Joint Frequency Scheduling and Power Allocation for CubeSat Communication

Wenkai Zhang*, Alireza S. Behbahani*, Ahmed M. Eltawil†,
*Department of EECS, The University of California, Irvine, Irvine, CA, USA,
{wenkaiz1, sshahanb}@uci.edu
†King Abdullah University of Science and Technology (KAUST), Thuwal, Saudi Arabia,
ahmed.eltawil@kaust.edu.sa

Abstract—CubeSats, a type of miniaturized satellites with the benefits of low cost and short deployment period, have attracted intensive research interest recently and have been regarded as the promising future for satellite communication. With increasing service demands, uncoordinated inter-satellite communication without any intelligent scheduling or budgeting of frequency and power can no longer satisfy the need for development. In this work we evaluate the benefit of frequency scheduling in improving transmission data rate of CubeSats, using different operating frequencies, including microwave, millimeter wave and optical frequencies. A joint frequency scheduling and power allocation scheme is designed to provide the optimal transmission rate data under transmit power and throughput constraints. Simulation results demonstrate the inter-satellite links of CubeSats with frequency scheduling and power allocation can achieve higher transmission data rate than traditional operation conditions with fixed frequency or fixed power.

Index Terms—CubeSats, Satellite Communications, RF, Millimeter wave, Optical communication, Frequency scheduling, Power allocation

I. INTRODUCTION

In recent decades, the increasing interest in space-related exploration research is at the forefront of cutting-edge science and innovations. The growing worldwide demand for space communication and exploration is creating new opportunities for the deployment of CubeSats. The CubeSat is a picosatellite with dimension of 10 cm × 10 cm × 10 cm, weighing less than 1.33 kilograms [1]. CubeSats benefit from low design costs and low power consumption, which become promising candidates for earth monitoring, space exploration, Internet of things (IoT) etc. [2].

In order to meet the demands of diverse missions, coupled with the need to support IoT applications reliably, achieving higher data rates in inter-satellite links (ISLs) has become a significant need [3]. However, current ISLs can only support low data rate with high delay principally using the VHF/UHF band. In addition, fixed frequency operation is widely used and selection of frequency is largely based on distance, link performance, power consumption etc [4]. Hence, in order to achieve higher data rate, the frequency range will have to extend towards the millimeter wave(mmWave) and the optical frequency to as shown in Fig. 1.

A comparative study of link performance for different operation frequencies: radio frequency (RF), mmWave and optical communication in CubeSats is investigated in [5]. The CubeSats operating on different frequencies have different ISL performance, in particular, there is a crossover region in channel capacity between mmWave and optical frequencies. Moreover, recent advancement in CubeSats technology has demonstrated potential of having multi-band connectivity in a wide range of spectra including RF, mmWave, optical frequencies [6]. Therefore, different operation frequencies can be chosen by CubeSats under different conditions to improve ISL performance metrics.

Furthermore, the current approach of using fixed transmit power allocation for ISL, while simple, is ineffective and not optimal, leading to wasteful management of resources. This may have been acceptable for larger satellites with reserve resources, but is certainly not acceptable for small form-factor CubeSats. A dynamic power allocation scheme can efficiently reduce the total energy consumption while achieving the desired quality of service (QoS) of ISL [7], [8].

This paper investigates and illustrates the advantage of frequency scheduling and/or power allocation for ISL of CubeSats in two scenarios. First, for a fixed power allocation, we demonstrate frequency scheduling alone can provide superior data transmission rate. Second, for a dynamic power allocation, we show a joint power allocation and frequency scheduling scheme can achieve higher transmission data rate performance. Moreover, we validate the data rate improvement
of the proposed joint scheme with actual satellite operation data of the Iridium NEXT and provide simulation results that confirm performance gains.

The remainder of the paper is organized as follows. In Sec. II, the CubeSat model setup and link parameters are defined. In Sec. III, total transmission data rate optimization is described. In Sec. IV, the simulation and performance analysis of frequency scheduling scheme, joint frequency scheduling and power allocation and scheme are given respectively. Finally, the conclusion is drawn in Sec. V.

II. CUBE SAT MODEL SETUP AND LINK PARAMETERS

In this paper, we consider a two-CubeSat model, which has ISL with multi-band connectivity across RF, mmWave, and optical frequencies. Based on CubeSat formation function, the inter-satellite distance between two CubeSats is periodic as shown in Fig. 2. The total transmission time is set as 40 minutes. From 0 to 20 minute, the two CubeSats get further apart from each other and the inter-satellite distance becomes larger. From 20 to 40 minutes, the inter-satellite distance becomes smaller and it concludes one period. The communication between two CubeSats are considered in each discrete unit time slots \( i \in \{1, 2, \ldots, 40\} \) with time steps of 1 min to simplify the calculation and analysis. The model assumes a minimum data transmission rate requirement of 1 Mbps at each time slot due to the fact that the CubeSat system needs to guarantee a basic level of throughput at all times.

