Enabling Ultra-Dense UAV-Aided Network with Overlapped Spectrum Sharing: Potential and Approaches

Lu Wang, Hailiang Yang, Jinfeng Long, Kaishun Wu, and Jiming Chen

Abstract

UAV aided communication technology holds tremendous potential to upgrade outdoor link throughput and provide on-demand wireless services. The flexible deployment characteristic makes UAV-aided networks competent at emergency situations, including natural disasters and sudden traffic hotspots. In this backdrop, UAVs are required to be densely deployed to accommodate the huge volume of data traffic, where interference amid the neighboring cells turns out to be extremely challenging. To break this stalemate, this article systematically investigates spectrum sharing technology for ultra-dense UAV-aided networks from the architecture level down to the physical layer. We shed light on design principles and key challenges in utilizing overlapped spectrum for interference-enabled concurrent transmissions. With these principles in mind, we introduce SpecShare, which utilizes coding redundancy at the PHY layer for UAV spectrum sharing. We explore the optimal UAV placement strategy in the network layer to fully unleash the potential of such spectrum sharing capacity. We discuss the feasibility of SpecShare, and demonstrate its effectiveness in terms of network throughput.

Introduction

The proliferation of outdoor wireless traffic introduces a paradigm shift in cellular network architecture, from fixed terrestrial infrastructure to mobile connectivity "from the sky" [1]. Unlike the traditional cellular networks that heavily rely on the fixed ground base stations (BSs), using unmanned aerial vehicles (UAVs) such as drones and aircrafts as aerial mobile base stations or access points (APs) possesses the ability to provide on-demand wireless services with no infrastructure restraints. In this backdrop, both industry and academia have placed growing interest in UAV-aided wireless network architectures, as they present many opportunities for mitigating urgent communication issues in a cost-effective approach, such as prompt service recovery after natural disasters, traffic offloading in sudden traffic hotspots, and ubiquitous coverage against severe shadowing [2]. This flexibility on deployment and reconfiguration makes UAV-aided networks a promising architecture in future communication systems.

A representation of a UAV-aided network is depicted in Fig. 1. To realize the above visions, UAVs are normally equipped with a cellular backhaul (LTE/5G) connected to a ground BS, and a WiFi interface to build a WiFi network by hovering above a certain area. The clients communicate with UAVs via WiFi links, and the backhaul network operates via LTE/5G links backward to the ground base station. If there is an emergency situation, such as the failure of a terrestrial infrastructure, or a sudden and temporary increase in traffic demand, the UAVs relay and offload the clients' traffic to the remote functional ground BS station. Note that these situations are considered to be two critical scenarios that need to be effectively addressed in 5G wireless communication systems. With UAV-aided networks, traffic offloading is more flexible and efficient. In case of emergency, UAVs are required to be densely deployed to accommodate a sudden traffic explosion.

The ever-increasing density in UAV-aided networks has placed considerable pressure on the network design [3]. Unlike terrestrial communications where the attainable communication range is limited to a certain range by obstacles, UAV communications with a higher altitude have a larger communication range. With less shadowing and multipath from the terrestrial obstacles, line of sight (LOS) links dominate the communication among UAV APs and clients. As UAV deployment grows ultra dense, interference amid neighboring cells becomes inevitable and extremely challenging. The limited spectrum cannot afford non-overlapping between spectrum adopted by neighboring cells [4]. It is unavoidable that a huge amount of UAV APs and clients in range of each other operate on overlapped channels. The network operators need to find the optimal UAV separations in both frequency and spatial domain to guarantee wireless services. This problem is non-trivial, with considerable design issues entangled from the architecture level down to the physical layer.

In the literature, several attempts have been made to share spectrum on overlapped channels. The authors in [5] leveraged direct sequence spread spectrum (DSSS) to leverage partial channel interference for concurrent transmissions. As DSSS spreads each particular bit information over the whole spectrum, the SINR is adequate to recover the bit information even with partial channel interference. However, when it comes to the prevailing orthogonal frequency division multiplexing (OFDM) modulation, the feasibility does

Lu Wang, Hailiang Yang, Jinfeng Long and Kaishun Wu are with Shenzhen University; Jiming Chen (corresponding author) is with Zhejiang University.

