Massive MIMO for Drone Communications: Applications, Case Studies and Future Directions

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Abstract

Unmanned aerial vehicles (UAVs), or drones, are proliferating. Several applications, such as surveillance, disaster management, and drone racing, place high requirements on the communication with the drones – in terms of throughput, reliability, 3D connectivity, and latency. Existing wireless technologies, notably WiFi, that are currently used for drone communications are limited to short ranges and low-mobility situations. A new, scalable technology is needed to meet future demands. Massive MIMO, a promising technology component of emerging 5G cellular networks, has the potential to meet these requirements. Specifically, Massive MIMO offers significant range extensions, support for fast-moving drones, and the possibility to spatially multiplex entire swarms of drones communicating simultaneously.

Drone Technology is Proliferating

During the past decades, unmanned aerial vehicles (UAVs) in the form of drones have been predominantly used for military applications such as battlefield and airspace surveillance, and border patrol. More recently, due to technological advancements in battery and control technology, and miniaturization of electronics, the use of drones for civilian applications is exploding. Such applications include traffic and crowd monitoring, search-and-rescue operations during earthquakes, flooding and other disasters, inspection of non-reachable areas, and the transportation of goods [1]–[3]. Inexpensive light-weight drones are widely available for diverse personal uses such as aerial photography and drone racing. Several 5G use cases for drones were identified by 3GPP [4]: broadband access to under-developed areas, hot-spot coverage during sporting events, and rapidly deployable “on-demand” densification. More applications are likely to emerge [5].

The potential of multi-drone networks is particularly significant. Many small drones can be deployed in a short time to cover a large geographical area. In many applications, a goal for the drones would be to stream high-quality imagery or videos to a ground station (GS) within stipulated reliability and latency constraints. As the required throughputs are very high, existing wireless technologies are incapable of providing the required service. In this article, we make the case that Massive MIMO [6], an emerging 5G physical-layer technology, can enable communication with large multi-drone networks that stream big amounts of real-time data to the ground.

In a recent paper, [7], we presented various rather technical results on Massive MIMO for aerial communications. The object of the article at hand is to summarize important conclusions...
to a wider readership, discuss applications in more detail, and summarize open issues that remain for future research.

**Drone communication requirements and challenges**

Table I exemplifies communication requirements of drone networks for various use cases [1], [2], [5]. Some general issues are:

- Maintaining connectivity is challenging [8], because the channel between the GS and the drones is most likely line-of-sight (LoS). Since the drones are moving in 3D, the gains and polarizations of the their antennas vary with time. Therefore, antennas must be designed such that polarization losses are manageable.

- The throughput requirement depends on the type of mission, and the capability of the on-board image processing module. In some cases, it is preferable to transmit raw (uncompressed) video or images. For example, the training of machine learning algorithms can benefit from the use of uncompressed data.

- Connectivity to multiple drones must be ensured simultaneously. This requires either time- or frequency-sharing, which is inefficient, or spatial multiplexing.

- Reliability and latency are important concerns in many applications. For example, in drone racing, the end-to-end delay should be below 100 ms.

- High-mobility support is important. Typical flying speeds of drones range from 5 m/s (e.g., agricultural crop monitoring, site inspection) to 30 m/s (e.g., disaster management) at different altitudes.

**A NEW COMMUNICATION TECHNOLOGY IS NEEDED**

**Propagation characteristics**

The propagation conditions in aerial communications are different from terrestrial land-mobile radio environments. Especially, LoS conditions are generally prevalent with Ricean K-factors typically exceeding 25 dB [9]. Measurement results with vertically polarized antennas in the C-band (5.03–5.091 GHz), show that the average root-mean-square delay spread is on the order of 10 ns (with an average UAV altitude of 600 m and link ranges from 860 m to several kilometers) in over-water, hilly and mountainous terrain, and 10–60 ns in suburban and near-urban environments [9]. Hence, the coherence bandwidth, if defined as the frequency separation associated with a correlation of 0.5, varies between 3 MHz and 20 MHz.

Although measurement results are unavailable at mmWave frequencies (30 GHz to 300 GHz), due to the reduced number of multipath components, one can expect even higher coherence bandwidths than at sub-5 GHz frequencies.

