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Performance evaluation of unmanned aerial vehicle communication by increasing antennas of cellular base stations

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ABSTRACT

The utilization of unmanned aerial vehicles (UAVs) increases with increased performance of their communication link with the ground remote station. Integrating UAVs with existing cellular networks provides the possibility of enhanced performance of communication links. The base stations of existing cellular networks are installed with fixed number of antennas. The performance of UAV communication links can be further enhanced by increasing antennas of cellular base stations of existing networks using multiple antenna techniques such as multiple input multiple output (MIMO). In this proposed scheme, Massive MIMO technology is used for UAV communications, wherein hundreds of antennas are mounted on cellular base stations. This set up provides significant advantage in terms of enhancement in performance of UAV communication links, as compared to existing methods of UAV communication. In this paper, performance evaluation of UAV communication links is carried out by increasing the number of antennas at base stations of existing cellular networks. For this evaluation, firstly basic multiple antennas techniques such as point-to-point MIMO and multi-user MIMO (MU-MIMO) are covered based on existing studies and findings. Subsequently, an antenna dependent closed form expression for uplink channel capacity of massive MIMO based UAV communication links is derived, with few numerical results.

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1. INTRODUCTION

The proliferation of communication technology has led to enhanced utilization of unmanned aerial vehicles (UAVs) in the field of battlefield surveillance, aerial photography, wildlife conservation, and goods transportation [1]-[3]. For their effective use, the UAVs have few typical requirements and features such as longer range of operation from ground control station, very high aerial mobility and higher throughput for their communications [4]-[7]. Such typical requirements can only be provisioned by latest communication technologies [8]. Already established and existing cellular communication network technology has the requisite capability in terms of worldwide availability, higher bandwidth, earmarked frequency spectrum, easy identification, channel security and superior efficiency, which can be effectively utilized to satisfy all requirements of UAV communication [9], [10]. Figure 1 depicts the possibility of use of cellular networks for UAV communication. Advanced communication technologies such as 4G/5G has the potential to provide higher throughput to large number of devices simultaneously. Thus, 4G/5G cellular communication technologies present strong case for their implementation in UAV communications. However, UAV communication based on cellular networks has inherent challenges in form of altitude of operation, channel modelling, deployment, security, and efficiency [11], [12].

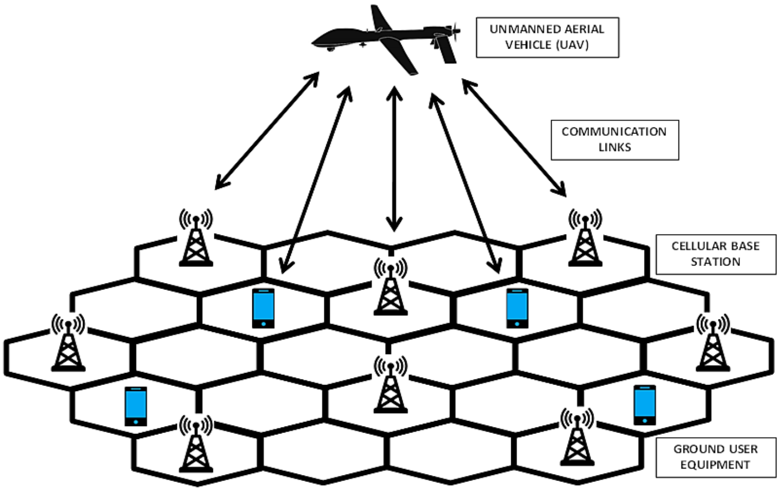

Figure 1. UAV connectivity with existing cellular network

2. LITERATURE REVIEW

Researchers have brought out specific requirements, characteristics and issues in UAV communications [1]-[2]. Various existing studies have deliberated on number of issues in providing reliable cellular based UAV communication and performance evaluation communication links of UAVs with cellular networks based on broad factors such as channels, propagation data, power control, coverage, deployment, frequency bands, and heterogenous networks [13]-[18]. However, there is a scope to present a renewed viewpoint of the performance evaluation of UAV communication links based on effects of increasing number of antennas at cellular base stations by employing modern communication technology such as Massive MIMO. Following gaps exists in the performance evaluation of UAV communication links: i) Increase in number of antennas at cellular base stations will have direct impact on explicit features of UAV communication link such as range, mobility, deployment, authentication, authorization, and trajectory control. ii) Performance of UAV communication links can be increased by use of multiple antennas at cellular base stations. iii) For performance evaluation UAV communication links and to understand the impact of using hundreds of antennas at cellular base stations, an antenna dependent relationship of performance metric may be formulated.

2.1. Paper organization

This paper provides elementary understanding of the principles of use of multiple antennas for UAV communications. In section 2, we discuss performance of various basic multiple antenna techniques based on existing study [13]. These techniques can be optimally utilized for enabling cellular based communication to UAVs. In section 3, we describe the performance of multi user multiple input multiple output (MU-MIMO) enabled UAV communication, based on recent findings [14], which bring out the fact that when number of antennas at cellular base station are increased, then performance of UAV communication link also increases. This gives rise to the possibility of exploiting massive MIMO technology for establishing much higher capacity cellular communication links with UAVs. Recent studies have been carried for provisioning such massive MIMO enabled UAV communication using existing cellular networks [15]-[17]. However, to understand the impact of using hundreds of antennas at cellular base stations, an antenna dependent relationship of performance metric is required. In section 4, we bring out the impact of further increase of antennas at cellular base station using massive MIMO technology, by deriving antenna dependent closed form expression for uplink channel capacity of UAV communication links based on massive MIMO. In section 5, we do comparative analysis of performance of UAV communication links of different types of antenna techniques based on increase in number of antennas at cellular base stations. The results prove that the performance of UAV communication links improves significantly when cellular base stations with hundreds of antennas are employed using massive MIMO technology. Finally in section 6, conclusion is presented.

3. BASIC MULTIPLE ANTENNA TECHNIQUES FOR UAV COMMUNICATION: SIMO, MISO AND MIMO

3.1. Channel capacity

Channel capacity is considered as performance metric for evaluating the communication link as it is given by number of bits per symbol which can be sent without any error [18]. For a basic communication channel with transmitted symbol *x*, received signal *y*, channel gain *β*, and noise *n*, shown in Figure 2. The channel capacity *C* is given as $C = \log_2(1 + \frac{q\beta}{N_o})$ bits per symbol, where, q is the energy per symbol, β is the channel gain, and N_0 is the noise variance. This is a complex valued signal which is denoted by B complex samples per second, where, B is bandwidth. Thus, the channel capacity expression becomes $C = B\log_2(1 + \frac{q\beta}{N_o})$ bits per second, where, number of symbols is B symbols per second. With q being represented as $q = \frac{P}{B}$ where, P is power, the channel capacity expression becomes $C = B\log_2(1 + \frac{P\beta}{BN_o})$ bits per second, where, $\frac{P\beta}{BN_o}$ is the SNR.

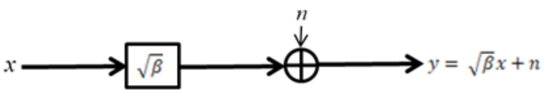

Figure 2. Basic communication channel

3.2. Basic multiple antenna techniques

Single input single output (SISO): SISO communication link uses single antenna to send and single antenna to receive. Channel capacity is represented by $C = \log_2(1 + \frac{q|g|^2}{N_o})$ bits per symbol. Here, basic communication channel has, channel gain β, channel response g and square root of channel gain is channel response ie $\sqrt{\beta} = g$ or $\beta = g^2$.

Single input multiple output (SIMO): SIMO communication link uses single antenna to send and M antennas to receive. The channel capacity is represented by $C = \log_2(1 + \frac{q\|g\|^2}{N_o})$ bits per symbol. Here, $\|g\|^2$ is sum of absolute values of square of channel responses for each of M antennas i.e squared norm of channel vector. $\|g\|^2 = \sum_{m=1}^{M}|g_m|^2$, when channel responses are equal, M times strong signal is received (beamforming gain) $\frac{|g^H y|}{\|g\|}$.

