Proposal for Allocation of 2.4 GHz and 5.8 GHz bands to Small Satellites in LEO

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Abstract - Small satellites have been growing in popularity over recent years and more than 1200 are in LEO. The corporate sector plans for further growth in constellation sizes and due to their relative low cost and complexity, operators are now able to deploy and operate in space more readily than ever. These operators are providing cheap planetary imaging, accurate weather forecasting, atmospheric analysis, search and rescue functions and public research platforms to name a few. The current frequency allocations used by small satellites are heavily populated resulting in limited bandwidth and as such, research into additional allocations is agenda item 1.7 at the World Radio Conference in 2019. We propose the authorised use of the 2.4/5.8GHz amateur and/or ISM bands for all LEO small satellite users providing them with the desired data rates for current and emerging technologies. This paper conducts research into the compatibility of these bands while exploring interference mitigation techniques to protect incumbent services such as highly directional ground station antennas and null steering. We detail a model predicting the probability of two satellites residing in the same ground station beam area and hence, potential for interference. We show this probability to be as high as 1.5% at 10° Latitude and 3.97% at 67° Latitude. A link budget confirms the viability of these bands and data rates based on current technology. We use the AD9361 SDR (which will be used in a UNSW CubeSat in 2018) as a test transceiver and attain data rates of 56Mb/s at 2.41GHz. Finally, a simple null steering technique is explored where complete spatial isolation is achieved and an interfering source of identical power and frequency is removed from the received signal. This research supports the allocation the 2.4/5.8 GHz amateur and/or ISM bands to small satellites in LEO reducing or negating the requirement for other interference mitigation methods such as Frequency, Time or Code Division Multiple Access techniques.

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NOMENCLATURE
RCS = Radar Cross Section
LEO = Low Earth Orbit
ITU = International Telecommunications Union
WRC = World Radio Conference
ISM = Industry, Science, Medicine
VHF = Very High Frequency
UHF = Ultra High Frequency
API = Advance Publication Information
ACMA = Australian Communications and Media Authority
FCC = Federal Communications Commission
NTIA = National Telecommunications and Information Administration
FHSS = Frequency Hopping Spread Spectrum
DSSS = Direct Sequence Spread Spectrum
RNSS = Radionavigation-Satellite Service
TLE = Two Line Element
ISRO = Indian Space Research Organisation
AMSL = Above Mean Sea Level
SDR = Software Defined Radio
ISS = International Space Station
FEC = Forward Error Correction
EIRP = Equivalent Isotropic Radiated Power
QPSK = Quadrature Phase Shift Keying
SER = Symbol Error Ratio
BER = Bit Error Ratio

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I. INTRODUCTION

In 1999, a satellite revolution began when the CubeSat standard was developed [1]. Although small satellites are not a new idea, this standard allowed unprecedented access to space at a fraction of the cost. Since the standard was developed, the amount of CubeSat’s in LEO has grown to approximately 400 [2]. There are more than 800 additional small satellites with an RCS of less than 1m² providing various services globally. At present, small satellite communication frequencies are neither regulated nor allocated and have been “operating on an unprotected basis and subject to not causing harmful interference” [3]. For this reason, small satellite users including amateurs, academia and commercial entities operate almost entirely within the VHF and UHF ISM and amateur bands [3]. In response to this, the ITU has invited research into allocations of additional frequency bands for small satellite communications for the WRC in 2019 [4].

Small satellites are increasing in popularity amongst all sectors of society due to their low cost from conception to deployment and short development timeframes. Several operators such as Spire, Planet Labs and numerous universities have operational constellations in LEO providing a myriad of services. These services include cheap planetary imaging, accurate weather forecasting, atmospheric analysis, search and rescue functions, public research platforms and climate monitoring. The list of possibilities is exhaustive and as time and technologies advance, so do small satellite capabilities. As small satellite technology evolves and constellations expand, larger data rates will be required and as such, bandwidth will continue to be a valuable commodity [5].

The current frequencies used for the majority of small satellite communications and telemetry are within the VHF and UHF bands with some operators also utilising channels within the L, S, C and X bands [2]. In most cases, operators have been transmitting and receiving under an experimental classification or did not file notification to the ITU and are operating outside of regulations. It is important to note that as of 2014, only 43 of the 341 small satellites launched had reached notification status in filing for ITU API [5]. Many operators were either unaware of the regulations or were unable to resolve filing issues prior to launch due to inexperience. Due to the particular nature of the small satellite industry with inexperienced space operators, short development times, high volume launches and short orbital lives, it is easy to understand why regulations have been overlooked. Ignorance should not be seen as an excuse although the ITU should look to adopt procedures and guidelines that are appropriate for small satellites.