The mobility pattern of drones is different from that of terminals in cellular communications. Pitch, roll and yaw angles of the drones can change rapidly, and may result in polarization mismatch losses.

**Inadequacy of existing technologies**

Standardization of PHY- and MAC-layer protocols for communication with drones is underway, and mostly based on existing wireless technologies such as WiFi and XBee-PRO. However,
### TABLE I: Communication requirements of drones in different use cases [1], [2]

| Use cases                                                | Data type               | Data rate per drone                  | Number of drones                                                                 | Range              | Mobility   | Latency   |
|----------------------------------------------------------|-------------------------|--------------------------------------|---------------------------------------------------------------------------------|--------------------|------------|-----------|
| Crowd Surveillance, Event coverage, Environment monitoring | Video                   | Hundreds of Mbps (uncompressed)      | 10 – 100 depending on the size of the area                                      | 100 m – 3 km       | 10 – 20 m/s | 10 – 100 ms|
|                                                          |                         | Tens of Mbps (compressed)            |                                                                                 |                    |            |           |
|                                                          |                         |                                      |                                                                                 |                    |            |           |
| Agriculture                                              | Image and video         | Tens of Mbps                         | 1 – 100 depending on the size of the area and, image and video resolution        | 5 m – 3 km         | 5 – 20 m/s | 10 – 100 ms|
| Disaster management, Search and rescue operation         | Video                   | Hundreds of Mbps (uncompressed)      | 10 – 100 depending on the size of the area and, image and video resolution        | 50 m – several km  | 0 – 30 m/s | < 40 ms   |
|                                                          |                         | Tens of Mbps (compressed)            |                                                                                 |                    |            |           |
| Aerial videography                                       | Image and video         | Hundreds of Mbps (uncompressed)      | 1 – 10                                                                          | 100 m – 3 km       | 0 – 10 m/s | 100 ms    |
|                                                          |                         | Tens of Mbps (compressed)            |                                                                                 |                    |            |           |
| Drone racing                                             | Video                   | Tens of Mbps (uncompressed)          | 50 – 100                                                                        | 50 m – 1 km        | 55 m/s     | < 40 ms   |
these technologies are unsuitable for drone networks. Since these technologies were originally
designed for indoor wireless access with very low mobility, they perform poorly in high-mobility
conditions [8]. Particularly, due to limitations in the PHY- and MAC-layer protocols, the latency
is typically hundreds of milliseconds. Experimental results show that under LoS conditions, the
maximum range of WiFi and XBee-PRO is 300–500 m (with 10 Mbps, single drone) respectively
1 km (with 250 kbps). Furthermore, and more seriously, when multiple drones share the resources,
the throughput per drone decreases proportionally. Existing technologies cannot meet
the requirements listed in Table I.

Recently there has been interest in utilizing cellular networks, such as LTE, for aerial com-
munication. However, cellular networks are unsuitable for aerial communications for the several
reasons. First, since the BS antennas are typically tilted towards ground, coverage is limited to
low altitudes. Second, cellular networks are not available in many relevant mountainous and sea
environments, and they may be unavailable in relevant emergency response use cases such as
search-and rescue.

**Massive MIMO is a suitable technology for drone communications**

A new dedicated technology is required for drone networks. A major advantage of developing
a new technology for drone networks is that one can design the PHY- and MAC-layer protocols
from a clean slate, accounting for the specific requirements of aerial communications.

Massive MIMO is a multi-antenna multi-user wireless technology originally proposed for
cellular communications [6]. The two main features of Massive MIMO are (i) array gain, which
translates into a coverage extension; and (ii) spatial multiplexing, which permits the service
of many tens of terminals in the same time-frequency resource. In principle, every extra base
station antenna adds one spatial degree of freedom, which can be used to provide service to
one additional terminal. Substantially all signal processing complexity resides at the BS. Hence,
Massive MIMO allows low-power and low-complexity terminals. These attractive features of
Massive MIMO naturally make the technology suitable for drone communications.

