IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received October 10, 2018, accepted October 30, 2018, date of publication November 9, 2018, date of current version December 3, 2018.

Digital Object Identifier 10.1109/ACCESS.2018.2879637

Integrating Communications and Control for UAV Systems: Opportunities and Challenges

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This work was supported in part by the National Natural Science Foundation of China under Grant 61531011, Grant 61771274, and Grant 61831013, in part by the Beijing Natural Science Foundation under Grant 4182030, in part by the Guangdong Key Laboratory Project under Grant 2017B030314147, and in part by the Key Laboratory of Universal Wireless Communications, Ministry of Education, China. G. Ding was supported by the National Natural Science Foundation of China under Grant 61871398.

ABSTRACT Unmanned aerial vehicle (UAV) communications play an important role in building the space-air-ground network and realizing the seamless wide-area coverage thanks to its long-range connectivity, high maneuverability, flexible deployment, and low latency. Different from the traditional ground-only communications, the control techniques tightly impact UAV communications, which could be jointly designed to enhance the performance of data transmission. In this paper, we explore the opportunities and challenges of combining the communications and control in UAV systems. For single-UAV scenario, we introduce a new frequency-dependent 3D channel model. We then show how to perform channel tracking with a flight control system as well as how to mechanically and electronically formulate the transmission beams. For multi-UAV scenario, we present new techniques as cooperative communications, self-positioning, trajectory design, resource allocation, and seamless coverage. In the end, we provide some interesting discussions over communication protocol, secrecy, 3D dynamic topology heterogeneous networks, and low-cost design for practical UAV applications.

INDEX TERMS UAV, communications, flight control, swarm.

I. INTRODUCTION

With the rapid development of computing, caching, sensing, communications, and control, unmanned aerial vehicles (UAVs) raise ever increasing interest in military, industry, as well as the academic communities [1]–[3]. Currently, UAVs have been adopted into many applications like military strike, air defense early warning, border surveillance, disaster response, traffic monitoring, transportation of goods, and communications. Among various applications, UAV assisted communications could provide long-range connectivity, high maneuverability, flexible deployment, and low latency transmission, and is thus of great importance for the future broadband communication network.

Willink *et al.* [4] measured the low-altitude UAV air to ground (A2G) channel, and provided the insights for the development of the A2G communication system. Following [4], Azari *et al.* [5] proposed a generic framework for the analysis and optimization of the A2G systems, and derived analytical expressions for the optimal UAV height that minimizes the outage probability of an arbitrary A2G link. Multiple UAVs were simultaneously exploited to communicate with a ground station in [6], and the achievable capacity was explored under the line of sight (LoS) condition. Su *et al.* [7] derived the asymptotic capacity of the UAV muti-input multi-output (MIMO) wireless communication system, and the necessary and sufficient condition of capacity threshold permits us to appropriately choose the system parameters that could reach the possible highest system capacity.

Apart from the communications, many UAV designs in the past two decades focused on the system control, such as flight control, trajectory design, and attitude adjustment, etc. For example, the robust UAV navigation method was presented in [8], where the global positioning system (GPS), inertial navigation system (INS), and peer-to-peer radio ranging are adopted for sensor fusion and flight control. Meanwhile, [9] derived a theoretical model for the propulsion energy consumption of fixed-wing UAVs as a function of the flying speed, direction, and acceleration, and designed an energy-efficient trajectory for UAV systems. Mozaffari *et al.* [10] proposed a UAV attitude estimation method, where the unscented Kalman filter (UKF) based attitude heading reference device is utilized to improve the precision of attitude estimation.

Actually, the communications and control are highly coupled in the UAV systems. For instance, the UAV attitude variation will affect the beam direction of data communications. Besides, the communication interference and blockage effect can be dramatically decreased by changing the spatial location of UAVs. Moreover, the UAV navigation formulates a three dimension (3D) dynamic topology whose performance can be optimized with the trajectory design, etc. All the above facts motivate integrating the communications and control for UAV systems to benefit the performance.

In this paper, we will highlight the opportunities and challenges of integrating communications and control for UAV systems. We first present a frequency-dependent 3D geometric model to characterize the UAV to ground channel. Then, the flight control system (FCS) is exploited for channel tracking, where the UAV movement and control information are utilized to simplify the channel tracking procedure. Meanwhile, the joint mechanical and electrical beamforming strategy is introduced for data transmission. We further investigate several key techniques to integrate the control in the multi-UAV communications, such as collaborative communications, self-positioning, seamless coverage, trajectory design, resource allocation. In the end, we discuss some other interesting issues like communications protocol, secure communications, heterogeneous network with 3D dynamic topology, and low-cost designs for the practical UAV communications.

II. COMMUNICATIONS AND CONTROL FOR VARIOUS UAV APPLICATIONS

Due to the advantages of high mobility and easy deployment, UAVs are anticipated to be widely exploited in the future wireless communications. Typical circumstances of UAV communications are shown in Fig. 1, including but not limited to:

- **Hot spot coverage:** Employing UAV as aerial base station (BS) could enhance the wireless coverage for the hot areas like the railway station, stadium, office work place, kermis, etc., due to the additional spatial degree of freedom provided from the high sky.