Multiple input single output (MISO): MISO communication link uses M transmit antenna and one receive antenna. The channel capacity is represented by $C = \log_2(1 + \frac{q\|g\|^2}{N_o})$ bits per symbol. Therefore, when M antennas are used for transmission and M antennas are used for reception, M times larger signal to noise ratio is achieved in channel capacities of SIMO and MISO. When M antennas are used for transmission, directive transmission happens using beamforming toward UAV. This happens due to constructive addition of M copies of signals. When M antennas are used for reception and only one antenna is transmitting, dissimilar copies of signal having dissimilar channel responses are constructively added using Maximum ratio combining. Thus, in both cases of use of multiple antennas at transmitter and receiver, beamforming gain proportional to M is achieved. These basic multiple antennas techniques are diagrammatically represented in Figure 3 [13]. The comparative analysis of performance of various multiple antenna techniques is given at Table 1 [13].

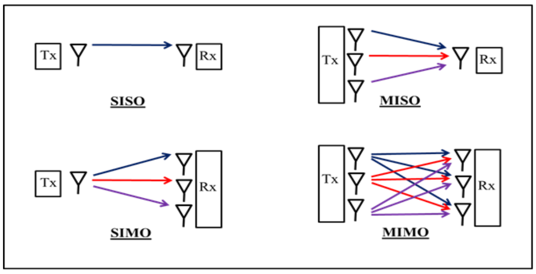

Figure 3. Basic multiple antenna techniques

Point to point multiple input multiple output (MIMO): MIMO communication link uses k antennas to send and m antennas to receive. The channel capacity is represented by $C = \max_{q_1 \geq 0 \ldots q_s \geq 0} \sum_{k=1}^{S} \log_2(1 + \frac{q_k S_k^2}{N_o})$ bits per symbol, where q_k denotes transmit power, S_k denotes singular value and N_o denotes noise power spectral density.

Table 1. Comparative analysis of performance of multiple antenna techniques

Antenna technique	Channel capacity (bits per symbol)
SISO	$C = \log_2(1 + \frac{q\lvert g\rvert^2}{N_o})$
SIMO	$C = \log_2(1 + \frac{q\lVert g\rVert^2}{N_o})$
MISO	$C = \log_2(1 + \frac{q\lVert g\rVert^2}{N_o})$
Point to point MIMO	$C = \max_{q_1 \geq 0 \ldots q_s \geq 0} \sum_{k=1}^{S} \log_2(1 + \frac{q_k S_k^2}{N_o})$

4. UAV COMMUNICATION SUPPORT BY MULTIUSER MIMO (MU-MIMO)

Main benefit of MIMO is Multiplexing gain, wherein much larger channel capacity is achieved because many signals are multiplexed spatially at the same time. But at higher SNR, the achieved multiplexing gain is much less for NLOS. In addition, as the multiplexing gain is represented by minimum (M,K), there is a need to have many antennas at transmitter as well at receiver. But the UAVs have capability to mount limited antennas only. Therefore, multiuser MIMO (MU-MIMO) is considered wherein the UAVs have single antenna and base stations have multiple antennas. This concept of MU-MIMO is depicted in Figure 4, wherein, UAVs are located at different locations and are transmitting at the same time to base station. The uplink is the link from UAVs to base station in form of multi point to point MIMO. The point to multi point link from base station to UAVs is the downlink. The concept is referred as MIMO because, UAVs placed at different locations depict different multiple antennas and base station as such has multiple antennas [14].

Consider only two UAVs are communicating with the base station, each having power as P watts, bandwidth as B and noise power spectral density as N_0. As UAVs are sharing bandwidth, UAV1 gets αB bandwidth and UAV2 gets (1-α) B. Both UAVs have similar channel quality with β as the channel gain. The rates are given by $R1 = \alpha B \log_2(1 + \frac{P\beta}{\alpha B N_0})$ and $R2 = (1-\alpha) B \log_2(1 + \frac{P\beta}{(1-\alpha) B N_0})$. Different rate can be achieved for different values of α. By means of using orthogonal multiple access UAV1 and UAV2 can transmit at the same bandwidth using time sharing. Therefore, this is the motivation to cater for multiple UAVs simultaneously in uplink. Consider base station with M antennas and K single antenna UAVs, as depicted in Figure 5.

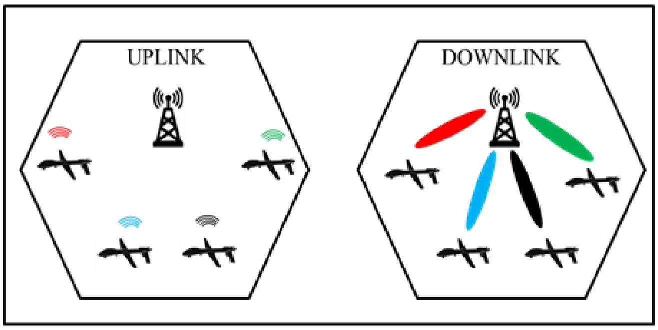

Figure 4. Uplink and downlink UAV communication Links

If UAV i, is sending signal and j is base station antenna which is receiving signal, then g_i^j is channel response between UAV i and antenna j. The data signals $x_1, \ldots, x_K$ are signals transmitted by K UAVs and data signals $y_1, \ldots, y_M$ are received at the base station. All antennas at base station receive signals from UAV1. Similarly, the base station antennas receive signals from all the UAVs. The task of base station is to separate the signals. This task becomes easy if base station has at least similar number of antennas as number of UAVs. The received signal y is given as $y = \sqrt{\rho_{ul}}Gx + w$, where x is transmitted signal, $\sqrt{\rho_{ul}}$ is SNR normalised i.e $\sqrt{\rho_{ul}}$ includes noise variables and therefore, w has I_M . Expressing these in matrix form:

$$y = \begin{bmatrix} y_1 \\ \vdots \\ y_M \end{bmatrix} G = \begin{bmatrix} g_1^1 & \dots & g_K^1 \\ \vdots & \ddots & \vdots \\ g_1^M & \dots & g_K^M \end{bmatrix} x = \begin{bmatrix} x_1 \\ \vdots \\ x_K \end{bmatrix} w = \begin{bmatrix} w_1 \\ \vdots \\ w_M \end{bmatrix}$$

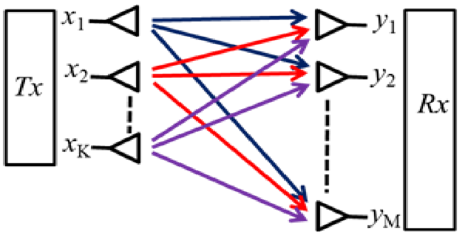

Figure 5. Communication links of K UAVs with M base station antennas

SNR is ρ_{ul}, as the parameters are normalized and signal from each UAV is power limited to $E\{|x_K|^2\} \leq 1$ with normalized noise as w ~ CN(0,I_M). This concept is similar to MIMO with variations in terms of capacities of each UAVs, data signals from each UAV, and power budget of each UAV. Considering channel matrix G is deterministic with all UAVs are utilizing full power for transmission, covariance matrix is identity matrix x ~ CN (0,I_M), because all the elements in x are independent and have noise variance as 1. Its similar to point-to-point MIMO channel having covariance matrix Q = I_M. Then, the capacity of MU-MIMO based UAV communication system is given by sum rate R_1 + R_2 …..+R_k = $\log_2(det(I_M + \rho_{ul}GG^H))$ [14]. With uplink capacity region as K=2 having all (R_1,R_2) in the region, conforming to $R_1 \leq \log_2(1 + \rho_{ul}\, \|g_1\|^2)$ and $R_2 \leq \log_2(1 + \rho_{ul}\, \|g_2\|^2)$. Thus,

$$R1 + R2 = log_2(det(I_M + \rho_{ul}GG^H)) \ where \ G = [g_1, g_2] \ [14]$$

therefore, the achievement of larger multiplexing gains is difficult to achieve practically in point-to-point MIMO system. MU-MIMO has same system model but with variations in terms of power, performance and independent UAVs.