**WHAT AND HOW MUCH MASSIVE MIMO CAN PROVIDE FOR DRONE COMMUNICATIONS?**

The fundamental principle of Massive MIMO operation is to obtain channel state information
(CSI) between the antenna array and all drones at the GS, and then apply smart signal processing
algorithms. For exemplification here, we consider time-division duplex (TDD) operation, which
is the preferred operation of Massive MIMO. In TDD, uplink-downlink channel reciprocity holds
as long as the uplink and downlink transmissions take place within the channel coherence time.

Let the maximum speed of the drones be \( v \) m/s. The corresponding coherence time is
\( T_c \approx \frac{c}{2v f_c} \) s, where \( f_c \) is the carrier frequency and \( c \) is the speed of light. If the coherence bandwidth
is \( B_c \) (Hz), then the number of samples per coherence interval is \( \tau = B_c T_c \). Taking the coherence
bandwidth to be 3 MHz, the drone speed to be 30 m/s, and the carrier frequency to be 2.4 GHz,
results in \( \tau = 6250 \) samples. During the uplink training phase, all drones simultaneously transmit
predefined orthogonal pilot sequences to the GS. Upon receiving the pilots, the GS estimates
the channel vectors between the GS array and all drones in the system. The number of samples
used for pilot transmission must be at least equal to the number of drones.
(a) Illustration of the geometric model. The elevation and azimuth angles determine the channel responses of the drones.

(b) Interference as function of angular separation, quantified in terms of $\sin \theta_k \sin \phi_k - \sin \theta_j \sin \phi_j$. The actual range of this quantity is between $-2$ to $2$ but for clarity, only the range $[-0.1, 0.1]$ is shown.

Fig. 1: Impact of drone positions on the interference with 100 antennas. The aperture length is 6.25 m, the same for both carriers (2.4 and 60 GHz). The spacing between the elements is half a wavelength for 2.4 GHz and 12.5 wavelengths at 60 GHz. At 60 GHz, the mainlobe is 25 times narrower as compared to at 2.4 GHz.

For the examples presented here, we assume that the GS comprises a uniform linear or rectangular array with a large number of antenna elements. The drones, in contrast, are equipped
with a single antenna. There is LoS propagation (no multipath) between the GS antenna array and the drones. The channel between each GS antenna and the drone’s antenna is characterized by a free-space path loss, a polarization mismatch loss, an antenna gain, and a phase shift.

The pilot power of the drones is chosen based on the maximum possible distance and the worst-case combined effect of antenna gain and polarization mismatch factor (averaged over all antenna elements), so that a pre-determined pilot signal-to-noise ratio (SNR) is maintained at the GS. Polarization mismatch losses, per antenna, can be severe due to the drones’ movements. However, the overall loss can be made small by an appropriate choice of polarization and orientation of GS array elements [7].

Through broadcasting of (non-directional) downlink pilots, the drones measure their path loss. During uplink data transmission, all drones apply channel inversion power control in order to maintain the same data SNR at each receive antenna.

The GS uses maximum-ratio combining (MRC) processing to detect the uplink symbols transmitted by the drones. We use the uplink ergodic rate as a performance metric. The justification is that the multi-user interference experienced by a drone depends on the relative positions of the other drones, and the strength of this interference fluctuates quickly as the drones move. As an illustration, for the geometric model in Figure 1(a), Figure 1(b) shows the strength of the interference that one drone is causing to another, as a function of their angular separation. The computation of ergodic capacity entails the averaging of the instantaneous throughput over all possible drone positions.

**Simultaneous high throughput transmission from a large number of drones**

By virtue of the spatial multiplexing capability of Massive MIMO, many drones can simultaneously transmit high-resolution imagery to the GS. We first, for simplicity, consider that the GS array elements are identically oriented. We then discuss the general case in the next section. Figure 2 exemplifies the sum throughput versus the number of drones over a 20 MHz bandwidth with 100 antennas for different data SNR values. The sum throughput increases up to a certain number of drones and then decreases. This is because the pilot overhead per coherence block is proportional to the number of drones, such that the number of samples available for uplink data transmission decreases with the number of drones.