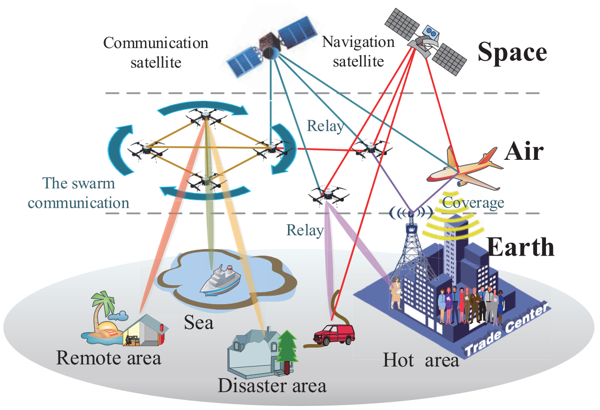

FIGURE 1. The integrated space-air-ground network.

- **Range extension:** UAV could be deployed for users without communication infrastructure, such as the remote mountain village and ocean sailing. It can also be used as emergency communications for natural disaster areas with complete infrastructure damage.
- **Relay communications:** UAV could act as relay between two specific users, which is especially important for the military circumstance when the commands need to be timely delivered between the remote command center and the frontier soldiers.
- **UAV satellite communications:** UAV could communicate with the satellite during navigation, i.e., a type of satellite communication on the move (SOTM), and UAV needs to constantly direct the beam towards the satellite to maintain the communication link.
- **Multi-UAV cooperative communications:** Multiple UAVs can corporate to build a wireless sky network and cover a large area, where the coordinated multiple points (CoMP) techniques from the terrestrial cellular network can be utilized to improve system performance.
- **Swarm communications:** The swarm is composed of a large number of mini-UAVs and is mainly used in battle applications. Since the mini-UAVs are tightly deployed, the swarm formulates a virtual large-scale array and can coordinate to enhance the spectrum efficiency.

The UAV system is mainly composed of the communications subsystem, FCS, and the aircraft subsystem to meet the various UAV applications. The communication subsystem is responsible for the information transfer, while FCS manages the UAV navigation which further consists of sensors like GPS and mechanical micro inertial unit (MIMU). FCS is usually mounted in the body frame (b-frame), whose x_b, y_b, and z_b axes are in the directions of right, forward, and up, respectively. The aircraft subsystem executes the control demands from FCS to maintain UAV navigation, whose frame (n-frame) is usually selected as the local geodetic frame, i.e, x_n-axis, y_n-axis, and z_n-axis pointing to the north,

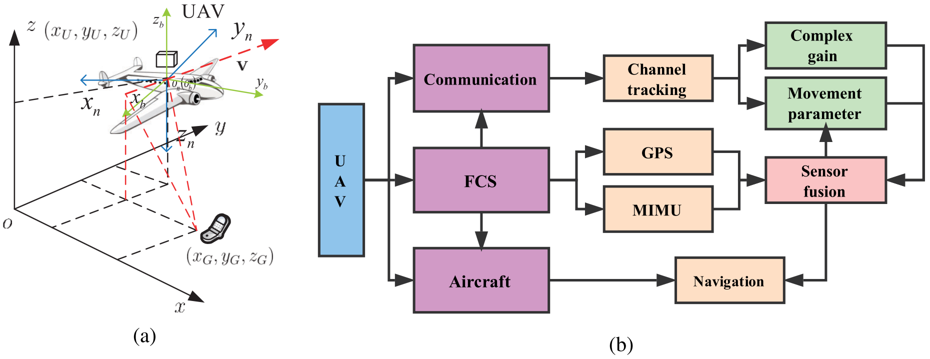

FIGURE 2. **The integrated UAV communication and control. (a) Channel model. (b) Channel tracking strategy.**

east, and downwards, respectively. The corresponding UAV communication system is shown in Fig. 2(a).

Traditionally, FSC and communications subsystem are separately implemented. Nevertheless, the communications and control are highly coupled in the UAV systems. Control can be exploited to adjust both the trajectory and attitude for much more desirable communication performance, while the communications can inversely enhance the precision of UAV control. These facts motivate integrating the communications and control for UAV systems to benefit the performance.

III. COMMUNICATIONS AND CONTROL FOR SINGLE UAV

During UAV navigation, its attitude would vary all the time, and hence will affect beam direction and decrease the communication quality. Therefore, the control such as attitude adjustment need to be jointly designed with communications to bring the full performance benefits of UAV systems. In this section, we will explore the key techniques of integrating communications and control for UAV systems, including UAV channel modeling, FCS aided channel tracking, and joint beam tracking with mechanical and electrical adjustment.