5. UAV COMMUNICATION SUPPORT BY MASSIVE MIMO

5.1. Comparison of massive MIMO vs MU-MIMO supported UAV communication

MU-MIMO uses UAVs per cell as $K \leq 4$, antennas at base station as $M \leq 8$ and it generally does not reach capacity gain to minimum (M,K)=K. Ideally such system should generate capacity gain equalling minimum of number of antennas at base station and number of UAVs. This would always be equal to number of UAVs as there will always be lessor number of UAVs than the number of antennas. But such amount of gains are generally not achieved, as it is difficult to operate such systems in view of channel estimation considerations. This problem is solved by use of Massive MIMO, which has capability of having UAVs per cell as $K \approx 10$ or more and antennas at base station as $M \approx 100$. Massive MIMO enables better signals, large beamforming gain, lessor interference between UAVs and more directive signals. Prominent aspect of massive MIMO is achievement of minimum (M,K)=K capacity gain, with much more antennas at cellular base station than UAVs in a cell.

5.2. Concept of channel coherence

Generally, the wireless communication channel is non time invariant, but for short duration of time period it becomes time invariant. Coherence time (T_C) is the time period which is time invariant, where analysis of channel can be carried out by utilizing everything known. It is given as $T_C = \frac{\lambda}{2\nu}$, where, λ is wavelength and ν is speed. Other property of channel is time dispersiveness, which determine spreading out of signal in time. Multiple propagations cause some dispersion over time domain. In frequency domain, there would be dispersion on change of frequency. But for short duration od frequency, the frequency response appears to be constant. The bandwidth over which, the frequency response $G(f) \approx g$ is almost constant is called Coherence bandwidth (B_C). This implies in time domain, the channel response is $g(t) = g.\delta(t)$, where g is constant. Thus, the channel can be represented as only complex valued constant. Due to more and less rapid changes in various scenarios, the coherences bandwidth varies a lot and is given by $B_C = \frac{c}{|d_{max}-d_{min}|}$ Hz, where d_{min} is shortest propagation path and d_{max} denotes distance of maximum propagation delay. Depiction of coherence interval is given at Figure 6. Entire bandwidth and time period is divided into different pieces of width B_C and intervals T_C respectively. Every block is referred as Coherence interval, described by a scalar $\tau_C = B_C T_C$ complex samples within a coherence interval, having constant channel between a transmitting antenna and a receiver antenna. The use of this channel within a coherence interval can be determined. Thus, overall process of communication system is bundled as coherence intervals and channel behaviour in coherence intervals can be learned [18], [19].

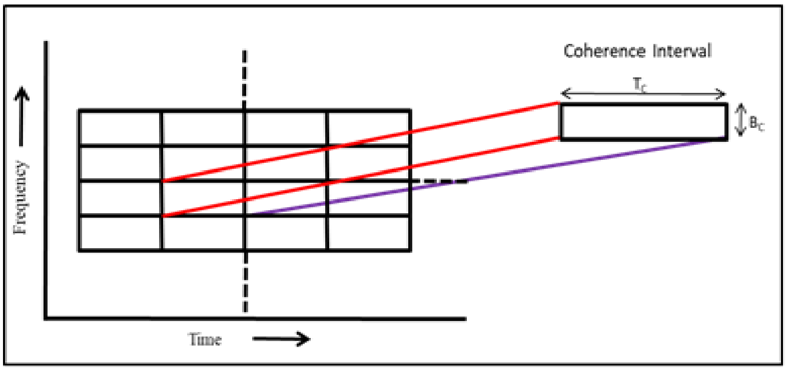

Figure 6. Coherence interval

5.3. Motivation for UAV communication support by massive MIMO

Favourable propagation: Consider only two UAVs as K=2. Then, Sum capacity of system is $R_1+R_2=\log_2\big(det(I_M + \rho_{ul} G G^H)\big)=\log_2\big(det(I_M + \rho_{ul} G^H G)\big)$. If $G = [g_1, g_2]$, then $G^H G = \begin{bmatrix} \|g_1\|^2 & {g_1}^H g_2 \\ {g_2}^H g_1 & \|g_2\|^2 \end{bmatrix}$. Expanding the sum capacity $\log_2\big(det(I_M + \rho_{ul} G G^H)\big) = \log_2((1+\rho_{ul}\,\|g_1\|^2)\log_2(1+\rho_{ul}\,\|g_2\|^2) - {\rho_{ul}}^2 |{g_1}^H g_2|^2) \leq \log_2(1+\rho_{ul}\,\|g_1\|^2) + \log_2(1+\rho_{ul}\,\|g_2\|^2)$. Here, first term $\log_2(1+\rho_{ul}\,\|g_1\|^2)$ is the first UAV's capacity and second term $\log_2(1+\rho_{ul}\,\|g_2\|^2)$ is second UAV's capacity. If and only if the value ${g_1}^H g_2 = 0$, then only above equation will be equal and sum capacity is equal to individual UAVs capacities. As both the UAVs depict orthogonal vectors, there is no interference and capacity region is square, which is requirement of practical system. Therefore, the goal is to ensure the channel vectors of all UAVs are orthogonal, which has become the motivation for massive MIMO namely Favourable Propagation [18], [19]. For two channels of M antennas as g_1 & g_2. $|{g_1}^H g_2|/M$ converges to zero as $M \to \infty$. This shows that the interference decreases with increase in number of antennas. This is because of beamforming gain and beam width, which has enabled better focusing of signal towards the UAV with lessor interference into any other direction.

Channel hardening: For channel of M antenna having channel vector g ~ CN (0,I_M), the Normalized channel gain $\frac{\|g\|^2}{M}$, has mean M/M=1 and variance 1/M. This shows that number of antennas does not affect mean value but reduce the variance. With increase in number of antennas the value comes closer to mean value, as variance is further reduced. Therefore, due to spatial diversity, the squared norm of channel vector is given by $\|g\|^2 = E\{\|g\|^2\}$, where $E\{\|g\|^2\}$ is the mean value. For larger setup squared norm would be closer to mean value. Also, when M is large beamforming gain is $\|g\|^2 \approx M$ [18]-[20].

Asymptotic motivation: Let x_k for K=1 or 2 be the uplink signal sent by two UAVs. Then, Channel is $g_K = [{g_K}^1 \;\; \ldots \;\; {g_K}^M]^T \sim CN\,(0, I_M)$, noise is $w \sim CN\,(0, I_M)$ and received signal is $y = g_1 x_1 + g_2 x_2 + w$. Consider y is received for UAV1, $\tilde{y}_1 = {a_1}^H y = {a_1}^H g_1 x_1 + {a_1}^H g_2 x_2 + {a_1}^H w$. Due to the property of channel hardening the signal remains ${a_1}^H g_1 = \frac{g_1}{M} g_1 = \frac{\|g\|^2}{M} \xrightarrow[M\to\infty]{} E[|g_1^1|^2] = 1$. Due to property of favourable propagation, the interference vanishes and noise vanishes [18]. ${a_1}^H g_2 = \frac{g_1^H}{M} g_1 \xrightarrow[M\to\infty]{} E[g_1^{1*} g_2^1] =$

0. $a_1{}^H w = \frac{g_1^H}{M} w \xrightarrow[M\to\infty]{} E[g_1^{1*} w_1] = 0$. Thus, $\tilde{y} = 1 + 0 + 0 = 1 \; or \; x_1$, which means interference free communication $\tilde{y} \xrightarrow[M\to\infty]{} x_1$.

5.4. Channel response estimation

Primary challenge of massive MIMO communication support to UAVs is to learn channel response for each coherence interval. Overall channels are for K number of UAVs having M length channel vectors. This means, for learning every coherence interval, there is a need to estimate MK coefficients. Estimation is carried out by sending predetermined and known pilot signal between transmitter and receiver, and detecting the state of the channel. Designing and sending of pilot have to be carefully executed as large number of coefficients are to be learned. In case only single pilot is used for estimation of all coefficients, single transmit antenna send single pilot which is received by all receive antennas, thus all channels $g_{1,}g_{2}......g_M$ are estimated. In case M pilots are used for estimation of all coefficients, M transmit antenna send M pilots which is received by single receive antenna. Thus, number of transmit antennas determine number of pilots [18]. The same is depicted in Figure 7.

