ANALYSIS OF SPECTRUM SHARING FOR UNMANNED AERIAL SYSTEMS

Jaber Kakar (jaberk@vt.edu)[1], Vuk Marojevic (maroje@vt.edu)[1], and Jeffrey H. Reed (reedjh@vt.edu)[1]

[1]Bradley Dept. of Electrical and Computer Engineering, Virginia Tech, Blacksburg, Virginia

ABSTRACT

The expected growth of the unmanned aerial vehicle (UAV) industry brings along new challenges and spectrum management is one of them. The application domains include agriculture, exploration, transportation, and entertainment. Whereas UAV flight operation control signalling requires low throughput, and spectrum will likely be allocated for this purpose, the data rates for transmitting the information content that the UAV sensors gather can be significant and will grow with technology advancements. Hence, a third dimension to the terrestrial spectrum sharing approaches needs to be added and different scenarios are discussed in this paper. Based on our UAV growth prediction models and interference analysis, we conclude that dynamic spectrum management is feasible and necessary along with advances in communications technology. Fundamental and practical research is needed to ensure a natural evolution of communications systems in line with the deployment of commercial UAVs. Low range and low altitude small and micro UAVs will most likely dominate the airspace and are the target of our analysis.

1. INTRODUCTION

In military, unmanned aerial systems (UAS) already outnumber traditional manned aircraft systems. The physical aircraft is referred to as unmanned aerial vehicle (UAV) or, simply, unmanned aircraft (UA). UAVs tend to be small and light. UAV technology is already fairly well-developed and development as well as maintenance costs are significantly lower than that of traditional manned aircraft systems [1]. Not only are UAVs cost-effective, but the applications for government and commercial purposes are versatile: transportation, communications infrastructure, humanitarian and public safety deployments, among others [2]. For instance, as part of Google Project Loon, high altitude and large-scale UAV eNode-Bs were proposed as alternatives for terrestrial eNode-Bs [3].

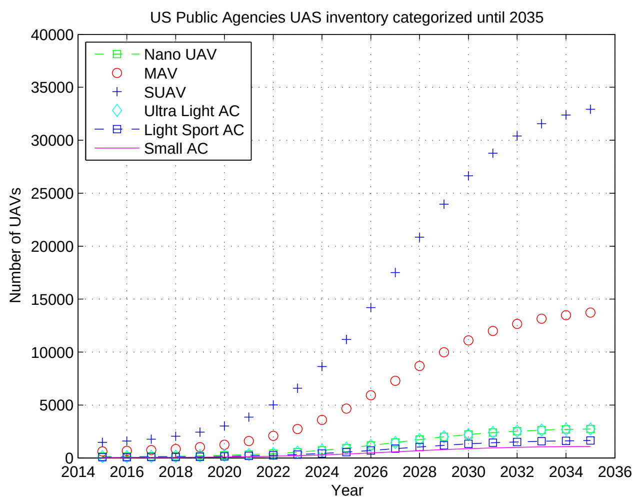
Small and micro UAVs (SUAV/MAV) are low-altitude UA alternatives for dense urban scenarios and can be used for mobile relaying, for instance. Recognizing the potential of SUAV, several companies, including GoogleX and Amazon Prime Air, have formed the small UAV coalition [4]. AeroVironment, for example, is examining the applicability of SUAVs to quickly re-establish critical communications infrastructure after a natural or man-made disaster [5]. Recent predictions, conducted by the US National Transportation Center, reveal that the number of UAVs for commercial purposes will outnumber UAVs owned by DoD by a factor of 10 or more by 2035. SUAVs and MAVs of less then 10 feet and under 55 pounds will likely dominate the airspace. The radio communications links of SUAVs and MAVs will mostly be line of sight (LoS) for typical deployments because of their limited range.

The goal is to safely integrate these types of UAVs into the existing airspace, in particular Class E and G of controlled and uncontrolled airspace [6]. It is expected that the advances in UAS technology and benefits of UAS for commercial and other civilian operations will bring along new challenges: safety of operation and real-time exchange of throughput-intensive data that is captured by the UAV sensors. Both challenges reduce to the fundamental problem in wireless communications: spectrum management. UAV spectrum in the 1755 MHz band is considered for relocation in the US and worldwide spectrum allocation for future UASs will be discussed in the upcoming World Radiocommunications Conference (WRC) in 2015. The exchange of rich content data or streaming high-definition video, for example, requires a significant amount of spectrum, proportional to the desired throughput and quality. When the air becomes more congested, more bandwidth will be needed to accommodate the desired communication needs.