A. UAV CHANNEL MODELING

The channel of UAV communications exhibits several unique characteristics that are different from the ground communications due to the continuous navigation in the high sky. For instance, numerical measurements have demonstrated that the UAV channel is naturally sparse and the LoS path is dominant [11]. Meanwhile, the UAV channel encounters continuous Doppler effect (reduce to discrete Doppler shifts with sparse paths), and therefore faces severe time selective effect [12]. Besides, the LoS transmission makes the communications vulnerable to blockage.

In order to support high information rate either for data transmission or for wireless backhaul, Xiao *et al.* [11] proposed to adopt mmWave (30-300GHz) frequency band in UAV communications that could bring gigahertz bandwidth. Meanwhile, thanks to the tiny mmWave wavelength, massive number of antennas can be packed onto the small UAVs[1] and offer enormous spatial gain to combat the large path-loss of the mmWave band.

We here take a mmWave UAV communication system with $M \times N$ uniform planar array (UPA) as example. It is recently shown in [13] that the wideband transmission with massive array antenna would encounter the frequency-dependent spatial steering vector, also named as beam squint effect. The frequency domain uplink channel of block-l can be characterized by the 3D geometric model

$$\mathbf{H}(l,f) = \frac{\alpha}{[D]^{\gamma}} e^{-j2\pi f_d l N_b T_s} \mathbf{A}\left(\phi, \theta, f, f_c\right), \tag{1}$$

where N_b is the number of symbols in each block, α is the complex channel gain, D is the distance between the user terminal and UAV, γ is the large-scale fading coefficients, f_d is the Doppler shift, T_s is the sampling interval, f_c is the carrier frequency, ϕ is the azimuth angle relative to array antenna plane, and θ is the elevation angle relative to array antenna plane. Moreover, $\mathbf{A}\left(\phi, \theta, f, f_c\right)$ is the frequency-dependent spatial steering vector, whose (m, n)-th element is given by

$$\mathbf{A}\left(\phi, \theta, f, f_c\right) = e^{j\frac{2\pi d}{\lambda_c}[(m-1)\sin\phi\cos\theta + (n-1)\sin\phi\sin\theta]\left(1+\frac{f}{f_c}\right)}. \tag{2}$$

Note that, the azimuth angle ϕ and the elevation angle θ will change with the variation of UAV attitude, and thus affect the channel value. In this case, the traditional channel transceiver structure such as [14] and [15] would not work.

For mmWave massive MIMO systems, the large channel dimension increases the complexity of the channel estimation. Nevertheless, according to the 3D geometric model (1), the high dimension channel can be determined by a few physical parameters such as f_d, D, ϕ, and θ, as well as the complex value α. Therefore, estimating the high-dimensional channel can be simplified into estimating these parameters. Normally, the downlink channel can be directly obtained from the uplink channel in the time duplex division (TDD) system due to the channel reciprocity, which however does not hold for frequency duplex division (FDD) system. Interestingly, the unique property of UAV communications is that the parameters ϕ and θ are frequency insensitive while f_d has explicit relationship with ϕ, θ, and f. Hence, even for

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[1] UPA with 16 × 8 antennas at 30 GHz mmWave only occupies an area of 26.25 cm^2.

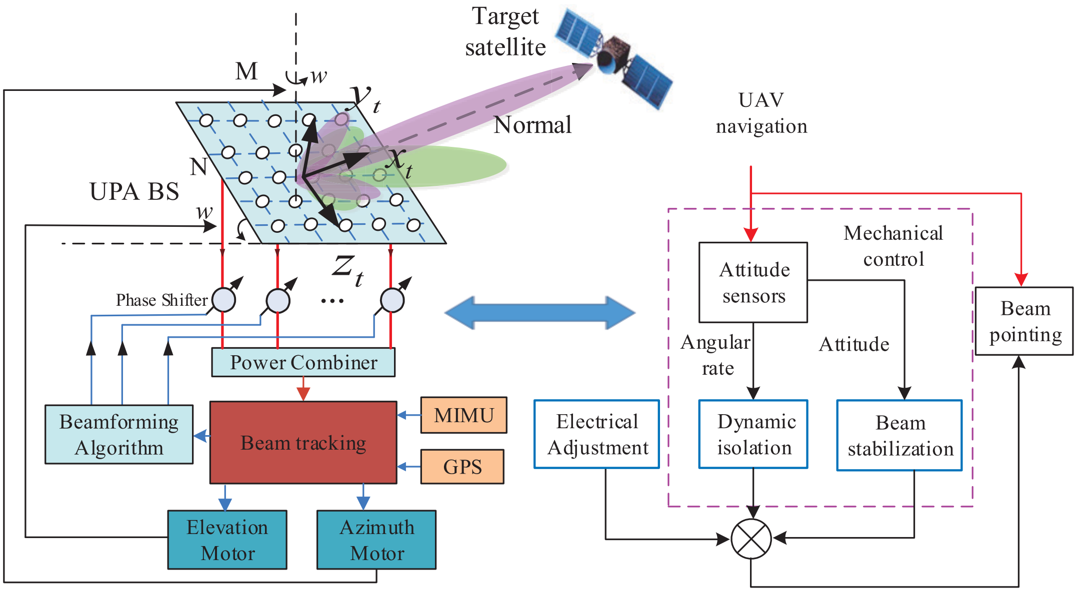

FIGURE 3. Beam tracking with joint mechanical and electrical adjustment for UAV satellite communications.