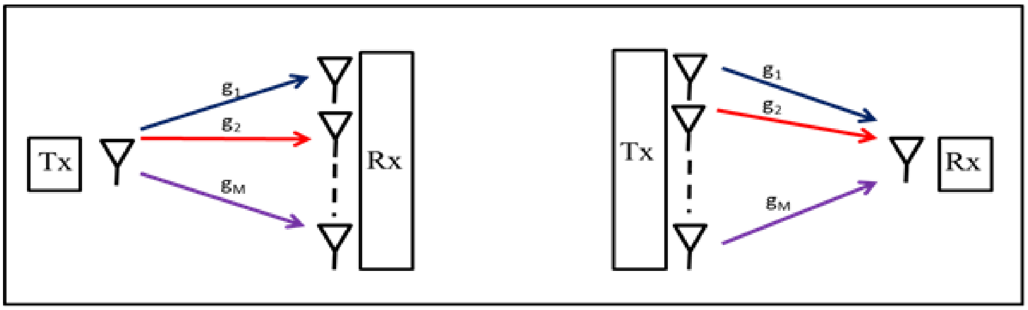

Figure 7. Pilot transmission

5.5. Concept of time division duplexing (TDD) in UAV communication support by massive MIMO

Time division duplexing (TDD) is a way to divide frequency and time resources between uplink and downlink [18]. In each coherence interval block switching of uplink and downlink happens quickly enough to ensure that channel remains fixed in one coherence interval block, as depicted in Figure 8. Uplink and downlink are actually time separated and K number of pilots are required to learn all channels in TDD. Decision of sending pilot needs to be taken for uplink and downlink. In uplink K pilots are required for K UAVs and in downlink M pilots are required for M antennas at the base station. As very less UAVs are there, compared to antennas at base station, a system with only K pilots can be designed. Whereas for Frequency division duplexing (FDD), K pilots are required for uplink and M pilots for downlink, forcing the system to support M pilots for separating uplink and downlink in frequency [21]. A typical Frame structure matched to coherence intervals is depicted in Figure 9. The analysis of individual coherence intervals can be carried out as per frames comprising of pilots, uplink and downlink values.

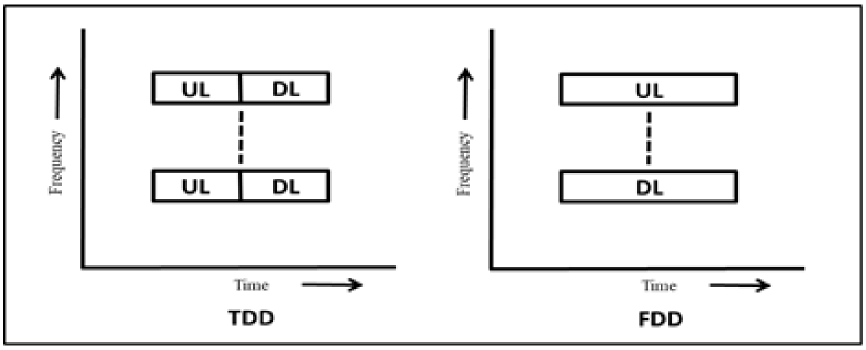

Figure 8. Time division duplexing

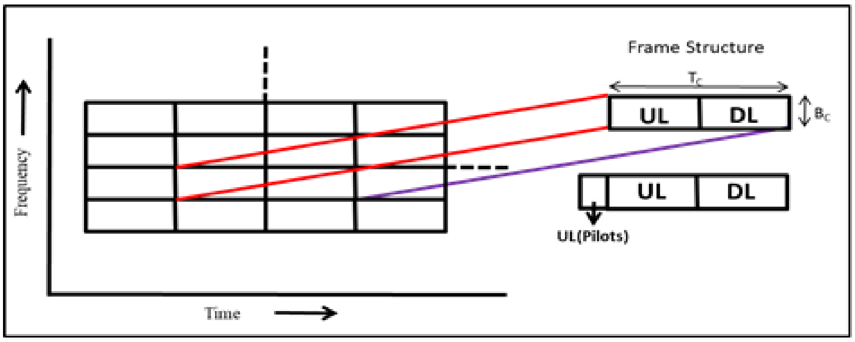

Figure 9. Frame structure

5.6. UAV communication system model for massive MIMO uplink

Time frequency resources can be divided into Frames as per coherence interval sizes with coherence time T_C secs and coherence bandwidth B_C Hz and channel interval $\tau_C = B_C T_C$ complex samples. For UAV Communication System Model for Massive MIMO Uplink, the received signal is $y = \sqrt{\rho_{ul}}\, Gx + w$, which can be represented in matrix form as $y = \begin{bmatrix} y_1 \\ \vdots \\ y_M \end{bmatrix}$ $G = \begin{bmatrix} g_1^1 & \cdots & g_K^1 \\ \vdots & \ddots & \vdots \\ g_1^M & \cdots & g_K^M \end{bmatrix}$ $x = \begin{bmatrix} x_1 \\ \vdots \\ x_K \end{bmatrix}$ $w = \begin{bmatrix} w_1 \\ \vdots \\ w_M \end{bmatrix}$. With normalized parameters, Maximum power is ρ_{ul}, $x_1, \ldots, x_K$ has the power ≤ 1 and channel of UAV K $g_K^1, \ldots, g_K^M \sim \mathrm{CN}(0, \beta_K)$ where β_K is large scale fading coefficient and normalized noise $w_1, \ldots, w_M \sim \mathrm{CN}(0, I_M)$. the maximum SNR of the UAV K is $\rho_{ul}\, \beta_K$. Here, $\rho_{ul} = (UL$ radiated power $\times$ Antenna gain$)/BN_O$. With bandwidth B and noise power spectral density N_O. y is M length vector with M receive antennas at base station. For G matrix, x is a K length vector comprising of signals from all UAV 1 to UAV K along with known pilot sequences and individual column describing channel of one UAV to all antennas at base station. Estimation of the channel is carried out with multiple of x, each transmitted in sequence.

Consider for UAV 1 and UAV 2, the pilot signals/sequence are $\emptyset_1$ & $\emptyset_2$, which will be used for estimation of the channel. Pilots have length τ_P and length vector $\emptyset$. Pilot matrix is now sent $\sqrt{\tau_P}\emptyset = \sqrt{\tau_P}[\emptyset_1 \ldots \emptyset_K]$ over τ_P UAVs of the channel, $y_P = \sqrt{\tau_P \rho_{ul}}\; G\, \emptyset^H + w_P$. Where, pilot matrix is $\sqrt{\tau_P}\emptyset$, written with pilot sequences $\sqrt{\tau_P}[\emptyset_1 \;\; \ldots \;\; \emptyset_K]$, number of rows is τ_P and number of columns is K. one row corresponds to channel of one UAV. Over τ_P channel users, the received signal y is written. Stacking τ_P of them as per columns to create y_P. Each UAV transmits its individual pilot sequence as each row is transmitting at a time [18]. Estimation process involves few steps on receiving y_P by the base station. Dispreading the pilot signal $y_P' = y_P\emptyset = \sqrt{\tau_P \rho_{ul}}\; G\, \emptyset^H \emptyset + w_P \emptyset$ by multiplying received signal with pilot sequence $\emptyset$. $\sqrt{\tau_P \rho_{ul}}$ is constant, $\emptyset^H \emptyset$ is I_K. Here, G is required to be observed. Estimation of channel is done by Mean square error $E\{|\hat{g} - g|^2\}$, where E denotes average/mean, $\hat{g}$ denotes estimate and g denotes the true value. For observing g , being gaussian distributed and observed in gaussian noise, minimum mean square error (MMSE) estimator is $\hat{g} = E\{g|y\} = \frac{\sqrt{P}\beta}{1+P\beta} y$, where $P = \sqrt{\tau_P \rho_{ul}}$. As y is complex gaussian distributed, $\hat{g}$ is also complex gaussian distributed. Estimation error is given by $\tilde{g} = (\hat{g} - g) \sim \mathrm{CN}\left(0, \beta - \frac{P\beta^2}{1+P\beta}\right)$, where, β is original variance of g and $\frac{P\beta^2}{1+P\beta}$ is variance of estimate. Estimate is given by $\hat{g} \sim \mathrm{CN}\left(0, \frac{P\beta^2}{1+P\beta}\right)$. Estimate of channels is given by $[Y_P']_{mk} = \sqrt{\tau_P \rho_{ul}}\; g_k^m + [w_P \emptyset]_{mk}$, where, m depicts row and k depicts column, $\sqrt{\tau_P \rho_{ul}}$ is constant, $[w_P \emptyset]_{mk}$ is noise, g_k^m is to be estimated, and is a complex gaussian distributed channel coefficient between UAV k and antenna m at base station. Thus, Minimum mean square error (MMSE) estimate of g_k^m from UAV k to antenna m, is given by estimate $\hat{g}_k^m = E\{g_k^m | Y_P'\} = \frac{\beta_k \sqrt{\tau_P \rho_{ul}}}{1+\tau_P \rho_{ul} \beta_k} [Y_P']_{mk} \sim CN(0, \gamma_k)$, where γ_k depicts variance of estimated channel. Estimation error is given by $\tilde{g}_k^m = \hat{g}_k^m - g_k^m \sim CN(0, \beta_k - \gamma_k)$, where β_k is variance of true channel and γ_k is variance of estimated channel, $\gamma_k = \frac{\tau_P \rho_{ul} \beta_k^2}{1+\tau_P \rho_{ul} \beta_k}$. Thus, Mean square error (MSE) is given by $E\{|\hat{g}_k^m - g_k^m|^2\} = E\{|\tilde{g}_k^m|^2\} = \beta_k - \gamma_k = \beta_k - \frac{\tau_P \rho_{ul} \beta_k^2}{1+\tau_P \rho_{ul} \beta_k}$. The value of MSE approaches zero in case of accurate estimate, as $\rho_{ul} \to \infty$, meaning very high uplink power or pilot sequence length $\tau_P \to \infty$, as $\beta_k - \beta_k = 0$ [18], [22].