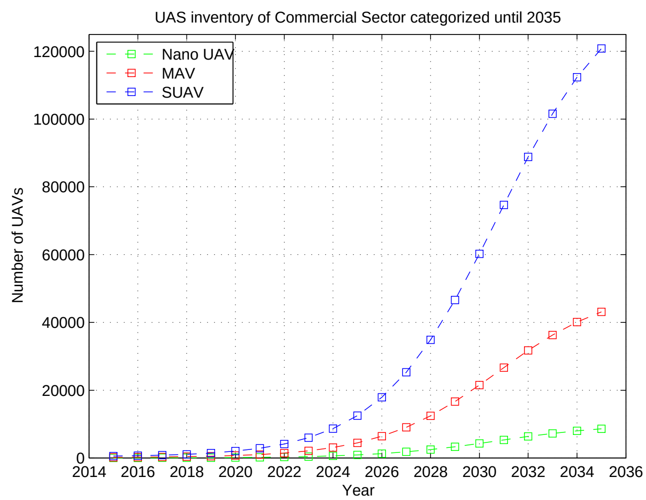
Bandwidth calculations done by the ITU are rather pessimistic because they only account for time-sparse video data exchange for S&A (sense and avoid) applications in environments with relatively low UAV densities. We believe that future air-to-ground (ATG) links will be throughput-intensive and enough dedicated spectrum will not be available. New ways of spectrum management thus need to be considered. Spectrum sharing is an efficient concept to satisfy bandwidth demand in an opportunistic way, when and where needed. Future spectrum sharing might occur between UAS and terrestrial communications systems, such as 4G cellular.

Little research on UAS spectrum sharing has been published. In reference [7, 8], the authors suggest the deployment of a policy-based cognitive radio for UAV spectrum sharing. Furthermore, [7] talks about adaptation of policy-based radios. In [9], Dynamic Spectrum Access (DSA) is proposed as solution to address the problem of (static) UAS spectrum scarcity in military scenarios. The paper identifies system benefits of using the DSA approach over a static frequency allocation.

This paper will analyze to what extent spectrum sharing is



(a) Projection of public agency UAV quantities (without DoD).



(b) Projection of commercial UAV quantities.

Figure 1: Projection of UAV numbers.

needed and how it can be effectively applied in the context of UASs. Without loss of generality, our analysis focuses on direct ATG LoS links. First we develop new predictive models for the growth of the UAS sector to estimate the bandwidth requirements (Section 2). Then we analyze to what extent UAV to ground control station (GCS) communications would interfere with existing ground communications networks and vice versa (Section 3). This interference analysis will be the main reference here for discussing the viability of spectrum sharing. We discuss three spectrum sharing scenarios (Section 4) and conclude that different spectrum sharing opportunities exist and will be the topic of research along with spectrally-efficient waveforms (Section 5).

2. PROJECTION OF UAS GROWTH AND SPECTRUM REQUIREMENTS

Predicting the numbers of UAVs is an important step to determine spectrum requirements. A UAS consist of a ground control station (GCS) and one or several UAVs. To address the spectrum requirements for control and non-payload communications (CNPC), ITU and NASA have conducted projections on the evolution of UAVs [2, 10]. We believe that the figures are rather conservative (cf. [11]) and use [11, 12] to quantify the national UAV-type specific numbers from 2015 until 2035. We classify UAVs based on Table 8 of [11] into Nano UAVs, Micro UAVs (MAV), Small UAVs, Ultralight Aircrafts (AC), Light Sport Aircrafts, Small Aircrafts and Medium Aircrafts. The aforementioned reference predicts future demand of UAVs for DoD, public safety and the commercial sectors. Reference [11] suggests an s-curve shaped functional relationship for characterizing the number of UAVs between 2015 and 2035 for the commercial and public sectors. Hence, we estimate the number of UAV between 2015 and 2035 by

$$f(x) = p_1 + \frac{(p_2 - p_1)}{1 + 10^{p_4(p_3 - x)}}, \qquad (1)$$

where $x = t_{year} - 2015$. The curve fitting results for commercial UASs and total public agencies (including DoD) are shown in Table 1.

