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Optimizing spectrum efficiency in 6G multi-UAV networks through source correlation exploitation

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Abstract

In the context of 6G and 5G communication networks, particularly in disaster-stricken areas with a surging demand for connectivity and the rapid evolution of the internet of everything (IoE), the imperative for augmenting spectrum efficiency in unmanned aerial vehicles (UAVs) communication-enabled wireless networks becomes ever more pronounced. This work embarks on the mission of significantly enhancing spectrum efficiency by capitalizing on redundancies, such as correlations inherent in data sources like co-located video sensors. While the intuitive potential of exploiting redundancies for spectrum efficiency enhancement is apparent, our approach is systematically structured. We introduce a linear programming framework designed to meticulously allocate bandwidth to individual links based on their respective demands, while judiciously adhering to spatial spectrum reuse constraints. Subsequently, we employ this linear program to empirically quantify the improvements in spectrum efficiency engendered by source correlations. Furthermore, we elucidate various strategies for harnessing these correlations to maximize spectrum efficiency gains, while navigating the trade-off terrain between computational complexity and precision. Our findings resoundingly underscore the trans-formative power of identifying the precise set of source correlations, resulting in spectrum efficiency enhancements of up to two orders of magnitude. In terms of network performance, the judicious exploitation of source correlations grants admission to nearly 100% of delay-intolerant traffic, alongside substantial reductions in mean delay for delay-tolerant traffic."

Keywords: Unmanned aerial vehicles (UAVs), 6G networks, Spectrum efficiency, IoT, Source correlations

1 Introduction

Unmanned Aerial Vehicles (UAVs) have garnered significant attention within the realm of wireless communication [1]. In situations where natural disasters disrupt public communication networks or access to essential resources in urban areas becomes challenging, UAVs emerge as a reliable solution [2]. What sets this technology apart is its ability to establish wireless network systems without necessitating the construction of new ground-based infrastructure. This makes UAV-based wireless technology exceptionally agile, adaptable, and cost-effective. Equipped with sensor nodes (SNs) and communication platforms, UAVs are versatile tools that find applications in diverse domains, enabling the resolution of intricate scenarios. The inherent mobility and positioning flexibility of UAVs empowers them to transmit information with reduced path loss effects [3, 4]. Consequently, UAV-based communication has become a focal point of interest, continually drawing attention.

While the deployment of 5G networks has been ongoing since 2019, research into the forthcoming sixth generation (6G) of wireless communication has already commenced [5]. A primary objective of 5G is to establish ubiquitous and seamless wire-less connectivity. However, relying solely on terrestrial infrastructure cannot fully realize this goal. In areas that are inaccessible, such as deserts, oceans, or off-grid regions, deploying terrestrial base stations (BSs) poses considerable challenges [6]. As a remedy, UAVs are positioned to act as aerial base stations (BSs) in both 6G and 5G networks, guaranteeing high-quality services for a wide range of users and applications in response to the surging demand for wireless communication [7–9]. Nonetheless, despite their potential, UAVs face significant challenges related to spectrum resource limitations, exacerbated by the rapid growth of the Internet of Everything (IoE) and escalating data traffic within networks [10, 11]. UAVs have found applications in various domains, including military operations, military radios [12], fire control, aviation radar tracking, and surveillance [13], wilderness search and rescue, disaster relief efforts, and wildlife monitoring [14].

In UAV networks, the value of communication is particularly pronounced during cooperative obstacle avoidance scenarios. For instance, data collection and the transmission of video and images by UAVs inherently involve substantial amounts of extraneous data, including coding redundancy, spatial redundancy, and temporal redundancy [15]. Consequently, these devices engage in extensive computational processes, yielding decisions replete with inherent redundancies [16]. Moreover, these devices are often co-located and generate information with underlying correlations [17, 18].[1] This intrinsic redundancy presents an opportunity for augmenting spectrum efficiency.[2] Furthermore, our study initially explores the advantages of harnessing redundancy in terms of energy consumption. However, it's important to clarify that, at this stage, our research is primarily focused on spectrum efficiency enhancement, with energy consumption being a potential avenue for future investigation. Additionally, it is worth noting that multi-UAV configurations have demonstrated remarkable potential for substantially enhancing spectrum efficiency and overall system performance. This is achieved through their capacity to facilitate coordinated resource allocation and foster collaborative communication [20].

As an illustrative example, consider a typical multi-UAVs emergency network in a disaster area, as shown in Fig. 1. Information from a public park (through UAVs as surveillance application [21]), hospital, street, and information from public transport stations are conveyed to public safety agencies like the police, fire engine, and ambulance. Typically, information is transmitted over links. Links A, B, C transmit information from the park and since they are all adjacent (share a common node), they use

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[1] It is important to note that the information sources may exhibit non-linear dependencies in addition to correlations. However, this study focuses solely on the analysis of correlations. Later in our research, we demonstrate how this analysis can be extended to encompass non-linear dependencies as well.

[2] Spectrum efficiency is quantified as the amount of information transmitted per unit of available bandwidth [19].

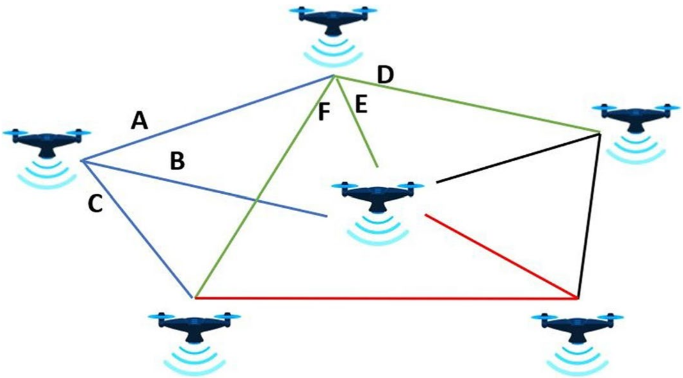

Fig. 1 A typical multi-UAV emergency network to demonstrate the effectiveness of exploiting redundancies in the transmitted information. Links A, B, C exhibit inherent redundancies. If the information on each link, A, B, C, require b units of bandwidth, then without exploiting redundancies, a total bandwidth of 3b would be required. However, the same amount of information can be transmitted by transmitting over only one of the links (using bandwidth, b) and estimating the un-transmitted information by exploiting the redundancies in the information transmitted on links, A, B, C should be centered

disjoint portions of the bandwidth. If each link requires a bandwidth, b to transmit information, then a total bandwidth of $3b$ is required to transmit all information carried by links, A, B and C.

However, since all three links transmit information about the park, they are bound to exhibit large correlations. Then, information relayed on links B and C can be estimated from that relayed on link A (using linear or non-linear regression techniques). Intuitively, one would imagine that the same information can be transmitted only on one of the links using a bandwidth of only b, thus enhancing spectrum efficiency by a factor of 3. This assumes that there is the Pearson correlation coefficient [22] between the information transmitted on different links is 1. In practice though, the Pearson correlation coefficient takes values between -1 and 1 [22].

The core objective of this study is the augmentation of spectrum efficiency within UAV communication networks through the strategic exploitation of redundancies, particularly source correlations. These correlations, often prevalent in scenarios featuring co-located video sensors, serve as a vital resource that can be harnessed to optimize bandwidth allocation. In pursuit of this objective, this research delivers several pivotal contributions that revolutionize the landscape of spectrum efficiency optimization in UAV communication networks. At its core, it introduces an innovative linear programming framework meticulously designed to allocate bandwidth optimally. This allocation process takes into account the unique demands of each link while diligently adhering to spatial constraints, ensuring a fine balance between resource utilization and spectrum optimization.

Moreover, this study stands as a trailblazer in the art of leveraging source correlations to enhance spectrum efficiency. It introduces a diverse array of mechanisms, each offering distinct trade-offs between accuracy and computational complexity, allowing network operators to tailor their approach to meet specific requirements. In essence, this research empowers operators with the tools and strategies required to navigate the intricate spectrum landscape efficiently and effectively.

Crucially, the tangible results of this study underscore the transformative potential of these methodologies. Numerical simulations have unequivocally demonstrated substantial enhancements in spectrum efficiency, accompanied by tangible reductions in delay and notable improvements in blocking probability. In synthesis, this research epitomizes a pioneering endeavor that marries theoretical innovation with practical applicability, promising to usher in a new era of efficiency and performance in UAV communication networks.

