Proactive Sensing and Interference Mitigation in Multi-link Satellite Networks

Irmak Aykin and Marwan Krunz
Department of Electrical and Computer Engineering
University of Arizona
Tucson, AZ 85721
Email: {aykin, krunz}@email.arizona.edu

***Abstract*—Satellite communications (SATCOM) are prone to both intentional and unintentional interference, which can significantly degrade the reliability of packet transmissions. Here, we investigate different approaches for interference mitigation in SATCOM based on dynamic frequency hopping (DFH). We consider a star topology, where multiple LEO satellites transmit packets to a common GEO satellite. The FH pattern of each LEO-GEO link is adjusted according to an outcome of out-of-band proactive sensing scheme, carried out by a cognitive radio (CR) module that resides in the GEO satellite. Based on sensing results, channels with high predicted interference are replaced with better channels, without disrupting the communications of other satellites in the network. In searching for replacement channels, we aim to ensure that all satellite links are assigned channels such that their SINR requirements are met. At the same time, the total transmission power and the communication overhead resulting from altering the FH patterns are minimized. We formulate the problem as a multi-objective minimization problem. Continuous-time Markov chain analysis is used to predict future channel conditions. The proposed scheme is compared with two other schemes, namely best-channel-to-closest-user and best-channel-to-farthest-user. Finally, we use simulations to study the effects of different system parameters on the performance of the proposed DFH design.**

I. Introduction

Cognitive radios (CRs) have the ability to sense the spectrum environment and adapt their transmission parameters to maximize system capacity while co-existing with legacy wireless radios. Spectrum sensing methods for CR applications have been extensively researched (see, [1] and the references therein). In [1], the authors discussed the network functions related to spectrum management, spectrum mobility, and spectrum sharing. They also investigated the influence of these functions on the performance of upper-layer protocols, such as routing and transport. In our paper, we study the use of CRs for reliable satellite communications. Rather than improving the spectrum utilization, here the aim is to utilize CRs to improve robustness against intentional or unintentional interference. Enabling satellites to communicate effectively with each other requires an agile CR platform at the receiver. CRs for space/satellite communications are readily available, e.g., SWIFT [2] and GD [3]. They provide the required network awareness and cognition.

In general, wireless transmissions rely on spread spectrum techniques, namely frequency hopping (FH) and direct sequence, for interference mitigation [4]. Some examples of satellite systems that employ FH are the Advanced Extremely High Frequency (AEHF) [5] and the Military Strategic and Tactical Relay (MILSTAR) satellite systems [6]. FH is extensively used in military satellite systems to secure communications under adversarial (jamming) conditions [7]. Traditional FH is done by switching a carrier among possible frequency channels, using a fixed pseudorandom noise (PN) sequence, known to both the transmitter and receiver. Although this approach tends to work well under random interference, it performs poorly in the presence of persistent interference/jamming over specific channels [8]. For example, a smart eavesdropper may (eventually) learn portions of the fixed FH sequence and may persistently target certain frequency channels in certain time slots.

One way to address the limitations of the static FH approach is to modify the FH sequence according to channel quality and interference conditions. Dynamic frequency hopping (DFH) has been studied in [9] to ensure a certain quality of service (QoS) in wireless regional area networks (WRANs) without affecting licensed users. DFH was also used in [8] to combat intentional and unintentional interference over a single satellite link. Similar to our approach, the authors used proactive sensing to adjust the FH sequence in order to transmit data packets reliably. In contrast to [8], here we consider multiple satellite links, which makes the problem fundamentally different.

In this paper, we explore a novel DFH approach for multi-link satellite-to-satellite communications. Specifically, we consider communications between several LEO satellites and one receiving GEO satellite. This scenario involves a channel assignment problem, where the nodes are capable of DFH. Channel assignment problem has been widely studied [10][11]. In [11], the problem of assigning channels to CR transmissions was investigated, with the goal of maximizing the number of feasible concurrent CR transmissions. In contrast to [11], in our scheme we aim at jointly minimizing the transmission (Tx) power and changes to the FH sequences while ensuring the maximum possible number of concurrent transmissions. Minimizing the changes in the nominal FH sequences is par-

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ticularly beneficial, when the feedback channel is not always available/reliable. Since the channel assignments are made at the receiver, a feedback channel is necessary to report the changes in the FH sequence and the required Tx powers to the transmitter.