Table 1: Modeling parameters for (1) based on [11] (2 digit precision)

	p_1	p_2	p_3	p_4
Commmercial	487.95	$2.03 \cdot 10^5$	15.75	0.18
Federal Agencies	207.22	$1.02 \cdot 10^4$	9.73	0.18
State and Local Agencies	$1.87 \cdot 10^3$	$4.64 \cdot 10^4$	12.49	0.19

We can differentiate among different types of UAVs. Figure 1 shows the evolution of UAV numbers per type distinguishing between public agency owned (1a) and commercial UAVs (1b). The subfigures show that the commercial UAVs will outnumber public agency UAVs. (The DoD expects a linear increase of their UAV fleets, which will be outnumbered by commercial UAVs within the next 10 years.) We use the total numbers for each type (including estimates for DoD-owned UAVs) to determine the probability mass function (pmf) of UAV types. The time-dependent pmf for 2015-2035 can be seen in Figure 2. It shows that SUAVs and MAVs are expected to dominate the UAV market. Because of their low cost, around 22% and 67% will be of type MAV and SUAV by 2035. This results in higher airspace densities for *controlled* airspace of Class E and uncontrolled airspace of Class G, where they will likely operate.

To estimate the bandwidth requirement for CNPC in 2030, we use ITU's methodology 1, which was proposed in [2]. Table 2 of [2] specifies the data rate requirements in bps for command & control, air traffic control (ATC) relay, S&A (including

Table 2: Estimation of average UAV densities in 2030.

			UAV		
			Small	Medium	Large
Effective Number of UAVs in operation by 2030			7,229	8,919	760
UAV Density [UAV/10000km^2]	Low Altitude	$<$ 1500 m	7.33	–	–
	Medium Altitude	$>$ 1500 m and $<$ 6000 m	–	9.05	–
	High Altitude	$>$ 6000 m	–	–	0.77

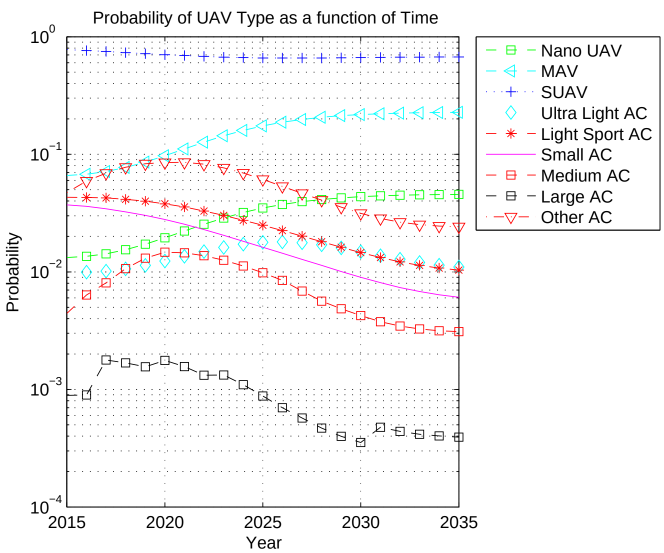


Figure 2: Probability mass function of UAV types over time.

video and weather radar data) based on the current altitudes of the UAVs. Command & control links include navigational information and telecommands in the uplink and telemetry and navigational display data in the downlink. In the presence of ATC, i.e. in controlled airspace classes A, B, C, D and E, information between GCS and ATC can be relayed through the UAV. S&A data mainly consists of target tracking (3D position, velocity, timestamp, etc.), weather radar and non-payload video data for temporary awareness of the environment.

