Enhancing URLLC in Integrated Aerial Terrestrial Networks: Design Insights and Performance Trade-offs

Muhammad Awais[1], Haris Pervaiz[1], Muhammad Ali Jamshed[2], Wenjuan Yu[1], Qiang Ni[1]
[1]School of Computing and Communications, Lancaster University, Lancaster LA1 4YW, UK;
[2]James Watt School of Engineering, University of Glasgow, Glasgow G12 8QQ, UK;
E-mails: {m.awais11, h.b.pervaiz, w.yu8, q.ni}@lancaster.ac.uk, muhammadali.jamshed@glasgow.ac.uk

***Abstract*—Non-orthogonal multiple access (NOMA) is a promising radio access technique that enables massive connectivity and increased spectral efficiency. The deployment of aerial base stations (ABSs) as a relay is also an optimistic goal that fairly serves a large number of internet of things (IoT) devices. On one side, ABS-assisted communication leverages effective communication services for secondary IoT devices in smart cities. On the other hand, NOMA allows several IoT devices to concurrently acquire the same frequency-time resource. To this end, weighted sum-rate (WSR) is an essential goal because it allows numerous trade-offs between user fairness and sum-rate efficiency. Therefore, this work aims to investigate the WSR for an integrated aerial terrestrial network subject to cellular power and delay constraints in downlink NOMA. Herein, a theoretical insight-based low-complexity iterative solution is provided for optimal power and blocklength allocation to achieve maximum sum-rate. For this purpose, the mixed-integer non-linear problem is formulated and a low-complexity near-optimal solution is proposed. Numerical results show that the proposed scheme achieves a near-optimal solution and outperforms baseline techniques, i.e., the performance gain of 5.18% over the legacy OMA system for NOMA with two IoT devices per subcarrier.**

I. INTRODUCTION

The advancement in the wireless communication industry is grown significantly over the last few decades [1]. It is expected that mobile data traffic will increase by 1000 folds to accommodate the internet of things (IoT) traffic [2]. To meet the dramatic increase in user demands, ultra-reliable low-latency communication (URLLC) is considered one of the key applications for next-generation wireless networks that is more intriguing and challenging as it forces the quality of services (QoS) to achieve a delay of less than 1 millisecond and reliability greater than 99.99% [3]. Similarly, the integration of aerial base stations (ABSs) with future generation wireless networks is another key alternative that helps to maintain these QoS [4]. As an instance, it helps to deliver various civil services and facilities (such as serving IoT devices) in smart cities. Furthermore, it provides services like security and manufacturing in smart industrial communication networks due to their on-demand deployment features [5].

In contrast to legacy orthogonal multiple access (OMA), non-orthogonal multiple access (NOMA) technologies with finite blocklength regimes are becoming a key technology to support URLLC requirements [6]- [7]. In comparison to OMA, the use of successive interference cancellation (SIC) at the receiver end allows more than one user to share the same resource block, hence providing better spectral efficiency. Therefore, the use of NOMA in cooperative communication has also attracted much attention for providing efficient spectral efficiency where there is an uneven demand pattern.

II. RELATED WORKS

Considering delay-sensitive applications, NOMA-assisted aerial terrestrial network in conjunction with a finite blocklength regime is also considered a key enabler for URLLC. Authors in [8] exploit the intrinsic attributes of power domain NOMA (PD-NOMA) to accommodate maximum devices without compromising the weighted sum-rate (WSR). Driven by real-time benefits, the concept of hybrid NOMA-OMA is also taken into consideration to support aerial-based communication. For example, a comparative analysis of OMA and NOMA is performed with a hybrid NOMA-OMA scheme by using fairness-based resource allocation [9]. Afterward, a lagrangian duality and dynamic programming (LDDP) based scheme is proposed for the collective channel and power assignment problem to maximize the sum-rate [10]. Further, it is noted that the Shannon-capacity formula is not applicable to predict the maximum rate in finite blocklength-based communication. Therefore, a finite capacity model is introduced, in which the length of the actual data remains the same as its meta-data [11]. Thereby, NOMA with finite blocklength presents a significant performance in terms of low latency and high-reliability constraints [12]. The latter work solely considers the deployment positions of IoT devices and positions of ABSs are optimized for link capacity and quality to/from ABS to determine opportunistic channel gain differences between each IoT device [13].

There is very limited work on utilizing the different access techniques and optimizing the system sum-rate for multi-hop integrated aerial terrestrial networks in a finite block-length regime. Therefore, we aim to maximize the sum-rate across the multi-hops for downlink multi-carrier NOMA (MC-NOMA) systems with the following contributions: 1) a projected gradient-based low-complexity near-optimal algorithmic solution is proposed for sum-rate maximization subject to delay and power constraints by using heterogeneous links, 2) the mixed-integer nonlinear optimization problem is formulated to achieve a near-optimal solution. At first, resource allocation and selection of cooperative ABS are performed. Afterward, blocklength and power allocation are optimized in each hop. The power control for each subcarrier is also a non-convex problem. Thereby, the selection of each IoT device per subcarrier is solved using dynamic programming and a projected gradient-based algorithmic solution is proposed to optimize power control by emphasizing real-time power constraints and 3) comparative analysis of the proposed optimal approach is also performed against two benchmark approaches, i.e., fixed blocklength approach, random blocklength approach using legacy OMA (commonly used in literature) and NOMA schemes. Monte-Carlo simulations show that the proposed scheme (optimal NOMA) has effectively maximized the WSR over the benchmark scheme (optimal NOMA) and high complexity LDDP scheme.