5.7. UAV communication uplink performance

In case of point-to-point MIMO based communication link with UAV, the receiver knows the channel perfectly. Therefore, the exact capacity computation in different cases of links was carried out. Practically, the receiver just can not identify the channel perfectly. Therefore, receiver forms an estimate $\hat{x}$ on accessing y and channel information Ω. As shown in communication model in Figure 10. Channel information is around the channel coefficient g. The exact value of g is not know practically due to estimation error. Therefore, exact channel capacity may not be computed. Instead, capacity lower bound can be computed [22], [23]. Capacity lower bound is:

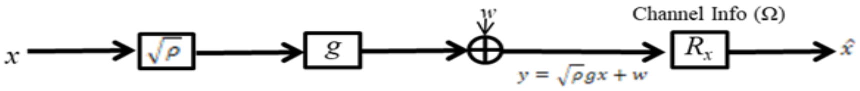

Figure 10. Communication model

$$C \geq E\left\{\log_2\left(1 + \frac{\rho|E\{g|\Omega\}|^2}{\rho Var\{g|\Omega\} + Var\{W|\Omega\}}\right)\right\} \quad (1)$$

where, SNR is $\frac{\rho|E\{g|\Omega\}|^2}{\rho Var\{g|\Omega\} + Var\{W|\Omega\}}$, ρ is the power and $|E\{g|\Omega\}|^2$ denotes the absolute value square of channel. The channel not exactly actual g but it is the estimate of g given Ω. Uncertainty around $E\{g|\Omega\}$ is $\rho Var\{g|\Omega\}$ and variance of noise is $Var\{w|\Omega\}$. As the channel being considered is fast fading channel, the channel realization will be changing throughout. So, it will be depicted by random number as $\log_2(1 + SNR)$. The expectation is E which is over diverse realization of channel. When the knowledge of channel is perfect then the capacity is equal to *C*, otherwise it will be always smaller than *C* [24], [25].

In case of data transmission in uplink, *y* is the received signal which is denoted as $y = \sqrt{\rho_{ul}}\,Gx + w$. The signals $x_k = \sqrt{\eta_k} q_k$, where, $q_k \sim CN(0,1)$ is data symbol with complex Gaussian variance 1 and power is controlled by $0 \leq \eta_k \leq 1$. Power control coefficient is η_k and every signal from UAV is divided into x_k. Power control coefficient determines whether UAV is transmitting with full power i.e 1 or no/zero power i.e 0. By keeping the power control coefficient constant, the channel of the UAV k is $g_k^1 \cdots g_k^m \sim CN(0, \beta_k)$ and $w \sim CN(0, I_M)$. Therefore, rewriting this model by using only η_k, q_k and without *x* because of linear receiver processing, the received signal becomes.

$$y = \sqrt{\rho_{ul}}\, G D_\eta^{1/2} q + w, \text{ where } \sqrt{\eta_k} \sim \sqrt{D_\eta} \sim D_\eta^{1/2}\ .\ D_\eta = \begin{pmatrix} \eta_1 & 0 & 0 \\ 0 & \ddots & 0 \\ 0 & 0 & \eta_k \end{pmatrix}\ q = \begin{pmatrix} q_1 \\ \vdots \\ q_k \end{pmatrix}$$

On receiving *y*, the receiver would guess transmitted $q_{1 \ldots} q_k$ signals. In case of UAV i, a receiver filter a_i is used such that $a_i^H y = \sqrt{\rho_{ul}}\ a_i^H G D_\eta^{1/2} q + a_i^H w = \sum_{k=1}^{k} a_i^H g_k \sqrt{\rho_{ul}\eta_k}\, q_k + a_i^H w \approx q_i$. Therefore, by multiplying with a_i^H, q_i is obtained, as for k = i, $a_i^H g_k \sqrt{\rho_{ul}\eta_k}$ becomes 1. This term and the noise term are desired to be 0, for all other UAVs signals which are interfering. For selecting appropriate a_i, performance or capacity lower bound is required to be kept in mind.

$$C \geq E\left\{\log_2\left(1 + \frac{\rho|E\{g|\Omega\}|^2}{\rho Var\{g|\Omega\} + Var\{W'|\Omega\}}\right)\right\}, a_i \text{ should be selected to maximize } C \quad (2)$$

There is a need to compute each term in this expression. Here, $\rho = \rho_{ul}\eta_i$, $g = a_i^H g_i$, $x = q_i$ and $\Omega = \{\hat{g}_1, \ldots, \hat{g}_k\}$ MMSE estimates and $w' = \sum_{k=1, k\neq i}^{k} a_i^H g_k \sqrt{\rho_{ul}\eta_k}\, q_k + a_i^H w$, with all of terms being added except k = I and the noise term.

Here, numerator is given as:

$$E\{g|\Omega\} = E\{a_i^H g_i|\hat{g}_1, \ldots, \hat{g}_k\} = a_i^H E\{\hat{g}_i|\hat{g}_1, \ldots, \hat{g}_k\} - a_i^H E\{\tilde{g}|\hat{g}_1, \ldots, \hat{g}_k\} = a_i^H \hat{g}_i$$

where, $\hat{g}_i$ depicts estimate's expected value and $\tilde{g}$ depicts estimation error's expected value. $g_i = \hat{g}_i - \tilde{g}_i$ and $E\{\tilde{g}_i|\hat{g}_1, \ldots, \hat{g}_k\} = E\{\tilde{g}_i\} = 0$. Selection of a_i is based on $\Omega = \{\hat{g}_1, \ldots, \hat{g}_k\}$ and $g = a_i^H g_i$. In the denominator, $Var\{g|\Omega\} = E\{|g|^2|\Omega\} - |E\{g|\Omega\}|^2$,

where,

$E\{|g|^2|\Omega\} = E\{|a_i^H g_i|^2|\Omega\} = a_i^H E\{\hat{g}_i\hat{g}_i^H + \tilde{g}_i\tilde{g}_i^H - \hat{g}_i\tilde{g}_i^H - \tilde{g}_i\hat{g}_i^H|\Omega\}a_i = a_i^H(\hat{g}_i\hat{g}_i^H + (\beta_i - \gamma_i)I_M - 0 - 0)a_i = a_i^H(\hat{g}_i\hat{g}_i^H + (\beta_i - \gamma_i)I_M)a_i$.