We use the estimates for commercial and public agency UAVs for 2030 due to Figure 1a and 1b to determine the CNPC bandwidth requirements for LoS communication. We assume that around 88% of commercial UAVs in Figure 1b belong to the agricultural sector [11]. This percentage is not considered for CNPC bandwidth computation. Furthermore, we assume that about 15% of all public UAVs will be used on regular basis. Using the probability of Figure 2 and the typical altitude of operation of small, medium and large UAV, we can calculate the altitude-specific UAV densities (using the US total area of around 9.8 Mio. km^2) based on [2]. The results are shown in Table 2. Note that small, medium and large in Table 2 is used to classify the altitude of operation and should not be confused with the UAV type definitions. For further details see Table 33 of [2]. The UAV densities we have computed differ from ITU's results by a factor of approximately 1.2 for the small and large cases and by a factor of 5.8 for the medium case.

The determined densities are used to compute the number of UAVs per cell. ITU defines cell types A, B, C and D (see pp. 64–65 in [2]) for terrestrial communication to accommodate UAVs with different operational altitudes. Using the exact same link and cell configurations as [2], our CNPC bandwidth estimates are 69.5 MHz for a terrestrial communications infrastructure with video and weather radar data and 39.5 MHz without video and weather radar data. For comparison, ITU's values are 33.9 and 15.9 MHz, respectively. It is interesting to mention that [2] considers a spectral efficiency of 0.75 bps/Hz for all CNPC links.

In order to cover the CNPC bandwidth requirement (including video and weather radar data) according to our estimates with the designated bandwidth of 34 MHz *only*, the spectral efficiency needs to improve to about 1.53 bps/Hz. The CNPC links are not supposed to carry throughput-intensive videos of 1-2 Mbps [13] and neither would the designated 34 MHz be sufficient to consider video data transmission. As a result we conclude that future UAS communications systems need to be more spectrally efficient. In addition, a more effective spectrum management is needed to enable real-time video streaming, among others, from UAVs to GCSs.

3. UAV-TO-GROUND COMMUNICATIONS CHANNEL AND INTERFERENCE MODEL

Feng et al. [14] determine probabilities for LoS, obstructed LoS (OLoS) and non-LoS (NLoS) as a function of the UAV transmit elevation angle θ. All three links are short-range links, where LoS has a strong direct path component, OLoS has an attenuated direct path component, and NLoS contains dominant reflected paths. The authors conclude that path-loss and shadowing also depend on θ (see Figure 3). Their finding are based on a large-scale measurement campaign for frequencies from 200 MHz up to 5 GHz in a central region of Bristol, UK.

References [15, 16] use experimental results from [14] to provide LoS/NLoS probabilities $p(\epsilon|\theta)$ ($\epsilon = \{\text{LoS}, \text{NLoS}\}$) characterizing UAV-to-ground propagation as a function of the elevation angle θ ranging from 0 to 90°. These two sources do not account for foliage attenuation by OLoS propagation. For a particular angle θ_0, we know that $p(\epsilon = \text{NLoS}|\theta = \theta_0) = 1 - p(\epsilon = \text{LoS}|\theta = \theta_0)$. The equation that Al-Hourani et al. [15] provide

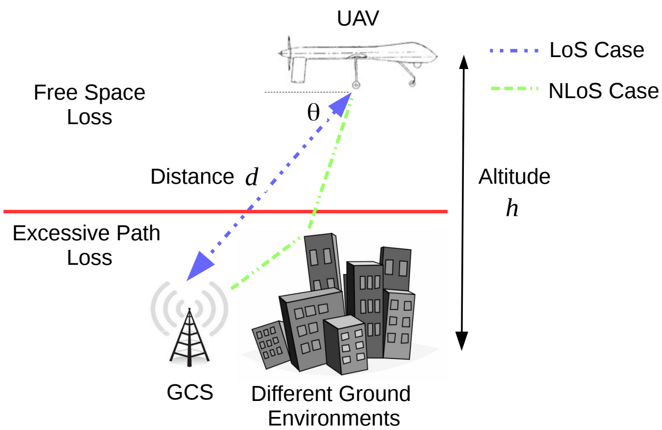


Figure 3: Air-to-ground signal propagation.

is

$$p(\epsilon = \text{LoS}|\theta) = \frac{1}{1 + ae^{-b(\theta - a)}}, \quad (2)$$

where the coefficients a and b differ for different ground environments. The authors determine a functional relationship between a, b and statistical ground environment parameters α, β and γ (see also [17]). Intuitively, it is obvious that having a LoS component for small θ is very unlikely. For that reason $p(\text{LoS}|\theta)$ is monotonously increasing. The general rule is that ground environments with a high density of building and high variability of building heights make LoS propagation less likely. For instance, for $\theta_0 = 40°$, $p(\text{LoS}|\theta_0)$ corresponds to approximately 100% for suburban and 20% for urban high-rise environments.