**Pseudo-randomly oriented circularly polarized antenna elements enable stable link conditions**

The GS array may comprise simple antennas, for example, cross-dipoles. The signal loss due to polarization mismatch can be significantly reduced by pseudo-randomly orienting the GS array elements. Then, irrespective of the location and orientation of the drones, the probability that a drone experiences bad link conditions can be greatly reduced. For example, when the GS array elements are pseudo-randomly oriented, for the same parameters as in Figure 2, the coverage probability is 90% with linearly polarized antennas and 99.99% with circularly polarized antennas [7].

Furthermore, the array geometry affects the throughput performance, since it determines the angular resolvability. A rectangular array is preferred over linear and circular arrays due to its 3D
Fig. 2: Sum throughput vs. the number of drones. The drones are uniformly and randomly located in a spherical shell with inner radius 20 m and outer radius 500 m. The antenna element spacing is one-half wavelength, 6.25 cm. The throughput is achievable only when the drone is under coverage of the GS, that is, the drone’s uplink power is sufficient to compensate for the distance dependent path-loss and polarization mismatch loss. If the drone’s roll, pitch, and yaw angles are independently and uniformly distributed, and the GS array elements are identically oriented, then with a transmit power of 100 mW, noise spectral density of $-167$ dBm/Hz, and a target SNR of 0 dB, the coverage probability is 80% with linearly polarized antennas and 97% with circularly polarized antennas [7].

resolving capability and reduced space occupancy. For 2.4 GHz and 60 GHz carrier frequencies, with half-wavelength spacing, the space occupied by a rectangular array with 400 elements is approximately $1.25 \times 1.25$ m respectively $5 \times 3$ cm.

In practice, the choice of element spacing is important. For uniformly distributed drone positions inside a spherical shell, and MRC signal processing, the throughput is maximized when the GS array elements are spaced at a distance equal to an integer multiple of one-half wavelength [7]. For other distributions of drone positions, the optimal antenna spacing may be different.

**High mobility support**

In many environments, the drone speed has only slight impact on the data rate. For example, in over-water and mountainous settings, with 100 drones, at 2.4 GHz carrier frequency, 3 MHz coherence bandwidth, and if 90% of samples per coherence interval are used for uplink
transmission, then if we change the drone speed from 0 m/s to 30 m/s, the reduction in throughput is less than 2%. In other environments and at larger carrier frequencies, this loss might become more significant.

By exploiting the characteristics of LoS propagation, one might reduce the channel estimation frequency. For example, if a drone is moving along a known trajectory, the channel will experience a predictable phase shift. Hence, if the channel is known at a specific point in time, it may be predicted during many wavelengths of motion without the transmission of additional pilots. This could further increase the number of samples available for data transmission.

**Micro-wave versus mmWave frequencies**

Massive MIMO can be used for drone communications at both micro-wave and mmWave frequencies. Here we make the following general observations:

- At mmWave frequencies, the orthogonality between the channel responses of the drones improves with increasing carrier frequency (see Figure 1(b)). However, the energy efficiency is negatively affected with increasing the carrier frequency, due to decreased effective antenna areas. Suppose that the number of antennas and the target SNRs are fixed. Let $P_1$ and $P_2$ be the transmit powers required by a drone to maintain a target SNR at a particular distance with carrier frequencies $f_{c1}$ and $f_{c2}$, respectively. From Friis’s free-space equation, assuming unit antenna gains and perfect polarization match, the required transmit powers are related as $P_2 = P_1 \left(\frac{f_{c2}}{f_{c1}}\right)^2$. For example, if $f_{c1} = 2.4$ GHz and $f_{c2} = 60$ GHz, then $P_2 = 625P_1$.

- Increasing the transmit power of the drones does not always increase the ergodic rate, since interference often is the limiting factor. As an illustration, Figure 3(a) shows the sum throughput as function of the data SNR for different numbers of drones. The sum throughput saturates as the scenario becomes interference limited. Also, due to increased pilot overhead at mmWave frequencies (shorter channel coherence), the sum throughput at 60 GHz is lower than that at 2.4 GHz.