The remaining sections of the paper are organized as follows. Section 2 provides an overview of related work in the field, setting the context. Section introduces the methodology, emphasizing our innovative linear programming framework. Section 4 presents the system models, while Sects. 5 and 6 delve into bandwidth allocation strategies and numerical results, respectively. Finally, Sect. 7 provides a concise conclusion and outlines potential directions for future research.

2 Related works

Spectrum efficiency is the main challenge faced by UAV-enabled wireless networks today. Spectrum efficiency with UAVs communication network systems has been studied in [23–27]. Luo and Xiti [23] presented a spectrum sensing algorithm based on gated recurrent units (GRU) tailored for multi-UAV networks. When combined with collaborative spectrum sensing, it enhances system stability and operational longevity for multi-UAV scenarios. To make a full use of spectrum, the authors in [24] considered a 3D spectrum mapping based on Return On Investment (ROI)-driven UAV deployment in a smart city. The work in [25] delved into the growing use of UAV communication, highlighting its potential for enhancing wireless systems' capacity and coverage. By introducing new mathematical expressions, it investigates the spectral efficiency and energy efficiency of cell-free massive multiple input multiple output (CF-mMIMO) technology in UAV communication, providing valuable insights for optimizing this emerging field. Maximizing the spectrum efficiency of UAV-enabled cognitive radio network (CRN) was the aim of the work in [26], where the UAVs were considered as secondary users (SU). The spectrum efficiency optimization issue was solved using the dichotomy and alternative iterative optimization (AIO) algorithm. Due to the decreasing of spectrum sensing as a result of the multi-path fading and shadowing effect, the authors in [27] proposed CRN and UAVs spectrum sensing optimization, for maximizing the throughput of the UAV with fixing interference throughput.

Bandwidth allocation for multi-UAV systems has been extensively studied, and several methods and approaches have been proposed in the literature. One such approach is the Consensus-Based Bundle Algorithm (CBBA), which assigns tasks to UAVs while ensuring that each task is assigned to no more than one UAV [20]. The CBBA algorithm has been further enhanced by duplicating cooperative tasks to improve task allocation [20]. Another approach involves utilizing multiagent reinforcement learning techniques to allocate bandwidth and control the trajectory of multiple UAVs serving as edge computing devices for the Internet of Vehicles (IoV) [28]. A hierarchical game framework has also been proposed to jointly solve the problems of access selection and bandwidth allocation for multi-UAV video streaming [29]. Joint optimization techniques have been developed for multi-UAV-aided Mobile Edge Computing (MEC) systems, which consider factors such as transmit power, bandwidth allocation, and UAV trajectories [30]. Lastly, resource allocation in vehicular networks with multi-UAV served edge computing has been investigated, where UAVs share limited bandwidth resources and are equipped with edge computing servers to serve the vehicles [31]. These approaches highlight the diverse range of methods that have been explored to address the challenges of bandwidth allocation in multi-UAV systems.

It appears that the provided information acknowledges a lack of detailed quantitative analysis and mechanisms to establish the improvement in spectrum efficiency when exploiting redundancies, specifically in the context of a multi-UAV network. Additionally, there is a lack of information regarding the demand of each link in this scenario. Without specific quantitative analysis or mechanisms, it becomes challenging to provide precise insights into the improvement in spectrum efficiency and overall network performance when exploiting source correlations.

Consequently, the study utilizes simulation to explore how exploiting source correlation impacts spectrum efficiency in 6G multi-UAV network. It compares bandwidth bandwidth allocation with and without redundancy exploitation, using metrics like spectrum efficiency and network performance. The controlled UAV mobility scenario isolates source correlation effects, establishing a foundation for future research on dynamic channel conditions. Virtual UAVs and simulation nodes represent participants, with statistical techniques analyzing the performance of proposed mechanisms. The findings are presented through graphs, offering insights into the effectiveness of the studied approaches.

3 Methods

3.1 Study design

This study employed a simulation-based experimental approach to investigate the impact of source correlation exploitation on spectrum efficiency in 6G multi-UAV networks. The study aimed to compare the spectrum efficiency achieved when redundancies in the source, such as co-located video sensors, are exploited. A linear program was formulated to allocate bandwidth optimally to the links based on their demands while satisfying spatial spectrum reuse constraints. Different mechanisms were identified to exploit correlations and maximize spectrum efficiency, considering a trade-off between accuracy and computational complexity.

3.2 Setting

The study was conducted in a simulated environment that accurately models the 6G multi-UAV network scenario. The simulation environment provided a controlled platform to evaluate the proposed techniques for enhancing spectrum efficiency through source correlation exploitation. Various network configurations and scenarios were simulated to assess the effectiveness of the mechanisms. UAV mobility is indeed a critical factor that affects wireless communication links, leading to variations in channel conditions. However, due to the complexity associated with modeling and compensating for these dynamic channel changes, I deliberately kept our analysis confined to a controlled scenario to isolate the effects of source correlations on spectrum efficiency. This allowed me to establish a foundation for future research endeavors where I can systematically delve into the complexities of UAV mobility, dynamic channel variations, and their interplay with source correlations.

3.3 Participants or materials

The participants in this study were virtual UAVs and associated communication platforms represented as simulation nodes. The simulation nodes emulated the behavior of real-world UAVs and their communication capabilities. Additionally, source data with inherent correlations, such as video and image information, were generated within the simulation to simulate the presence of redundancies.

3.4 Interventions and comparisons

The interventions in this study consisted of comparing the spectrum efficiency achieved through two different approaches:

- *Bandwidth allocation without redundancy exploitation*: In this approach, bandwidth was allocated to each link independently, without considering redundancies or correlations in the transmitted information. The linear optimization model was used to allocate bandwidth optimally based on the link demands and spatial reuse constraints while ignoring the presence of correlations.
- *Bandwidth allocation with redundancy exploitation*: In this approach, the proposed mechanisms were employed to exploit source correlations and enhance spectrum efficiency. The linear optimization model was extended to incorporate correlations and allocate bandwidth accordingly, considering the interdependence of the information transmitted on different links.

3.5 Analysis

The performance of the different approaches was evaluated based on the following metrics:

- *Spectrum efficiency*: Spectrum efficiency was measured as the amount of information transmitted per unit of available bandwidth. It quantified the effectiveness of the bandwidth allocation strategies in utilizing the limited spectrum resources efficiently.
- *Network performance*: The impact on network performance was assessed by evaluating call blocking and mean delay for delay-intolerant and delay-tolerant services, respectively. Call blocking referred to the percentage of delay-intolerant traffic that could not be admitted into the network, while mean delay measured the average delay experienced by delay-tolerant traffic.

The simulations were executed for multiple scenarios, varying the correlation levels and network configurations. The results were analyzed using statistical techniques such as descriptive statistics, hypothesis testing, and graphical representations to assess the significance of the improvements achieved through correlation exploitation. The findings were presented in the form of graphs, and comprehensive discussions to provide a clear understanding of the experimental outcomes.

4 Systems models

Consider a Multi-UAV network comprising D nodes, as depicted in Fig. 1. In this network, two nodes that communicate with each other directly by possibly transmitting at the highest power are termed "*one-hop neighbors*" and are said to share a link. The communication within this network occurs via links, thus bandwidth requests are made for links rather than individual nodes. Consequently, this multi-UAV network comprises N links, with the ith link having a bandwidth demand of d_i, where $1 \leq i \leq N$. The entire network shares a total available bandwidth, denoted as B, and adheres to spatial reuse constraints. To efficiently allocate spectrum resources while satisfying the reuse constraints, we employ the concept of the Maximal Independent Set (MIS) within the link graph. An MIS is defined as a maximal subset of links that can share the same portion of bandwidth. In other words, it is a set of links that cannot be further expanded without violating the spatial reuse constraint. The problem of sharing bandwidth between links to satisfy these reuse criteria can be equivalently viewed as allocating disjoint portions of bandwidth to all MIS.

Let $\mathbf{A}$ represent the link-MIS incidence matrix with dimensions $M \times N$, where M is the number of MIS and N is the number of links. Each element a_{ij} of this matrix is defined as follows:

$$a_{ij} = \begin{cases} 1 & \text{link } i \in \text{MIS } j \\ 0 & \text{otherwise,} \end{cases} \tag{1}$$

For a given demand vector $\mathbf{d} = [d_1, d_2, ..., d_N]^T$ (where d_i is the demand for bandwidth on link i, let X_j represent the amount of bandwidth allocated to MIS j. The corresponding optimization problem is formulated as follows:

$$\min \sum_{j=1}^{M} X_j \tag{2}$$

$$\text{subject to } \sum_{j=1}^{M} X_j a_{ij} \geq d_i, \quad \forall i, j \tag{3}$$

$$\sum_{j=1}^{M} X_j \leq B \tag{4}$$

The optimization problem described in the given formulation can be categorized as a linear programming (LP) problem. It used to make efficient decisions regarding the allocation of limited resources, in this case, bandwidth B, in a Multi-UAV network. Optimization involves finding the best possible solution to a problem among a set of feasible options while adhering to specific constraints and objectives.