The path loss PL_ϵ is given by the sum of a free-space path loss (FSPL) model and an excessive path loss component χ_ϵ (cf. Figure 3) [16], i.e.

$$PL_\epsilon = \underbrace{20log_{10}(d) + 20log_{10}(f_c) + 20log_{10}\left(\frac{4\pi}{c_0}\right)}_{PL_{\text{FSPL}}} + \chi_\epsilon, \quad (3)$$

where $\chi_\epsilon = \mathcal{N}\big(\mu_\epsilon(\theta), \sigma_\epsilon(\theta)\big)$. Holis et al. [16] specify $\mu_\epsilon(\theta)$ and $\sigma_\epsilon(\theta)$. It is intuitive that the effect of shadowing gains more weight for lower LoS $p(\text{LoS}|\theta)$ probabilities and higher carrier frequencies f_c. Hence, $\mu_\epsilon(\theta)$ and $\sigma_\epsilon(\theta)$ are decreasing functions in θ. As an example, a vertically-polarized 5.5 GHz carrier has a mean of $\mu_\epsilon(\theta_0)$ =11 (7) dB and a standard deviation of $\sigma_\epsilon(\theta_0)$ =32 (15) dB for θ_0 =10° (85°).

The received power at the j-th GCS from the i-th UAV for both LoS and NLoS is based on the simple link-budget equation

$$P_{RX,j} = P_{TX,i} + G_{TX}(\theta_i, \phi_i) + G_{RX}(\theta_j, \phi_j) - PL_\epsilon. \quad (4)$$

This equation is also applicable for UAV-to-UAV links, where $\chi_\epsilon \equiv 0$. The ITU-R M.2238 report [18] proposes an antenna gain pattern for small unmanned aircrafts of $G_{TX}(\theta, \phi) \equiv G_{TX}(\theta)$ and the corresponding GCS (omnidirectional in azimuth) antenna pattern as a function of the off-axis angle. Table 7 in [18] indicates that the main relative 3dB antenna gain is between $-50°$ and $7.5°$. A negative angle here means that the transmissions points in upward direction. The maximum UAV antenna gain at $\theta_{max} = -10°$ equals 3 dBi.

Based on (4), it is possible to determine the interference power level at the ground (caused by UAVs) for a pre-defined elevation angle range $[\theta_1, \theta_2]$. This power level would be of importance for spectrum sharing scenario 3, which is introduced in the next section.

4. SPECTRUM SHARING ANALYSIS AND SCENARIOS

UAV missions can be either of individual or cooperative nature. Routes are either pre-planned (point-to-point or aerial-based) or unplanned [2]. Reference [19] suggests using an adaptive channel assignment approach that maximizes the overall throughput for cooperative UAVs in a master-slave topology. Due to spectrum scarcity, UAVs with throughput intensive (TI) communications demands (TI-UAVs) may need to access spectrum allocated to CNPC on secondary basis. We distinguish between spectrum sharing for individually and cooperatively operating UAVs (cf. Figure 4 and 5).

We discuss three spectrum sharing scenarios: The first case considers using CNPC spectrum that is availably form higher-tier UAVs, i.e. UAVs operating at higher altitudes than TI-UAVs. In the second case, spectrum sharing happens at the same tier or altitude either between individually operating or cooperatively operating UAVs. In the third case, unused spectrum from terrestrial communications systems can be opportunistically used for the UAV downlink.

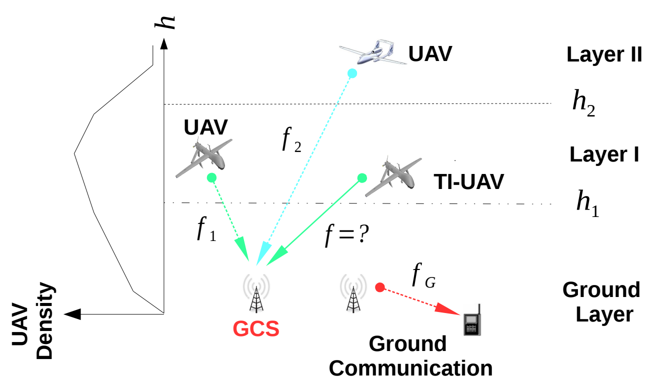


Figure 4: Spectrum sharing use case for individual UAV missions.