And $Var\{w'|\Omega\} = Var\left\{\sum_{k=1,k\neq i}^{k} a_i^H g_k\sqrt{\rho_{ul}\eta_k}q_k + a_i^H w \,\middle|\Omega\right\}$. $E\{w'|\Omega\} = 0$, as $E\{q_k\}$ and $E\{w\} = 0$. Thus, $Var\{w'|\Omega\} = E\{|w'|^2|\Omega\} = \sum_{k=1,k\neq i}^{k} E\{|a_i^H g_k|^2|\Omega\}\sqrt{\rho_{ul}\eta_k}E\{|q_k|^2|\Omega\} + E\{|a_i^H w|^2|\Omega\} = \sum_{k=1,k\neq i}^{k} a_i^H(\hat{g}_k\hat{g}_k^H + (\beta_k - \gamma_k)I_M)a_i\sqrt{\rho_{ul}\eta_k} + a_i^H I_M a_i$.

Incorporating these values in the main equation of capacity, we get

$$C \geq E\left\{\log_2\left(1 + \frac{\rho_{ul}\eta_i|a_i^H\hat{g}_i|^2}{a_i^H B_i a_i}\right)\right\} \tag{3}$$

where $B_i = \sum_{k=1,k\neq i}^{k}\rho_{ul}\eta_k\hat{g}_k\hat{g}_k^H + \sum_{k=1,k\neq i}^{k}\rho_{ul}\eta_k(\beta_k - \gamma_k)I_M + I_M$ and the term $\frac{\rho_{ul}\eta_i|a_i^H\hat{g}_i|^2}{a_i^H B_i a_i}$ has the mathematical structure similar to generalized Rayleigh quotient $|a^H b|^2/a^H B a$. Considering matrix B and vector b, the maximum ratio is obtained by $a = B^{-1}b$. If matrix B is removed or replaced with identity matrix I_M, maximum ratio is obtained by a=b. the other term B^{-1} depicts whitening. Maximum ratio combining is achieved on obtaining no estimation error or interference, as b becomes an identity matrix. In case of interference the interference and noise terms get whitened. Therefore, if a and b are pointing in same direction and are same then $|a^H b|^2/a^H a$ is maximum. Thus, the receiver filter equal to the existing channel is selected in maximum ratio combining. Same result can be used in capacity lower bound equation to maximize it.

5.7.1. Process for maximization of uplink capacity lower bound

The term $\frac{\rho_{ul}\eta_i|a_i^H\hat{g}_i|^2}{a_i^H B_i a_i}$ in the capacity equation has the mathematical structure similar to generalized Rayleigh quotient $|a^H b|^2/a^H B a$. Considering matrix B and vector b, the maximum ratio is obtained by $a = B^{-1}b$. If matrix B is removed or replaced with identity matrix I_M, maximum ratio is obtained by a=b. the other term B^{-1} depicts whitening. Maximum ratio combining is achieved on obtaining no estimation error or interference, as b becomes an identity matrix. In case of interference the interference and noise terms get whitened. Therefore, if a and b are pointing in same direction and are same then $|a^H b|^2/a^H a$ is maximum. Thus, the receiver filter equal to the existing channel is selected in maximum ratio combining. Same result can be used in capacity lower bound equation to maximize it. Incorporating these values in capacity equation, we get

$$C \geq E\left\{\log_2\left(1 + \frac{|a_i^H b_i|^2}{a_i^H B_i a_i}\right)\right\} \tag{4}$$

where $b_i = \sqrt{\rho_{ul}\eta_i}\,\hat{g}_i$ and $B_i = \sum_{k=1,k\neq i}^{k}\rho_{ul}\eta_k\hat{g}_k\hat{g}_k^H + \sum_{k=1}^{k}\rho_{ul}\eta_k(\beta_k - \gamma_k)\,I_M + I_M$.

Maximize this by selecting $a_i = B^{-1}b_i = \sqrt{\rho_{ul}\eta_i}B_i^{-1}\,\hat{g}_i$. This process is MMSE combining wherein the mean square difference between the inner product and q_i is minimized as $a_i^H y = q_i$ is desired. $\hat{g}_1$ is the channel estimate of desired UAV $\hat{g}_i$ in specific direction. In the process of selection of receive filter, when a_i is placed in line or alignment with that of channel estimate, then the channel gain in numerator of SNR expression is maximized. However, the denominator of SNR expression can be minimized when a_i points in between zero and channel estimate direction or orthogonally which means taking $\hat{g}_1$ and rotating it using B_i^{-1}.

5.7.2. Method of maximum ratio processing

Sum capacity in communication support to UAV by massive MIMO uplink having two UAVs with K=2 and channel matrix $G = [g_1 g_2]$ is (5):

$$R_1 + R_2 = \log_2\left(det(I_2 + \rho_{ul}G^H G)\right) = \log_2\left(I_2 + \rho_{ul}\begin{bmatrix}\|g_1\|^2 & g_1^H g_2\\ g_2^H g_1 & \|g_2\|^2\end{bmatrix}\right) \tag{5}$$

Here, $\|g_1\|^2$ is squared norm of one of the channel vector, $\|g_2\|^2$ is squared norm of other channel vector, ρ_{ul} is SNR, $g_1^H g_2$ is inner product of two channel vectors, $G^H G$ is product of channel matrix and Hermitian transpose of itself and I_2 is identity matrix of size 2 for two UAVs. All vectors are m dimensional, as there are M antennas at the base station. Therefore:

$$R_1 + R_2 = \log_2((1+\rho_{ul}\|g_1\|^2)(1+\rho_{ul}\|g_2\|^2) - \rho_{ul}^2 |g_1^H g_2|^2)$$
$$\leq \log_2(1+\rho_{ul}\|g_1\|^2) + \log_2(1+\rho_{ul}\|g_2\|^2)$$

Individual terms depict point to point channel capacity of individual UAVs. Larger capacity can be achieved when both the vectors are orthogonal and the inner product between these two vectors $g_1^H g_2$ is zero. With orthogonality between vectors both UAVs get maximum capacity simultaneously, which is the case of favourable propagation. $\{g_k\}$ being collection of channel vectors shall offer the favourable propagation in case $g_k^H g_i = 0$ for k,i=1,…..,k, k≠1. This make possibility of communication by k UAVs simultaneously at same frequency and time as if they are alone. Orthogonality of channel vectors enables the base station to separate the vectors easily in space. Generally, this does not happen satisfactorily. But asymptotic favourable propagation happens satisfactorily, which means $\frac{1}{M} g_k^H g_i \to 0$ as M→ ∞ k,i=1,…,k k≠i. Which suggest that increasing the number of antennas would make larger array, smaller beamwidth and directive signals [18], [19].

Effect of adding more number of antennas is described by assuming a sequence of random variables $x_1, x_2, \ldots\ldots$ which are identically distributed and independent. If $E\{X_i\} = \mu$ for i=1,2... and $Var\{X_i\} = \sigma^2 < \infty$ for the values of i=1,2,3…, then the sample average is given as $\bar{X}_n = (X_1 + X_2 + \cdots + X_n)/n$ which converges to an expected value $\bar{X}_n \to \mu$ as $n \to \infty$. Variance is given as $Var\{\bar{X}_n\} = \frac{(Var\{X_1\}+\cdots+Var\{X_n\})}{n^2} = \frac{n\sigma^2}{n^2} = \sigma^2/n$. As per law of large numbers, the sequence in vector g_k gets longer with additional terms, when number of antennas are increased. Such an arrangement give possibility of favourable propagation as well as channel hardening. If squared norm of channel vector is divided by number of M terms. Then this becomes the sample average of absolute value square of g_k vector. By increasing number of antennas, $\frac{1}{M}\|g_k\|^2 \to \beta_k$ for $M \to \infty, k = 1, .. k$, where β_k is the mean of each of individual absolute value squares, which equals its variance. Thus, as consequence of diversity gain, with increase in number of antennas, a deterministic value of gain is obtained, which is channel hardening. Asymptotic favourable propagation is offered as $\frac{1}{M} g_k^H g_i \to 0$, for $M \to \infty, k = 1, .. k$ & $k \neq i$. Overall sample average converges to mean when the summation is carried over M different terms. Thus, the approximations when M is very large, are represented as $\frac{1}{M}\|g_k\|^2 \approx \beta_k$ & $\frac{1}{M} g_k^H g_i \approx 0$. However, exact channel is not known but only channel estimate is known at receiver,