In the context of the system models section, the optimization problem aims to allocate available bandwidth X_j to different MIS_j within the network. This allocation is carried out in a way that minimizes the total amount of allocated bandwidth while ensuring that the bandwidth demands d_i of individual links are met (as specified by Eq. 6). Additionally, the total allocated bandwidth cannot exceed the available bandwidth B, as indicated by Eq. 7. So, the optimization problem seeks to find the optimal distribution of bandwidth among the MIS_j while satisfying these constraints. The objective is to use the available spectrum resources most efficiently, reducing waste and improving the overall performance of the Multi-UAV network.

The goal of this work is to improve spectrum efficiency in communication for multi-UAVs in the context of 5G and 6G. The focus is on exploiting redundancies to enhance spectrum efficiency. To do that, we post the following research questions:

RQ1 What is an appropriate analytical formulation to determine the minimum bandwidth required to satisfy the demands *on all the links satisfying spatial re-use constraints?*

RQ2 How do we factor arbitrary source correlations into the formulation and show that exploiting source correlations *always* results in larger spectrum efficiency?

Section 5.1 address RQ1 and RQ2 is addressed in Sect. 5.2.

5 Bandwidth allocation and redundancy exploitation

Bandwidth Allocation and Redundancy Exploitation focuses on the allocation of bandwidth in the network and the exploitation of redundancies to enhance performance. To address these questions (RQ1 and RQ2), we provide a comprehensive analysis in tow main sections.

In Sect. 5.1, we present the bandwidth allocation scheme without exploiting redundancy. Here, we outline the approach for allocating bandwidth to individual links based on their respective demands, considering the spatial reuse constraints. We discuss the optimization problem formulation and provide insights into the methodology employed to achieve this objective. The objective is to efficiently allocate bandwidth while meeting the demands of each link.

In Sect. 5.2, we delve into the exploitation of redundancies. We explain how the untransmuted data can be estimated from the partially transmitted data, allowing for the use of lesser bandwidth. We discuss the concept of correlation between links and its role in improving spectrum efficiency. We present a framework for harnessing these redundancies and examine its impact on the system's overall performance.

5.1 Bandwidth allocation without redundancy exploitation

Bandwidth allocation plays a crucial role in optimizing network performance and meeting the demands of different links. In this section, we focus on the problem of allocating bandwidth without exploiting redundancy. Our objective is to devise an effective approach or algorithm for distributing the available bandwidth among the links while satisfying the given demand constraints. To shed light on this problem, we introduce a theorem that characterizes the solution set to the linear program defined by the bandwidth allocation problem. This theorem provides valuable insights into the properties and implications of the optimal solutions, facilitating a deeper understanding of the feasibility and optimization aspects of bandwidth allocation without redundancy exploitation.

The following theorem enables characterize the solution set to the linear program. Theorems 1 and 2 provide a quantitative means to satisfy all demands on all the links by expending minimum bandwidth.

Theorem 1 *Let* $\widetilde{B}$ *be the solution to the linear program,*

$$\tilde{B} = \min \sum_{j=1}^{M} X_j \tag{5}$$

$$\text{subject to } \sum_{j=1}^{M} X_j a_{ij} \geq d_i, \quad \forall i, j \tag{6}$$

$$\sum_{j=1}^{M} X_j \leq B \tag{7}$$

Then, $\widetilde{B}$ *is the minimum amount of bandwidth required to meet the demand,* **d** *while satisfying re-use constraints.*

Proof If X_j amount of bandwidth is given to MIS_j then $\sum_{j=1}^{M} X_j$ represents the total bandwidth expended because different MIS use disjoint portions of the bandwidth. Constraint (7) ensures that this is less than the available bandwidth in the system. $\sum_{j=1}^{M} X_j a_{ij}$ provides the total bandwidth allocated to link i from the definition of a_{ij} from Eq. (1) and X_j. Therefore, constraint (6) implies that the demand on all links are met. ■

Thus, minimizing (5) subject to (6) and (7) ensures that all links meet their demands using minimum bandwidth.

Theorem 2 *The allocated bandwidth* $\widetilde{B}$ *is minimum when constraint (6) is met with equality. In other words,*

$$\tilde{B} = \min \sum_{j=1}^{M} X_j \tag{8}$$

$$\text{subject to } \sum_{j=1}^{M} X_j a_{ij} = d_i, \quad \forall 1 \leq i \leq N \tag{9}$$

Proof Follows from the property of linear programs (That solutions occur at extreme points [32]). ■

It is observed that the formulation according to the Theorem 2 does not exploit any redundancy (linear or non-linear) in the data transmitted on multiple links. Before the redundancies can be formulated or exploited to enhance spectrum efficiency, it is essential to study the characteristics of the used bandwidth, under different demands on different links. The following Lemma provides a basis leading to Theorems 3 in this subsection and later, Theorem 5 in the next subsection to quantify the benefits of exploiting redundancies in the data.

Lemma 1 *A demand vector,* $\boldsymbol{d} > 0$ (i.e., $d_i \geq 0,\ 1 \leq i \leq N$ and $\exists, i',\ 1 \leq i' \leq N,$ *such that* $d_{i'} > 0$ *), results in an allocated bandwidth,* $B > 0$.

Proof Consider a demand vector, with $d_{i'} > 0$. Then, the minimum bandwidth $\widetilde{B}$ is obtained by minimizing the objective function in (8) subject to the constraints in (9). If $\widetilde{B} = 0$, then $X_j = 0, \forall j$, i.e, violating constraint (9) for $i = i'$. Therefore, B >0. ■

Lemma 1 actually suggests that if any one link has a non-zero (positive) demand then a positive bandwidth is needed to satisfy the demand. While it is intuitively obvious, we require a formal proof in order to obtain Theorem 3, which, in turn, is essential to establish the benefits of exploiting correlations.

Theorem 3 *Let* $\boldsymbol{d}_1 = [d_{11}d_{21}d_{31}\ldots d_{N1}]^T$ *and* $\boldsymbol{d}_{12} = [d_{12}d_{22}d_{32}\ldots d_{N2}]^T$ *be two demand vectors so that* $d_{1j} \geq d_{2j}$, $\forall j (1 \leq j \leq N)$ *(this is also denoted as* $\boldsymbol{d}1 \geq \boldsymbol{d}2$*). Let* B_1 *and* B_2 *be the minimum amount of bandwidth required to meet the demand vectors,* d_1 *and* d_2*, respectively. Then* $B1 \geq B2$.

Proof Consider $X^{(1)}$ and $X^{(2)}$ be the amount of bandwidth allocated to MIS j in order to meet the demand vector, $\mathbf{d}_1$ and $\mathbf{d}_2$, respectively. From constraint (9),

$$\sum_{j=1}^{M} X_j^{(1)} a_{ij} = d_{i1}, \forall i \tag{10}$$

$$\sum_{j=1}^{M} X_j^{(2)} a_{ij} = d_{i2}, \quad \forall i \tag{11}$$

Therefore,

$$\sum_{j=1}^{M} (X_j^{(1)} - X_j^{(2)}) a_{ij} = d_{i1}, \quad \forall i \tag{12}$$

Let $d_{i1} - d_{i2}\widetilde{d}_i \geq 0, \forall i$. Let $X_j^{(1)} - X_j^{(2)}\widetilde{X}j$. Now consider the optimization problem

$$\tilde{B} = \min \sum_{j=1}^{M} \widetilde{X}j \tag{13}$$

$$\text{subject to } \sum_{j=1}^{M} \widetilde{X}j a_{ij} = \widetilde{d}_i, \quad \forall i \tag{14}$$

■

The above problem is identical to the optimization problem in (8) subject to constraint (9), for a demand vector, $\widetilde{\boldsymbol{d}} \geq 0$ and according to Lemma 1, $\widetilde{B} = \widetilde{B}_1 - \widetilde{B}_2 \geq 0$, i.e. $\widetilde{B}_1 \geq \widetilde{B}_2$.

Theorem 3 indicates that as demands increase, additional bandwidth is required, which is intuitively true. Theorem 3 (and it's proof) provides an analytical evidence, which will be used to answer RQ2 posed earlier in this section. In the following subsection, we demonstrate formally, how Theorem 3 can be utilized to enhance the spectrum efficiency when source correlations are exploited. Theorem 3 indicates that as demands increase, additional bandwidth is required, which is intuitively true.