In assessing the VHF and UHF bands, the available bandwidth limits the capabilities of small satellites, especially considering the existing channelization within the available band. When assessing frequencies above 10 GHz, atmospheric attenuation more significantly degrades link budgets and transceivers become more complex and costly [6]. This is counterproductive for small satellites and for these reasons, operating in the 2.4 GHz and 5.8 GHz bands offers an attractive solution for the foreseeable future.

When considering current bands used by small satellites, the 2.4 GHz and 5.8 GHz bands provide great potential due to their bandwidths and data rates. Both bands experience negligible atmospheric attenuation, can be used with cheap commercial transceivers [6] and offer approximately 150 MHz and 200 MHZ of bandwidth respectively for Australia and 60 MHz and 275 MHz respectively for the USA [7] [8]. This is provided the entire allocation is used by each operating satellite rather than using forms of Frequency, Time and Code Division. Given a lack of coordination between satellites, one would assume that interference would be a problem. However, due to the small daily exposure windows for LEO satellites, the probability of any two satellites being above the horizon of a ground station and thus, able to cause interference, is very small. Additionally, interference can be mitigated with narrow ground antenna beamwidths (e.g. 2°), limiting elevation/mask angles and null steering techniques [9]. These methods avoid reduction in bandwidth, power loss and increased cost associated with the use of Frequency, Time and Code Division. They also avoid diminishing the potential for this advancing technology with unnecessary regulation.

II. THE CASE FOR SPATIAL REUSE

Interference is a key concern in communications and as such, regulation is employed to reduce this. The ITU conducts this regulation allocating frequency bands worldwide through organisations such as ACMA and USA’s FCC and NTIA. Regulation of frequency bands comes in the form of Frequency Division and user coordination may involve Time Division, Code Division, Polarisation Division or Space Division (herein called Spatial Reuse) [10]. Frequency Division is where a band is divided into channels that are then licenced to operators. This reduces the chance of interference although it comes at the cost of bandwidth. As an example, C-Band (3.7-4.2 GHz) is divided into 40 MHz channels with 2 MHz guard bands giving an effective bandwidth of 36 MHz per channel. Each channel accounts for 7% of the potential bandwidth producing limitations on data rates and hence, the type of data and technology that can be utilised within a satellite [11]. An outline of the available downlink frequencies for satellites in Australia can be seen in Table 1 with the maximum bandwidth (ignoring channelisation) giving a representation on the constraints this form of regulation places on satellite communication systems.

For large satellites where cost and physical size are not as limiting comparatively, bandwidth can be increased by using several transmitters in unison. To fully utilise C-Band downlink communications, large satellites may employ...
24 transmitters spaced by 20 MHz with every other transmitter using orthogonal polarisation to maintain the required 40 MHz channel spacing. This will give the satellite approximately 500 MHz of bandwidth ignoring guard bands. This comes at a significant cost and requires space for the transmitters and the energy to power them. This solution is not possible at this time for small satellites.

The forms of user coordination will be discussed here briefly. Time Division occurs where the entire frequency band is allocated to an operator for a period of time. Once this time expires, a guard time exists to prevent interference and then the next operator can transmit for their given time allocation [10]. Although each operator gets the use of the full bandwidth, the time division restricts how much data can be transmitted. As the user base becomes larger, these time divisions can become smaller which results in data transfer limitations. Code Division involves FHSS or DSSS. FHSS involves the operating transmitter jumping between channels within the band based on a pseudorandom code. Transmission will occur for a small period of time before jumping although this still means that the largest bandwidth that can be achieved is that of the channel. DSSS on the other hand uses the entire band to transmit a modulated pseudo noise sequence which can be decoded at the receiver [10]. Although DSSS uses the entire bandwidth, the power is spread across the band leading to low spectral densities. DSSS also requires complex transceiver systems to encode and decode the low power transmissions. Polarisation Division uses polarisation techniques to transmit signals orthogonal to other signals in the same channel. This allows reuse of the band although the amount of polarisation options is limited meaning it cannot be effectively used to coordinate a band across a large number of satellites. Finally, regulation and coordination can be carried out using Spatial Reuse.

Spatial Reuse is the simplest form of regulation where interference is mitigated through physical separation of satellites and transmission isolation through highly directive ground station antennas. This results in true reuse of the frequency band where all satellites can transmit and receive on the same frequency at the same time. Antennas on the ground would use highly directive antennas to project a small footprint on the orbital plane of the satellite so the chance of interference relies on the probability that two satellites will reside in the same area of space at the same time [9]. This will be discussed in depth in section IV where Spatial Reuse is the recommended form of regulation/coordination for small satellite communications in LEO. Referring to Table 1, for frequencies of interest below 10 GHz (to reduce ground would use highly directive antennas to project a small footprint on the orbital plane of the satellite so the chance of interference relies on the probability that two satellites will reside in the same area of space at the same time [9]. This will be discussed in depth in section IV where Spatial Reuse is the recommended form of regulation/coordination for small satellite communications in LEO. Referring to Table 1, for frequencies of interest below 10 GHz (to reduce guard bands). The two channels achieving this bandwidth are 1164 – 1215 MHz and 1559 – 1610 MHz although both are protected and allocated to the RNSS [13]. Of the other available channels, bandwidth and data rates are significantly lower than those above 10 GHz which presents a problem for the advancing technology in small satellites.

