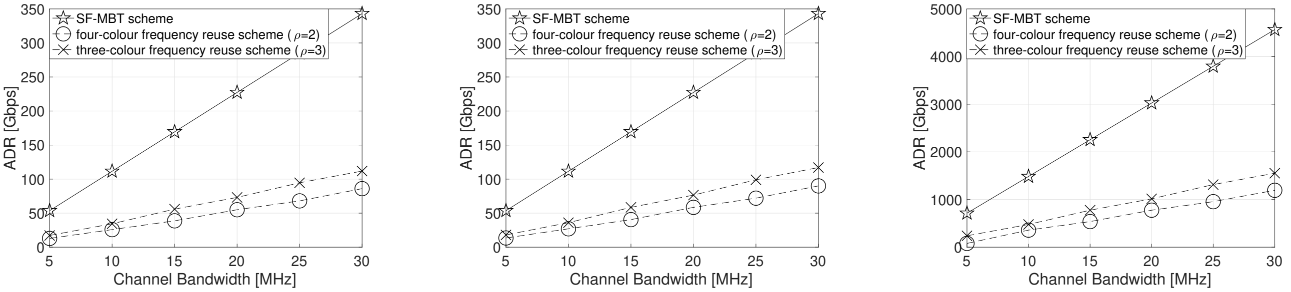
(d) Suburban

(e) Urban

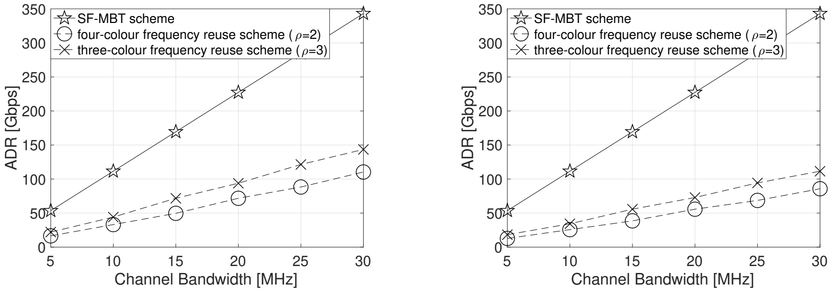
Fig. 5: System spectral efficiency for SF-MBT, four-color, and three-color frequency re-use schemes with a varying number of NTN terminals per beam.

is worth noting that the choice of the SF-MBT parameters is affected by the worst CSI perceived by the NTN terminals in that area; hence, the most robust modulation is selected. In contrast, the transmission parameters for both four-color and three-color frequency re-use schemes are chosen on a per-beam basis.

Therefore, the SF-MBT transmission may depend already on a single NTN terminal with poor channel conditions,

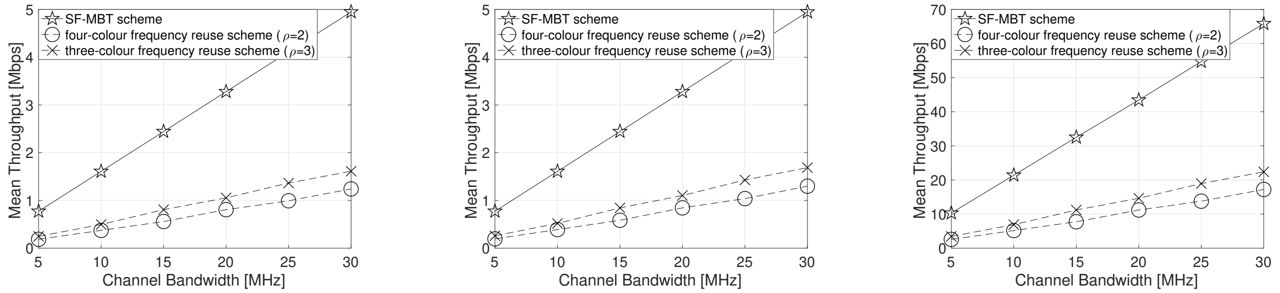


(a) Heavy Tree Shadowed (b) Intermediate Tree Shadowed (c) Open

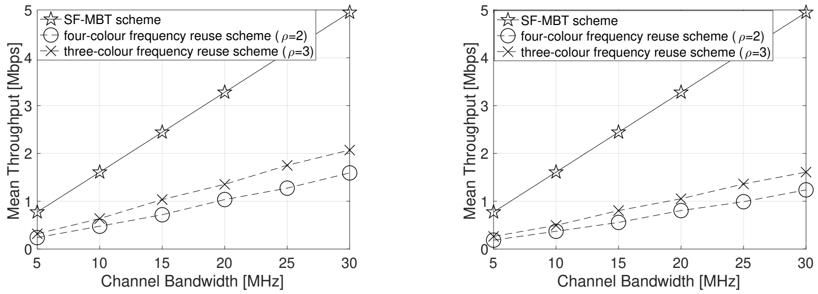


(d) Suburban (e) Urban

Fig. 6: ADR for SF-MBT, four-color, and three-color frequency re-use schemes with a varying channel bandwidth.