We now present the final result of this subsection, which represents the existence of a demand vector that achieves the saturation condition, i.e., utilizes the entire bandwidth, B available at the network.

Theorem 4 $\exists \boldsymbol{d}^*$ *such that the minimum bandwidth required to satisfy the demand vector,* $\boldsymbol{d}^*$ *is the total available bandwidth in the network, B.*

Proof Consider, N links, M MIS and a demand vector, $\mathbf{d}$ so that the bandwidth allocated is $\widetilde{B} < B$. Therefore, $\sum_{j=1}^{M} X_j a_{ij} = d_i, \forall i$ and $\sum_{j=1}^{M} X_j = \widetilde{B} < B$. Then, $\forall j, 1 \leq j \leq M$, let $X_j^* = X_j + \frac{B-\widetilde{B}}{M}$ and if M_i is the number of MIS that link i belongs to, then make $d_i^* = d_i + \left(\frac{M_i}{M}\right)\left(B - \widetilde{B}\right)$. This results in $\sum_{j=1}^{M} X_j a_{ij} = \sum_{j=1}^{M} X_j a_{ij} + \frac{B-\widetilde{B}}{M} \sum_{j=1}^{M} a_{ij} = d_i + \left(\frac{M_i}{M}\right)\left(B - \widetilde{B}\right) = d_i^*, \forall i.$ Thus satisfying constraints (9). In this case, $\sum_{j=1}^{M} X_j^* = \sum_{j=1}^{M} X_j + \sum_{j=1}^{M} \left(B - \widetilde{B}\right)/M = \widetilde{B} + B - \widetilde{B} = B$, i.e., $\exists \mathbf{d_i^*} = \left[d_i^*\right]_{1 \leq i \leq N}$, such that the total bandwidth required to satisfy the demand vector, $\mathbf{d}^*$ is B. ∎

Overall, these findings answer the first question RQ1 regarding the characterization and optimization of bandwidth allocation without redundancy exploitation. In the following subsection, we demonstrate formally, how Theorem 3 can be utilized to improve spectrum efficiency when data transmitted on different links exhibit mutual redundancy and answer the second question RQ2.

5.2 Redundancy exploitation for enhanced performance

Redundancy between the data transmitted on multiple links can be measured by evaluating the joint probability density function (pdf) of the data on different links. Since the number of such joint pdfs are exponentially large,[3] we reduce the computational complexity by considering only linear dependences or the correlation coefficients of the data transmitted on multiple links.

Since information is transmitted on links and bandwidth demands are made on links, we define two links that carry correlated information as correlated sources or say that the corresponding links exhibit source correlation. For a network with N-links, let ρ_{ij} be the correlation coefficient between the information on link i and link j (If links i and j are

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[3] For N-links we have $\binom{N}{1} + \binom{N}{2} + \binom{N}{3} \cdots + \binom{N}{N} = 2^N - 1$ combinations.

not adjacent, then $\rho_{ij} = 0$).[4] Note that $\rho_{ij} = \rho_{ji}, \forall i, j$ and $-1 \leq \rho_{ij} \leq 1, \forall i, j$ [33]. Let $\boldsymbol{\rho}$ be the correlation coefficient matrix given by:

$$\rho = \begin{pmatrix} 1 & \rho_{12} & \rho_{13} & \cdots & \rho_{1N} \\ \rho_{21} & 1 & \rho_{23} & \cdots & \rho_{2N} \\ \rho_{31} & \rho_{32} & 1 & \cdots & \rho_{3N} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \rho_{N1} & \rho_{N2} & \rho_{N3} & \cdots & 1 \end{pmatrix} \tag{15}$$

The source (transmitting node) needs to transmit only *partial data* on a link. In other words, the part of the data not transmitted on a link i can be estimated (using linear regression [33]) using the data transmitted on all neighboring links to link i. Thus, if the demand on link i, was d_i, then only $d_i(1 - \sum_{i \neq j} |\rho_{ij}|)$ amount of data need to be transmitted on link i and the rest can be estimated from the data transmitted on link j; $i \neq j$.

Remark 1 Since $\rho_{ij} = 0$ if link i and j are not adjacent, we can use this for any i, j combination (not restricted only to neighboring links).

Remark 2 Since $-1 \leq \rho_{ij} \leq 1, \forall i, j$ we use $|\rho_{ij}|$.

Remark 3 It is impractical to estimate the data transmitted on *all* links. Therefore, some links need to transmit all the true data. Typically, the links expected to transmit large amount of data (i.e., link i with large d_i) should transmit partial data. Thus, the modified demands on all the links are given by:

$$\widehat{d_i} = \begin{cases} d_i \left(1 - \sum\limits_{i \neq j} \left|\rho_{ij}\right|\right), & \sum\limits_{i \neq j} \left|\rho_{ij}\right| \leq 1 \\ d_i, & \text{otherwise} \end{cases}, \tag{16}$$

The following theorem shows that exploiting source correlations enhances spectrum efficiency, thus answering RQ2.

Theorem 5 *Let η be the spectrum efficiency obtained when bandwidth is assigned to links to meet a demand* $\mathbf{d}$ *without exploiting correlations. Let η be the spectrum efficiency when the bandwidth is allocated to meet the demand vector,* $\mathbf{d}$, *after exploiting correlations. Then, $\widetilde{\eta} \leq \widehat{\eta}$.*

Proof From (16),$\widehat{d_i} \leq d_i, \forall i$. Then $\widehat{\mathbf{d}}\left[\widehat{d_i}\right]_{1 \leq i \leq n} \leq \mathbf{d}$. Let $\widetilde{B}$ and $\widehat{B}$ be the amount of bandwidth required to satisfy demands, $\mathbf{d}$ and $\widehat{\mathbf{d}}$, respectively. From theorem 3, $\widehat{B} \leq \widetilde{B}$. The spectrum efficiency without exploiting correlations is $\widetilde{\eta} = \sum_{i=1}^{N} d_i / \widetilde{B}$ and that after exploiting correlations,[5] $\widehat{\eta} = \sum_{i=1}^{N} d_i / \widehat{B}$. Since $\widetilde{B} \geq \widehat{B}, \widetilde{\eta} \leq \widehat{\eta}$. ■

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[4] The exact measurements of $\rho_{ij}, \forall i, j$ is usually by numerically computing and updating the Pearson correlation coefficient [33]. The exact measurement mechanisms and protocol to update this information among nodes is beyond the scope of this paper.

[5] Since the effective of data transmitted on link i is still d_i after estimating the non-transmitted data on link i from the transmitted data on neighboring link to link i.

Theorem 5 not only gives an analytical proof that exploiting source correlations enhances spectrum efficiency, but also provides a quantitative handle on the exact amount of enhancement. The following theorems provide a result that depicts one of the major benefits of exploiting source correlation. $\exists \mathbf{d}^*$ such that the minimum bandwidth required to satisfy the demand vector, $\mathbf{d}^*$ is the total available bandwidth in the network, B.

Theorem 6 *Certain demand vectors that cannot be satisfied when correlations are not exploited, may be met when correlations are exploited. Formally stated, if a demand vector,* $\widetilde{\boldsymbol{d}}$ *requires the entire bandwidth, B (such a demand vector exists from Theorem 5) when correlations are not exploited, then a demand vector* $\boldsymbol{d^*} > \widetilde{\boldsymbol{d}}$ *may be admitted when correlations are exploited.*

Proof It is observed that since $d^* > \tilde{d}$, it requires a bandwidth, $B^* > B$ (from Theorem 5) and hence will not be admitted, if correlations are not exploited. Consider a demand vector, $\hat{d}$, obtained from a demand vector $d^* > \tilde{d}$, after exploiting correlations using (16). There could be tow cases for the amount of bandwidth, B, required to satisfy the demand vector, $\hat{d}$. Case (1): $\hat{B} \leq B$, in which case, d^* can be admitted when correlations are exploited and Case (2) $\hat{B} > B$, in which case, d^* cannot be admitted even after correlations are exploited. ■

Thus, certain demand vectors, $\mathbf{d}^*$ which cannot be admitted when correlations are not exploited may be admitted when correlations are exploited if they fall under Case (1) above. The exact characterizations of such vectors are too complex and beyond the scope of this paper.