Main Contributions: In this paper, we investigate three techniques for dynamic channel assignment in satellite networks that employ FH. One technique aims to minimize a weighted sum of the total Tx power and the communication overhead resulting from altering the FH sequences, while meeting the SINR requirements of LEO transmissions. Other two techniques are simpler, yet still efficient; and depending on the system parameters, any one of these three techniques can outperform the other two. We use a continuous-time Markov chain (CTMC) analysis to predict future states of sensed channels. The predictions are used as input to the channel assignment algorithm. In addition, we present an efficient scheme for reporting the changes in the FH sequence, and investigate the performance of dynamic channel assignment under erroneous channel feedback.

II. System Model and Problem Formulation

We consider a system that consists of T LEO satellites that communicate with a common GEO satellite (see Figure 1). The GEO satellite relays data from a LEO satellite to Earth. Each LEO-to-GEO link is pre-assigned a "nominal" FH sequence, drawn from a set of narrowband frequencies. The GEO satellite is capable of performing multi-user FH communications with various LEO satellites. To avoid interference between two uplink transmissions, any given frequency cannot be used by more than one uplink at the same time.

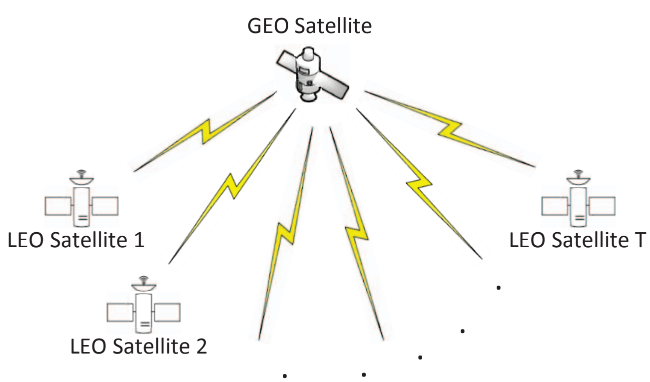


Fig. 1: Representative topology of the underlying satellite-to-satellite communications system.

A sniffer, which resides within the CR module of the GEO satellite, is used to simultaneously detect the energy over several channels that are not being used for uplink transmission at that moment. The outcome of the energy detector is used to predict the future states of these sensed channels if they were to be used later on for uplink transmission according to the nominal FH sequences. Depending on the predicted state, the CR module may recommend modifying the nominal FH sequence or keeping it as is. In the latter case, the CR module may also recommend boosting the Tx power to combat relatively mild levels of interference. If there is a need to adjust the FH sequence, the CR module will also search for appropriate replacement frequencies, taking into account the frequencies assigned to other links. The spectrum sensing results are then reported back to the transmitter over the reverse link. The time lag between the current time and the time of the monitored frequency channel is designed to allow for the feedback message to be received back at the LEO satellite. By focusing on "future" frequencies in the FH sequence, our approach prevents transmissions over channels with high interference, which reduces the bit error rate (BER) and avoids unnecessary energy consumption.

In our formulation, the number of concurrently sensed channels is taken as an input parameter. The sensing time per channel is a controllable parameter that can be selected according to channel conditions (i.e., more measurements may be needed in highly varying channel conditions). This sensing time is assumed to be considerably smaller than the transmission slot in the FH sequence, allowing the CR module to sequentially sense several frequencies within one transmission slot.