Digital Object Identifier: 10.1109/MNET.2018.1700464

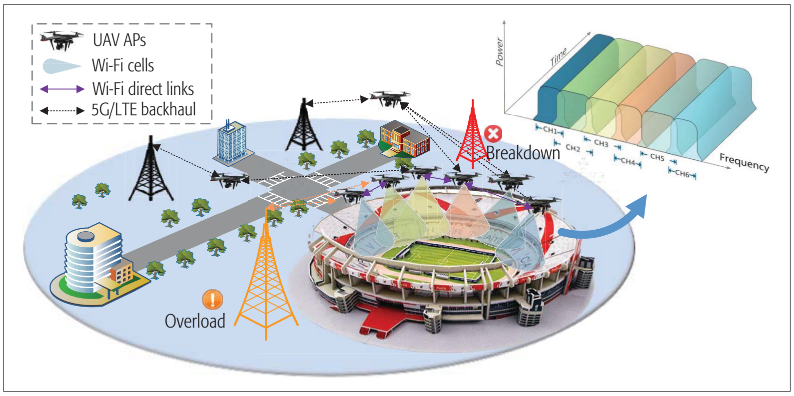

FIGURE 1. An illustrated example of ultra-dense UAV-aided network with overlapped spectrum sharing.

not hold. OFDM partitions the spectrum into a bundle of subcarriers, each sustaining a bit information. High data rate makes OFDM vulnerable to partial channel interference, as the SINR on the overlapped portion is inadequate for bit recovery. In [6], the authors proposed to harness multiple retransmissions in the time domain to sort out the collision-free bit information. Another solution in [7] exploited overlapped spectrum sharing via spectrum fragments, with the overlapped subcarriers nulled to avoid interference. Despite the growing interest in partially overlapped spectrum sharing, the existing endeavor requires sacrifice in certain domains (e.g., code, time or frequency), and thus fails to satisfy the demand for a large volume of traffic in ultra-dense UAV-aided networks. The flexible deployment feature of UAV provides a novel degree of freedom (DoF) for network optimization, and thus requires new thoughts and insights in the spectrum sharing architecture.

In this article, we investigate these key challenges of spectrum sharing in ultra-dense UAV-aided networks, and discuss possible solutions to harness partially overlapped spectrum along with UAV spatial DoF for concurrent transmissions. Through comprehensive analysis of the existing encoding capacities, we present a novel UAV-aided network structure, termed SpecShare, with both PHY layer and MAC layer design. SpecShare reaps the benefits of coding redundancy at the PHY to enable concurrent transmissions in the overlapped spectrum. It further explores the spatial DoF for UAV placement strategy at the MAC to fully unleashe the potential of overlapped spectrum sharing capacity. We demonstrate the benefits of the SpecShare architecture through experimental evaluations, and offer suggestions about future lines of research in ultra-dense UAV-aided network designs.

SpecShare: Design Principles and Challenges

A potential UAV-aided network with overlapped spectrum sharing is illustrated in Fig. 1. We consider a typical ultra-dense UAV-aided network scenario with a sports event held inside a stadium. As the ground BS is highly overloaded by the crowd, UAVs are densely deployed as mobile APs for traffic offloading. The dominant LOS links between UAVs and clients raise the probability of inter-cell interference. In this section, we consider the possibility of interference-enabled spectrum sharing on overlapped channels. Clients transmit concurrently with UAV APs on partially overlapped channels, leading to an increase in traffic volume. For internal traffic, where communication can be conducted within the cell, the UAV APs handle the traffic cooperatively, without involving the local ground BS. For external traffic that has to be transmitted via the local ground BS, the UAV APs relay the traffic to the remote ground BSs for load balancing. With the help of UAV APs, overlapped spectrum sharing can improve network throughput in a much more efficient way. We first review the existing spectrum sharing and UAV deployment technologies. Then we investigate the coding redundancy that can be leveraged for interference-enabled spectrum sharing. We also discuss the challenges of enabling overlapped spectrum sharing for ultra-dense UAV-aided networks.

Spectrum Sharing and UAV Deployment

In recent years there has been an explosion in wireless network deployment [8]. Earlier investigations indicated that the existing neighboring WiFi cells always operate on overlapped channels. The authors in [5] demonstrated that spectrum sharing on partially overlapped channels is viable in WiFi 802.11b with DSSS. As OFDM becomes more prevalent, the authors in [6] and [7] proposed overlapped spectrum sharing via multiple retransmissions and subcarrier nulling in 802.11ac to improve network throughput. Nevertheless, the existing endeavor requires sacrifice in certain domains, and is not robust against link dynamics, and thus cannot satisfy the ever-increasing traffic demand in ultra-dense UAV-aided networks.

UAVs hold promising potential to assist the terrestrial cellar infrastructures. In [9], a multi-tier UAV architecture was proposed for cellular networks. The authors in [10] investigated an optimal UAV placement algorithm to cover the maximum number of users with the minimum transmit power. The authors in [11] further considered user splitting, bandwidth allocation and UAV trajectory jointly for UAV offloading. However, none of the above work utilized overlapped spectrum sharing. Thus, spectrum usage efficiency is deficient for ultra-dense UAV-aided networks.