It is observed that the enhancement in spectrum efficiency follows from the fact that the un-transmitted data can be estimated from the partially transmitted data, by using lesser bandwidth. When there are more redundancies in the systems, more pairs, whose correlation are exploited, will be communicate. Consequently, there will be more improvement in Spectrum efficiency.

6 Numerical results and discussion

For numerical computations, we consider a UAV network with 20 nodes with a bandwidth, of $B = 50$ MHz. Random geometric graphs are generated to obtain different typologies. We consider three demand scenarios-; (1) all nodes have uniform demand for bandwidth, (2) dense nodes (nodes with a large number of neighbors) have larger demands for bandwidth and (3) sparse nodes (nodes with fewer neighbors) have lesser demands for bandwidth. The three scenarios are achieved as follows. For scenario (1) (Uniform Traffic) we make traffic $= 1/D$, for all nodes. For scenario (2), we take traffic in a node $d = \left(\text{degree of node } d\right)/\left(\text{sum of degreed of all nodes}\right)$. For scenario (3) we take traffic on node $d = D\text{-}1$-node degree(u) and normalize it so that the sum of the traffic of all nodes is one. The traffic on each link is computed assuming nodes communicate with all their neighbors with equal probability. To exploit correlations, we generate $\rho_{ij} \sim U(-1,1)$ (uniformly distributed in $(-1, 1)$) between links i and j, make $\rho_{ii} = 1, \forall i$. We perform 100,000 simulations on UBUNTU Linux.

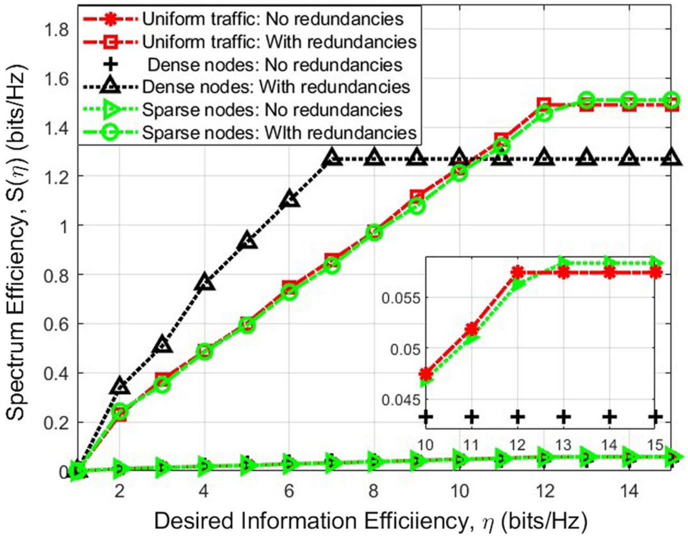

Fig. 2 The achieved spectrum efficiency for the three scenarios: uniform traffic (indicating equal demands from all nodes), more traffic at dense nodes (indicating demands being an increasing function of the degree of the nodes) and more traffic at sparse node (indicating demands being a decreasing function of the degree of the nodes) with and without exploiting correlations

Figure 2 presents the achieved spectrum efficiency without and with exploiting correlations. It is observed that exploiting correlations result in an improvement in spectrum efficiency by one to two orders of magnitude. As it is shown, uniform traffic and more traffic in sparse nodes provide better result compared to more traffic at dense nodes with the presents of redundancies. Generally, the spectrum efficiency with exploiting redundancies performs better result than the spectrum efficiency without exploiting redundancies.

While it is intuitive that exploiting source correlations will result in better spectrum efficiency, Fig. 2 provides a quantitative measure, which has not been described before in current literature. At this point, we pose another research question, RQ3: How does improvement in spectrum efficiency actually impact the network performance?

To answer RQ 3, we consider two types of traffic: delay intolerant traffic (that may suffer losses in the form of a fraction of traffic not being admitted into the system but cannot tolerate delay and therefore cannot be buffered) and delay tolerant traffic (that have to be admitted into the system but can tolerate delay and therefore can be buffered until bandwidth becomes available for transmission). The amount of bandwidth allocated to link i, $bi = 50S(\eta)g_i$ and the number of channels allocated to link i, $m_i = \frac{b_i}{10000}$ assuming each channel to support 10 kHz of traffic [34]. We then take the load to be 80% of m_i on link i.

The figure shows the improvement of the achieved spectrum efficiency with the desired spectrum efficiency for three scenarios, uniform traffic, more traffic at dense nodes, and more traffic at sparse nodes. As it is shown, uniform traffic and more traffic in sparse nodes provide better results compared to more traffic at dense nodes with the presents of redundancies. The main reason for that is contributed to the high number of links on dense nodes winch incident on them. It is not only that but also when they generate more traffic, then more links that cannot reuse bandwidth

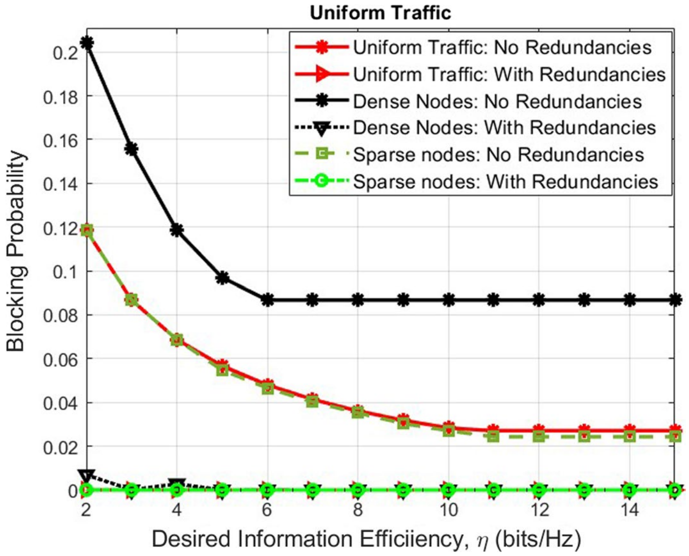

Fig. 3 The blocking probability (fraction of traffic not admitted in the system) for delay intolerant traffic. Exploiting correlations admit almost 100% of the incoming traffic

inject more traffic into the network. This led to less reuse overall, and consequently lower achieved spectrum efficiency. Generally, the achieved spectrum efficiency with exploiting redundancies performs better results than the achieved spectrum efficiency without exploiting redundancies.

Figure 3 depicts the blocking probability (fraction of traffic blocked due to insufficient bandwidth availability) for delay intolerant traffic for the systems with and without exploiting correlations for the scenarios uniform traffic, more traffic at dense nodes, and more traffic at the sparse node. The system that exploits correlations results in lower call blocking probability because of larger resource availability or being able to support larger demands (according to Theorem 6). As the desired information efficiency (and hence, achieved spectrum efficiency) increases, the system that exploits correlations admits almost 100% of all incoming traffic, while the system that does not exploit correlations results in a significant portion of incoming traffic that is blocked (as large as 20% when dense nodes generate more traffic). The comparison of the blocking probabilities is performed using the Erlang-B blocking formula for an *M*/*M*/*c*/*c* system assuming Poisson arrival process for incoming traffic [35].

For delay tolerant traffic, we again assume the incoming traffic to follow a Poisson process and apply the mean delay expression for *M*/*M*/*c* Erlang-C delay formula [34] and compare the mean delay for the systems with and without exploiting correlations. As observed from Fig. 4, the mean delay reduces by 50% (for more traffic at dense nodes) to 66% (for uniform traffic) and as large as 88% for more traffic at dense nodes for low values of desired information efficiency. Generally, the blocking probability with exploiting redundancies performance beater then the scenarios without exploiting redundancies. It can be inferred from the curves that blocking probability reduces as desired spectrum efficiency increases. This change is more prominent in uniform traffic and more traffic at sparse node; showing a significant improvement in the

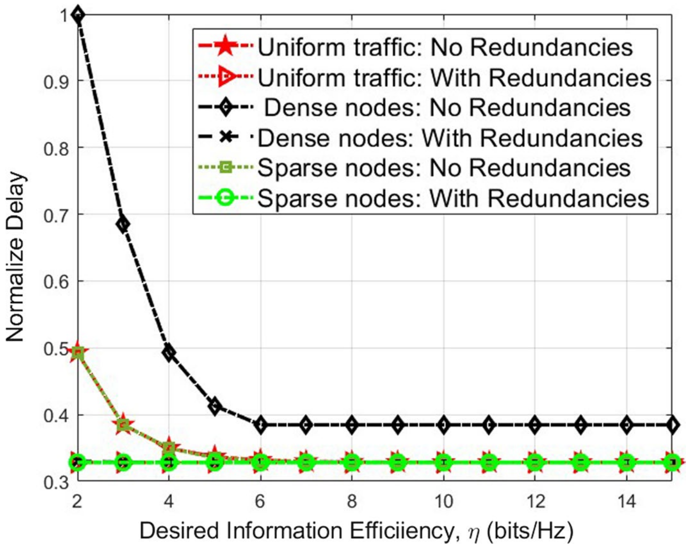

Fig. 4 The normalized mean delay (normalizing maximum mean delay to 1) suffered by delay-tolerant traffic. Exploiting correlations reduces mean delay by 50–88%