FDD system, most parameters of the downlink channel can be directly obtained from the uplink channel, while one only needs to spend very few pilots to estimate the downlink channel gain α. In this way, not only the complexity of channel estimation can be greatly decreased, but also the TDD/FDD transmission protocols could be unified.

B. CHANNEL TRACKING WITH FCS

Tracking the channel variation is important for UAV communications during the continuous navigation, which is especially challenging when the massive number of antennas are employed at mmWave band. According to channel model (1), the large dimensional channel is only determined by a limited number of parameters, such as α, f_d, D, ϕ, and θ. Since most of these parameters are related with the UAV's physical movement and position, it is possible to utilize FCS to simplify their obtaining and hence reduce the training overhead during the tracking.

For example, the UAV movement state regulations such as the doppler shift f_d, the distance D, the azimuth angle ϕ, and the elevation angle θ can be derived from the perturbation analysis of the FCS outputs based on the inertial navigation equation [12]. Then, one simple way to realize the FCS based channel tracking is as follows: the UAV movement related parameters are firstly derived by sensor fusion of GPS and MIMU, and then a few pilots are sent to estimate the remaining channel parameters. Meanwhile, Kalman filter could be utilized to improve the realtime and channel tracking precision of the UAV systems. To be specific, in the perdition step of Kalman filter, the UAV kinematic equation and measurement equation can be exploited to speculate the UAV movement parameter, f_d, D, ϕ, as well as θ. Then, in the updating procedure of Kalman filter, the remaining channel gain α is generated by the Kalman innovation value. Moreover, parameter learning can be exploited to further enhance the channel tracking precision with Kalman filter, where the parameters in the UAV kinematic equation and measurement equation for Kalman filter can be learned by intelligent algorithm such as expectation and maximization (EM) method. The corresponding channel tracking procedure is shown in Fig. 2(b).

C. BEAM TRACKING WITH JOINT MECHANICAL AND ELECTRICAL ADJUSTMENT

For UAV communications, it is important to formulate directional beams towards the desired terminals in order to achieve large spatial gain and combat the path loss. For instance, two distant UAVs need to continuously adjust their respective beams towards each other to realize inter-UAV communications. Another typical scenario is UAV assisted satellite communications, where UAV needs to adjust its beam towards the target satellite. Nevertheless, UAV navigation would lead to the attitude variation all the time, which directly affects the spatial beam pointing. Though one can rely on electrical beamforming, sometimes the irregular UAV attitude would make the target stay outside the array pattern. Moreover, the array gain is proportional to the projected area of the array aperture in the direction of the target, and thus it is practically preferred to formulate beam from the normal of the antenna array [16], as is shown in Fig. 3. In these cases, purely relying on electric beamforming cannot provide the best performance and sometimes may even fail to point the beam towards the target.

One possible solution is to adopt the mechanical control to physically change the direction of the array plane and help to formulate the beam direction [17]. Specifically, two motors need to be installed at the back of the array antenna for the mechanical control of the azimuth angle and the elevation angle. Besides, some measures should be adopted for the security of mechanical control such as the hurricane globe installed to keep out the wind effect. Let us then take the UAV satellite communications as an example, where the mechanical and electrical control are jointly implemented to stabilize the beam.

For UAV satellite communications, the spatial beam is stabilized at the antenna beam frame (t-frame), whose origin is the center of gravity of the antenna array, axis x_t points to the satellite, axis y_t is identical with the direction of electric field, and axis z_t is perpendicular to the plane spanned by the axis x_t and y_t. By exploiting the UAV attitude information and satellite location information provided by FCS, the coordinate transformation from the n-frame to the t-frame can be applied to derive the azimuth angle and elevation angle of the direction of the target satellite, which could approximately stabilize the beam. During UAV navigation, the corresponding angular rates arising from attitude variation are coupled with the direction of the beam through friction. In this case, the azimuth and elevation control motors could be jointly utilized to adjust the spatial beam and compensate for the effects of UAV navigation. Specifically, the eventual angular rates of the spatial beam should be zero to overcome the effect of attitude variation and realize dynamic isolation of the navigation, which requires complex coordinate transformation and solving nonlinear equation to derive the angular compensation rates.

Meanwhile, since the attitude sensors have finite precision to cut down the production cost, there generally exist the system errors and the measurement errors. In this case, the mechanical adjustment might roughly point the spatial beam to the target satellite. Hence, the electrical adjustment should be further applied to calibrate the beam pointing. In order to guarantee the beam pointing in a precise direction, one way is to make the received signal power at UAV side as large as possible. In this case, the zero-knowledge beamforming method can be utilized to sequentially perturbs the phase shifters and maximize the received signal power. Meanwhile, the array structure aided simultaneous perturbation can be exploited to accelerate the convergence speed. An explicit display of the beam tracking with the joint mechanical and electrical adjustment is shown in Fig. 3.