III. System Model

A. System Model

As illustrated in Fig 1, we consider a downlink hybrid OMA-NOMA system having single macro base station (MBS) and a set of ABSs ready to communicate (having the enough battery capacity to communicate) denoted by $\mathcal{U}$ = $\{1, 2, ..., |\mathrm{U}|, |\mathrm{U}{+}1|, ..., |\mathrm{J}|\}$ and $u \in \mathcal{U}$, which is further divided into two categories, i.e., set of serving and cooperative ABSs denoted by $\mathcal{U}_u$ and $\mathcal{U}_h$, respectively. Where, $|.|$ represents the cardinality of a finite set. The set of $\mathcal{U}_u$ is represented as $\mathcal{U}_u = \{1, 2, ..., |\mathrm{U}|\}$, $u_u \in \mathcal{U}_u$ and the set of $\mathcal{U}_h$ is represented as $\mathcal{U}_h$ = $\{|\mathrm{U}{+}1|, |\mathrm{U}{+}2|, ..., |\mathrm{J}|\}$, $u_h \in \mathcal{U}_h$. The set of both serving and cooperative ABSs are not fixed, they can vary depending upon different scenarios but in our work they cannot be more than $\mathcal{U}_h$ and $\mathcal{U}_u$. Cooperative ABSs are used as relay to extend the MBS coverage (using OMA) while the serving ABSs are used to provide coverage to IoT devices within its transmission range (using PD-NOMA).

The set of IoT devices covered by MBS is represented by $\mathcal{M} = \{1, 2, ..., |\mathcal{M}|\}$, $m \in \mathcal{M}$ and the set of IoT devices covered by each $u_u \in \mathcal{U}_u$ is denoted by $\mathcal{I}_{u_u}$ $=\{1, 2, ..., |\mathcal{I}_{u_u}|\}$, $i_{u_u} \in \mathcal{I}_{u_u}$. It is noted that the channel state information (CSI) is determined by using pilot signals and each serving ABS in $\mathcal{U}_u$ can serve $i_{u_u} \in \mathcal{I}_{u_u}$ IoT devices having different weights to provide fairness among them. The total bandwidth W is divided into $|\mathcal{N}|$ orthogonal subcarriers $\mathcal{N} = \{1, 2, ..., |\mathcal{N}|\}$, $n \in \mathcal{N}$ which are further subdivided into two sets denoted by $\mathcal{N}_1$ and $\mathcal{N}_2$. The subcarriers belonging to set $\mathcal{N}_1$ are distributed orthogonally among $u_h \in \mathcal{U}_h$ and $m \in \mathcal{M}$ represented by $\underline{\mathcal{N}_1}$ and $\overline{\mathcal{N}_1}$. Whereas, subcarriers belonging to the subcarrier set $\overline{\mathcal{N}_1}$ are also shared among the links between $u_h \in \mathcal{U}_h$ and $u_u \in \mathcal{U}_u$. The subcarriers belonging to the subcarrier set $\mathcal{N}_2$ are orthogonally shared between $\mathcal{U}_u$.

In case of PD-NOMA, we denoted the set of clusters in each serving ABS $u_u \in \mathcal{U}_u$ as $\mathcal{C}_{u_u}$ = $\{1, 2, ..., |\mathrm{C}_{u_u}|\}$,

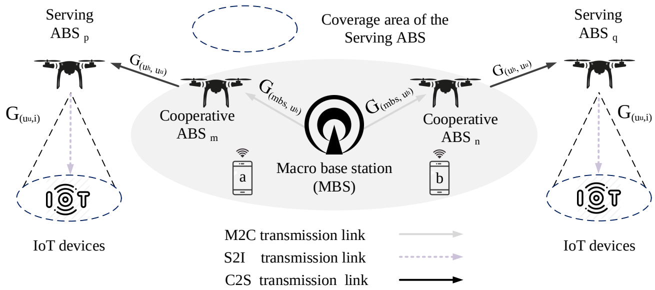

Fig. 1: A description of system model with set of cooperative ABS $\mathcal{U}_h = \{m, n\}$, set of serving ABS $\mathcal{U}_u = \{p, q\}$, $|\mathcal{M}|$ IoT devices within the coverage area of MBS and $|\mathcal{I}_{u_u}|$ IoT devices within the coverage area of serving ABS $u_u \in \mathcal{U}_u$.

$c_{u_u} \in \mathcal{C}_{u_u}$ having different number of IoT devices in each cluster. Further, the number of superposed signals on each subcarrier should be no more than $|\mathrm{S}|$ which will restrict the total number of active IoT devices on a given subcarrier. The decoding order on given subcarrier is defined as a permutation function over all the IoT devices, i.e., $\pi_{n_2} : \{1, 2, ..., |\mathrm{S}|\} \rightarrow \mathcal{I}_{u_u}$. For $i_{u_u} \in \{1, 2, ..., |\mathrm{S}|\}$, $\pi_{n_2}(i_{u_u})$ returns the index of the $(i_{u_u})^{th}$ decoded IoT device while $\pi_{n_2}^{-1}(i_{u_u})$ returns the decoding order of IoT device i_{u_u}. Since, SIC can decode the multiplexed signals successfully, if its received signal to residual interference ratio $\Gamma_{i_{u_u}}^{n_2}$ is equal to or higher than a reference threshold $\hbar$; therefore it must satisfy $(G_{u_u, i_{u_u}}^{n_2} P_{u_u, i_{u_u}}^{n_2})/\Gamma_{i_{u_u}}^{n_2} \geq \hbar \geq 1$. Whereas, $G_{u_u, i_{u_u}}^{n_2}$ is the channel gain for transmission link between serving ABS u_u and IoT device i_{u_u}, and $P_{u_u, i_{u_u}}^{n_2}$ is the transmitted power allocated by the serving ABS u_u to the IoT device i_{u_u}. Whereas, $\Gamma_{i_{u_u}}^{n_2} = \sum_{j=\pi_{n_2}^{-1}(i_{u_u})+1, j\neq i}^{|\mathrm{S}|} G_{\pi(j), i_{u_u}}^{n_2} P_{\pi(j), i_{u_u}}^{n_2}$.