For this reason, the allocation of the 2.4 GHz and 5.8 GHz bands for open Spatial Reuse presents an opportunity for large bandwidths and data rates at the cost of a higher chance of signal collision. Table 2 shows the frequency bands currently allocated to amateur or ISM use (as per ACMA and NTIA frequency allocation charts) which could be extended to small satellite use.

### Table 1. Australian satellite services spectrum available allocations (February 2017) [12].

<table>
<thead>
<tr>
<th>Downlink Frequency (MHz)</th>
<th>Bandwidth (MHz)</th>
<th>QPSK Data Rate (Mb/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>137 - 138</td>
<td>1</td>
<td>1.4</td>
</tr>
<tr>
<td>400.05 - 400.15</td>
<td>0.1</td>
<td>0.14</td>
</tr>
<tr>
<td>400.15 - 401</td>
<td>0.85</td>
<td>1.19</td>
</tr>
<tr>
<td>1164 - 1215</td>
<td>51</td>
<td>71.4</td>
</tr>
<tr>
<td>1215 - 1260</td>
<td>45</td>
<td>63</td>
</tr>
<tr>
<td>1525 - 1559</td>
<td>34</td>
<td>47.6</td>
</tr>
<tr>
<td>1559 - 1610</td>
<td>51</td>
<td>71.4</td>
</tr>
<tr>
<td>1613.8 - 1626.5</td>
<td>12.7</td>
<td>17.78</td>
</tr>
<tr>
<td>2170 - 2178.5</td>
<td>8.5</td>
<td>11.9</td>
</tr>
<tr>
<td>2178.5 - 2184</td>
<td>5.5</td>
<td>7.7</td>
</tr>
<tr>
<td>2184 - 2193</td>
<td>9</td>
<td>12.6</td>
</tr>
<tr>
<td>2193 - 2200</td>
<td>7</td>
<td>9.8</td>
</tr>
<tr>
<td>2483.5 - 2500</td>
<td>16.5</td>
<td>231</td>
</tr>
<tr>
<td>11700 - 12750</td>
<td>1050</td>
<td>1470</td>
</tr>
<tr>
<td>18800 - 19300</td>
<td>500</td>
<td>700</td>
</tr>
</tbody>
</table>

### Table 2. Potential frequency allocations for small satellites in Australia and the USA [7] [8].

<table>
<thead>
<tr>
<th>Country</th>
<th>Frequency (GHz)</th>
<th>Bandwidth (MHz)</th>
<th>BPSK Data Rate (Mb/s)</th>
<th>QPSK Data Rate (Mb/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>USA (Amateur)</td>
<td>2.300 - 2.310</td>
<td>10</td>
<td>7</td>
<td>14</td>
</tr>
<tr>
<td>USA (Amateur)</td>
<td>2.390 - 2.450</td>
<td>60</td>
<td>42</td>
<td>84</td>
</tr>
<tr>
<td>USA (ISM)</td>
<td>2.400 - 2.450</td>
<td>50</td>
<td>35</td>
<td>70</td>
</tr>
<tr>
<td>Australia (Amateur)</td>
<td>2.300 - 2.450</td>
<td>150</td>
<td>105</td>
<td>210</td>
</tr>
<tr>
<td>Australia (ISM)</td>
<td>2.400 - 2.500</td>
<td>100</td>
<td>70</td>
<td>140</td>
</tr>
<tr>
<td>USA (ISM)</td>
<td>5.650 - 5.925</td>
<td>275</td>
<td>192.5</td>
<td>385</td>
</tr>
<tr>
<td>Australia (Amateur)</td>
<td>5.650 - 5.850</td>
<td>200</td>
<td>140</td>
<td>280</td>
</tr>
<tr>
<td>Australia (ISM)</td>
<td>5.725 - 5.850</td>
<td>125</td>
<td>87.5</td>
<td>175</td>
</tr>
</tbody>
</table>

### III. SMALL SATELLITE DISTRIBUTION

To build a model defining the probability of interference, it is important to understand how satellites are distributed around the Earth. To analyse this, a catalogue of small satellites was compiled based on specific criteria from...
The criteria for the catalogue required Type to be ‘Payload’, RCS to be ‘small’ or ‘medium’, and Apogee to be less than 2000 km. Note that launch year, purpose and operational status were not used to thin the data set, so the distribution represents typical satellite orbits to make the model as representative as possible. This resulted in 1237 satellites compiled into a TLE file and consequently loaded in the satellite orbital prediction software, Orbitron. Figure 1 shows the results of plotting the instantaneous position of all 1237 satellites as at 10:42 UTC, 01 June 2017.