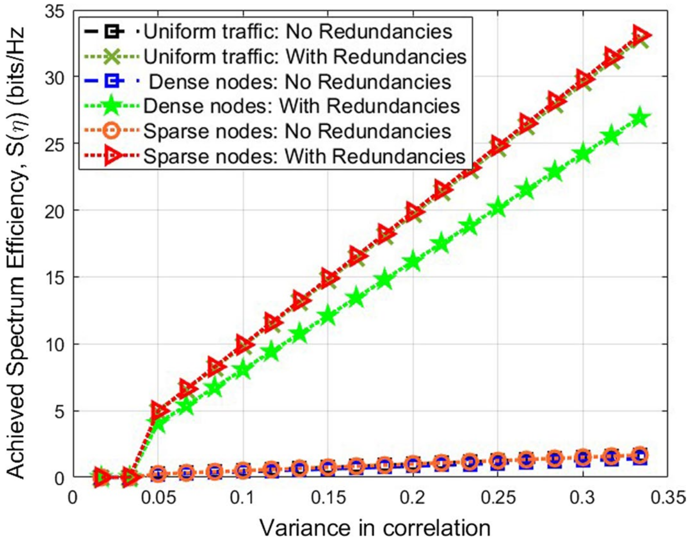

Fig. 5 The spectrum efficiency as a function of variance in correlation. For a variance, *v* the correlation co-efficient $\sim U(-\sqrt{3v}, \sqrt{3v})$. As variance in correlation increases the actual values of correlation coefficients go closer to 1, thus resulting in improved spectrum efficiency

blocking probability comparing to the systems without exploiting redundancies. This improvement is attributed to the different of demand for each link and the number of neighbors for each node.

In this study, we investigate the relationship between the variance in correlation and the improvement in spectrum efficiency, as well as the error in estimation. The correlation coefficient is assumed to follow a uniform distribution in the range of $(-\rho_{\max}, \rho_{\max})$, where $\rho_{\max}$ is the maximum correlation coefficient. Thus, yielding a variance of $\frac{\rho_{\max}^2}{0.33}$, since $\rho_{\max} \leq 1$ [33]. By varying the variance of correlation between 0 and 0.33, we examine how it impacts the spectrum efficiency and the error in

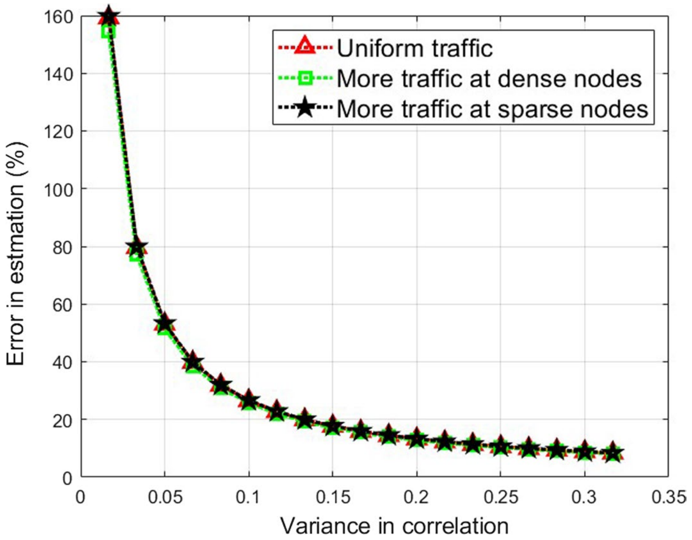

Fig. 6 Error in estimation while exploiting correlations. As variance in correlation increases the actual values of correlation coefficients go closer to 1, thus resulting in reduced estimation error

estimation. We study the improvement in spectrum efficiency Fig. 5 and then the error in estimation in Fig. 6. As the variance in correlation increases as seen in Fig. 5, the correlation coefficients tend to be closer to 1. This means that there is a stronger correlation between the information transmitted on different links.

Consequently, the spectrum efficiency, which measures the amount of information transmitted per unit available bandwidth, increases with a larger correlation. The improvement in spectrum efficiency indicates that exploiting correlations leads to a more efficient utilization of the available spectrum resources. When the correlation between the transmitted information is high, redundant information can be estimated and reconstructed, allowing for more efficient transmission and reducing the need for additional bandwidth.

Furthermore, as the correlation increases in Fig. 6, the error in estimation decreases. This is because the higher correlation enables more accurate prediction and estimation of the untransmuted information based on the received information. The decrease in estimation error contributes to the overall improvement in spectrum efficiency. Overall, the study demonstrates the positive impact of exploiting correlations in enhancing spectrum efficiency. Higher correlation values lead to improved spectrum utilization and reduced estimation errors, highlighting the importance of considering correlation in optimizing wireless communication systems.

Figures 7, 8, 9, 10, 11, 12, 13, 14 and 15 are illustrated different techniques to compare and evaluate their effectiveness in relation to the proposed method" Exploited fullest correlation" and these techniques are the legends in the next figures. The legend, "Linear program" shows the basic spectrum allocation without exploiting redundancies (analysis in Sect. 5.1), "Principal.

Submatrix" and" Minimum Sum Sub-matrix". where the Principal Sub-matrix approach involves identifying the principal sub-matrix of the correlation matrix. The principal sub-matrix represents the strongest correlations among the links. By

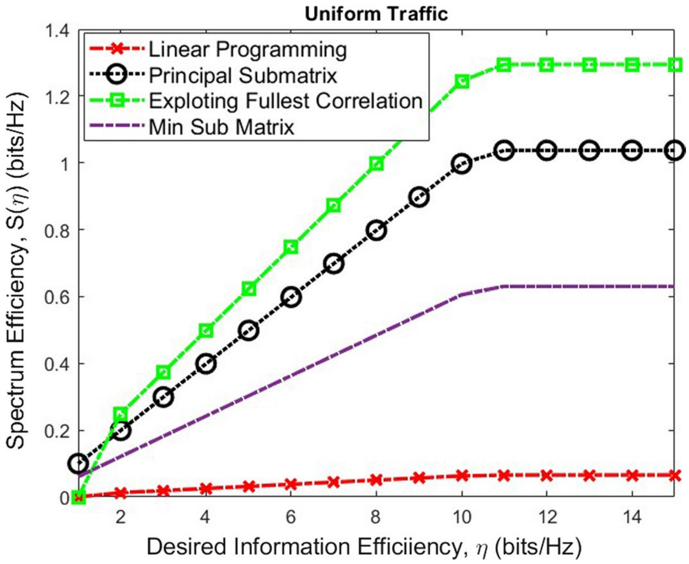

Fig. 7 The achieved spectrum efficiency when all nodes generate uniform traffic

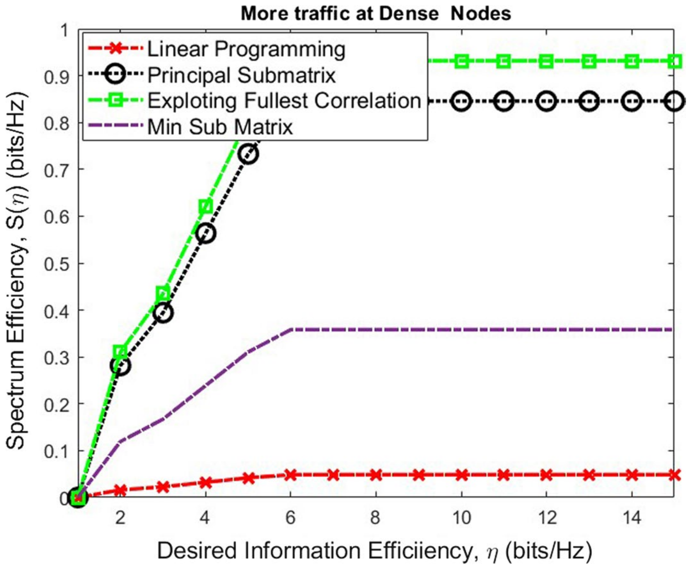

Fig. 8 The achieved spectrum efficiency using more traffic at dense nodes

exploiting the correlations within this sub-matrix, spectrum allocation can be optimized to achieve higher efficiency. Minimum Sum Sub-matrix approach focuses on finding the minimum sum sub-matrix of the correlation matrix. The minimum sum sub-matrix represents a subset of links with the lowest total correlation. By allocating spectrum resources to this sub-matrix, redundancies can be minimized, leading to improved spectrum efficiency. Also, we present the next figures with three different scenarios Uniform traffic, More Traffic at Dense Node and More Traffic at Sparse Node.