Motivation

To investigate whether we could harness the distinct PHY layer structure in WiFi networks for overlapped spectrum sharing, we measure the subcarrier superposition effect under partial-channel interference on a GNU radio testbed. The bit error rate (BER) in 1/4 overlap is close to 10^{-2}, which is acceptable in a communication system. For 1/2 and 3/4 overlap, the BER is less then 10^{-1}. The result reveals that the existing coding schemes still have the capacity to tolerate extra errors. We refer to this capacity as "coding redundancy." This coding redundancy inspires us to borrow the wisdom of concurrent transmissions on partially overlapped channels in DSSS-based systems. If we exploit coding redundancy properly, for example, dispersing the partial channel interference over the entire channel to some extent, the corrupted bit information can be restored. Therefore, we could facilitate concurrent transmissions in UAV-aided networks via overlapped spectrum sharing, and achieve maximized throughput under ultra-dense deployment.

Design Principles and Challenges

The ultimate goal of UAV-aided networks is to complement the existing infrastructure and provide swift and seamless offloading. With dense deployment, for example, sudden traffic hotspots or service recovery after natural disasters, the need for orders-of-magnitude capacity enhancement is essential. Specifically, the UAV-aided network should provide the following capacities.

Interference-Enabled Transmission: The network should have the capacity to accommodate concurrent transmissions upon LOS interference from ambient mobile infrastructures (UAV APs), and the underlying coding structure should be robust against link dynamics introduced by UAV mobility.

Flexible Spectrum Sharing: In the frequency domain, the network should be able to exploit as much available overlapped spectrum as possible, while introducing no interference to the terrestrial infrastructure (ground APs).

Optimal UAV Placement: In the space domain, the network should jointly consider the client distance/density/requirement for UAV placement, so that the transmission quality is guaranteed and the overlapped spectrum sharing capacity is fully utilized.

To embrace the interference amid neighboring cells in ultra-dense UAV-aided networks, we need appropriate UAV partition in both the frequency and space domains, so that the LOS interference can be transformed from peril to advantage. As we envisioned before, the proper use of coding redundancy can recover bit information from interference. If we intentionally designate two neighboring UAV cells to transmit concurrently on partially overlapped channels, two transmission portion are obtained: the overlapped portion with interference, and the non-overlapped portion with clean bit information. Intuitively, the overlapped portion has inadequate SINR for decoding. Yet with coding redundancy on the non-overlapped portion, it is possible to recover the corrupted bit information, and the clean bit information remains decodable even with contamination.

The swift deployment of UAV brings new opportunities along with design challenges, which requires rethinking from the architecture level down to the physical layer. First, as UAV mobility introduces link dynamics, to properly leverage the coding redundancy upon fragile OFDM subcarriers, so that the bit information can be successfully recovered even with link dynamics and LOS interference. Second, in the case of ultra-dense networks, we need to strike a balance between the interference and concurrent transmission to maximize spectrum usage efficiency. Third, the UAV placement strategy should jointly consider the client density/requirement along with space and spectrum separation. Thus, the network can fully benefit from the overlapped spectrum sharing capacity.

SpecShare Enabled UAV-Aided Networks

In this section, we describe the SpecShare architecture that leverages overlapped spectrum for interference-enabled concurrent transmissions in ultra-dense UAV-aided networks.

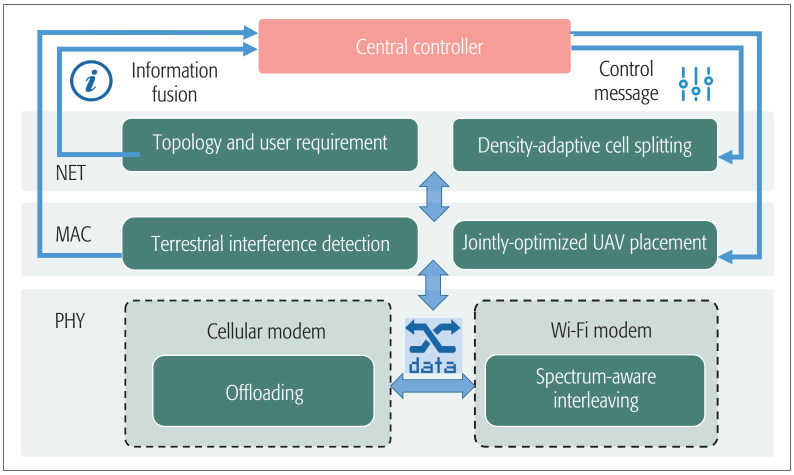

FIGURE 2. SpecShare architecture building blocks.