First note the train of satellites in polar orbit with mid-morning LTAN (Local Time of Ascending Node) passing from Antarctica, up over western Europe and down over western Russia and New Zealand. We temporarily ignore the clustering of the satellites in LTAN and assume from this figure that the small satellite density is close to that of a uniform distribution about the globe. There appears to be a relatively even distribution of satellites between lines of latitude at any instant of time and this is verified by simulating the constellation through a number of orbits where the distribution shows negligible change. This is misleading though as this map is a Plate Carree projection which distorts area to preserve shape. This misrepresents the area within each Latitudinal band and hence, misinterprets the density and distribution. A more accurate representation of area between lines of Latitude can be found in the Hammer projection. A comparison between the projections can be seen in Fig 2.

So assuming a uniform distribution of satellites on a Plate Carree projection as per Fig 2, a Hammer projection highlights this distribution as one which increases in density toward the poles. This infers that the satellites in this catalogue have a tendency toward high inclination (polar) orbits as opposed to low inclination (equatorial) orbits.
Examination of the catalogue of 1237 satellites shows 1006 (81%) have inclinations larger than 70° and 624 (50%) have inclinations larger than 80°. Further evidence is found when analysing the visible satellites at various locations around the Earth. Polar plots were obtained at 216 locations spaced by 5° Latitude and 30° Longitude with each location showing how many satellites were visible above the horizon. The number of visible satellites was noted and converted into a percentage of the total satellites in orbit. Fig 3 shows the statistical analysis of the global satellite distribution.

**Fig. 3.** Polar plots were obtained to analyse the global satellite distribution. The result fits closely to that of a raised Cosine function. The theoretical distribution indicates that the current population of LEO satellites tend toward high angles of inclination and polar orbits. For comparison purposes, curves are shown indicating majority equatorial orbit and majority polar orbit satellite populations.

The global distribution of satellites shows satellite density to be 12.32±0.28% at -85° Latitude, 12.55±0.22% at 85° Latitude and 5.53±0.68% at the equator. This distribution fits closely to that of a raised cosine function as per (1) where \( N_{\text{vis}} \) is the number of satellites visible at a specific Latitude (L) with total satellites in orbit denoted by N. This equation is examined further in Section IV and forms the basis of a probability of signal collision model.

\[
N_{\text{vis}} = -0.04 \cos \left( \frac{2\pi}{180} L \right) + 0.08 \ast N
\]  

(1)

The global distribution detailed here does not take into account the distribution of altitude. Small satellites are often “piggy backed” onto existing large satellite missions when launched and their orbital altitudes are at the mercy of the primary payload. Often, a small satellite operator will choose an existing mission to launch with which places their satellites as close to the desired altitude as possible. Further to this, launch vehicle operators desire to keep costs down by increasing payload volume. This leads to mass launches at a single pre-determined altitude. An example of this can be found with the deployment of 103 small satellites from the launch vehicle PSLV-C37 by the ISRO at an altitude of 505 km [15]. Further, the ISS (International Space Station) in conjunction with the company Nanoracks can launch 96 1U CubeSat’s per mission at altitudes below 420km. Referring to Fig 4, the altitudes of small satellites show significant peaks in some areas but no clear trend. Of note is the aforementioned launch by the Indian Space Organisation at 505 km.

**Fig. 4.** The concentration of satellites at each altitude can be seen with two distinctive distributions centred at 600km and 1400km. The peak around 500km is due to the recent successful launch of 103 small satellites by the Indian Space Research Organisation [15].

At this stage, missions dedicated to small satellites are not commonplace so the altitude distribution will continue to follow orbit for the primary load. To gain further insight, the company Spaceflight offers worldwide launch scheduling for satellite deployment and the planned launches give a good indication of future satellite altitudes. Between Q4 2017 and Q4 2019, there are 34 launches scheduled with 21 deploying at altitudes between 450 km and 630 km and 8 deploying from the ISS at altitudes between 220 km and 420 km [16]. It can therefore be safely assumed that small satellite altitudes will be clustered around 500 km for the foreseeable future.