IV. COMMUNICATIONS AND CONTROL WITH MULTIPLE UAVs

Communications in the complex missions and the harsh environments motivate the deployment of multiple UAVs. Since multi-UAV communications is a nascent technique, it is urgent to develop innovative communication technologies to support the ultra-reliable remote command and control of the multiple UAVs.

A. COOPERATIVE COMMUNICATIONS AND SELF POSITIONING

The multi-UAV communications deploys large amounts of UAVs with single or multiple antennas to support the ground users, which offers several advantages: First, the number of the antenna array is not constrained by the UAV size, while the multi-UAV communications could jointly provide high spatial resolution. Second, the beamforming towards any 3D direction could be effectively implemented by fully utilizing the mobility and flexibility of multi-UAVs, and meanwhile the spatial gain of the antenna array can be increased dynamically by adjusting UAV positions. Third, the robustness of communications would be greatly strengthened by the multi-UAV cooperation, since the damage to one UAV would not affect the overall communication performance. A typical multi-UAV system is shown in Fig. 4, where a certain number of UAVs are deployed to provide wireless service. The channels for multi-UAV communications can be categorized into UAV-to-UAV channel and UAV-to-ground channel, while the adjacent UAVs are separated by the guard distance to avoid collisions.

The multi-UAV systems operate in specific formation to meet the complex missions and tasks, and multiple UAVs need to be able to perform reconfiguration and re-tasking in order to adapt to the various missions. Different from the traditional ground communications, the virtual massive MIMO of the collaborative UAVs would face several new challenges. For example, the relative position of different UAVs are dynamic and unknown, and it is difficult to locate the UAV position and maintain the stability and reliability of multi-UAV communications. Besides, all the deployed UAVs need to be kept synchronous in time, and the virtual array need to be calibrated [18], [19]. Moreover, all the UAVs should maintain connectivity for information sharing. The above requirements demand for precise positioning, control and cooperative communications.

According to the physical characteristics of the UAV communications, the channel could also be decomposed into the direction of arrival (DOA) information θ, ϕ, and the UAV position vector $\mathbf{p}$ that describes the relative position of each UAV at the local geodetic frame (n-frame), and the channel gain information α. In this case, the array signal processing theory, sensor fusion, game theory, optimal control, machine learning, and optimization theory could be jointly utilized to design the cooperative communications. Fan *et al.* [20] applied an interesting DOA estimation method, called rank reduction (RARE), for swarm system which could successfully obtain the DOA information regardless of the relative position of each UAV. Meanwhile, the number of DOAs that RARE can resolve could be greater than the number of antennas in one single UAV, as long as the overall number of antennas of multi-UAVs satisfies certain constraints. This proves that the cooperation of multi-UAVs could handle jobs that one-single UAV cannot. Moreover, the inter-UAV distances can be self-calculated without any additional training whenever there are more than three users/targets in the service regions. Then, the remaining channel gain can be estimated by a small amount of training resources. Nevertheless, the approach in [20] only provides a simple strategy for the cooperative communication and self positioning. How to ensure the maximum performance of the multi-UAV deployment and realize efficient multi-UAV communications remains to be investigated.

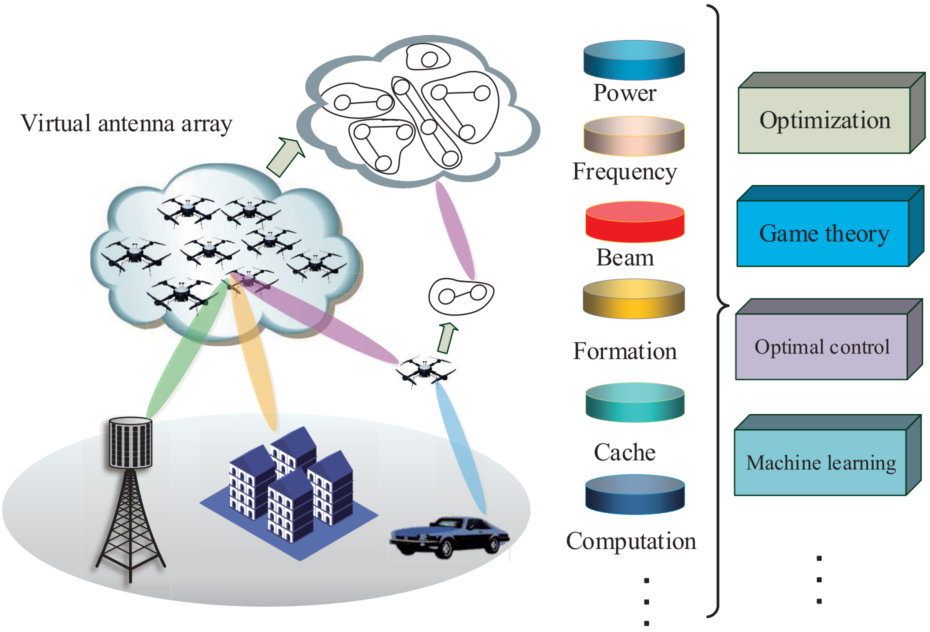

FIGURE 4. The multi-UAV communications with resource allocation.