- The abundant bandwidth available at mmWave frequencies can be utilized for achieving high sum throughput (in the order of 10 Gbps). However, due to limitations on the drones’ transmitted power, the coverage range might be limited. Suppose the uplink transmit power of a drone is limited to 100 mW. Let the noise spectral density be $-167$ dBm/Hz. At 60 GHz carrier frequency, for 20 drones, and a target data SNR of 0 dB, Figure 3(b) illustrates the range and sum throughput as functions of bandwidth. The range decreases with increasing bandwidth, since when power is fixed and bandwidth is increased, the SNR decreases. However, the sum throughput linearly increases with the bandwidth, for the indicated range. For 20 drones, with 100 antennas and a target data SNR of 0 dB, over a 200 MHz bandwidth, we can achieve a sum throughput of 8.9 Gbps, but only up to 63 m distance (190 m with 145 antennas and $-10$ dB data SNR).

**Coverage extension removes the need for multi-hop solutions**

Another important feature of Massive MIMO is the coverage extension offered by the coherent beamforming gain. In LoS channel conditions, when compared with a single-antenna system, if
(a) Throughput performance comparison at 2.4 GHz and 60 GHz for 100 antennas, 20 MHz bandwidth, 3 MHz coherence bandwidth, 30 m/s drone speed, 20 dB pilot SNR, and maximum range 300 m. The transmit power for 60 GHz is 625 times the transmit power for 2.4 GHz.

(b) Range and sum throughput at 60 GHz as a function of bandwidth, for 3 MHz coherence bandwidth.

Fig. 3: Performance at 2.4 and 60 GHz carrier frequencies.

the transmitter (or receiver) is equipped with $M$ antennas, then as a consequence of the Friis's
transmission equation, the coverage distance can be extended by a factor of $\sqrt{M}$. In multi-drone networks, as illustrated in Figure 3(b), a significant range extension can be achieved. Thus Massive MIMO technology appears to be a promising alternative to multi-hop solutions, which suffer from issues with reliability and latency, and difficulties in coordinating the transmissions.

**Channel and interference hardening make low latency communication possible**

In wireless links, variations in the channel lead to frequent retransmissions. This often results in increased latency. But in Massive MIMO, due to channel hardening, the effective channel gain becomes deterministic (both in LoS and in fading). In multi-drone networks, similar to channel hardening, *interference hardening* takes place with large number of antennas even in LoS propagation conditions. Therefore, an increased number of antennas at the GS reduces the variations in the SINR. Stable SINR conditions help satisfy low latency requirements.

**CASE STUDY I: EMERGENCY RESPONSE AND DISASTER MANAGEMENT**

After natural disasters such as earthquakes or massive flooding, drone swarms may be deployed rapidly and help rescue teams to assess the situation in real time (see Figure 4(a)). The video received at the GS should have high quality, and in order to obtain high-resolution imagery the drones have to fly at low altitudes. For example, for a given dimension of the camera sensor (resolution: $2664 \times 1496$, focal length: $5 \times 10^{-3}$ m and pixel size: $2.3 \times 10^{-6}$ m), for achieving ground sampling distances (GSDs) of 2, 20 cm, and 1 m, the required drone altitudes are approximately equal to 44, 435, and 2174 m, respectively.

**How many drones required for the mission?:** Consider a geographical region to be covered with an area of $4 \text{ km} \times 4 \text{ km}$, a drone camera resolution of $2664 \times 1496$, and a required GSD of 20 cm. The area covered by each camera image is $533 \text{ m} \times 300 \text{ m}$. With a single drone moving at 20 m/s, the total time required to cover the area is more than seven hours. As the flying time of small drones is often limited to 10–30 minutes, a single-drone mission would additionally require a frequent return to base. In contrast, a swarm of drones could cover the area in a short time. For example, to complete the mission in 20 minutes, about 23 drones working in parallel are sufficient.

**How much data need to be transmitted by a drone?:** The uplink (drone to GS) data rate requirement depends on the desired quality of the imagery. JPEG2000 is a lossless compression standard which gives compression ratios of up to $4 : 1$. H264 and STD are commonly used lossy video compression standards that achieve compression ratios in the range $20 : 1$ to $200 : 1$. Table II gives the sum throughput requirement (computed via a formula given in [7]), with a compression ratio of $200 : 1$ and a GSD of 2 cm. A 4K resolution compressed video requires the sum throughput of 1.46 Gbps. Depending on the environment, more than 200 antennas are required to achieve this throughput.