B. Channel Model

The signal to noise ratio (SNR) $\varrho_{\text{mbs}, u_h}^{n_1}$ at u_h is given as $\varrho_{\text{mbs}, u_h}^{n_1} = \theta_{\text{mbs}, u_h}^{n_1} P_{0, u_h}^{n_1} G_{\text{mbs}, u_h}^{n_1} d_{\text{mbs}, u_h}^{-\alpha_{\text{mbs}}} / \delta_{\text{mbs}}^2$, where $\theta_{\text{mbs}, u_h}^{n_1}$ is a subcarrier allocation index, i.e., $\theta_{\text{mbs}, u_h}^{n_1} = 1$, if subcarrier $\underline{n_1}$ is allocated to cooperative ABS u_h; otherwise 0. Moreover, δ_{mbs}^2 is additive white gaussian noise (AWGN), $P_{0, u_h}^{n_1}$ shows the transmitted power of the MBS at a given subcarrier, $d_{\text{mbs}, u_h}^{-\alpha_{\text{mbs}}}$ represents the pathloss between MBS and cooperative ABS u_h having pathloss exponent α_{mbs} and $G_{\text{mbs}, u_h}^{n_1}$ denotes the channel gain for the given link. The achievable rate for this hop is calculated as in [1]:

$$R_{\text{mbs}, u_h}^{n_1} = W_{\underline{n_1}} \log_2(1 + \varrho_{\text{mbs}, u_h}^{n_1}) - \sqrt{\frac{V_{\text{mbs}, u_h}^{n_1}}{m_{u_h}}} \frac{Q^{-1}(\epsilon_1)}{\ln 2}, \quad (1)$$

where, $W_{\underline{n_1}}$ is the bandwidth at the subcarrier $\underline{n_1}$ and m_{u_h} is the blocklength for the transmission link between MBS to cooperative ABS u_h. Moreover, decoding error probability is denoted by ϵ_1 and $Q^{-1}(\cdot)$ is the inverse of Gaussian Q-function [16]. The channel dispersion for this link is calculated as $V_{\text{mbs}, u_h}^{n_1} = 1 - (1 + \varrho_{\text{mbs}, u_h}^{n_1})^{-2}$ and its value will be equal to zero, if $\theta_{\text{mbs}, u_h}^{n_1} = 0$. The SNR at IoT device m within the MBS is computed as $\varrho^{\overline{n_1}}_{\text{mbs},m} = \frac{\theta^{\overline{n_1}}_{\text{mbs},m} P^{\overline{n_1}}_{0,m} G^{\overline{n_1}}_{\text{mbs},m} d^{-\alpha_{\text{mbs}}}_{\text{mbs},m}}{\delta^2_{\text{mbs}} + P^{\overline{n}_1}_{u_h,u_u} G^{\overline{n}_1}_{u_h,m} d^{-\alpha_{\text{mbs}}}_{u_h,m}}$. Here, $\theta^{\overline{n_1}}_{\text{mbs},m}$ is the subcarrier allocation index, $P^{\overline{n_1}}_{0,m}$ shows the transmitted power allocated by the MBS to the IoT device m at a given subcarrier, $G^{\overline{n_1}}_{\text{mbs},m}$ is the channel gain between MBS and IoT device m and $d^{-\alpha_{\text{mbs}}}_{\text{mbs},m}$ is the channel pathloss for the given link. Whereas, $P^{\overline{n_1}}_{u_h,u_u}$ is the power allocated by MBS to the cooperative ABS u_h at the given subcarrier, $G^{\overline{n}_1}_{u_h,m}$ is the channel gain between cooperative ABS u_h and the IoT device m and $d^{-\alpha_{\text{mbs}}}_{u_h,m}$ is the pathloss for the given link. The achievable rate of this link is calculated as

$$R^{\overline{n_1}}_{\text{mbs},m} = W_{\overline{n_1}} \log_2(1 + \varrho^{\overline{n_1}}_{\text{mbs},m}) - \sqrt{\frac{V^{\overline{n_1}}_{\text{mbs},m}}{m_m}} \frac{Q^{-1}(\epsilon_1)}{\ln 2}, \quad (2)$$

where, $W_{\overline{n_1}}$ is the subcarrier bandwidth, m_m is the blocklength for the given link and $V^{\overline{n_1}}_{\text{mbs},m} = 1 - (1 + \varrho^{\overline{n_1}}_{\text{mbs},m})^{-2}$ is the channel dispersion. The received signal to interference and noise ratio (SINR) is computed as $\varrho^{\overline{n}_1}_{u_h,u_u} = \frac{\theta^{\overline{n}_1}_{u_h,u_u} P^{\overline{n}_1}_{u_h,u_u} G^{\overline{n}_1}_{u_h,u_u} d^{-\alpha_{\text{mbs}}}_{u_h,u_u}}{\delta^2_{\mathcal{U}_u} + \sum_{m \in \mathcal{M}} \xi^{\overline{n}_1}_{\text{mbs},m} P^{\overline{n}_1}_{0,m} G^{\overline{n}_1}_{mbs,u_u} d^{-\alpha_{\text{mbs}}}_{\text{mbs},u_u}}$. Herein, $\theta^{\overline{n}_1}_{u_h,u_u}$ is the subcarrier allocation index, $\delta^2_{\mathcal{U}_u}$ is the AWGN, $G^{\overline{n}_1}_{u_h,u_u}$ is the channel gain between u_h and u_u and $d^{-\alpha_{\text{mbs}}}_{u_h,u_u}$ denotes the pathloss at the given subcarrier. Whereas, $\xi^{\overline{n_1}}_{\text{mbs},m}$ is the binary indicator for the reused subcarrier, $G^{\overline{n}_1}_{mbs,u_u}$ represents the channel gain between MBS and serving ABS u_u and $d^{-\alpha_{\text{mbs}}}_{\text{mbs},u_u}$ denotes the pathloss. The achievable rate for this transmission link is given as

$$R^{\overline{n}_1}_{u_h,u_u} = W_{\overline{n_1}} \log_2(1 + \varrho^{\overline{n}_1}_{u_h,u_u}) - \sqrt{\frac{V^{\overline{n}_1}_{u_h,u_u}}{m_{u_h,u_u}}} \frac{Q^{-1}(\epsilon_2)}{\ln 2}. \quad (3)$$