**IV. PROBABILITY OF SIGNAL COLLISION**

To ensure complete Spatial Reuse at 2.4/5.8 GHz is a viable option, the probability is determined for two satellites transmitting within the same ground station beam area. With the satellite population centre of mass at 500 km altitude, a probability model was built assuming all satellites of interest are at the same altitude. Noting that we cannot have an infinite amount of satellites at the poles, it can be inferred that data fits closely to that of a raised cosine function as per (1). The number of visible satellites (\( N_{\text{vis}} \)) is shown in Equations (1) and (2) as a function of orbital constant (\( C_{\text{orb}} \)), the offset by \( C_{\text{off}} \), the frequency \( \omega \) which is one cycle every 180° (assuming identical paths either side of the poles), the total number of satellites in orbit (\( N \)) and the latitude of interest (\( L \)). The variable \( C_{\text{orb}} \) indicates whether the

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concentration of satellite orbits tends toward polar or equatorial. Values that tend toward \(-C_{off}\) indicate majority polar orbits and values that tend to \(C_{off}\) indicate majority equatorial orbits.

\[
N_{\text{vis}} = (C_{\text{orb}} \cos(\omega L) + C_{\text{off}}) \times N
\]  

(2)

Referring to (1) and (2), the theoretical fit to the measured data shows that \(C_{\text{orb}}\) is \(-0.5C_{\text{off}}\) indicating approximately 75% of the satellites in the data set tend toward polar orbits. This closely correlates with the catalogue where 81% of the satellites were inclined at angles larger than 70°. With the relationship defined for \(N_{\text{vis}}\), a function is derived which will determine the probability that two satellites will occupy the same area and hence, the probability of interference or lost communications.

**Fig. 5.** As the mask angle \(\epsilon\) reduces from Zenith at 90° to the horizon at 0°, the projected beam area transitions from circular to elliptical and the area grows significantly [17].

To calculate the beam area \((A_B)\) that the ground station projects on the orbital surface as per Fig 5, the Earth central angle \((\gamma)\) in (3) and slant range \((D)\) in (4) are required based on the satellite altitude \((r_s)\), Earth mean radius \((r_e)\) and mask angle \((\epsilon)\).

\[
\gamma = \cos^{-1}\left(\frac{r_s \cos(\epsilon)}{r_e + \epsilon} - \epsilon\right)
\]  

(3)

\[
D = \sqrt{r_e^2 + (r_s + r_e)^2 - 2r_e(r_s + r_e) \cos(\gamma)}
\]  

(4)

The beam area is accurately approximated by dividing into two sections above and below beam centre bound by beam upper slant range \((D_u)\) and beam lower slant range \((D_L)\). The width of the beam \((\omega)\) should be narrow to reduce beam area so throughout this analysis a 2° beam width is assumed. With the upper \((S_{MAJ_u/L})\) and lower \((S_{MAJ_L})\) semi-major axis and semi-minor axis \((S_{MIN})\) calculated as per (5) and (6), the beam area is calculated as per (7).

\[
S_{MIN} = D \sin\left(\frac{\omega}{2}\right)
\]  

(5)

\[
S_{MAJ_u/L} = \sqrt{\left(D_{u/L} \sin\left(\frac{\omega}{2}\right)\right)^2 + (D - D_{u/L})^2}
\]  

(6)

\[
A_B = \frac{\pi}{2} (S_{MAJ_u/L} S_{MIN} + S_{MAJ_L} S_{MIN})
\]  

(7)

**Fig 6.** Beam area is shown for mask angles from Zenith to horizon and altitudes up to 2000 km.
With the projected beam area on the orbital surface known at various mask angles and altitudes (Fig 6), the probability of signal collision ($P_c$) from another satellite in the same beam area is calculated by as per (10) by substituting (2) into (8). Note that $A_x$ is the total orbital area visible from a ground station at sea level calculated in (9).

$$ P_c = 1 - \left( 1 - \left( \frac{\frac{A_x}{A_z}}{\frac{A}{A}} \right) \right)^{N_{\text{lim}}} $$(8)

$$ A_x = 2\pi r_x (r_x + r_e) $$ (9)

$$ P_c = 1 - \left( 1 - \left( \frac{\frac{A_x}{A_z}}{A} \right) \right)^{N(-0.04 \cos\left(\frac{2\pi L}{180}\right)+0.08)} $$ (10)

Equation (10) shows that for a satellite population of 1237 satellites at altitudes up to 1400 km with a mask angle limit of 10°, the probability at 10° Latitude is $0.13% < P_c < 1.5%$ and at 67° Latitude $0.33% < P_c < 3.97%$. Operators toward the poles will experience higher $P_c$ although this comes with the benefit of higher rates of passes leading to higher satellite exposure. Note that this population includes satellites launched from 1959 to present day and assumes all 1237 satellites are transmitting. Therefore, all values of $P_c$ are indicative of future populations of LEO satellites. Plots of $P_c$ verse mask angle at Latitudes of 10° and 67° are shown in Fig 7.

![Fig 7. The probability of signal collision is shown for locations on lines of Latitude at 10° and 67° at altitudes between 300km and 1400km.](image)

In assessing future launches, the probability of signal collision can provide insight to aid altitude selection and mask angle minimums to attain a certain level of communications reliability. It is important to note here that the probabilities calculated are based on the assumption that all satellites are transmitting all the time. Not only is this unrealistic but the ITU requires that satellites only transmit when required and very few are required to transmit consistently throughout their orbital period [3]. A more realistic model would take into account the average periods of transmission which can be as low as 10-15 minutes per orbital period [3]. Although this is outside of the scope of this report, this only serves to cement the proposal for Spatial Reuse as probability values could only decrease and the amount would be substantial.