The spectrum access system for the first scenario needs to be highly *reliable* since CNPC information is of highest importance for operational safety and must not be interfered with. This means that the location of the UAV in Layer II needs to be known by TI-UAVs. To avoid interference, we suggest getting information about neighborhood from a database. The obtained location information can be supported through spectrum sens-

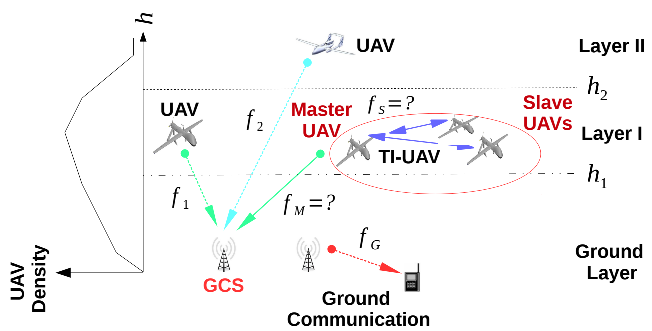


Figure 5: Spectrum sharing use case for cooperative UAV missions.

ing. In this case, if a spectrum hole exists or the higher layer UAV is far away, the individual TI-UAV or the master TI-UAV would use channel f_2 of the higher layer UAV. If the UAV of the higher layer is in the phase of take-off or landing, spectrum sharing should not be encouraged. Hence, defining UAS-specific airspace classes can support spectrum sharing. Although the CNPC has limited resources (35-54 MHz [2]), it is still attractive because being within the UAS management domain.

The second scenario builds around the concept of frequency reuse. It might also be possible to reuse channel f_1 for direct master-slave (or slave-master) communications. By adjusting the power levels, the interference levels among distant UAVs or UAV groups can be limited. If the UAV fleet can operate truly autonomously, information caching and time-multiplexed spectrum sharing can be applied for the different UAV-to-GCS links in a given area.

The third spectrum sharing scenario makes use of the high NLoS probability and the augmented shadowing effect for low elevation angles. Channels with frequencies f_G can for instance be reused for master-slave or slave-master links if cooperative UAVs are located at similar altitudes leading to low elevation angles. In this case, the antenna pattern has to be narrow around $\theta = 0°$ and the deployed power low enough to avoid interference with terrestrial communications systems. A database is needed to inform about channel usage. This database needs to be frequently updated and accessible to the GCSs, which would signal the available frequency and transmission time slot to the UAV.

Except of scenario 3, all other scenarios consider reusing designated CNPC spectrum. In scenario 3, ground communications frequencies are carefully reused by UASs.

We believe that spectrum sharing based on sensing is not suitable for the UAS context. Rather, sensing can support DSA. Knowledge about neighboring UAVs (location, pre-determined route, phase of flight, etc.) needs to be available to make accurate decisions about opportunistic spectrum access. If we go one step further, we may plan missions based on a-priori knowledge of spectrum availability. In other words, we suggest specifying the spectral requirements, when possible, and making reservations along with the flight route planning.

5. CONCLUSION

This paper has provided new predictive figures for the evolution of UAVs as a basis for deriving future bandwidth demands. In contrast to ITU's predictions, we believe that more spectrum and more spectrally-efficient resource use and management are needed for accommodating CNPC and throughput intensive data links. That is, to overcome the problem of spectral scarcity, we identify two lines of research: (1) development of spectrally efficient and agile UAV waveforms and (2) more effective spectrum management based on spectrum sharing principles.

Based on the presented interference analysis, we have introduced three spectrum sharing scenarios. These scenarios are mutually exclusive and can be applied together. Further research is needed to quantify the gain in spectrum occupation for each scenario. The interference analysis also needs to be refined to develop multiple levels of spectrum sharing. We need to collect spectrum occupation statistics for the bands that are considered for sharing and quantify the UAV densities for spectrally congested urban areas.