Here, $W_{\overline{n_1}}$ denotes the bandwidth at the given subcarrier and ϵ_2 is the required decoding packet error probability. Whereas, the blocklength from hop 2 is given by m_{u_h,u_u} and $V^{\overline{n}_1}_{u_h,u_u} = \left(1 - (1 + \varrho^{\overline{n}_1}_{u_h,u_u})^{-2}\right)$ is channel dispersion. Whereas, the SINR for each IoT device i_{u_u} is expressed as $\tau^{n_2}_{u_u,i_{u_u}} = \frac{\theta^{n_2}_{u_u,i_{u_u}} P^{n_2}_{u_u,i_{u_u}} (G^{n_2}_{u_u,i_{u_u}} / PL_{\text{avg},i_{u_u}})}{\overline{\Im}_{n_2,i_{u_u}} + \Gamma^{n_2}_{i_{u_u}}}$, here, $\theta^{n_2}_{u_u,i_{u_u}}$ represents the subcarrier allocation index and $PL_{\text{avg},i_{u_u}}$ is the average pathloss between serving ABS to IoT device i_{u_u} computed by using (8) in [5]. Whereas, $\overline{\Im}_{n_2,i_{u_u}}$ is the received normalized noise power. The achievable rate for this hop is calculated as

$$R^{n_2}_{u_u,i_{u_u}} = W_{n_2} w_{i_{u_u}} \log_2(1 + \tau^{n_2}_{u_u,i_{u_u}}) - \sqrt{\frac{V^{n_2}_{u_u,i_{u_u}}}{m_{i_{u_u}}}} \frac{Q^{-1}(\epsilon_3)}{\ln 2}, \quad (4)$$

here, W_{n_2} denotes the bandwidth at the given subcarrier. Whereas, $w_{i_{u_u}}$ and $m_{i_{u_u}}$ represent the weight and blocklength for the following IoT device, respectively.

IV. Problem Formulation

The fundamental aim of the work is to design an optimal approach to maximize the total achievable rate by optimizing the blocklength across each hop. It is worth noting that cooperative ABSs that are used to relay the required information from MBS to IoT devices within the vicinity of serving ABS; therefore, the rate of the links between MBS to cooperative ABSs is only included in the optimization problem. Thus, we formulate the proposed optimization problem as

$$\begin{aligned}
P1: \max \quad & \min \Big(R^{n_1}_{\text{mbs},u_h}(\theta^{n_1}_{\text{mbs},u_h}, m_{u_h}, P^{n_1}_{0,u_h}), R^{\overline{n}_1}_{u_h,u_u} \\
& (\theta^{\overline{n}_1}_{u_h,u_u}, m_{u_h,u_u}, P^{\overline{n}_1}_{u_h,u_u}), R^{n_2}_{u_u,i_{u_u}}(\theta^{n_2}_{u_u,i_{u_u}} \\
& , m_{i_{u_u}}, P^{n_2}_{u_u,i_{u_u}}) \Big) \\
\text{s.t.} \quad & C1: \textstyle\sum_{n_1 \in \mathcal{N}_1} \theta^{n_1}_{\text{mbs},u_h} \leq 1, \sum_{\overline{n_1} \in \overline{\mathcal{N}_1}} \theta^{\overline{n}_1}_{u_h,u_u} \leq 1 \\
& \textstyle\sum_{n_2 \in \mathcal{N}_2} \theta^{n_2}_{u_u,i_{u_u}} \leq |\mathrm{S}|, \\
& C2: \overbrace{\sum_{m \in \mathcal{M}} m_m}^{m_{\text{mbs}\to m}} + \overbrace{\sum_{u_h \in \mathcal{U}_h} m_{u_h}}^{m_{\text{mbs}\to u_h}} + \overbrace{\sum_{u_u \in \mathcal{U}_u} m_{u_h,u_u}}^{m_{u_h \to u_u}} \\
& \quad + \overbrace{\sum_{u_u \in \mathcal{U}_u} \sum_{c_{u_u} \in \mathcal{C}_{u_u}} m_{c_{u_u},u_u}}^{m_{u_u \to c_{u_u}}} \leq M_{\max}, \\
& \quad \forall\, (m_m, m_{u_h}, m_{u_h,u_u}, m_{c_{u_u},u_u}) \in \mathbb{Z}^+ \\
& C3: \left(x^2 + y^2\right) \leq r^2_{\max} \\
& C4: \textstyle\sum_{i_{u_u} \in \mathcal{I}_{u_u}} \sum_{n_2 \in \mathcal{N}_2} \propto^{n_2}_{u_u,i_{u_u}} P^{n_2}_{u_u,i_{u_u}} \\
& \quad \leq P^{\max}_{u_u}, \forall u_u \\
& C5: (G^{n_2}_{u_u,i_{u_u}} P^{n_2}_{u_u,i_{u_u}}) / \Gamma^{n_2}_{i_{u_u}} \geq \hbar, \ \forall i_{u_u}, \forall n_2.
\end{aligned} \quad (5)$$

The constraint $C1$ ensures that each subcarrier should not be allocated to more than $|\mathrm{S}|$ IoT devices, e.g., in case of OMA $|\mathrm{S}| = 1$. The constraint $C2$ ensures that the maximum transmission delay does not exceed $M_{\max}$ and ensures that blocklength is a positive integer, i.e., $\{m_{\text{mbs}\to m} + m_{\text{mbs}\to u_h} + m_{u_h \to u_u} + m_{u_u \to c_{u_u}}\} \leq M_{\max}$, here $m_{u_u \to c_{u_u}}$ is the blocklength of the cluster c_{u_u} laying with the coverage of serving ABS u_u. Constraint $C3$ guarantees that the position of the MBS should lie within the serving cell having radius $r_{\max}$. Constraint $C4$ represents the entire power budget $P^{\max}_{u_u}$ at the serving ABS. $\propto^{n_2}_{u_u,i_{u_u}}$ is a binary indicator, i.e., $\propto^{n_2}_{u_u,i_{u_u}} = 1$ if a serving ABS u_u is serving IoT device i_{u_u} on the given subcarrier n_2, otherwise it is 0. Constraint $C5$ ensures that SIC can easily remove the interference from the received signal, i.e., valid for NOMA case, where $|\mathrm{S}| > 1$.