Estimate of channel is given as $\hat{g}_k^m = E\{g_k^m | Y_P'\} = \frac{\beta_k \sqrt{\tau_P \rho_{ul}}}{1+\tau_P \rho_{ul} \beta_k} [Y_P']_{mk} \sim CN(0, \gamma_k)$, where γ_k depicts the variance of the estimated channel. Estimation error is given as $\tilde{g}_k^m = \hat{g}_k^m - g_k^m \sim CN(0, \beta_k - \gamma_k)$, where β_k depicts the variance of the true channel and γ_k depicts the variance of the estimated channel. $\gamma_k = \frac{\tau_P \rho_{ul} \beta_k^2}{1+\tau_P \rho_{ul} \beta_k}$. Putting these in vector notation, $\hat{g}_k = \begin{bmatrix} \hat{g}_k^1 \\ \vdots \\ \hat{g}_k^M \end{bmatrix} \sim CN(0, \gamma_k I_M)$, which is the representation of estimated channel from antenna 1 to M of UAV k. the variance γ_k is same for all. $\tilde{g}_k = \begin{bmatrix} \tilde{g}_k^1 \\ \vdots \\ \tilde{g}_k^M \end{bmatrix} \sim CN(0, (\beta_k - \gamma_k) I_M)$. Thus, it offers the property of channel hardening $\frac{1}{M}\|\hat{g}_k\|^2 \to \gamma_k$ for $M \to \infty, k = 1, .. k$, as estimated channels is independently distributed as $\hat{g}_k \sim CN(0, \gamma_k I_M)$. Simultaneously it offers property of asymptotic favourable propagation $\frac{1}{M} \hat{g}_k^H \hat{g}_i \to 0$, for $M \to \infty, k = 1, .. k$ & $k \neq i$. Thus, when M is very large the approximations are given as $\frac{1}{M}\|\hat{g}_k\|^2 \approx \gamma_k$ & $\frac{1}{M} \hat{g}_k^H \hat{g}_i \approx 0$. Therefore, in the capacity lower bound expression, when g is constant deterministic channel, the deterministic channel coefficient is $g(\Omega = \{g\})$ which is expected value of g given Ω is g, $E\{g|\Omega\} = g$. Therefore, as the channel is known, expectation is not anymore required and $Var\{g|\Omega\} = 0$ as when g is known $\Omega = \{g\}$ (6).

$$C \geq E\left\{\log_2\left(1 + \frac{\rho |E\{g|\Omega\}|^2}{\rho Var\{g|\Omega\} + Var\{W|\Omega\}}\right)\right\} = \log_2\left(1 + \frac{\rho |g|^2}{Var\{w\}}\right) \quad (6)$$

5.7.3. UAV uplink capacity lower bound

The uplink received signal by base station is:

$$y = \sum_{k=1}^{k} g_k \sqrt{\rho_{ul}\eta_k}\, q_k + w = \sum_{k=1}^{k} \hat{g}_k \sqrt{\rho_{ul}\eta_k}\, q_k - \sum_{k=1}^{k} \tilde{g}_k \sqrt{\rho_{ul}\eta_k}\, q_k + w,$$

Here, the sum of all transmitted signals by all the UAVs is denoted by summation, true channel is g_k, data signal is q_k, channel estimate is $\sum_{k=1}^{k} \hat{g}_k \sqrt{\rho_{ul}\eta_k}\, q_k$ and estimation error is $\sum_{k=1}^{k} \tilde{g}_k \sqrt{\rho_{ul}\eta_k}\, q_k + w$, which is unusable part as noise, estimation error and data signal is not known, hence is shown by w'. For the combining or detector vector, assign a_i receive filter for UAV i, $a_i^H y = a_i^H \hat{g}_i \sqrt{\rho_{ul}\eta_i} q_i + \sum_{k=1,k\neq i}^{k} a_i^H \hat{g}_k \sqrt{\rho_{ul}\eta_k}\, q_k + a_i^H w'$, where, $a_i^H \hat{g}_i \sqrt{\rho_{ul}\eta_i} q_i$ is through which the information is extracted and is treated as desired part for k=i. and $\sum_{k=1,k\neq i}^{k} a_i^H \hat{g}_k \sqrt{\rho_{ul}\eta_k}\, q_k$ is considered as the interference from all UAVs except from k=i. For ensuring desired part as large, incorporate $\hat{g}_i \sim CN(0, \gamma_k I_M)$, which value of a_i maximizes the ratio $\frac{|a_i^H \hat{g}_i|}{\|a_i\|}$. Utilize the equality of $a_i = c\hat{g}_i$ for some constant $c \neq 0$, in Cauchy Schwartz Inequality $\frac{|a_i^H \hat{g}_i|}{\|a_i\|} \leq \frac{\|a_i\|\|\hat{g}_i\|}{\|a_i\|} = \|\hat{g}_i\|$, which emphasize that largest value is obtained on multiplication of two parallel complex vectors i.e $a_i = c\hat{g}_i$. Thus, by selecting receiver filter equalling channel estimate $\hat{g}_i$ of same user multiplied with non zero constant, desired part of the received signal is made as large as possible called Maximum Ratio (MR) processing. Thus, MR processing of $a_i = c\hat{g}_i$ is similar to maximum ratio combining in point-to-point MIMO for $c = 1/\|\hat{g}_i\|$. Substituting $a_i = \frac{1}{M}\hat{g}_i$ for MR processing, we get:

$$a_i^H y = \frac{g_i^H \hat{g}_i}{M} \sqrt{\rho_{ul}\eta_i} q_i + \sum_{k=1,k\neq i}^{k} \frac{g_i^H \hat{g}_k}{M} \sqrt{\rho_{ul}\eta_k}\, q_k + \frac{g_i^H}{M} w'$$

where $\frac{g_i^H \hat{g}_i}{M} \approx \gamma_k$ because of channel hardening, $\frac{g_i^H \hat{g}_k}{M} \approx 0$ because of favourable propagation and $\frac{g_i^H}{M} w' \approx 0$. Thus, with increase in number of antennas, interference and noise terms become very small and after MR processing desired signal term approximate to a deterministic number q_i, even if there is a fading channel. Receive filter $a_i = \frac{1}{M}\hat{g}_i$ is computed using channel estimate and it is observed that the term $\frac{g_i^H \hat{g}_i}{M}$ is deterministic. Now, channel estimate is no more required to be remembered. Therefore,

$$a_i^H y = \gamma_i \sqrt{\rho_{ul}\eta_i} q_i + \left(\frac{g_i^H \hat{g}_i}{M} - \gamma_i\right) \sqrt{\rho_{ul}\eta_i} q_i + \sum_{k=1,k\neq i}^{k} \frac{g_i^H \hat{g}_k}{M} \sqrt{\rho_{ul}\eta_k}\, q_k + \frac{g_i^H}{M} w'$$

where, desired part with deterministic channel is first term $\gamma_i \sqrt{\rho_{ul}\eta_i} q_i$ and balance terms being interference and noise w. With this deterministic channel having, transmit power $\rho = \rho_{ul}\eta_i$, desired signal $x = q_i$ and known channel coefficient $g = \gamma_i$, the capacity bound is given as $C \geq \log_2\left(1 + \frac{\rho|g|^2}{Var\{w\}}\right)$, where $\rho|g|^2 = \rho_{ul}\eta_i\gamma_i^2$ and $Var\{w\} = \frac{\gamma_i}{M}\left(\sum_{k=1}^{k} \rho_{ul}\eta_k\beta_k + 1\right)$. Thus, by using MR processing and forgetting the channel estimate, capacity lower bound is given as (7).

$$C \geq \log_2\left(1 + \frac{M\rho_{ul}\eta_i\gamma_i}{\sum_{k=1}^{k} \rho_{ul}\eta_k\beta_k + 1}\right) \tag{7}$$

As there no other expression in the equation which is required to be computed, this becomes a closed form expression. By increasing antennas, estimation equality γ_i and power $\rho_{ul}\eta_i$, the coherent beam gain grows. The terms in the denominator include summation of non coherent interference signals from all the UAVs plus the noise variance 1. The interference term $\sum_{k=1}^{k} \rho_{ul}\eta_k\beta_k$ has sum of all the UAVs with their respective transmission power $\rho_{ul}\eta_k$and channel variance β_k. It is concluded that by increasing the number of base station antennas for receiving the signals in the uplink, the desired signals are amplified. At the same time, the interference is not amplified.