The spectrum efficiency performance when Uniform traffic (Fig. 7), Dense Node (Fig. 8) and Sparse Nodes (Fig. 9). From Figs. 7, 8 and 9, it is observed that Exploiting

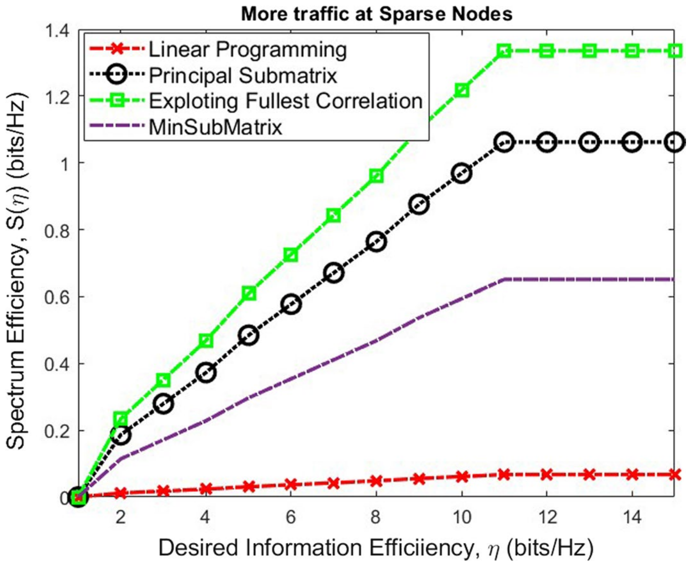

Fig. 9 The achieved spectrum efficiency with more traffic at sparse nodes

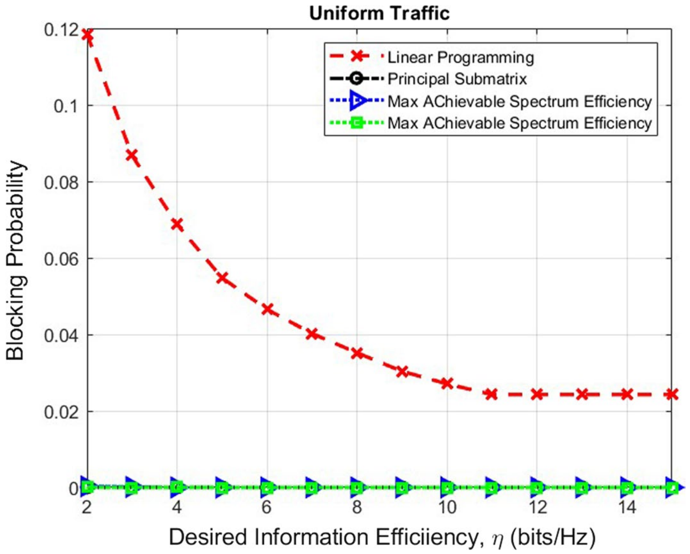

Fig. 10 The blocking probability for delay intolerant traffic for uniform traffic

Fullest Correlations provides 90−100% improvement in spectrum efficiency over the basic spectrum allocation described in Sect. 5.1, while the principal sub-matrix method provides 30−50% improvement and Minimum Sum Sub-matrix method provides 10−20%.

We then proceed to measure the improvements in blocking probability for delay intolerant traffic and when using the spectrum efficiency enhancements, in Figs. 10, 11 and 12. It is observed from the figures that the scenarios with Fig. 10 uniform traffic and Fig. 11 more traffic at dense networks provide better results than Fig. 12 more traffic at sparse nodes. The scenario with Max achievement spectrum efficiency results in a lower call-blocking probability. It can be inferred from the curves that

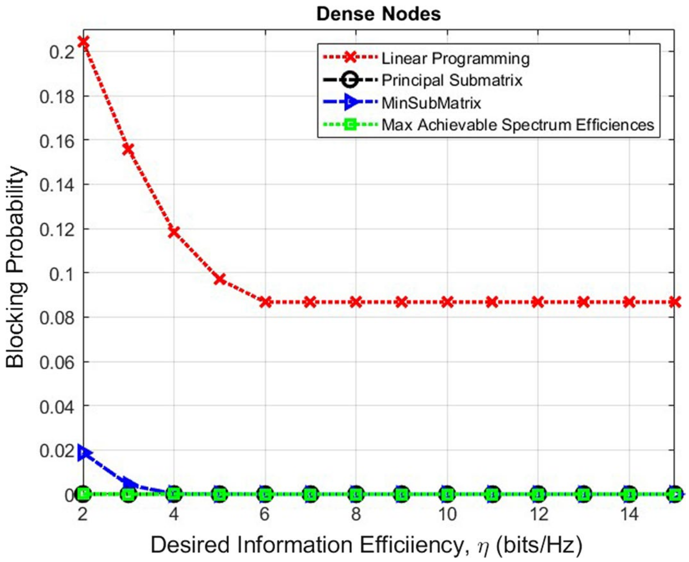

Fig. 11 The blocking probability for delay intolerant traffic for more traffic at dense networks

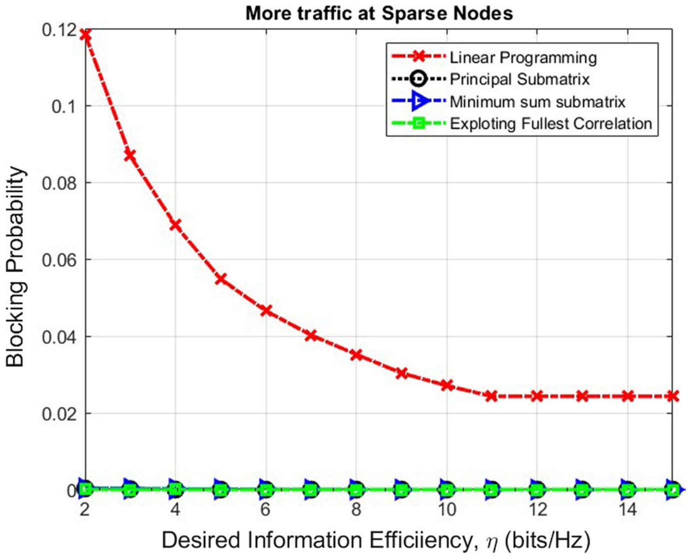

Fig. 12 The blocking probability for delay intolerant traffic for the scenarios with more traffic at sparse nodes

blocking probability reduces as desired spectrum efficiency increases. Also, the mechanisms explained in this section decrease the blocking probability to almost zero, thus motivating the spectrum efficiency enhancement using the principal sub-matrix and the exploiting fullest correlations. Since the performances of exploiting fullest correlations and the principal sub-matrix method are similar, it shows that the principal sub-matrix method provides the same blocking performance while being computationally more efficient.

The achieved spectrum efficiency improves as the variance in correlation increases as observed from Figs. 13, 14 and 15. Once again, we use the *M/M/c/c* model for the delay intolerant traffic and *M/M/c* model for delay tolerant traffic.