B. 3D SEAMLESS COVERAGE

Compared to ground cellular networks with fixed BSs, the mobility of UAVs would provide flexible cellular coverage for various service demands, such as cell-edge services and intermittently emerging hot spots, by intelligently moving their positions and harnessing their mutual cooperation. During this procedure, the shapes of coverage cells will be changing irregularly and dynamically, formulating the so called *amorphous cells*. However, since LoS path is the dominant one, the small objects between UAV and users might lead to turbulence and blockage, which is a tough hurdle for UAV communications.

For short-time blockage, say, blockage from a tree, the data transmission can be paused shortly and resumed when the path is not blocked again. For long-time blockage, say, blockage from successive building, the only way is to physically resort to another UAV from a non-blocked direction. With massive antenna array, one UAV could offer multiple high resolution beams and simultaneously serve multiple users with different DOA information. Conversely, one user could also be scheduled to more than one UAVs that have non-blocked links from different directions. Such a DOA based wireless service fall in to the category of angle division multiple access (ADMA) [21], where the angles of the scheduled users k in the same group $\mathcal{U}$ should be different, also guarded by an interval Ω, i.e.,

$$\mathcal{U} = \{k|, |\theta_m - \theta_l| \geq \Omega, \forall\, m,\ l \in \mathcal{U}\}. \tag{3}$$

The cooperation among UAVs would improve the user scheduling probability and suppress the signal blockage since the possibility of users being sheltered from multiple UAVs is small. In the worst case, if all UAVs are blocked from a specific user, then one UAV could change its route to where the transmission is not blocked, thanks to its maneuverability.

The UAVs could collect the prior information of the service areas, like the users' distribution, the shelter location, channel statistics, and then build a blockage fingerprint such that most blockage can be anticipated. One may also use optimization tools to design the number of UAVs, their deployment strategy, the route of each UAV, etc., in order to decrease the overall blockage probability. Moreover, the Kalman filter techniques can be applied to dynamically predict the blockage when UAVs are cruising with the pre-designed routes. Another possibility is that UAV could collaborate with the ground BS, if any, where the ground BS can remove the blockage with low frequency (below 6 GHz) transmission [22]. Therefore, the whole UAV networks could provide the seamless coverage based on its fluid topology, which is illustrated in Fig. 5.

C. TRAJECTORY DESIGN AND RESOURCE ALLOCATION

Properly designing the UAV trajectory could enhance the communication performance when the distance of the desired users is reduced while the distance of the interference is enlarged. Therefore, efficient exploitation of the UAV's high mobility is the key to dig the full potential of the UAV-based wireless networks. On the other side, due to the limited UAV power, it is necessary to design valid resource allocation strategies, like power, frequency, beam, formation, trajectory, cache, dynamic topology, and computation resources to provide an efficient multi-UAV wireless networks, as shown in Fig. 4. Wu *et al.* [23] studied joint trajectory and transceiver design for multi-UAV enabled wireless networks, where the minimum throughput over all users is maximized by optimizing the multiuser communications scheduling and power control.

The resource allocation tightly impacts the multi-UAV networks, and a practical performance metric could be set

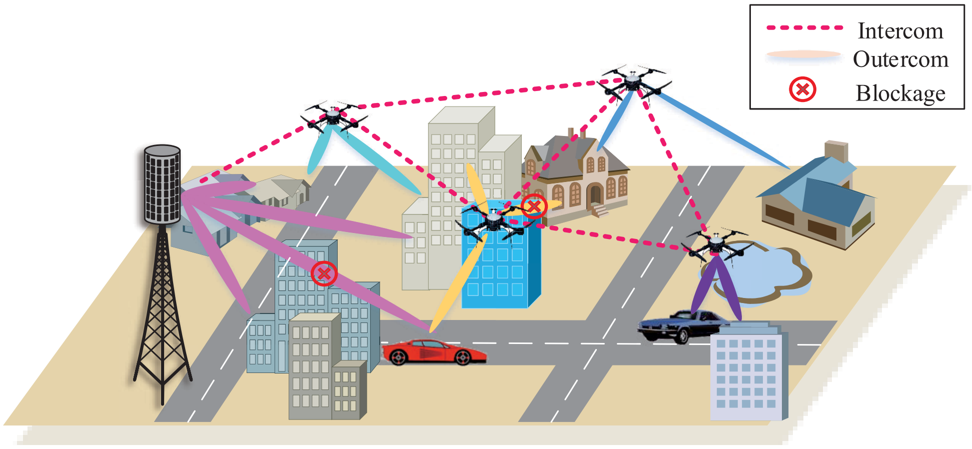

FIGURE 5. 3D Seamless coverage with multi-UAV deployment and cooperation, where "Intercom" represents the UAV to UAV inter communications, while "Outercom" represents the UAV to ground communications.

as the time cost to serve all scheduled users. Such time cost mainly consists of two parts: the wireless transmission time cost and the flight control time cost. The former is related with the transmit rate as well as the power allocation, while the latter is related with the user spatial distribution and the UAV velocity. It is obvious that a low time cost represents the short flight time, small power consumption, and low latency.