**CASE STUDY II: REAL-TIME VIDEO STREAMING AT SPORTS EVENTS**

At large-scale sports events, 20 or more quadcopters equipped with 4K ($4096 \times 2160$) resolution 360-degree cameras can be used to capture the players’ actions at multiple angles (see Figure 4(b) [10]). The captured videos can be sent to an access point equipped with a massive antenna...
TABLE II: Massive MIMO design parameters for different case studies

| Case study          | Drone parameters: | Camera parameters: | Required uplink sum Throughput \((K \times S)\) | Channel parameters: | Massive MIMO design parameters: |
|---------------------|-------------------|--------------------|-----------------------------------------------|---------------------|---------------------------------|
|                      | \(K\)             | \(v\)              | Pixel resolution \((PR)\), Compression ratio \((CR)\), Framers per second \((FPS)\), Field of View \((FoV)\), Number of bits per pixel \((NBP)\) | Coherence bandwidth \((B_c)\), Coherence time \((T_c)\), Coherence interval \((\tau)\) | Carrier frequency \((f_c)\), Bandwidth \((B)\), Number of samples for downlink transmission \((\tau_{dl})\), Number of antennas \((M)\), Data SNR \((\rho_u)\), Range \((R)\) |
| I. Disaster management | \(K = 23\)        | \(v = 20\) m/s    | \(PR = 4K\)                                   | \(B_c = 3\) MHz in sea and mountain environments (300 kHz in urban) \(T_c = 3.125\) ms \(\tau = 9375\) symbols | \(f_c = 2.4\) GHz \(B = 20\) MHz \(\tau_{dl} = \frac{\tau}{10}\) \(M = 245\) (260 in urban) \(\rho_u = 0\) dB \(R = 15\) Km |
|                     | \(v = 20\) m/s    | \(v = 20\) m/s    | \(CR = 200 : 1\)                              | \(T_c = 3.125\) ms \(\tau = 9375\) symbols |                        |
|                     | \(P_t = 1\) W     | \(P_t = 1\) W     | \(FPS = 60\)                                  | \(T_c = 3.125\) ms \(\tau = 9375\) symbols |                        |
|                     | \(Altitude = 100\) m | \(PR = 4K\)       | \(NBP = 24\)                                  | \(T_c = 3.125\) ms \(\tau = 9375\) symbols |                        |
| II. Sport streaming | \(K = 20\)        | \(v = 20\) m/s    | \(PR = 4K\)                                   | \(B_c = 3\) MHz \(T_c = 0.125\) ms \(\tau = 375\) symbols | \(f_c = 60\) GHz \(B = 300\) MHz \(\tau_{dl} = \frac{\tau}{10}\) \(M = 227\) (845 with \(B = 200\) MHz) \(\rho_u = 0\) dB \(R = 160\) m |
|                     | \(v = 20\) m/s    | \(v = 20\) m/s    | \(CR = 200 : 1\)                              | \(T_c = 3.125\) ms \(\tau = 9375\) symbols |                        |
|                     | \(P_t = 1\) W     | \(P_t = 1\) W     | \(FPS = 60\)                                  | \(T_c = 3.125\) ms \(\tau = 9375\) symbols |                        |
|                     | \(FoV = 90^\circ\) | \(FoV = 90^\circ\) | \(NBP = 24\)                                  | \(T_c = 3.125\) ms \(\tau = 9375\) symbols |                        |
|                     | \(NBP = 24\)      | \(NBP = 24\)      |                                           | \(T_c = 3.125\) ms \(\tau = 9375\) symbols |                        |
| III. Drone racing   | \(K = 25\)        | \(v = 30\) m/s    | \(PR = 640 \times 480\)                       | \(B_c = 3\) MHz \(T_c = 0.862\) ms \(\tau = 2586\) symbols | \(f_c = 5.8\) GHz \(B = 20\) MHz \(\tau_{dl} = \frac{\tau}{10}\) \(M = 415\) (855 for \(K = 50\)) \(\rho_u = 0\) dB \(R = 2\) Km |
|                     | \(v = 30\) m/s    | \(v = 30\) m/s    | \(CR = 1 : 1\)                                | \(T_c = 3.125\) ms \(\tau = 9375\) symbols |                        |
|                     | \(P_t = 100\) mW  | \(P_t = 100\) mW  | \(FPS = 60\)                                  | \(T_c = 3.125\) ms \(\tau = 9375\) symbols |                        |
|                     | \(v = 30\) m/s    | \(v = 30\) m/s    | \(FoV = 120^\circ\)                          | \(T_c = 3.125\) ms \(\tau = 9375\) symbols |                        |
|                     | \(P_t = 100\) mW  | \(P_t = 100\) mW  | \(NBP = 8\)                                   | \(T_c = 3.125\) ms \(\tau = 9375\) symbols |                        |
|                     | \(v = 30\) m/s    | \(v = 30\) m/s    |                                           | \(T_c = 3.125\) ms \(\tau = 9375\) symbols |                        |
|                     | \(P_t = 100\) mW  | \(P_t = 100\) mW  |                                           | \(T_c = 3.125\) ms \(\tau = 9375\) symbols |                        |
array. This enables real-time virtual reality for the viewers. However, it requires very high throughput of the wireless link, depending on the desired field of view (FoV). For example, using a head-mounted display, with a horizontal FoV of 90 degrees, at any given moment the viewer can see only one-fourth of the scene (or one-third of the scene with a 120-degree FoV). Thus with 4K resolution and 90-degree FoV, each frame will have $16000 \times 8000$ pixels. With 60 frames per second and 24 bits/pixel, every camera produces approximately 184 Gigabits per second. With a 200 : 1 compression ratio, the bit rate required by the wireless link is 920
Mbps. If there are 20 drones covering the event, the required sum throughput is 18.4 Gbps.