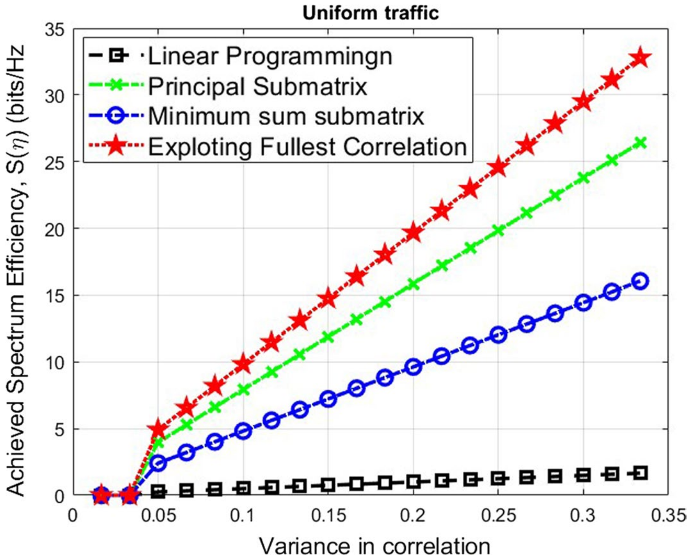

Fig. 13 The achieved spectrum efficiency as a function of variance in correlation for uniform traffic

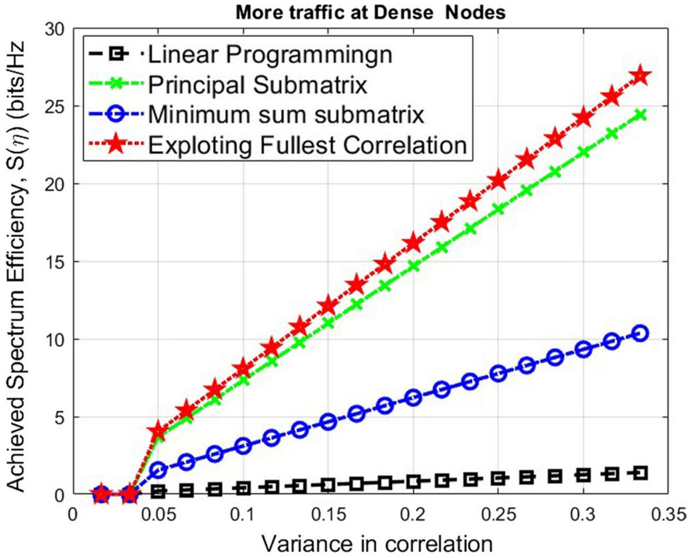

Fig. 14 The achieved spectrum efficiency as a function of variance in correlation for more traffic at dense nodes

Our results clearly demonstrate that exploiting correlations among nodes in a UAV network leads to significant improvements in spectrum efficiency. The achieved spectrum efficiency gains range from one to two orders of magnitude when compared to traditional resource allocation methods that do not consider correlations. This finding aligns with previous studies highlighting the benefits of exploiting correlations in various wireless communication scenarios. By leveraging the correlations among nodes, we can better utilize the available spectrum resources, resulting in increased network capacity and improved overall performance.

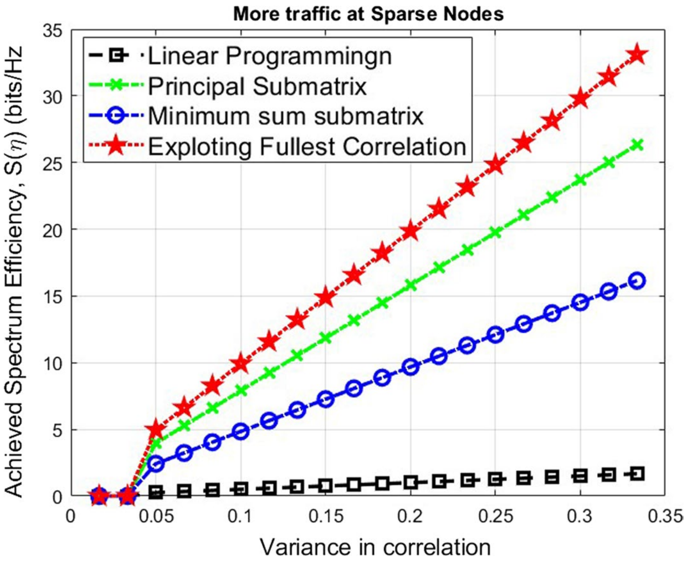

Fig. 15 The achieved spectrum efficiency as a function of variance in correlation for more traffic at dense nodes

Furthermore, our study reveals that the impact of correlation exploitation on spectrum efficiency varies depending on the demand scenario. Specifically, uniform traffic and more traffic at sparse nodes scenarios exhibit higher spectrum efficiency gains compared to the more traffic at dense nodes scenario. This suggests that the benefits of correlation exploitation are more pronounced when the traffic distribution is more evenly spread across the network or concentrated in sparsely populated areas. These findings provide valuable insights into the relationship between correlation exploitation and network traffic characteristics.

The observed improvement in spectrum efficiency through correlation exploitation has significant implications for the design and operation of UAV networks. By incorporating correlation-based resource allocation techniques, network operators can optimize the utilization of limited spectrum resources and improve the quality of service for UAV communication.

The findings of our study also highlight the importance of considering correlation as a fundamental factor in resource allocation strategies. While traditional resource allocation methods focus primarily on node characteristics and network topology, neglecting the correlation between nodes can lead to suboptimal resource allocation decisions. By explicitly accounting for correlations, network operators can achieve more efficient and effective resource allocation, leading to enhanced network performance and user experience.

Moreover, the reduction in blocking probability and mean delay observed in our study further emphasizes the positive impact of correlation exploitation on network performance. Lower blocking probability ensures a higher admission rate of traffic, reducing the likelihood of congestion and improving the overall reliability of the network. Similarly, the decrease in mean delay enhances the timeliness of data delivery, which is crucial for delay-tolerant applications in UAV networks.

While our study provides valuable insights into the benefits of correlation-based resource allocation in UAV networks, it is important to acknowledge its limitations. Firstly, our simulations were conducted on a specific network topology and demand scenarios. The obtained results may not fully capture the variations and complexities of real-world UAV networks. Further studies involving different network topologies, varying traffic patterns, and larger-scale deployments would provide a more comprehensive understanding of the implications of correlation exploitation.

Secondly, our study assumed a uniform distribution of correlation coefficients and did not consider dynamic changes in correlations over time. In practice, correlations may vary due to factors such as mobility, environmental conditions, and interference. Investigating the impact of time-varying correlations and developing adaptive resource allocation techniques that can effectively handle such dynamics would be a valuable direction for future research.

Lastly, our study focused on the spectrum efficiency aspect of correlation-based resource allocation. While spectrum efficiency is a crucial metric, it is essential to consider other performance indicators, such as energy efficiency, scalability, and robustness to varying network conditions. Future research should explore the multi-objective optimization of resource allocation strategies, considering these diverse performance aspects.

Based on the findings and limitations of our study, several avenues for future research and development can be identified. Investigating the impact of correlation exploitation on other performance metrics, such as energy efficiency, scalability, and robustness. Considering time-varying correlations and developing adaptive re-source allocation techniques that can handle dynamic correlation changes in UAV networks. Examining the effects of different network topologies and traffic patterns on correlation-based resource allocation to assess its generalizability and scalability. Exploring the application of correlation-based resource allocation techniques in other wireless communication systems beyond UAV networks, such as cellular networks and IoT deployments. Developing efficient algorithms and protocols for real-time correlation estimation and utilization in resource allocation decisions. By addressing these research directions, we can further advance the understanding and implementation of correlation-based resource allocation in UAV networks and other wireless communication systems, ultimately leading to more efficient and reliable network operations.

7 Conclusion

We presented a formal evaluation of the enhancements to spectrum efficiency and the improvement in network performance when the network exploits source correlations in multi-UAV communication systems. A linear formulation was presented and analytical proofs were produced to measure the improvement in spectrum efficiency. Numerical evaluations of the improvements in achieved spectrum efficiency as well as the performance of the network was provided when source correlations were exploited. About one to two orders of magnitude of improvement in the spectrum efficiency, about $50-88\%$ reduction in the mean delay for delay tolerant traffic and close to 100% call admittance for delay intolerant traffic was achieved. We presented an exhaustive set of correlations exploitation and a principal sub-matrix based method for choosing the right sets of links whose correlations can be exploited, to further enhance the spectrum efficiency. It was observed that the principal sub-matrix method yielded almost zero blocking and 80% improvement in the mean delay while being computationally more efficient than the exhaustive set of correlations exploitation. The analysis for self-similar (non-Poisson) traffic and power control for energy efficiency are currently being investigated in the context of this research.

Abbreviations

UAVs	Unmanned aerial vehicles
IoE	Internet of everything
6G	Sixth generation
5G	Fifth generation
SNs	Sensor nodes
BSs	Base stations
QoS	Quality of service
IoT	Internet of things
MIS	Maximal independent sets
D2D	Device-to-device
ROI	Return on investment
DGC	Dynamic graph coloring
CRN	Cognitive radio network
SU	Secondary users
AIO	Alternative iterative optimization
CBBA	Consensus-based bundle algorithm
IoV	Internet of vehicles
MEC	Mobile edge computing

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Author contributions

AM was responsible for all work in this article.

Availability of data and materials

The author keeps the analysis and simulation data sets, but the data sets are not public.

Declarations

Competing interests

The author declares that they have no competing interests.

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