6. NUMERICAL RESULTS AND KEY INSIGHTS

The effects of increasing number of antennas at cellular base stations on UAV communication links can be demonstrated through a numerical setup of a cellular base station having capability to have communication links with UAVs. An antenna dependent relationship of performance metric has enabled formulation of results with such numerical set up. The experimental set up comprises of a single cell having standard dimensions with only single base station. As per the selection of different antenna techniques, we can mount as much antennas on the base station. The parameters as well as values being considered in numerical setup are shown in Table 2.

Table 2. Set up parameters

Parameters	Values
Cell numbers	Single
Base stations	1
Antennas mounted on base station	M
UAVs in each cell (K)	2
Channel gain (β)	-100 dB
Noise variance (N_o)	-80 dBm
Transmit power Uplink	20 dBm
Pilot sequences Length (τ_P)	10
Variance of the true channel (β_i)	10 dB
Power control coefficient (η_i)	1

6.1. Performance of UAV communication links based on number of antennas

In order to carry out performance analysis, the multiple antenna techniques considered are SIMO with single antenna, point to point MIMO with two antennas, MU-MIMO with eight antennas and massive MIMO with 100 antennas. The comparison of channel capacities of UAV communication links utilizing different antenna techniques has been carried out. As shown in Figure 11, it is found that by using up to eight antennas on cellular base station, maximum channel capacity achieved is only 46 Mbps. But by increasing antennas to 100, the channel capacity achieved is 971 Mbps. This enhanced performance of communication link is directly dependent on increase in number of antennas. Massive MIMO technology utilizes Beamforming gain, Spatial multiplexing and Spatial diversity to the maximum and is most suitable for UAV communication links. The same is brought out while deriving capacity lower bound expression for uplink of UAV communication, wherein channel capacity is found to be directly proportional to number of antennas at base station.

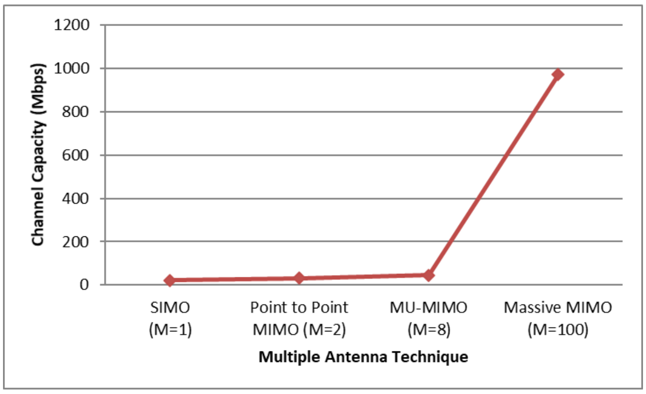

Figure 11. Result of comparison of performance of UAV communication links of different antenna techniques based on number of antennas

6.2. Performance of massive MIMO enabled UAV communication link by increasing number of antennas

Figure 12 depicts the effect of increasing antennas on massive MIMO enabled UAV communication links. It is found that channel capacity of maximum 971 Mbps is achieved with the use of up to 100 antennas at cellular base station. However, with the use of up to 10000 antennas, channel capacity of 98284 Mbps is achieved. However, there are two factors that restrict the usage of such large number of antennas on the base station. First is the limit to the capability to instal large number antennas on the base station. And second is the high cost of designing and installing large number of antennas on the base station. These two factors are the delimiting factors in installing large number of antennas i.e up to ten thousand antennas, which further limits the channel capacity. However, installation of hundreds of antennas array is a standard in massive

MIMO technology, which is practical as well as cost effective and it cater for sufficient channel capacities for future employment of UAVs.

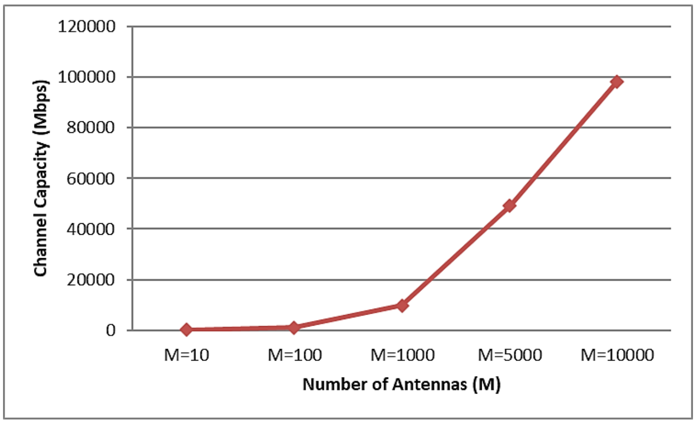

Figure 12. Results of comparison of performance of Massive MIMO enabled UAV communication links based on increase in number of antennas at cellular base stations

6.3. Performance of UAV communication links of various antenna techniques based on change in uplink transmit power

As shown in Figure 13, effect of change in uplink transmit power on performance of UAV communication links using various antenna techniques have been examined. The results prove that channel capacity of maximum 106 Mbps is achieved with the use of up to eight antennas at cellular base station with maximum UAV transmit power of 50 dBm. However, with the use of up to 100 antennas, channel capacity of 1939 Mbps is achieved.

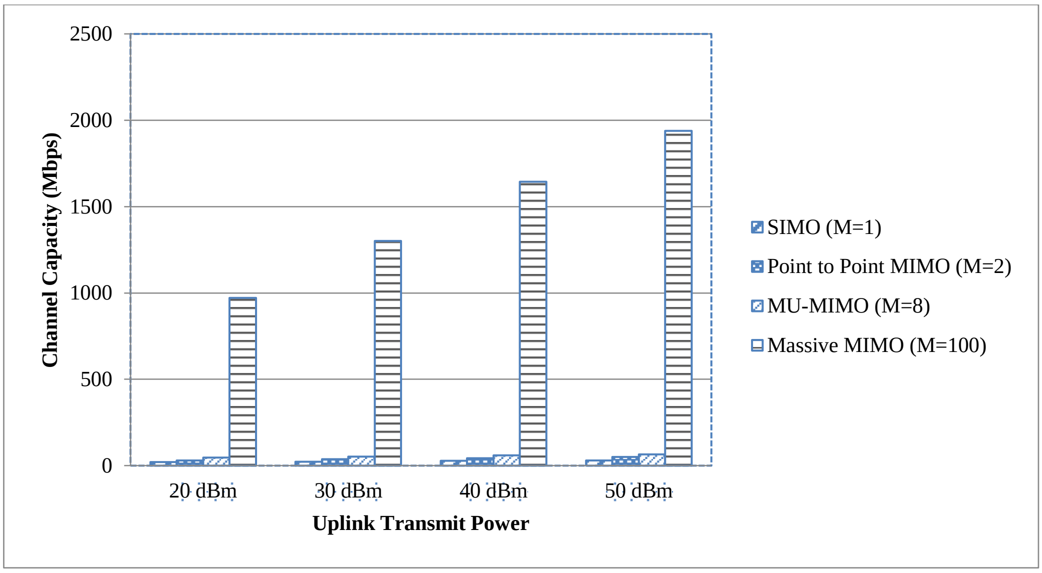

Figure 13. Results of comparison of performance of UAV communication links of different antenna techniques based on transmit power of UAV

7. CONCLUSION

With the enhanced applications of UAVs in all fields, the demand of UAVs is also increasing. Futuristic applications of UAVs envisage reliable communication links of UAVs with their control stations. Enhanced data rate of communication links is considered as most important factor for their futuristic employments. This research paper has brought out the possibility of integrating UAVs with the existing and already established cellular networks, by means of increasing the antennas at the cellular base stations using various multiple antenna techniques. Latest technologies such as massive MIMO enables mounting of hundreds of antennas on the base stations. It is validated that by using up to eight antennas on cellular base station, maximum channel capacity achieved by UAV communication link is only 46 Mbps. But with the increase in number of antennas to 100, the channel capacity of UAV communication link also increases to 971 Mbps. With the use of such technologies the performance of UAVs communication links can be increased manifold, which will generate tremendous opportunities for their futuristic usage.

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