V. GROUND STATION SEPARATION

For satellite operators incorporating a network of ground stations, the spacing between stations will determine the mask angle at which hand-over will occur. Hand-over should be designed so that operators get the most amount of throughput during the satellite exposure period with minimum infrastructure and cost. With the probability model detailed in Section IV, $P_c$ can be associated with the separation of ground stations. This provides satellite operators with insight to the reliability of signal transmission under the complete Spatial Reuse model based on the distance between each ground station.

![Fig. 8. Ground station separation effects the probability of signal collision and hand-over mask angles. Plots shown for 67° Latitude.](image)
Fig 8 (left) highlights the increase of $P_c$ as ground station separation increases. As $r_v$ increases, ground station separation has less of an impact as slant range increases. With satellites at lower altitudes, reduction of the distance between ground stations will ensure $P_c$ remains low. Fig 8 (right) shows the mask angle at hand-over dependant on ground station spacing. We now illustrate a scenario with operators at 67° Latitutude who have a satellite at 500 km. Selecting ground station spacing of 2000 km, stations will have a hand-over at 21º with a maximum of 1.6% $P_c$. This figure of 1.6% occurs only at 21º mask angle and reduces to 0.15% at zenith. If the satellite population were to grow from 1237 to 10000, the operator would need to reduce ground station separation from 2000 km to 470 km to maintain 1.6% $P_c$ or this value would increase to 12%.

VI. LINK BUDGET

The primary attraction of complete Spatial Reuse is the high data rates achievable with the increased bandwidth. Data rates for BPSK and QPSK can be conservatively assumed to be 0.7 b/Hz and 1.4 b/Hz respectively allowing for filter roll-off [11]. Table 2 details these data rates when using all available bandwidth. To give credence to these values we must ensure that there is sufficient link margin considering the low radiated power of small satellites. For this reason, only analysis of the downlink will be carried out as this will be the limiting factor in the majority of small satellite applications.

To begin we find the EIRP of the satellite as per (11). $P_t$ is the amplifier power minus amplifier back off losses. $L$ defines the losses such as insertion, transmission line and feeder. $G_t$ is the gain of the transmitting antenna. The received carrier power ($S$) is calculated as per (12) as a function of the EIRP, power density at the receiver and the effective area ($A_e$) as defined in (13).

$$EIRP = P_t + G_t - L$$  \(11\)
$$S = EIRP - 10 \log_{10}(4\pi r_v^2) + A_e$$  \(12\)
$$A_e = \frac{\eta \pi D^2}{4}$$  \(13\)

In digital communications, signal-to-noise ratios are defined by (15) as the energy per bit ($E_b$) over the noise power spectral density ($N_o$). $N_o$ is calculated as per (14) where $k$ is Boltzmann’s constant and $T_e$ is the equivalent temperature of the receiver as a function of noise figure (NF).

$$N_o = kT_e = k \times 290(NF - 1)$$  \(14\)
$$\frac{E_b}{N_o} = S - N_o - 10 \log_{10}(BR)$$  \(15\)

The value of $E_b/N_o$ gives an indication of the theoretical BER which is identical for BPSK and QPSK [10]. Fig 9 details the expected $E_b/N_o$ values for various satellite altitudes and mask angles at a bit rate of 50 Mbps. In this case, an S-band patch antenna (Endurosat Patch Antenna Type 1) is used as an example with 8.3 dBi of gain and 4 W maximum output power [18]. The receiver equivalent temperature $T_e = 203$ (NF = 1.7). In cases where the link margin is not sufficient, the bit rate can be reduced to obtain better $E_b/N_o$. If the bit rate is reduced to 25 Mbps, $E_b/N_o$ increases by 3 dB.

![Link Budget - Downlink (50 Mbps)](image)

Fig 9. Link budget for BPSK/QPSK with specifications as per Table 3 for altitudes from 300 km to 1400 km.

<table>
<thead>
<tr>
<th>Table 3. Link Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Satellite</strong></td>
</tr>
<tr>
<td>$P_t$</td>
</tr>
<tr>
<td>$L_t$</td>
</tr>
<tr>
<td>$G_t$</td>
</tr>
<tr>
<td>Bitrate (BR)</td>
</tr>
<tr>
<td>$f$</td>
</tr>
<tr>
<td><strong>Ground Station</strong></td>
</tr>
<tr>
<td>Efficiency ($\eta$)</td>
</tr>
<tr>
<td>$D$</td>
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VII. TERRESTRIAL LINK IMPLEMENTATION

A. DATA RATE VERIFICATION TEST

In the first quarter of 2018, UNSW Canberra plans to launch a CubeSat which will test various communications methods among other internally developed technologies. On board is an AD9361 RF Agile Transceiver chip to provide a customisable communication system and significantly higher bit rates than the vast majority of commercially available CubeSat S-Band transmitters. These chips are also incorporated into the Ettus B200 and B210 SDR’s and hence, these radios provide a realistic platform to test bit rates, bandwidth and interference mitigation techniques.