(a) Heavy Tree Shadowed (b) Intermediate Tree Shadowed (c) Open

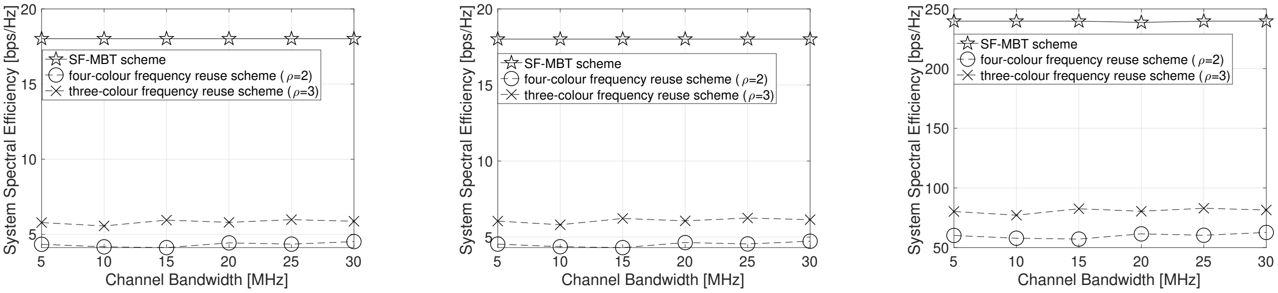


(d) Suburban (e) Urban

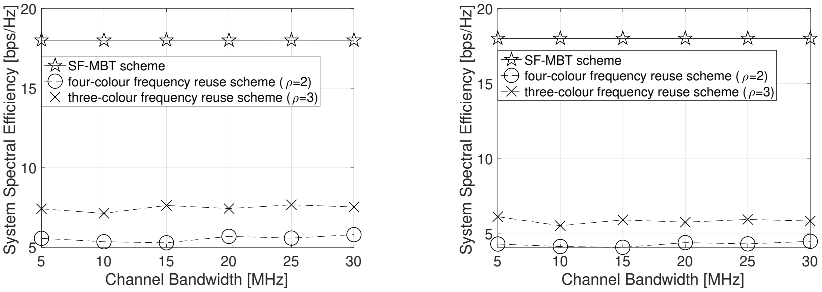
Fig. 7: Mean throughput for SF-MBT, four-color, and three-color frequency re-use schemes with a varying channel bandwidth.

whereas the frequency re-use based transmission varies beam by beam. In the latter case, the ADR (Fig. 3) is likely to differ from environment to environment for the two considered frequency re-use approaches. Indeed, with an increased number of NTN terminals in the system the mean throughput decreases since the probability to find at least one NTN terminal with worse channel conditions in each beam grows.

However, the mean throughput (Fig. 4) remains constant (i.e., 68 Mbps in the Open environment and about 5 Mbps in other environments) for the SF-MBT scheme as the number of NTN terminals grows since only one NTN terminal with adverse channel conditions in the NTN system suffices to yield



(a) Heavy Tree Shadowed (b) Intermediate Tree Shadowed (c) Open



(d) Suburban (e) Urban

Fig. 8: System spectral efficiency for SF-MBT, four-color, and three-color frequency re-use schemes with a varying channel bandwidth.

the most robust modulation for transmission. In Fig. 5, the system spectral efficiency provides information on the amount of data delivered per second over a given channel bandwidth. It follows the same trend as the mean throughput since the channel bandwidth is fixed at 30 MHz for the case A. The proposed scheme offers better utilization of the radio spectrum than the frequency re-use based approaches by attaining higher values of system spectral efficiency in all the considered environments.

2) Case B: Fig. 6, 7, and 8 demonstrate the ADR, mean throughput, and system spectral efficiency, respectively, for the three schemes in question under varying channel bandwidth. In all the environments, the proposed SF-MBT scheme reaches the highest values for all the metrics of interest with respect to the considered frequency re-use based approaches. Both ADR and mean throughput follow a growing trend for all the three schemes because an increased channel bandwidth (i.e., more radio resources) is considered. For the proposed SF-MBT scheme, the ADR (Fig. 6) ranges from 713 to 4560 Gbps in the Open environment and from 53 to 343 Gbps in other environments. Similar ADR values are achieved in Heavy Tree Shadowed, Intermediate Tree Shadowed, Urban, and Suburban environments due to a similar mean throughput performance.

The throughput depends on the modulation selected to allow all of the interested NTN terminals to decode the delivered data. In such environments, NTN terminals are likely to experience a varying channel, whose quality fluctuations can be irregular over time. Conversely, in the Open environment, the channel conditions of NTN terminals are excellent and do not vary drastically, which yields higher system-wide performance. As shown in Fig. 7, the mean throughput ranges from 10 to 67 Mbps in the Open environment while in other cases it spans from 791 kbps to 5 Mbps. Finally, in Fig. 8, the system spectral efficiency follows a near-constant trend for all the approaches in all the environments. However, the proposed SF-MBT scheme exploits the radio spectrum better than the frequency re-use options.

VI. CONCLUSION

In this paper, we proposed the SF-MBT (Single-Frequency Multi-Beam Transmission) scheme for broadcasting eMBB services through synchronous beam transmissions in 5G NR multi-beam NTN systems. Our SF-MBT approach expects that the beams of the same satellite are grouped into different MBAs (MBSFN Beam Areas), wherein all of the beams are synchronized in time to perform a simultaneous transmission of a certain service over the same radio resources. The MBAs can be *independent* or *overlapping*: an independent MBA comprises of beams wherein only one content item is delivered, whereas overlapping MBAs include at least one beam belonging to more MBAs, each delivering different content items.

Further, our SF-MBT scheme splits the radio resources among the overlapping MBAs to avoid interference during the data delivery, whereas all of the radio resources are allocated to independent MBAs. The proposed solution aims to overcome the limitations of the currently implemented policies, where different frequencies are re-used across the beams of the same satellite to avoid inter-beam interference. Finally, the effectiveness of the developed scheme is confirmed via extensive simulations that indicate its highest performance as compared to alternative frequency re-use approaches. Future work needs to address new radio resource management strategies for handling varying traffic demands.

VII. Acknowledgment

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