It is noted that our maximization problem is a mixed-integer non-linear which is generally NP-hard because of its non-convexity in combinatorial constraint $C2$ and non-convex normal approximation appearing in the objective function [16]. However, problem (5) can be solved using monotonic optimization in conjunction with a penalty approach at a high computational cost [17]. To this end, we solve it by using its decomposition property to simplify the problem. We decouple the original problem into two sub-problems by applying a standard relaxation mechanism, e.g., 1) selection of cooperative ABS and subcarrier allocation and 2) joint blocklength and power allocation optimization.

A. Proposed Solution

1) Subcarrier Allocation and Selection of Cooperative ABSs: We denote the blocklength vector as $\boldsymbol{B} = \left[m_{\text{mbs}\to m} \ m_{\text{mbs}\to u_h} \ m_{u_h \to u_u} \ m_{u_u \to c_{u_u}}\right]$ including blocklengths of each user (i.e., in our case ABSs and

IoT devices), the subcarrier indicator vector as $\boldsymbol{\theta} = [\theta^{\overline{n_1}}_{\text{mbs},m}\ \theta^{\underline{n_1}}_{\text{mbs},u_h}\ \theta^{\overline{n}_1}_{u_h,u_u}\ \theta^{n_2}_{u_u,i_{u_u}}]$ and the power allocation vector as $\boldsymbol{P} = [P^{\overline{n_1}}_{0,m}\ P^{\underline{n_1}}_{0,u_h}\ P^{\overline{n}_1}_{u_h,u_u}\ P^{n_2}_{u_u,i_{u_u}}]$ having power of each user. In this sub-problem, we solve the problem (6), with the fixed values of $(\boldsymbol{B}^{(i)}, \boldsymbol{P}^{(i)})$ to find the next iterative solution of subcarrier allocation.

$$\begin{aligned} \max \quad & \min\Big(R^{\underline{n_1}}_{\text{mbs},u_h}(\theta^{\underline{n_1}}_{\text{mbs},u_h}, m_{u_h}, P^{\underline{n_1}}_{0,u_h}), R^{\overline{n}_1}_{u_h,u_u}(\theta^{\overline{n}_1}_{u_h,u_u}, \\ & m_{u_h,u_u}, P^{\overline{n}_1}_{u_h,u_u}), R^{n_2}_{u_u,i_{u_u}}(\theta^{n_2}_{u_u,i_{u_u}}, m_{i_{u_u}}, P^{n_2}_{u_u,i_{u_u}})\Big) \\ \text{s.t.} \quad & C2 - C5. \end{aligned} \tag{6}$$

The subcarriers are allocated on the basis of maximum achievable rate. We compute $(\boldsymbol{\theta})^{i+1}$ as $\theta^{\overline{n_1}^{i+1}}_{\text{mbs},m} = \arg\max_{\overline{n_1}\in\overline{\mathcal{N}_1}} R^{\overline{n_1}}_{\text{mbs},m}(\text{mbs}, m, :),\ \forall\ m \in \mathcal{M}$, $\theta^{\underline{n_1}^{i+1}}_{\text{mbs},u_h} = \arg\max_{\underline{n_1}\in\underline{\mathcal{N}_1}} R^{\underline{n_1}}_{\text{mbs},u_h}(\text{mbs}, u_h, :),\ \forall\ u_h \in \mathcal{U}_h$, $\theta^{\overline{n_1}^{i+1}}_{u_h,u_u} = \arg\max_{\overline{n_1}\in\overline{\mathcal{N}_1}} R^{\overline{n}_1}_{u_h,u_u}(u_h, u_u, :),\ \forall\ u_u \in \mathcal{U}_u$ and $\theta^{n_2^{i+1}}_{u_u,i_{u_u}} = \arg\max_{n_2\in\mathcal{N}_2} R^{n_2}_{u_u,i_{u_u}}(u_u, i_{u_u}, :),\ \forall\ i_{u_u} \in \mathcal{I}_{u_u}$. Similarly, best cooperative ABSs are intelligently selected among all (to serve serving ABSs) on the basis of maximum achievable rate, which basically depends on the rate across MBS to cooperative ABS and cooperative ABS to serving ABS transmission link.

2) Joint Blocklength and Power Allocation Optimization: In this sub-section, firstly we solve the problem (7) with fixed values of $(\boldsymbol{\theta}^{(i+1)}, \boldsymbol{P}^{(i)})$ to find next optimal value of $\boldsymbol{B}^{(i+1)}$.

$$\begin{aligned} \max \quad & \min\Big(R^{\underline{n_1}}_{\text{mbs},u_h}(\theta^{\underline{n_1}^{i+1}}_{\text{mbs},u_h}, m_{u_h}, P^{\underline{n_1}}_{0,u_h}), R^{\overline{n}_1}_{u_h,u_u}(\theta^{\overline{n}_1^{i+1}}_{u_h,u_u}, \\ & m_{u_h,u_u}, P^{\overline{n}_1}_{u_h,u_u}), R^{n_2}_{u_u,i_{u_u}}(\theta^{n_2^{i+1}}_{u_u,i_{u_u}}, m_{i_{u_u}}, P^{n_2}_{u_u,i_{u_u}})\Big) \\ \text{s.t.} \quad & C3 - C5. \end{aligned} \tag{7}$$