Therefore, one may formulate the multi-UAV deployment problem as to minimize the overall time cost of all scheduled users. Nevertheless, the objective function might not be convex, and the optimization problem is hard to solve. In this case, the iterative algorithm could be a practical way, which could decouple the objective function as separatively minimizing the transmission time and the flight control time. Firstly, since the wireless transmission time are related with the antenna array gain, or equivalently the array manifold constituted by the multi-UAV, the transmission time could be minimized by optimizing UAV spacing and location. Then, the flight control time is dynamically optimized by designing the UAV trajectory and controlling the UAV velocity according to the optimal locations. In these iterations, the optimization theory could be utilized to derive the optimal solution. Besides, the mathematical optimal control theory such as *bang bang control theory* could be exploited to improve the control precision. Nevertheless, it might be challenging to guarantee the convergence of the original optimum problem.

Recently, machine learning based communication techniques attract wide public attention, while integrating the machine learning and multi-UAV communications might be a promising approach to realize the near-optimal UAV deployment and intelligent communications. To be specific, the extreme learning machine (ELM) or support vector machine (SVM) could be utilized to map out the complex relationship between UAV deployment and resource allocation, while the new bionic intelligent optimization algorithm such as the grey wolf optimizer algorithm (GWOA) could be utilized to enhance the spectrum efficiency through in-depth optimization of the resource allocation. Nevertheless, how to effectively utilize machine learning to jointly design the UAV trajectory and resource allocation is still an open problem.

V. PROSPECTS

In addition to the above key issues, there are many other interesting problems when integrating communications and control for the UAV systems.

- **The communication protocol:** The communication protocol needs to be investigated based on the UAV link features, network connectivity dynamics, and flight trajectory. Different from the traditional ground communications, the flexible UAV maneuverability should be taken into consideration for protocol design, say to synchronize among the multiple flying UAVs.
- **The communication security:** The security of UAV communications is composed of the information security and the navigation security. When integrating communications and control for UAV communications, the advanced signal processing method and flight control strategy need to be jointly designed to guarantee the security of UAV systems.
- **3D dynamic heterogeneous network:** Based on the UAV size, power, function, coverage ability, and load, UAV could dynamically establish the small cell or macro cell to serve various terminals either in the sky or on the ground. Besides, it is also very interesting to build the 3D heterogeneous network by exploiting the UAV flexible deployment in order to realize the multi-layer coverage.
- **Low-cost design:** With the increase of the number of UAVs, the system cost also increases. Therefore, it is necessary to design low-cost UAV system and balance the tradeoff between the cost and the performance for reliable UAV communications. Meanwhile, it is urgent to develop advanced signal processing method which could compensate for the effects of errors from the low-cost UAV systems.

VI. CONCLUSIONS

In this paper, we explored the opportunities and challenges of integrating communications and control for the UAV communications. For single-UAV system, we introduced a new frequency-dependent 3D channel model, investigated channel tracking method with FCS, and explored a joint mechanical/electronic beam tracking method. For multi-UAV system, we presented various new techniques such as collaborative communications, self-positioning, seamless coverage, trajectory design, and resource allocation. In the last part of the paper, we provided other prospects, such as communications protocol, secrecy, 3D dynamic topology heterogeneous network, and low-cost in practical UAV applications. Overall, UAV communications is a prosperous research area, which will play a growing role in the space-air-ground network. We wish this article could bring attention of researchers onto the integration of communications and control to promote the practical applications of UAV communications.

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, pp. 36–42, May 2016.

[2] Q. Wu *et al.*, "Cognitive Internet of Things: A new paradigm beyond connection," *IEEE Internet Things J.*, vol. 1, no. 2, pp. 129–143, Apr. 2014.

[3] Q. Wu, G. Ding, J. Wang, and Y.-D. Yao, "Spatial-temporal opportunity detection for spectrum-heterogeneous cognitive radio networks: Two-dimensional sensing," *IEEE Trans. Wireless Commun.*, vol. 12, no. 2, pp. 516–526, Feb. 2013.

[4] T. J. Willink, C. C. Squires, G. W. K. Colman, and M. T. Muccio, "Measurement and characterization of low-altitude air-to-ground MIMO channels," *IEEE Trans. Veh. Technol.*, vol. 65, no. 4, pp. 2637–2648, Apr. 2016.

[5] M. M. Azari, F. Rosas, K.-C. Chen, and S. Pollin, "Ultra reliable UAV communication using altitude and cooperation diversity," *IEEE Trans. Commun.*, vol. 66, no. 1, pp. 330–344, Jan. 2018.