REFERENCES

[1] R. Austin, *Unmanned Aircraft Systems: UAVs Design, Development and Deployment*. Wiley, May 2010.

[2] ITU, "Characteristics of unmanned aircraft systems and spectrum requirements to support their safe operation in non-segregated airspace," International Telecommunication Union, Tech. Rep. M.2171, December 2009.

[3] S. Colaner, "Google's Project Loon Reaches New Heights," http://www.tomshardware.com/news/google-project-loon-balloons-data,28176.html, accessed: 2015-12-05.

[4] L. Geiver, "GoogleX, GoPro, Amazon Prime Air join new sUAV Coalition," http://www.uasmagazine.com/articles/865/googlex-gopro-amazon-prime-air-join-new-suav-coalition, accessed: 2015-12-03.

[5] "AeroVironment to Deploy Small UAS for Federal Communications Commission Post-Disaster Communications Demonstration," http://www.unmannedsystemstechnology.com/2012/05/aerovironment-to-deploy-small-uas-for-federal-communications-commission-post-disaster-communications-demonstration/, accessed: 2015-12-03.

[6] Airspace. [Online]. Available: http://www.faa.gov/regulations_policies/handbooks_manuals/aviation/pilot_handbook/media/PHAK-Chapter14.pdf

[7] T. Brown and S. Jaroonvanichkul, "Policy-based radios for UAS operations," in *Globecom Workshops (GC Wkshps), 2012 IEEE*, Dec 2012, pp. 1614–1619.

[8] T. Brown and D. C. Sicker, "Secure Distribution of Spectrum Policies to Cognitive Radios in Unmanned Aircraft Systems," in *AIAA Infotech@Aerospace 2010*, April 2010.

[9] M. McHenry, Y. Zhao, and O. Haddadin, "Dynamic Spectrum Access radio performance for UAS ISR missions," in *MILITARY COMMUNICATIONS CONFERENCE, 2010 - MILCOM 2010*, Oct 2010, pp. 2345–2350.

[10] S. Henriksen, "Unmanned Aircraft System Control and ATC Communications Bandwidth Requirements," NASA, Tech. Rep. 2008-214841, February 2008.

[11] John A. Volpe National Transportation Systems Center, "Unmanned Aircraft System (UAS) Service Demand 2015 - 2035," U.S. Department of Transportation, Tech. Rep. DOT-VNTSC-DoD-13-01, September 2013.

[12] "Department of Defense Report to Congress on Future Unmanned Aircraft Systems Training, Operations, and Sustainability," April 2012.

[13] Video Compression Guidelines. [Online]. Available: http://vimeo.com/help/compression

[14] Q. Feng, J. McGeehan, E. Tameh, and A. Nix, "Path loss models for air-to-ground radio channels in urban environments," in *Vehicular Technology Conference, 2006. VTC 2006-Spring. IEEE 63rd*, vol. 6, May 2006, pp. 2901–2905.

[15] A. Al-Hourani, S. Kandeepan, and S. Lardner, "Optimal LAP Altitude for Maximum Coverage," *Wireless Communications Letters, IEEE*, vol. PP, no. 99, pp. 1–1, 2014.

[16] J. Holis and P. Pechac, "Elevation Dependent Shadowing Model for Mobile Communications via High Altitude Platforms in Built-Up Areas," *Antennas and Propagation, IEEE Transactions on*, vol. 56, no. 4, pp. 1078–1084, April 2008.

[17] ITU, "Propagation data and prediction methods required for the design of terrestrial broadband radio access systems operating in a frequency range from 3 to 60 GHz," International Telecommunication Union, Tech. Rep. P.1410, February 2012.

[18] ——, "Compatibility study to support line of sight control and non-payload communications links for unmanned aircraft systems proposed in the frequency band 5091-5120 MHz," International Telecommunication Union, Tech. Rep. M.2238, November 2011.

[19] I. Abualhaol and M. M. Matalgah, "Throughput optimization of cooperative uavs using adaptive channel assignment," in *Wireless Communications and Networking Conference, 2006. WCNC 2006. IEEE*, vol. 4, April 2006, pp. 2279–2284.