Tests were devised to ensure the chip was capable of the data rates detailed in this paper by using two B200’s and an interface through Simulink. A model is built and a script generates a random stream of 64 symbols with an 18 symbol header. This baseband signal is then QPSK modulated. The SDR is configured with a master clock of 56 MHz which sets the SDR bandwidth to 56 MHz and is the upper recommended limit with ADC and DAC sample rates of 61.44 MSps [19]. This is a quadrature sample rate and as such, high bit rates can be achieved with quadrature signals. The sampling frequency is set at 112 MHz with a symbol rate of 28 MSps to get four samples per symbol. The centre frequency is set to 2.41 GHz with interpolation and decimation set to 100. Siretta Delta 7 2.4 GHz omnidirectional dipole antennas are fitted to both SDR’s and the radios are separated by approximately one meter. Due to lack of pre amplifiers and low gain antennas (1.4 dBi), the radios must be kept in close proximity to ensure power transmission.

Upon transmission, the receiver detects the signal and imposes a random phase lock at \(\frac{\pi}{2}, \pi, -\frac{\pi}{2} \text{ or } 0 \text{ rad/s} \) [19]. A MATLAB script analyses the imaginary (Q) and real (I) components of the complex signal, detects the header and applies a phase offset (\(\phi\)) which rotates the QPSK constellation to ensure correct demodulation takes place. The test signal sequence is seen in Fig 10 where the AD9361 achieves the symbol rate of 28 MSps (Bit rate of 56 Mbps) with a SER of \(9.8 \times 10^{-4}\) tested over ten million symbols. This test verifies that the AD9361 is capable of high data rates with a high degree of accuracy. In practical applications, the SER would be significantly improved with implementation of an appropriate FEC algorithm.

![Fig 10. The baseband is modulated into a QPSK signal and transmitted from an SDR at a symbol rate of 28 MSps. The signal is received by a second SDR, demodulated and a phase offset (\(\phi\)) is applied to align the QPSK constellation.](image)

B. NULL STEERING TEST

As mentioned in Section I, null steering is a technique which can be used to mitigate interference. In the scenario that satellite congestion became a problem for satellite operators, null steering provides a means to aim a null of a phased array at a source to effectively eliminate that interfering signal. This is especially useful when considering the Spatial Reuse model where all satellites transmit on the same frequency.

Typically, a phased array is used to multiply the beam patterns of each individual antenna to achieve high gain beams which can be steered toward the target amplifying its signal. The opposite effect can also be achieved where a null is steered to attenuate a signal. This is a method that is ideal for spatial isolation. Using the Sensor Array Analyzer in MATLAB, a variety of array geometries and element types can be explored to determine the theoretical beam patterns. Referring to Fig 11, two isotropic radiators placed at half wavelength separation generates two nulls at \(\pm 90^\circ\). This is the simplest of phased arrays although it can demonstrate null steering effectively and is scalable.
A test was devised to show that if two sources are transmitting QPSK signals using the same centre frequency, a phased array can be used to steer a null toward one transmitter to remove the interference. This in turn allows us to extract the target transmission accurately ignoring interference. To implement this, a housing is constructed with two Siretta Delta 7 2.4 GHz omni-directional antennas at 6.22 cm separation. Each antenna connects to separate channels on a B210 SDR forming a phased array. Two B200 SDR’s are placed at 0° and 90° from the array boresight (Fig 14).

Before conducting tests on a QPSK signal, null steering was demonstrated by transmitting pure sine waves and nulling one source. A Simulink model is built to transmit a 1 kHz tone from B200 no. 1 at 0° and a 2 kHz tone from the B200 no. 2 at 90°. Both are modulated onto a 2.41 GHz PSK carrier and fine tuning of the phase offset is carried out to place B200 no. 2 as central to the null as possible attenuating the signal by approximately 30dB.

The demodulated signal on both channels shown in Fig 12 exhibits distortion caused from the mixing of the 1 kHz and 2 kHz tones. However, when the signals are summed, the 180° phase shift nulls the signal from B200 no. 2 leaving the 1 kHz tone from B200 no. 1. The resultant signal is an accurate reproduction of the transmitted 1 kHz tone with negligible distortion and almost no evidence of the interfering 2 kHz signal.