![Fig. 2: The simplified CubeSats model](image)

The goal of frequency scheduling and/or power allocation is to find the proper operation frequency and transmit power combination that results in the optimal data rate performance. The transmission data rate can be calculated in dB from the following equation [9],

\[
\Gamma = 10\log \left( \frac{C}{N_0} \right) - 10\log \left( \frac{E_b}{N_0} \right) \tag{1}
\]

Where \( \Gamma \) denotes transmission data rate, and the other parameters \( \frac{C}{N_0}, \frac{E_b}{N_0} \) represent ratio of carrier energy to noise energy density at receiver, ratio of bit energy to noise energy density at receiver, respectively. The received modulated carrier signal power \( (C) \) can be simplified as the receiver power \( (P_{rcv}) \), which can then be calculated in dB from the link budget equation [10] as follows.

\[
P_{rcv} = P_T - G_T - G_R - L - L_T - L_R - L_P \tag{2}
\]

where \( G_T \) represents the transmission antenna gain, \( G_R \) represents the receiver antenna gain, \( L \) represents the free space path loss. The equations are following:

\[
G_T = 20\log \left( \frac{\pi D_T f}{c} \right) \tag{3}
\]

\[
G_R = 20\log \left( \frac{\pi D_R f}{c} \right) \tag{4}
\]

\[
L = 20\log \left( \frac{c}{4\pi df} \right) \tag{5}
\]

In the above equations, transmission antenna diameter \( (D_T) \), receiver antenna diameter \( (D_R) \), velocity of light\( (c) \), transmitter feeder loss \( (L_T) \), receiver feeder loss \( (L_R) \), and pointing loss \( (L_P) \) are fixed values and are listed in Table I. The transmit power and operation frequency are denoted as \( P_T \) and \( f \) respectively.

Currently, CubeSats are assumed to have a transmit power \( P_T \) of maximum 1W at each unit time slot for the communication link. Additionally, due to the battery capacity limitations and prolonged periods of darkness, it is not feasible for CubeSats to always operate at this maximum transmit power at each unit time slot. Therefore, the total transmit power consumption in one period (40 minutes) needs to be less than 40 W. So the maximum total transmit power is simply set as 35 W for this model to make sure that CubeSats do not always operate at this maximum transmit power at each unit time slot.

The specific link parameters implemented in the two-CubeSat model are summarized in Table I [5].

<table>
<thead>
<tr>
<th>Pointing loss ( (L_P) )</th>
<th>RF</th>
<th>0.3 dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>mmWave</td>
<td>1.0 dB</td>
<td></td>
</tr>
<tr>
<td>Combined feeder loss ( (L_T, L_R) )</td>
<td>RF</td>
<td>3.0 dB</td>
</tr>
<tr>
<td>Optical</td>
<td>5.1 dB</td>
<td></td>
</tr>
<tr>
<td>mmWave</td>
<td>4.1 dB</td>
<td></td>
</tr>
<tr>
<td>Optical</td>
<td>3.0 dB</td>
<td></td>
</tr>
<tr>
<td>Transmitter antenna diameter ( (D_T) )</td>
<td>RF</td>
<td>100 mm</td>
</tr>
<tr>
<td>mmWave</td>
<td>100 mm</td>
<td></td>
</tr>
<tr>
<td>Optical</td>
<td>10 mm</td>
<td></td>
</tr>
<tr>
<td>Receiver antenna diameter ( (D_R) )</td>
<td>RF</td>
<td>100 mm</td>
</tr>
<tr>
<td>mmWave</td>
<td>100 mm</td>
<td></td>
</tr>
<tr>
<td>Optical</td>
<td>50 mm</td>
<td></td>
</tr>
<tr>
<td>Noise power density ( (N_0) )</td>
<td>-204 dB</td>
<td></td>
</tr>
<tr>
<td>Energy per bit to noise density ( (E_b/N_0) )</td>
<td>10 dB</td>
<td></td>
</tr>
<tr>
<td>Link margin</td>
<td>3 dB</td>
<td></td>
</tr>
<tr>
<td>Total operation period ( (T) )</td>
<td>40 minutes</td>
<td></td>
</tr>
<tr>
<td>Minimum data rate requirement ( (\sigma_{req}) )</td>
<td>1 Mbps</td>
<td></td>
</tr>
<tr>
<td>Maximum Transmit power ( (P_{txmax}) )</td>
<td>1 W</td>
<td></td>
</tr>
<tr>
<td>Total Transmit power ( (P_{total}) )</td>
<td>35 W</td>
<td></td>
</tr>
<tr>
<td>Average Transmit power ( (P_{av}) )</td>
<td>0.875 W</td>
<td></td>
</tr>
</tbody>
</table>
III. TOTAL TRANSMISSION DATA RATE OPTIMIZATION