Design Overview

Figure 2 depicts the overall architecture and the building blocks. Generally, SpecShare gathers the topology and client requirement information at the network layer for UAV cell splitting, and leverages spectrum-aware interleaving at the PHY layer to recover the corrupted bit information on the overlapped portion. With the support from these two layers, the MAC layer jointly optimizes the UAV placement in both the space and frequency domains, which aims to accommodate partial-channel interference to enhance spectrum usage. Specifically, SpecShare incorporates the following components.

Spectrum-Aware Interleaving: To exploit coding redundancy in the OFDM-based system. At the PHY layer, spectrum-aware interleaving disperses the partial channel interference over the entire channel, and creates uniform error distribution in terms of the overlapped portion.

Density-Adaptive Cell Splitting: To ensure the service quality, at the network layer, density-adaptive cell splitting divides the UAV AP cell volume according to the client density and requirements.

Jointly-Optimized UAV Placement: With the support from the PHY and network layers, we aim to find the optimal UAV placement strategy in both the space domain and spectrum domain, so that the network can fully utilize the overlapped spectrum sharing capacity.

Spectrum-Aware Interleaving

To exploit coding redundancy in the OFDM-based system, we leverage the interleaver design in the PHY layer. Traditional communication systems normally adopt a fixed interleaving strategy to overcome bursty errors [12]. Fixed interleaving is incompetent for overlapped spectrum sharing, as the UAV placement is swift in the space and frequency domains. Here we propose a spectrum-aware interleaver, which adaptively disperses the partial channel interference amid the collision-free portion. Therefore, we can obtain uniform error distribution despite the overlapped proportion.

We illustrate the idea of spectrum-aware with a toy example. As depicted in Fig. 3, we partition the 802.11ac channel subcarriers into 4 blocks. The overlapped portion includes n_{over-}

$_{lap}$ blocks ($0 \leq n_{overlap} < 4$). We need to find the uniform distribution among all of the subcarriers, which distributes the overlapped portion randomly enough inside the non-overlapped portion, so that the SINR on the entire channel subcarriers is acceptable. The spectrum-aware interleaver is built up with two permutations. The first permutation is block reshaping, with the purpose to insulate two neighboring overlapped blocks. The second permutation is block interleaver. This is the key idea to reduce the detrimental impact by the overlapped subcarriers and guarantees a uniform constant amid the non-overlapped subcarriers. The block interleaver is loaded row-by-column. As depicted in Fig. 3, the input sequence of bit information is written row-wise and read column-wise row-wise. At the receiver side, the deinterleaver executes the reverse operation. After the rotation of the block interleaver, we can recover the original block sequence before reshaping in terms of the overlapped portion. According to our study, when the overlapped proportion is above 1/2, the errors clearly exceed the affordable coding redundancy. Thus when enabling overlapped spectrum sharing, the proportion should be restricted to 1/2 to ensure the transmission quality.

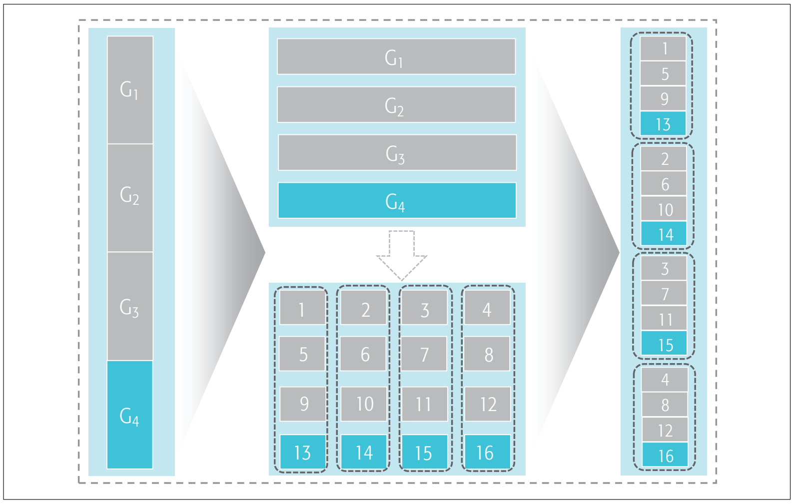

FIGURE 3. Illustration of spectrum-aware interleaver, with 1/2 overlap (in blue).