To compute optimal blocklength of each hop, variable $\boldsymbol{B}^{(i+1)}_{\text{low}}$ and $\boldsymbol{B}^{(i+1)}_{\text{high}}$ are initialized. Then, bisection search method is applied to search the range until an optimal values of blocklengths are computed. Secondly, we solve the problem (8) with fixed values of $(\boldsymbol{\theta}^{(i+1)}, \boldsymbol{B}^{(i+1)})$ to find next optimal value of $\boldsymbol{P}^{(i+1)}$.

$$\begin{aligned} \max \quad & \min\Big(R^{\underline{n_1}}_{\text{mbs},u_h}(\theta^{\underline{n_1}^{i+1}}_{\text{mbs},u_h}, m^{i+1}_{u_h}, P^{\underline{n_1}}_{0,u_h}), R^{\overline{n}_1}_{u_h,u_u}(\theta^{\overline{n}_1^{i+1}}_{u_h,u_u}, \\ & m^{i+1}_{u_h,u_u}, P^{\overline{n}_1}_{u_h,u_u}), R^{n_2}_{u_u,i_{u_u}}(\theta^{n_2^{i+1}}_{u_u,i_{u_u}}, m^{i+1}_{i_{u_u}}, P^{n_2}_{u_u,i_{u_u}})\Big) \\ \text{s.t.} \quad & C4 - C5. \end{aligned} \tag{8}$$

Since power allocation for the selected cooperative ABSs and IoT devices within MBS coverage area should meet the minimum QoS requirement R_{min}. Therefore, we use single-level water-filling to get optimal powers then perform multilevel water-filling with total transmit power P_0. As each communication link need to satisfy the minimum QoS requirements so their received SINR should be greater than or equal to the SINR threshold ϱ_{min} as follow:

$$\varrho^{\overline{n}_1}_{\text{mbs},m} = \left(\frac{\theta^{\overline{n}_1}_{\text{mbs},m} P^{\overline{n}_1}_{0,m} h^{\overline{n_1}}_{\text{mbs},m}}{\delta^2_{\text{mbs}} + P^{\overline{n}_1}_{u_h,u_u} h^{\overline{n}_1}_{u_h,m}}\right) \geq \varrho_{\text{min}}, \tag{9}$$

where $h^{\overline{n_1}}_{\text{mbs},m} = G^{\overline{n_1}}_{\text{mbs},m} \times d^{-\alpha_{\text{mbs}}}_{\text{mbs},m}$ and $h^{\overline{n}_1}_{u_h,m} = G^{\overline{n}_1}_{u_h,m} \times d^{-\alpha_{\text{mbs}}}_{u_h,m}$. The maximum power that can be allocated to the cooperative ABS and serving ABS communication links must be constrained in order to ensure that the IoT devices within the MBS must be able to satisfy their minimum QoS requirements is given by:

$$P^{\overline{n}_1}_{u_h,u_u} \leq \left(\frac{P^{\overline{n}_1}_{0,m} h^{\overline{n}_1}_{\text{mbs},m}}{\varrho_{\text{min}} h^{\overline{n}_1}_{u_h,m}} - \frac{\delta^2_{\text{mbs}}}{h^{\overline{n}_1}_{u_h,m}}\right) \leq P^{\text{max}}_{u_u}, \tag{10}$$

The received SINR of the serving ABS u_u from the co-operating ABS u_h on the subcarriers $\overline{n}_1$ (reused by the MBS and IoT devices link) is computed in section III. Hence, the minimum power $\overline{P}^{\overline{n}_1}_{u_h,u_u}$ that can be allocated to the link between the cooperative ABS and serving ABS must be able satisfy its minimum QoS requirements can be written as

$$\varrho^{\overline{n}_1}_{u_h,u_u} = \left(\frac{\theta^{\overline{n}_1}_{u_h,u_u} \overline{P}^{\overline{n}_1}_{u_h,u_u} G^{\overline{n}_1}_{u_h,u_u} d^{-\alpha_{\text{mbs}}}_{u_h,u_u}}{\delta^2_{\mathcal{U}_u} + \sum_{m\in\mathcal{M}} \xi^{\overline{n_1}}_{\text{mbs},m} P^{\overline{n}_1}_{0,m} h^{\overline{n}_1}_{u_u,m}}\right) \geq \varrho_{\text{min}}, \tag{11}$$

$$\overline{P}^{\overline{n}_1}_{u_h,u_u} \leq \frac{\left(\delta^2_{\mathcal{U}_u} + \sum_{m\in\mathcal{M}} \xi^{\overline{n_1}}_{\text{mbs},m} P^{\overline{n}_1}_{0,m} h^{\overline{n}_1}_{u_u,m}\right) \varrho_{\text{min}}}{G^{\overline{n}_1}_{u_h,u_u} d^{-\alpha_{\text{mbs}}}_{u_h,u_u}}, \tag{12}$$

where $\varrho^{\overline{n}_1,opt}_{u_h,u_u}$ is computed by setting $P^{\overline{n}_1}_{u_h,u_u} = P^{\overline{n}_1,opt}_{u_h,u_u}$.

$$P^{\overline{n}_1,opt}_{u_h,u_u} = \begin{cases} 0, & \text{if } \overline{P}^{\overline{n}_1}_{u_h,u_u} > P^{\overline{n}_1}_{u_h,u_u} \\ P^{\overline{n}_1}_{u_h,u_u}, & \text{if } \overline{P}^{\overline{n}_1}_{u_h,u_u} < P^{\overline{n}_1}_{u_h,u_u} \\ P^{\text{max}}_{u_u}, & \text{if } P^{\text{max}}_{u_u} \in [\overline{P}^{\overline{n}_1}_{u_h,u_u}, P^{\overline{n}_1}_{u_h,u_u}] \\ \min\left(P^{\overline{n}_1}_{u_h,u_u}, \max\left(P^{\text{max}}_{u_u}, \overline{P}^{\overline{n}_1}_{u_h,u_u}\right)\right), & \text{Otherwise.} \end{cases} \tag{13}$$