Two scenarios of optimal transmission data rate optimization are taken into account in this paper: I) The CubeSats are operating under fixed transmit power during the entire period. This scenario serves to evaluate the effect of frequency scheduling alone. II) The CubeSats are operating under dynamic transmit power during the entire period. This scenario requires frequency scheduling and power allocation.

A. Frequency scheduling and fixed transmit power

In scenario I, the CubeSats are operating using fixed transmit power during the whole operation period. Thus dynamic frequency scheduling needs to be considered to provide superior data rate performance. The frequency scheduling scheme can be expressed as the following optimization problem:

\[
\begin{align*}
\text{maximize} & \quad \sum_{i=1}^{T} \Gamma_i \\
\text{subject to} & \quad p_i = P_{av}, \ i = 1, 2, \ldots, T \\
& \quad \Gamma_i \geq \Gamma_{req} \\
& \quad 0 \leq p_i \leq P_{max} \\
& \quad \sum_{i=1}^{T} p_i \leq P_{total}
\end{align*}
\]  

(6)

The variables \(f_i\), \(p_i\), \(\Gamma_i\), \(\Gamma_{req}\), \(P_{av}\) respectively represent the minimum throughput requirement, average transmit power, and transmission data rate at time slot \(i\), respectively. \(T\) represents the total transmission time. The parameters \(\Gamma_{req}\), \(P_{av}\) respectively represent the minimum throughput requirement, average transmit power.

B. Frequency scheduling and dynamic power allocation

In reality, CubeSats operating constantly at average transmit power is not the optimal way to achieve higher data rate. Thus, in scenario II, dynamic power allocation is added to scenario I. Instead of fixing the transmit power, the joint power allocation and frequency scheduling scheme will adjust the transmit power and operation frequency combination to achieve higher data rate. The optimization equations are formulated as following:

\[
\begin{align*}
\text{maximize} & \quad \sum_{i=1}^{T} \Gamma_i \\
\text{subject to} & \quad \Gamma_i \geq \Gamma_{req}, \ i = 1, 2, \ldots, T \\
& \quad 0 \leq p_i \leq P_{max} \\
& \quad \sum_{i=1}^{T} p_i \leq P_{total}
\end{align*}
\]  

(7)

The total transmit power for the entire system is denoted as \(P_{total}\), and the maximum transmit power at each time slot is represented as \(P_{max}\). The variables \(f_i\), \(p_i\), \(\Gamma_i\), \(T\), \(\Gamma_{req}\) have the same definition as equation (6).

IV. RESULTS AND DISCUSSION

In this section, we first review the simulation results for Scenario I where frequency scheduling with fixed transmit power is investigated and demonstrate the improvement in transmission data rate. We then consider the joint power allocation and frequency scheduling introduced in Scenario II and demonstrate that the joint scheme maximizes the transmission data rate under a total transmit power constraint. Lastly, in order to approximate real-world CubeSat performance, we validate the proposed joint power allocation and frequency scheduling scheme on actual Iridium NEXT operation data.

A. Frequency scheduling with fixed Transmit power

Using equations (1) and (2) defined in Section II, the transmission data rates are calculated and compared among different operation frequencies: RF (2.4 GHz, 5 GHz), mmWave (34 GHz, 60 GHz) and optical frequencies (194 THz, 284 THz, 353 THz), as shown in Fig. 3. It can been seen that 2.4 GHz, 5 GHz and 194 THz could not meet the minimum data rate requirement and other frequencies can achieve higher data rate than 1 Mbps at each time slot. Based on the inter-satellite distance in Fig. 2, RF (2.4 GHz, 5 GHz) achieve lower data rate than mmWave and optical frequencies at any distance. In general, the optical frequencies achieve higher data rate than mmWave frequencies. However performance crossover does occur between mmWave and optical frequencies. In a half period (0-20 minute), the difference of transmission data rate of mmWave and optical communication decreases as the communication distance increases; The crossover performance between 353 THz and 60 GHz occurs at \(\approx 9\) minutes after they start communicating, the distance in the time is about 520 km; After a certain time, 60 GHz has better throughput performance than 353 THz.