A typical radius of a large football stadium is approximately 230 m. If we consider that the antenna array is placed on the rooftop of the stadium, the distance between the array and drones will be between 50–100 m. Due to this short range, Massive MIMO technology at mmWave frequencies is a suitable choice. As shown in Table II at 60 GHz frequency, over 300 MHz bandwidth, with drone’s transmit power of 1 W, it is possible to achieve 0 dB SNR at 160 m distance. For 20 drones, the number of antennas required to achieve the sum throughput of 18.4 Gbps is 227.

**Case study III: Drone Racing**

Drone racing, often referred as “the sport of the future,” is attracting big sponsorship deals and venues all over the world [11]. In drone racing contests, see Figure 4(c) pilots wearing goggles control the movement of quadcopters via First Person View (FPV). The drones can fly at speeds exceeding 100 km/h. Control of the drones movement requires very low latency (tens of milli-seconds). Currently, analog transmission is used to reduce the delay between the video capture and display. Due to limited capacity, the maximum number of drones in a race is also limited to 8. Using a massive antenna array, hundreds of drones could be simultaneously served on the same time-frequency resource with low latency.

**What is the maximum acceptable latency for drone control and video transmission?**

For video transmission, latency represents the time difference between the instant a frame is captured by the drone and the instant that frame is shown on the pilot’s display. Including the video capture time, and coding- and decoding delays, the overall end-to-end latency is more than 120 ms [12]. Specifically, standard compression techniques such as H264, STD introduce about 50 ms latency. This delay has serious impact as controlling a drone’s movement in a 3D space requires very low latency. For example, at 30 m/s, a quadcopter moves 3.6 meters during 120 ms. Adding this lag to the control loop for the pilot makes the flight extra challenging, especially in indoor environments.

One approach to reduce the latency is to transmit uncompressed videos. To simultaneously support 25 drones in a contest, with a moderate video quality, the sum throughput required for transmitting raw video is 1.84 Gbps (with latency less than 70 ms). As shown in Table II about 415 antennas are required to achieve 1.84 Gbps sum throughput.