In PD-NOMA, a two stage mechanism is adopted to distribute the total power among each cluster. Firstly, maximum available power of the serving ABS is distributed between each subcarrier denoted as $P^{n_2}_{u_u}$. Then optimal power for given subcarrier is computed in such a way that it should be greater than zero and less then the $P^{n_2}_{u_u}$. However, sum of the powers for all given subcarriers should be less than $P^{\text{max}}_{u_u}$. Secondly, this power is allocated to each IoT device which is active on the given subcarrier. The sum of the allocated powers between each IoT device within the same cluster must be less than or equal to $\overline{P}_{n_2}$. It is mathematically represented as

$$\overline{P}_{n_2} \geq \sum_{i_{u_u}=1}^{|S|} \propto^{n_2}_{u_u,i_{u_u}} P^{n_2}_{u_u,i_{u_u}}, \forall\ n_2 \text{ and } \forall\ u_u, \tag{14}$$

here, each IoT device must have the power greater than zero, i.e., $P^{n_2}_{u_u,i_{u_u}} > 0$ to be considered as active on the given subcarrier. The feasible set $\mathcal{R}'$ following the above constraints is expressed as $\mathcal{R}' = \{\sum_{n_2\in\mathcal{N}_2} \overline{P}_{n_2} \leq P^{\text{max}}_{u_u}$ and $0 < \overline{P}_{n_2} \leq P^{n_2}_{u_u}\}$. Here, $\overline{P}_{n_2}\ \forall\ n_2 \in \mathcal{N}_2$ are intermediate variables representing each subcarrier's power budget. The reformulated problem is solved in an iterative manner to achieve a near-optimum solution, i.e., it works in two stages as in the outer stage the values of blocklength are selected for the given subcarrier allocation and in the inner stage the power allocation is computed for the given subcarrier allocation and blocklength of all three hops. These two stages are repeated iteratively until the converged solution for both

Algorithm 1 Proposed Iterative Low Complexity Procedure for Problem $P1$

Input: Set $i = 0$, and randomly choose initial feasible points $\boldsymbol{\theta}^{(0)}$, $\boldsymbol{B}^{(0)}$ and
$\boldsymbol{P}^{(0)}$, iterative index $i = 1$, maximum number of iterations t_{max}
Output: $\{\boldsymbol{\theta}^{(*)}, \boldsymbol{B}^{(*)}, \boldsymbol{P}^{(*)}\}$
Repeat
Solve the problem (6), with the fixed values of $(\boldsymbol{B}^{(i)}, \boldsymbol{P}^{(i)})$to find the next
iterative solution of subcarrier allocation $\boldsymbol{\theta}^{(i+1)}$
Best cooperative ABSs are selected depending on achievable rate across
MBS to cooperative ABS and cooperative ABS to serving ABS transmission link
Solve (7) for fixed values of $(\boldsymbol{\theta}^{(i+1)}, \boldsymbol{P}^{(i)})$ to find next optimal value of
$\boldsymbol{B}^{(i+1)}$
Solve (8) for fixed values of $(\boldsymbol{\theta}^{(i+1)}, \boldsymbol{B}^{(i+1)})$ to find next optimal value of
$\boldsymbol{P}^{(i+1)}$
Set $i := i + 1$
Until: Convergence or $i > t_{\text{max}}$
end procedure

stages is achieved or $i > t_{\text{max}}$. More details can be found in Algorithm 1.

V. Simulations and Discussions

A. Simulations Setup

We consider MBS with $P_0 = 40$ Watts having $r_{\text{max}} = 500$ Meters. Further, we assume $\mathcal{M} = 5$, $\mathcal{U}_u = 2$, $\mathcal{U}_h = 5$. The radius of both serving ABSs is assumed to be 100 meters with their respective IoT devices set to $\mathcal{I}_p = 9$ and $\mathcal{I}_q = 11$, respectively. The altitude of ABSs is assumed to be 50 Meters having transmission power of 1 Watt each. We practice the radio propagation channel given in [1]. Whereas, the distance between cooperative to serving ABS transmission link is taken as 100 Meters. The total number of subcarriers are assumed to be $\mathcal{N} = 20$. The noise spectral density is set to -174 dBm/Hz. The values of some other parameters are $a = 12.08$, $b = 0.11$, $\epsilon_1 = 0.1\%, \epsilon_2 = 0.1\%, \epsilon_3 = 0.1\%$, $\epsilon = 10^{-2}$, $\alpha_{\text{mbs}} = 2$, $R_{\text{min}} = 2$ b/s/Hz and the error tolerance is set to 10^{-4}.

We consider multiple snapshots in which network dynamics are varied and the measured performance is averaged across the all snapshots. Moreover, we find the optimal values of m_{u_h}, m_{u_h,u_u} and $m_{c_{u_u},u_u}$ using constraint (2) with $M_{\text{max}} = 1500$. To this end, we consider two different benchmark approaches, i.e., fixed blocklength approache (a fixed value of $m_{c_{u_u},u_u} \in [5, 10, ..., M_{\text{max}} - m_{\text{mbs}\to u_h} - m_{u_h \to u_u}]$ is selected) and random blocklength approache (a random value of $m_{c_{u_u},u_u} \in [1 \;\; (M_{\text{max}} - m_{\text{mbs}\to u_h} - m_{u_h\to u_u})]$ is selected).