Consider a given uplink that is associated with a nominal FH sequence of a sufficiently large period. This sequence is also known to the receiving GEO satellite. Let τ_t be the duration of one slot (time spent transmitting at a given frequency). We assume that τ_t is equal to the transmission duration of one or more packets. Let $d(s)$ denote the frequency selected for transmission during a given time slot s. For example, if frequency i is used for transmission during slot 1, then $d(1) = i$. The GEO satellite has several receive chains that are used for concurrent reception of uplink transmissions (on different frequencies) as well as out-of-band sensing of currently unused frequencies. Let τ_s be the time spent sensing a given channel in the FH sequence (i.e., the sensing time). Without loss of generality, we assume $\tau_t = L\tau_s$ for some integer L, where L defines the number of channels that CR can sense within one transmission slot. Finally, let $\mathcal{J}$ denote the set of links and $\mathcal{I}$ denote the set of sensed channels.

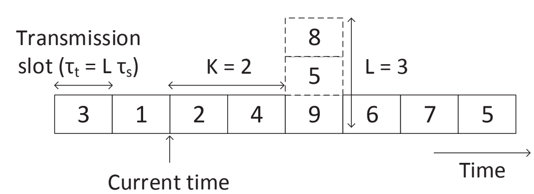


Fig. 2: Proactive sensing of "future" frequencies (K = 2, L = 3, single uplink case).

Now, consider an arbitrary time slot s. During that time slot, LEO and the GEO satellites will be tuned to frequency $d(s)$. At the start of that time slot, the sniffer in the GEO satellite will be sensing channel $d(s+K)$, where K (in slots) is called the *lag parameter*. If channel $d(s+K)$ does not satisfy the channel quality requirements described later, the sniffer will monitor up to L other frequency channels, until it can find a suitable channel to be used for transmission during slot $s+K$. If for a LEO j, a channel with the desired quality cannot be found, the receiver will instruct the transmitter to stay silent during slot $s+K$ (so as not to waste energy). The design parameters are explained with an example in Figure 2. The lag parameter allows for adequate time to report back the outcome of the sensing process. This time is called *the feedback time*, and is denoted by τ_f.

Let $P_j^{(i)}$ denote the Tx power of LEO j when communicating over channel i. $P_j^{(i)}$ is required to be between a nominal power, P_{nom}, and a maximum allowed Tx power $P_{\max}$. Our goal is to ensure that all satellites are assigned channels such that their SINR requirements are met. At the same time, we would like the total Tx power and the communication overhead resulting from altering the FH sequences to be minimized. To represent these objectives, let $A \triangleq \sum_{i=1}^{L}\sum_{j=1}^{T}\alpha_j^{(i)}P_j^{(i)}(\alpha)$ and $B \triangleq \sum_{i=1}^{L}\sum_{j=1}^{T}\alpha_j^{(i)}\ [i \neq d_{j,nom}]$, where $[\cdot]$ is the indicator function, $d_{j,nom}$ is the nominal frequency assigned to LEO j and $\alpha_j^{(i)}$ is a binary variable defined as

$$\alpha_j^{(i)} = \begin{cases} 1, & \text{if channel } i \text{ is assigned to LEO } j \\ 0, & \text{otherwise} \end{cases} \tag{1}$$

With this definition, we can formulate a multi-objective minimization problem and convert it to a single objective one by introducing an additional variable β, $0 \leq \beta \leq 1$, and using a linear combination of A and B. Then, the optimization problem becomes:

$$\begin{aligned} \underset{\{\alpha_j^{(i)}:\, i\in\mathcal{I},\, j\in\mathcal{J}\}}{\text{minimize}} \quad & \left(\frac{\beta A}{P_{\max}T} + \frac{(1-\beta)B}{T}\right) \\ s.t. \quad & \text{SINR}_j^{(i)} \geq \alpha_j^{(i)}\text{SINR}_{th}, \quad \forall j \in \mathcal{J}, \forall i \in \mathcal{I} \\ & P_{\text{nom}} \leq P_j^{(i)} \leq P_{\max}, \quad \forall j \in \mathcal{J}, \forall i \in \mathcal{I} \\ & \sum_{j=1}^{T}\alpha_j^{(i)} \leq 1, \quad \forall i \in \mathcal{I} \\ & \sum_{i=1}^{L}\alpha_j^{(i)} \leq 1, \quad \forall j \in \mathcal{J} \end{aligned} \tag{2}$$

where $\text{SINR}_j^{(i)}$ is the SINR of LEO j when it uses channel i for transmission, SINR_{th} is the minimum SINR that needs to be met for successful transmission, $\mathcal{J} = \{1, \cdots, T\}$, and $\mathcal{I} = \{1, \cdots, L\}$. Time indices are omitted for clarity. The first term of the objective function represents the normalized sum of all assigned Tx powers, and the second term represents the normalized total number of changes in the nominal FH sequence. Finally, last two constraints ensure that each LEO is assigned at most one channel, and each channel is assigned to at most one LEO.