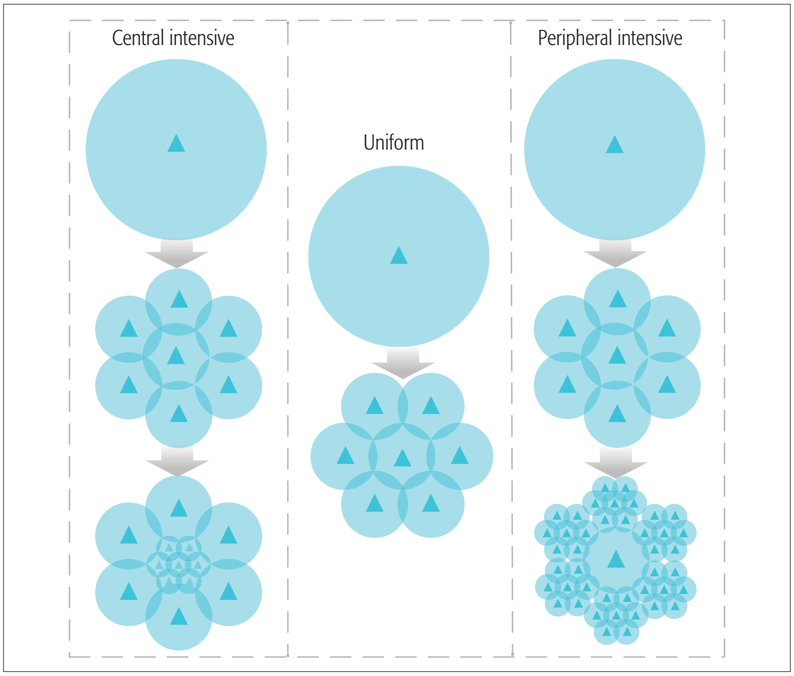

FIGURE 4. Illustration of three possible cell splitting results.

Density-Adaptive Cell Splitting

When encountering an emergency situation for a sudden traffic hotspot, client distribution is not always uniform. With swift deployment, each UAV AP can adapt its service range to fully utilize the overlapped spectrum sharing capacity. Therefore, we propose a density-adaptive cell splitting approach to maximize the UAV deployment efficiency.

We denote the service capacity of a UAV with overlapped spectrum sharing capacity as C_p. It is assumed that with a standard height, the UAV covers a standard service area. The coverage can be controlled by adjusting the UAV's height, as the wireless signal strength is in inverse proportion to the transmission distance. In particular, we uniformly divide the entire area into multiple cells with the same size. Afterward, we calculate the traffic demand of each cell as C_{area}. If C_{area} is larger than C_p, the cell will be further split into two smaller cells. The calculation repeats until the C_{area} is less then C_p. Figure 4 illustrates three typical splitting outcomes.

Central Intensive Distribution: Refers to the case when the clients are concentrated in the center, while the surrounding area is relatively sparse (e.g., gathering, lecture). As shown in Fig. 4, the central areas will be split until the system capacity meets the clients' demand.

Uniform Distribution: Refers to the case with evenly distributed clients (e.g., parade). As shown in Fig. 4, the entire area is split into comparable size.

Peripheral Intensive Distribution: Refers to the opposite case of central intensive distribution (e.g., gymnasiums, concerts). As shown in Fig. 4, the center area can be covered with the standard size, and the surroundings need to be split several times.

To obtain the client location and construct the network topology for cell splitting, the UAV APs periodically broadcast a routing information via the beacons. Upon receiving the beacon, the clients return their channel state information along with the GPS information. The APs then return the information to the central controller, which combines all the available information and constructs the global network topology.

Jointly-Optimized UAV Placement

For ultra-dense UAV-aided networks, the LOS links dominate the communication. With exposed complex interference, UAV deployment is quite diverse from the one in the terrestrial environment. We should jointly consider the placement in both the space and frequency domains, in the way that the UAV APs introduce no interference to the terrestrial infrastructures, and leverage the limited spectrum for high speed data transmission.

To avoid interference to the existing infrastructures, the central controller first obtains the spectrum usage information from the terrestrial APs. Each UAV AP broadcasts beacon frames to obtain the channel usage information from the terrestrial APs and feeds it back to the central controller. Through comprehensive analysis of the channel usage information (e.g., center frequency, bandwidth), the available spectrum can be obtained for UAV-aided networks.

To leverage the UAV flexibility for overlapped spectrum sharing, we propose a joint optimization UAV deployment in both the space and frequency domains. We formulate the UAV placement problem as a vertex coloring problem in an undirected graph. A UAV placement strategy $C(UAV_i)$, $UAV_i \in V$, is a mapping from the vertex set V to the color set $C : V \rightarrow \{1, 2, ..., m\}$, where V is a set of UAVs and m is the number of colors (available channels).

Placement for Non-Uniform Distribution: For non-uniform distribution, the placement should be prioritized to meet the diverse clients density/requirement. The central controller first sorts UAV APs in terms of the density degree, which is calculated according to service area range and the number of adjacent nodes of a UAV AP. Then it chooses a color C_i (unassigned channel) and assigns it to the UAV AP V_j with the highest degree, and assigns the same color to the UAV AP V_k that is not adjacent. The central controller repeats the assignment until all nodes are colored. Afterward, it calculates the global interference, which is the normalized interference level of all the neighboring cells. If the global interference is below a certain threshold, the last colored node is switched to a partially overlapped channel. The switching repeats until all the nodes are traversed.