![Fig. 3: Comparison of the transmission data rate of fixed operation frequencies and frequency scheduling](attachment:file.png)
that frequency scheduling shows a 5-6 order of magnitude higher total transmission data rate than mmWave, RF, and most optical frequencies. Compared to 353 THz, the frequency scheduling performs at a 2-3 order of magnitude higher because the operation frequency of 353 THz is the dominant one to achieve transmission data rate than 60 GHz in frequency scheduling. Therefore, the frequency scheduling will achieve higher transmission data rate than any other fixed operation frequency.

B. Frequency scheduling with dynamic power allocation

It can be proven that through frequency scheduling alone, we can effectively improve the data rate performance with fixed transmit power. Furthermore, transmission data rate can be improved by adding dynamic power allocation into consideration.

Simulation results of Scenario II are analyzed in two aspects. First, we compare the data rate at each time slot between a set of standard CubeSat parameters (fixed operation frequency 194 THz and fixed average transmit power 0.875W) and proposed joint power allocation and frequency scheduling scheme as shown in Fig. 5. It can be illustrated that the proposed joint scheme applies the maximum transmit power (1W) and choose optical frequency 353 THz as the operation frequency to realize higher data rate when the inter-satellite distance is smaller (the first and last 10 minutes of a period). However, when the distance becomes larger, the operation frequency is switched to mmWave 60GHz. The transmit power can be set at a much lower level around 15-25 minute to only maintain the minimum data rate requirement, yet still achieving higher total transmission data rate in one period.

Second, to demonstrate the overall superiority of the joint power allocation and frequency scheduling scheme, the comparison of total transmission data rate among different frequencies and power configurations in the entire duration measured is shown in Fig. 6. The blue bars show the difference of total transmission data between proposed joint scheme and fixed transmit power and operation frequency. The red bar shows the improvement of total data rate from the proposed joint scheme compared to frequency scheduling alone. It can be seen that our proposed joint scheme not only achieves the highest data rate than any other traditional fixed operation frequency and fixed transmission condition, but also presents a further improvement (approximately $5 \times 10^4$ Mbps) of data rate than frequency scheduling alone.

Building on the results of the Scenario II, we also want to examine the feasibility of proposed joint power allocation and frequency scheduling scheme on real orbital data. We use the data of Iridium NEXT constellation from STK as shown in Fig.7. The distance data is measured on July 2nd, 2020 from 7:22 pm to 8:03 pm with the total duration of 42 minutes (one half connection period). The connection period is slightly less than orbital period (101 minutes per orbit) because inter-satellite links will be dropped above 68° latitude, as the angular rates for the tracking antennas become high and little traffic is expected at these latitudes [11]. The maximum transmit power and total transmit power of satellite in Iridium Next are 200 W and 5000 W, respectively. Minimum data rate for each transmission time slot is 1 Mbps [12]. The comparison of total transmission data rate among different frequencies and power configurations in the entire period measured is shown in Fig. 8. It is evident that joint power allocation and frequency scheduling scheme achieves the best throughput.
Fig. 6: The difference of total transmission data rate between joint scheme and fixed power and frequencies, fixed power and frequency scheduling.

Fig. 7: Iridium Next System model performance (by about $10^4$ Mbps to next highest operation frequency 353 THz) than any other fixed transmit power and operation frequency condition.

V. CONCLUSION

This paper investigates the advantage of frequency scheduling and power allocation to maximize transmission data rate, which takes consideration of transmit power constraints and data rate requirement for CubeSat. In the first scenario, we provide the fact that frequency scheduling can achieve better throughput performance than any fixed operation frequency ranging from the mmWave to the optical band with the fixed average transmit power. Then we investigate a joint power allocation and frequency scheduling scheme that drastically improves the overall transmission data rate than frequency scheduling alone and fixed power and frequency. We validate the real world application impact of the joint power and frequency scheduling scheme using the Iridium NEXT constellation. It is demonstrated that, with real orbital data of the Iridium NEXT system, the joint power and frequency scheduling scheme can also generate approximately $10^4$ Mbps improvement on total transmission data rate in a certain time.

Fig. 8: Comparison of the total data transmission with existing Iridium NEXT frequency, fixed operation frequencies, and proposed joint transmit power and frequency scheduling scheme

REFERENCES