[6] P. Chandhar, D. Danev, and E. Larsson, "Massive MIMO for communications with drone swarms," *IEEE Trans. Wireless Commun.*, vol. 17, no. 3, pp. 1604–1629, Mar. 2018.

[7] W. Su, J. D. Matyjas, M. J. Gans, and S. Batalama, "Maximum achievable capacity in airborne MIMO communications with arbitrary alignments of linear transceiver antenna arrays," *IEEE Trans. Wireless Commun.*, vol. 12, no. 11, pp. 5584–5593, Nov. 2013.

[8] J. N. Gross, Y. Gu, and M. B. Rhudy, "Robust UAV relative navigation with DGPS, INS, and peer-to-peer radio ranging," *IEEE Trans. Autom. Sci. Eng.*, vol. 12, no. 3, pp. 935–944, Jul. 2015.

[9] Y. Zeng and R. Zhang, "Energy-efficient UAV communication with trajectory optimization," *IEEE Trans. Wireless Commun.*, vol. 16, no. 6, pp. 3747–3760, Jun. 2017.

[10] H. G. de Marina, F. J. Pereda, J. M. Giron-Sierra, and F. Espinosa, "UAV attitude estimation using unscented Kalman filter and TRIAD," *IEEE Trans. Ind. Electron.*, vol. 59, no. 11, pp. 4465–4474, Nov. 2012.

[11] Z. Xiao, P. Xia, and X.-G. Xia, "Enabling UAV cellular with millimeter-wave communication: Potentials and approaches," *IEEE Commun. Mag.*, vol. 54, no. 5, pp. 66–73, May 2016.

[12] J. Zhao, F. Gao, L. Kuang, Q. Wu, and W. Jia, "Channel tracking with flight control system for UAV mmWave MIMO communications," *IEEE Commun. Lett.*, vol. 22, no. 6, pp. 1224–1227, Jun. 2018.

[13] B. Wang, F. Gao, S. Jin, H. Lin, and G. Y. Li, "Spatial- and frequency-wideband effects in millimeter-wave massive MIMO systems," *IEEE Trans. Signal Process.*, vol. 66, no. 13, pp. 3393–3406, Jul. 2018.

[14] C. Xing, S. Ma, Y.-C. Wu, and T.-S. Ng, "Transceiver design for dual-hop nonregenerative MIMO-OFDM relay systems under channel uncertainties," *IEEE Trans. Signal Process.*, vol. 58, no. 12, pp. 6325–6339, Dec. 2010.

[15] C. Xing, S. Ma, Z. Fei, Y.-C. Wu, and H. V. Poor, "A general robust linear transceiver design for multi-hop amplify-and-forward MIMO relaying systems," *IEEE Trans. Signal Process.*, vol. 61, no. 5, pp. 1196–1209, Mar. 2013.

[16] H. Bolandhemmat, M. Fakharzadeh, P. Mousavi, S. H. Jamali, G. Z. Rafi, and S. Safavi-Naeini, "Active stabilization of vehicle-mounted phased-array antennas," *IEEE Trans. Veh. Technol.*, vol. 58, no. 6, pp. 2638–2650, Jul. 2009.

[17] J. Zhao, F. Gao, Q. Wu, S. Jin, Y. Wu, and W. Jia, "Beam tracking for UAV mounted SatCom on-the-move with massive antenna array," *IEEE J. Sel. Areas Commun.*, vol. 36, no. 2, pp. 363–375, Feb. 2018.

[18] Y.-C. Wu, Q. Chaudhari, and E. Serpedin, "Clock synchronization of wireless sensor networks," *IEEE Signal Process. Mag.*, vol. 28, no. 1, pp. 124–138, Jan. 2011.

[19] J. Zheng and Y.-C. Wu, "Joint time synchronization and localization of an unknown node in wireless sensor networks," *IEEE Trans. Signal Process.*, vol. 58, no. 3, pp. 1309–1320, Mar. 2010.

[20] D. Fan, F. Gao, B. Ai, Z. Zhong, and A. Nallanathan, "Channel estimation and self-localization for fleet of drones," to be published.

[21] J. Zhao, F. Gao, W. Jia, S. Zhang, S. Jin, and H. Lin, "Angle domain hybrid precoding and channel tracking for millimeter wave massive MIMO systems," *IEEE Trans. Wireless Commun.*, vol. 16, no. 10, pp. 6868–6880, Oct. 2017.

[22] C. Xing, S. Ma, and Y. Zhou, "Matrix-monotonic optimization for MIMO systems," *IEEE Trans. Signal Process.*, vol. 63, no. 2, pp. 334–348, Jan. 2015.

[23] Q. Wu, Y. Zeng, and R. Zhang, "Joint trajectory and communication design for multi-UAV enabled wireless networks," *IEEE Trans. Wireless Commun.*, vol. 17, no. 3, pp. 2109–2121, Mar. 2018.

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