Placement for Uniform Distribution: For uniform distribution, we aim to leverage non-orthogonal channels to improve spectrum usage efficiency. The central controller randomly picks up a UAV AP V_i, and assigns it a random color C_j. Then it assigns a set of overlapped channel $C_{(j-\delta)}$, ...$C_{(j+\delta)}$ to the adjacent UAV APs. The assignment repeats until all nodes are colored. Then the central controller calculates the global interference. If it is above a certain threshold, the node with the highest overlapped portion is switched to an orthogonal channel. The switching repeats until all the nodes are traversed.

Battery Life: As battery life could be a main constrain in UAV placement, the central controller should take this factor into consideration when deploying the UAV APs. Each UAV AP updates its battery life to the controller before transmission. If the battery life of a UAV AP is below a certain threshold, it will be moved to another set $V_{orthogonal}$. Within this set, the nodes are only assigned an orthogonal channel for transmission to avoid complex computing.

Performance Evaluation

This section evaluates the performance of SpecShare through experiments and simulations. We first validate the spectrum-aware interleaving on the GNU radio platform. The universal software radio peripheral 2 (USRP2) uses the RFX2450 daughterhood as the RF frontend, which operates in the 5.15–5.725GHz range. As the hardware platform has latency constraints, we then use trace-driven simulations interconnected with C++ and Matlab to evaluate the jointly-optimized UAV placement.

The preliminary implementation does not consider several issues concerning UAV-aided networks, such as battery life, instability, mobility and so on. Future UAV-aided networking schemes can factor these into consideration, and make the schemes more practical.

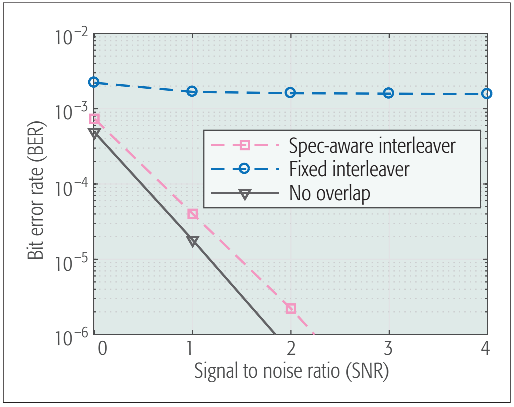

FIGURE 5. Decoding capacity under various interleaver.

Experimental Setup

In the following evaluations, we use a 64-point FFT on a 20 MHz channel. Channels 36–48 are selected with center frequency from 5.18 Ghz to 5.24 Ghz. 802.11ac, the de facto WiFi standard used today, and ASN [7], a representative overlapped spectrum sharing research algorithm with the best published result, are selected as comparisons. The detailed evaluation methodology is as follows:

Spectrum-Aware Interleaving: To verify the PHY layer decoding capacity, we use three USRP nodes, transmitter (N_t), receiver (N_r) and interferer (N_i) to conduct overlapped spectrum sharing on a GNU radio platform in our lab. N_i resides on channel 36, and keeps transmitting to N_r. N_t and N_r conduct transmission on channel 38 and 39 with carrier-sense disabled. In SpecShare, N_t adopts a spectrum-aware interleaver for 1/2 and 1/4 overlapped transmissions on channel 38 and channel 39, respectively. In 802.11ac, N_t adopts a fixed interleaver for overlapped transmissions on channels 38 and 39. In ASN, as the overlapped subcarriers are nulled at N_t , there is no partial channel interference.

Jointly-Optimized UAV Placement: We evaluate the performance of the MAC layer jointly-optimized UAV placement over the low altitude UAV propagation models described in [13]. A total of 100 clients are modeled as Poisson point process in C++, and the topology is imported to Matlab for cell splitting in 802.11ac, ASN and SpecShare. For spectrum access, 802.11ac follows the legacy carrier sense multiple access with collision avoidance (CSMA/CA). The UAV AP scans the entire spectrum and selects an idle channel. Binary exponential backoff is conducted when collision happens. ASN adopts ASN with direct access (ASN-DA) [7]. The sensing and transmission is more fine-grained than 802.11ac. If a portion of a channel is busy, the UAV AP nulls the corresponding subcarriers and aggregates the rest for transmission. Without loss of generality, we assume that they have saturated traffic. We run each simulation 1000 seconds,