The test is then expanded to encompass nulling of an interfering QPSK signal. Two random streams of 64 symbols are generated with an 18 symbol header for each sequence. Null steering is accomplished by transmitting the desired QPSK signal from B200 no. 1 and the interfering QPSK signal from B200 no. 2. Ten million samples are analysed resulting in an SER of $1.3 \times 10^{-3}$. This SER is comparable to that encountered without interference (Section VII.A). Referring to Fig 13, the I component closely correlates with the desired transmitted signal although shows evidence of the interfering QPSK signal between transitions. This is particularly clear when comparing the I and Q components in Fig 10.

This test shows that null steering can be implemented as an interference mitigation technique and does not require consideration of the technology on board the satellite. Throughout the orbital lifetime of the satellite, ground stations can be upgraded if required and null steering is shown to provide highly effective spatial isolation of target source reducing or eliminating the interfering signals.

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VIII. CONCLUSION

The global small satellite community has grown substantially over recent years and as technology improves and launch costs drop, it is expected that small satellite constellations in LEO will continue to grow. These satellites provide society with unprecedented access to space-based systems including functions pertaining to search and rescue, planetary imaging, atmospheric analysis, research platforms and climate analysis. As the number of satellites has grown, the communication regulations have lagged leading to hundreds of satellites operating without authorisation or outside of regulatory guidelines. In response to agenda item 1.7 of the WRC 2019, we have shown the allocation of the 2.4 GHz and 5.8 GHz bands to small satellites not only places small satellite communications within regulatory framework but it expands the bandwidth significantly allowing systems relying on higher data rates to be deployed.

As the current constellations of small satellites in LEO conform closely to a uniform distribution about Earth, the probabilities of signal collisions are shown to be acceptably low providing a communications solution in the form of Spatial Reuse. The probability of signal collision is less than 1.5% at 10º Latitude and 3.97% for 67º Latitude for all LEO altitudes and mask angles based on a satellite population of 1237. These calculations were based on the assumption that all satellites were transmitting constantly which is unrealistic and serves to show these probabilities are substantially higher than would be encountered in practice. This reduces or negates the need to regulate the bands with frequency, time or code division allowing complete use of the bandwidth for all users, all the time. This shifts the problem domain from the regulator to the operator where the operators have access to a myriad of interference mitigation techniques.

Guidance is provided for the separation of ground stations to attain the desired level of signal reliability while reducing overall infrastructure costs. Link budget analysis highlighted the viability of the high data rates with technology currently on the market.

A practical terrestrial link is constructed which shows the bit rates detailed are achievable with the AD9631 RF Agile Transceiver at a rate of 56 Mbps with SER of $9.8 \times 10^{-4}$. Finally, a two element linear phased array is shown to successfully null QPSK signals at 90º off boresight providing an SER of $1.3 \times 10^{-3}$. This form of interference mitigation is scalable and requires only ground station infrastructure to accomplish.

This paper shows that the 2.4 GHz and 5.8 GHz ISM/amateur bands are viable solutions to the current regulatory problem that small satellites in LEO present to the ITU and provides research to aid decision makers regarding agenda item 1.7 at WRC 2019.

IX. RECOMMENDATIONS

Much of the work on this paper was conducted on the probability model detailed in Section IV. This required a deep level of understanding of small satellites, orbital mechanics, satellite communications and probability theory. The outcomes are complete and there is little need to develop this further. As the aim of this paper is to pursued decision makers within the ITU about small satellite frequency allocations, it is recommended that further study be conducted into forms of interference mitigation techniques which do not increase cost and complexity to small satellites. One such avenue is the use of a technique similar to MIMO (Multiple In Multiple Out). Additionally, practical tests of the 2.4/5.8 Ghz bands using the described data rates should be conducted with satellites. This would provide information on SDR performance, real losses incurred and the potential to explore interference occurrence when two satellites are transmitting within the vicinity of one another.

A complementary technique to null steering is based on MIMO. This is where auto and cross correlations on the received signals from two or more antennas extract the desired signal and remove interference. This technique has been discussed in several papers over recent years although in most instances, there is mention of multiple receive antennas and multiple satellite transmitters. We do not believe this is necessary and only the receive function of MIMO needs to be implemented at the ground station. Initial attempts at testing this theory resulted in the realisation that one would require high gain antennas, pre-amplifiers and tens of meters of separation between antennas. This separation is due to the fact that satellite signals are not multipath and at least one symbol separation is required between receivers.

Finally, practical tests on satellites would provide validation for the laboratory tests and theoretical models producing further evidence to the ITU that this proposal is both beneficial and viable. This could involve using an existing or proposed satellite to transmit sequences at data rates utilising a large portion of the available bandwidth and characterising the link. Further to this, coordinating with other satellites which pass through the same beam area would provide a way of testing the probability of signal collision model.

X. ACKNOWLEDGMENTS

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XI. REFERENCES