B. Performance Evaluation

Fig. 2 illustrates the impact of the number of IoT devices on achievable WSR. Importantly, we simulate the implemented schemes for $\mathcal{I}$ = 5 to 30 because of its high computation time. As expected, the larger number of IoT devices leads to better throughput. Additionally, we see that the gain of OMA obtains the same WSR as NOMA systems. However, when $\mathcal{I} > 5$, NOMA systems outperform the OMA and the gap increases with the increase in IoT devices. This increase in NOMA is due to multiplexing gain and perfect SIC. In addition, the efficacy of the proposed scheme achieves better WSR compared to benchmark schemes. The increase

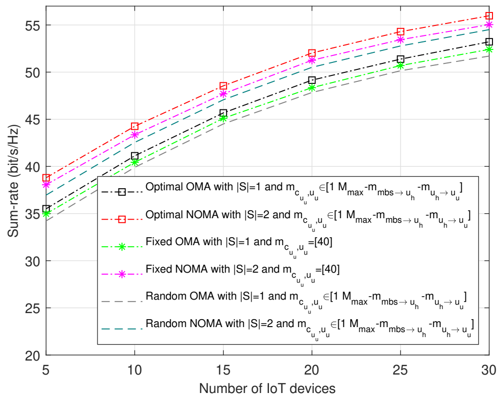

Fig. 2: Sum-rate vs number of IoT devices within serving ABSs, where $m_{u_h} = 1$, $m_{u_h,u_u} = 1$, and $M_{\text{max}} = 1500$.

in performance gain is because of the bigger packet size compared to the fixed blocklength scheme ($m_{c_{u_u},u_u} = 40$) and random blocklength scheme. The result of simulations validates that the productivity of the optimal NOMA system (achievable throughput) compared to the optimal OMA system is increased 5.18% for $|S|= 2$. It is also noted that the proposed scheme perform less number of operation than the benchmark LDDP scheme resulting in less computational complexity.

In Fig. 3, we examine the impact of finite blocklength ratio ($k = m_{u_h}/m_{u_h,u_u}$) on the achievable system WSR. The system throughput is enhanced with an increase in the ratio of blocklength for all the schemes. It is because the degree of freedom to transmit the data packets mainly depends on blocklength; therefore, the higher the blocklength higher is the system WSR. It is noted that the gain of the proposed scheme with the optimal blocklength approach outperforms the baseline approaches, i.e., fixed and random blocklength approaches. Moreover, it is observed from the figure that the effectiveness of the NOMA (having $|S|= 2$) is better than OMA (having $|S|= 1$). The increase in performance gain is because of the basic principle of the NOMA system, i.e., multiplexing multiple IoT devices on each subcarrier (within a cluster) and SIC. The results of simulations validate that the productivity of optimal NOMA having $|S|= 2$ over optimal OMA is 1.7%.

In Fig. 4, we study the impact of M_{max} on the system WSR. Herein, we investigate the proposed transmission scheme (with optimal blocklength) against two baseline transmission schemes. Furthermore, we evaluate the implemented schemes against two different multiplexing schemes such that OMA ($|S|= 1$) and NOMA ($|S|= 2$). It is interesting to note that system WSR improves with an increase in the ratio of M_{max}. It is because short-packet communication (finite blocklength) depends on maximum transmission delay constrain. We also derive that the proposed scheme (with optimal blocklength approach) outperforms the benchmarks (with fixed and random blocklength approach) in the counterpart. The key reason

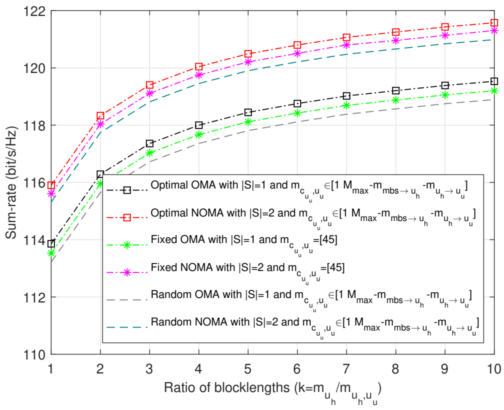

Fig. 3: Sum-rate vs ratio of blocklength, where $m_{u_h} = k \times m_{u_h,u_u}$, $m_{u_h,u_u} = 3$, and $M_{\max} = 1500$.

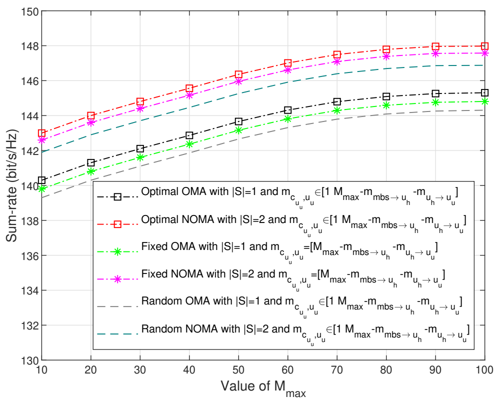

Fig. 4: Sum-rate vs $M_{\max}$, where $m_{u_h} = k \times m_{u_h,u_u}$, $m_{u_h,u_u} = 3$, $M_{\max} = 10 \times k$, and $k = \{1, 2, ..., 10\}$

behind this increase is the selection of optimal blocklength. On contrary, we select a fixed or random value of blocklength (independent of the fact that we are computing for WSR maximization) resulting in a decrease in system throughput. Moreover, it is noted from Fig. 4 that the efficacy of the optimal NOMA (having $|S|= 2$) is better than optimal OMA (having $|S|= 1$). The key reason behind this increase is the principle of NOMA in an infinite blocklength regime, i.e., superposition coding at the transmitter and SIC at the receiver. Results validate that initially, the system WSR remains at the minimum. Afterward, it increases up to 147.97 bits/s/Hz with a 3.48% surge (for NOMA with $|S|= 2$) and it almost remains the same till the end.

VI. Conclusion

In this paper, the concept of NOMA with cooperative relaying is investigated in an integrated aerial terrestrial network for smart IoT networks using short packet communication to guarantee high reliability and low latency. Thereby, a theoretical insight-based iterative solution is provided to maximize the WSR which motivates us to consider QoS to ensure fairness as a design criterion in a finite blocklength regime. To solve the NP-hard problem, the non-convex problem is re-formulated and a near-optimal solution is proposed. Numerical results validate the effectiveness of the proposed solution over baseline approaches, e.g., fixed and random blocklength over the legacy OMA system, i.e., 5.18% better for NOMA with two IoT devices per subcarrier.

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