**Future Research Directions**

*Scheduling, resource optimization and 3D trajectory optimization*

Resource allocation in autonomous multi-drone networks is a challenging task that requires detailed investigation [3]. In practice, there are situations where the channel is changing very slowly (for example, consider two hovering drones with the same azimuth and elevation angles). In such conditions the GS might not be able to spatially resolve the channels of the drones. To avoid such unfavorable propagation conditions, the GS has to schedule the interfering drones on different time-frequency resources. An alternative approach, if bandwidth is limited and throughput requirements are high, could be to jointly plan the 3D trajectories and the scheduling.

1A 360 video features a complete panoramic 360-degree horizontal view and a 180-degree vertical view.
New MAC layer design

A Massive MIMO enabled drone network requires a new MAC layer design. With Massive MIMO, the frequency of the effective interference variation depends on the GS array geometry, the flying speed and altitude, and range. Furthermore, if the mobility patterns of the drones are known, frequent pilot transmission for CSI estimation is not necessary. Also in many applications, uplink traffic is much higher than the downlink traffic. Therefore, a flexible TDD frame structure can be designed taking into account these factors.

New flexible MAC layer designs are possible, because unlike existing wireless standards, drone networks do not have backward-compatibility requirements. For video and image transmissions, along with Massive MIMO, efficient cross-layer designs can be utilized to enhance the performance of drone networks.

Air-to-ground channel models

Currently, air-to-ground channel measurement results are available only for linearly polarized (horizontal or vertical) antennas [9]. Measurement campaigns need to be carried out, preferably using circularly polarized antennas, over a wide range of carrier frequencies in various environments such as over-water, mountainous, and urban.

Spectrum management

A drone network’s bandwidth requirement depends on several factors, such as the environment, communication range, density of drones, carrier frequency, duplexing mode, power source, and throughput requirements [13]. In applications with low drone densities, the spectrum can be opportunistically shared with existing cellular and satellite communication systems. However, dedicated spectrum may be required in case of high drone densities. Furthermore, unlicensed spectrum may be utilized. The spatial multiplexing capabilities of Massive MIMO will be instrumental in reducing the spectrum requirements.

Which duplexing mode: FDD or TDD? TDD is generally more efficient in reciprocity-based MIMO systems [6]. In FDD mode, the number of samples required for CSI acquisition is the limiting factor. The number of uplink pilot symbols per coherence interval is at least equal to the number of drones in TDD. On the other hand, in FDD, it is at least equal to the sum of the number of GS antennas and the number of drones. However, due to the reduced number of multipath components in drone communication scenarios, beam tracking may be feasible, which would reduce the need for CSI acquisition. Detailed analysis is required of different duplexing modes in different environments and applications.

Security issues

Drone networks are vulnerable to spoofing attacks [3]. The LoS propagation increases the vulnerability to physical-layer attacks [14]. Analysis of secrecy capacity and similar metrics for security protocols for Massive MIMO-based drone communications is an important topic.

Furthermore, in addition to the communication benefits discussed earlier, the Massive MIMO antenna array may be used for accurate positioning of the drones, and for detection of unauthorized intrusion into the airspace.
**Networking challenges**

Future aerial networks will be heterogeneous, and consist of different types of drones: high-altitude and long-endurance UAVs, medium-range UAVs, short-range UAVs, and mini-drones [15]. Nodes in various parts of the network may move at different speeds and have different numbers of antennas. For example, the high-altitude platforms themselves may be equipped with antenna arrays. In some applications, the antenna elements can be distributed over a large geographical region. In such cases, with Massive MIMO, appropriate synchronization will be necessary.

Moreover, if transmissions from different GSs are uncoordinated, the SINR may fluctuate unpredictably and create highly non-stationary interference, known as *flashlight interference*. Suitable interference management techniques may be required for efficient operation of drone networks with multiple GSs.

**SUMMARY**

Drone networks have tremendous potential in many applications. We proposed to use Massive MIMO as an enabler for wireless communication with the drones. Compelling features of Massive MIMO for this application include: high throughput, spatial multiplexing, coverage extension and high-mobility support. We also identified several research problems that are relevant to future Massive MIMO-enabled drone communication networks.

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