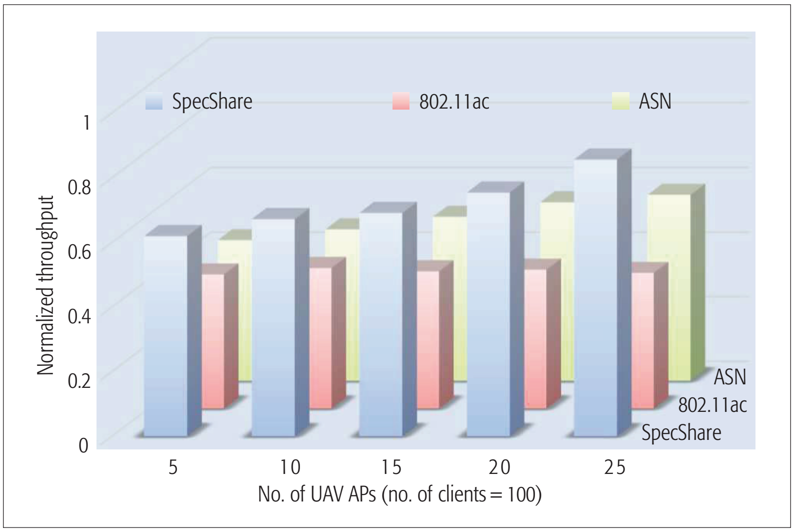

FIGURE 6. Throughput with a variety of UAV/client density.

and repeat 50 times to calculate the network normalized throughput.

Baselines

Figure 5 shows the decoding capacity of ASN,802.11ac and SpecShare. We use ASN with no overlap as the baseline, since it nulls the overlapped subcarriers to avoid interference. With partial channel interference, 802.11ac with fixed interleaver has a constantly high BER even as SNR increases. In contrast, in SpecShare, the spectrum-aware interleaver greatly reduces the BER. As SNR grows, the resulting BER rapidly declines below 10^{-5}, and has a curve comparable with ASN, verifying that the spectrum-aware interleaver has the capacity to leverage coding redundancy for overlapped spectrum sharing.

Figure 6 gauges the normalized throughput with a variety number of UAV APs. In 802.11ac, as the spectrum access is obtained exclusively, the throughput is not improved with increased UAV APs. Meanwhile, ASN successfully leverages the spectrum fragments, and thus the throughput is enhanced as the number of UAVs grows. SpecShare achieves even better results, as it reaps the benefit of partial channel interference for spectrum sharing. It recovers most of the packets corrupted by partial-channel interference even with high client density and UAV AP density, and achieves a 175 percent and 135 percent performance gain over 802.11ac and ASN, respectively.

The results verify the benefits of our architecture in leverage overlapped spectrum for ultra-dense UAV-aided networks. We show that it is feasible to optimize UAV placement in both the frequency and space domains to maximize network throughput. However, the preliminary implementation does not consider several issues concerning UAV-aided networks, such as battery life, instability, mobility and so on. Future UAV-aided networking schemes can factor these into consideration, and make the schemes more practical.

Conclusion

In this article, we discuss the history, principles and representatives of unmanned aerial vehicle (UAV) aided communication technologies. Through careful investigation of the pros and cons of existing approaches, we observe that the main hurdles of UAV-aided networks lie in the ineffective usage of the limited spectrum resources.

Under the design principles resulting from our investigation, we present a novel spectrum sharing architecture, termed SpecShare, with both PHY layer and MAC layer design. SpecShare utilizes overlapped spectrum for interference-enabled concurrent transmissions. In particular, it reaps the benefits of coding redundancy in the PHY layer for UAV-aided spectrum sharing. It further explores the UAV placement strategy in the space and frequency domains to fully unleash the potential of such spectrum sharing capacity. We illustrate the effectiveness of SpecShare through experiments. We believe that SpecShare can contribute to future 5G communication systems by accommodating more concurrent transmission opportunities [14, 15].

Acknowledgment

This research was supported in part by China NSFC grants 61872246, 61502313, 61872248, 61472259, and 61601308; Project 973 grant 2015CB352503; Shenzhen Science and Technology Foundation grants JCYJ20170817095418831, JCYJ20170302140946299, and JCYJ2017041211 0753954; Joint Key Project of the National Natural Science Foundation of China number U1736207; Guangdong Natural Science Foundation grant 2017A030312008; Guangdong Provincial Science and Technology Development Special Fund project 2017A010101033; Fok Ying-Tong Education Foundation for Young Teachers in the Higher Education Institutions of China grant 161064; Guangdong Talent Project 2015TX01X111 and GDUPS (2015); and the Tencent "Rhinoceros Birds"-Scientific Research Foundation for Young Teachers of Shenzhen University. Jiming Chen is the corresponding author.

References

[1] Y. Zeng, R. Zhang, and T. J. Lim, "Wireless Communications with Unmanned Aerial Vehicles: Opportunities and Challenges." *IEEE Commun. Mag.*, vol. 54, no. 5, 2016, pp. 36–42.

[2] Z. Md. Fadlullah *et al.*, "State-of-the-Art Deep Learning: Evolving Machine Intelligence Toward Tomorrow's Intelligent Network Traffic Control Systems," *IEEE Commun. Surveys & Tutorials*, vol. 19, no. 4, 2017, pp. 2432–55.

[3] D. Takaishi *et al.*, "Virtual Cell Based Resource Allocation for Efficient Frequency Utilization in Unmanned Aircraft Systems," *IEEE Trans. Vehicular Technology*, vol. 67, no. 4, 2018, pp. 3495–3504.

[4] F. Tang *et al.*, "AC-POCA: Anticoordination Game Based Partially Overlapping Channels Assignment in Combined UAV and D2D-Based Networks," *IEEE Trans. Vehicular Technology*, vol. 67, no. 2, 2018, pp. 1672–83.

[5] A. Mishra *et al.*, "Partially Overlapped Channels Not Considered Harmful," *ACM SIGMETRICS Performance Evaluation Review*, vol. 34, no. 1, 2006, pp. 63–74.

[6] L. Li *et al.*, "Retransmission Repeat: Simple Retransmission Permutation Can Resolve Overlapping Channel Collisions," *Proc. Sixteenth Annual International Conference Mobile Computing Networking*, ACM, 2010, pp. 281–92.

[7] X. Zhang and K. G. Shin, "Adaptive Subcarrier Nulling: Enabling Partial Spectrum Sharing in Wireless LANs," *Proc. 19th IEEE Int'l. Conf. Network Protocols (ICNP)*, IEEE, 2011, pp. 311–20.

[8] R. Deng *et al.*, "Energy-Efficient Cooperative Spectrum Sensing by Optimal Scheduling In Sensor-Aided Cognitive Radio Networks," *IEEE Trans. Vehicular Technology*, vol. 61, no. 2, 2012, pp. 716–25.

[9] S. Sekander, H. Tabassum, and E. Hossain, "Multi-Tier Drone Architecture for 5G/B5G Cellular Networks: Challenges, Trends, and Prospects," *IEEE Commun. Mag*., vol. 56, no. 3, 2018, pp. 96–103.
[10] M. Alzenad *et al*., "3-D Placement of an Unmanned Aerial Vehicle Base Station (UAV-BS) for Energy-Efficient Maximal Coverage," *IEEE Wireless Commun. Lett.*, vol. 6, no. 4, 2017, pp. 434–37.
[11] J. Lyu, Y. Zeng, and R. Zhang, "UAV-Aided Offloading for Cellular Hotspot," *IEEE Trans. Wireless Commun*., 2018.
[12] L. Wang *et al*., "Exploring Smart Pilot for Wireless Rate Adaptation," *IEEE Trans. Wireless Commun*.,vol. 15, no. 7, 2016, pp. 4571–82.
[13] X. Cai *et al*.,"Low Altitude UAV Propagation Channel Modelling," *Proc. 2017 11th European Conf. Antennas and Propagation (EUCAP)*, IEEE, 2017, pp. 1443–47.
[14] X. Lin *et al*., "SAGE: A Strong Privacy-Preserving Scheme Against Global Eavesdropping for Ehealth Systems," *IEEE JSAC*, vol. 27, no. 4, 2009, pp. 365–78.
[15] J. Chen *et al*., "Narrowband Internet of Things: Implementations and Applications," *IEEE Internet of Things J.*, vol 4, no. 6, 2017, pp. 2309–14.

Biographies

Lu Wang (wanglu@szu.edu.cn) is an assistant professor with the College of Computer Science and Software Engineering, Shenzhen University, China. Her research interests focus on wireless communications and mobile computing.

Hailiang Yang (hailiangyang2016@mail.szu.edu.cn) is an M.S. student at the College of Computer Science and Software Engineering, Shenzhen University. His research interests include WLAN and future generation cellular networks.

Jinfeng Long (jinfenglong2016@mail.szu.edu.cn) is working toward the M.S. degree at Shenzhen University, China. Her research interest is millimeter wave communications.

Kaishun Wu (wu@szu.edu.cn) is currently a distinguished professor at the College of Computer Science and Software Engineering, Shenzhen University. He has co-authored two books and published 80 refereed papers in leading international journals and premier conferences. His research interests include wireless networking, mobile computing, and Internet of Things.

Jiming Chen (cjm@zju.edu.cn) is a full professor with the College of Control Science and Engineering and the deputy director of the State Key Laboratory of Industrial Control Technology, Zhejiang University, Hangzhou, China. His research interests include sensor networks, networked control, and cyber security.