In the event that we cannot find a feasible solution for all links $j \in \mathcal{J}$ during slot $s+K$, we declare an outage event for the infeasible links and continue transmission for the feasible ones (i.e., assignments that require a Tx power less than $P_{\max}$).

Transformation of the Problem

One way of doing the channel assignment according to the above optimization problem is to use exhaustive search, which has exponential complexity. To reduce that, we use an algorithm that transforms this optimization into a maximum weighted perfect bipartite matching problem, which has a polynomial-time solution [11]. Without loss of generality, let us assume $L \geq T$, i.e., the number of sensed channels at each slot is larger than the number of LEO satellites.

Step 1. Compute the minimum required powers: For every link j and channel i, we compute $P_{j,req}^{(i)}$ using SINR_{th} and the power-SINR function (explained later). Then, we identify infeasible (i, j) pairs such that $P_{j,req}^{(i)} > P_{\max}$.

Step 2. Assign link weights and solve the matching problem: We create $L - T$ additional nodes to represent dummy radios and denote this set of dummy radios by $\mathcal{J}_D$. Every element in $\mathcal{I}$ will be connected to each element in $\mathcal{J} \cup \mathcal{J}_D$, and these links will be assigned a link weight as follows:

$$w_j^{(i)} = \begin{cases} \Gamma_1, & \text{if } P_{j,req}^{(i)} \leq P_{\max},\ i \in \mathcal{I},\ j \notin \mathcal{J}_D \\ \Gamma_2, & \text{if } P_{j,req}^{(i)} > P_{\max}, \text{ or } j \in \mathcal{J}_D \end{cases}$$

where $\Gamma_1 \triangleq \frac{\beta}{P_{max}}P_{j,req}^{(i)} + (1-\beta)\ [i \neq d_{j,nom}]$ and Γ_2 is a very large constant. This assignment problem can be solved using the well-known Hungarian algorithm [12], which requires a square cost matrix. This is the reason that we need to create $\mathcal{J}_D$ dummy radios.

III. PREDICTING FUTURE CHANNEL CONDITIONS

For proactive sensing, channel assignments need to be made according to future channel conditions, rather than current ones. To do that, we use an n-state CTMC to characterize channel variations. Let the outcome of the sensing process at time i be denoted by Y_i. The range of Y_i is divided into n regions: $R_1 \stackrel{\text{def}}{=} \{Y_i : 0 \leq Y_i < z_1\}, R_2 \stackrel{\text{def}}{=} \{Y_i : z_1 \leq Y_i < z_2\}, \cdots, R_n \stackrel{\text{def}}{=} \{Y_i : Y_i \geq z_{n-1}\}$ for some thresholds $z_1, z_2, \cdots, z_{n-1}$. Let $S = \{1, 2, \cdots, n\}$ denote the state space, where state m means that $z_{m-1} \leq Y_i < z_m$, $m \in S$. If $Y_i > z_n$, we say that the channel is unusable. The current state of the channel and the transition rates between states can be acquired using the sensing results. Using these, the future state of the channel can be obtained. Since the channel conditions are highly variable, the thresholds $z_1, z_2, \cdots, z_{n-1}$ should be sufficiently apart to increase the probability of a successful transmission (which also allows the MC to be birth-and-death type). The allocated Tx power versus measured interference and noise power graph is shown in Figure 3, and resulting MC is shown in Figure 4.

Let $\rho(x)$ denote the total rate at which the MC leaves state x, i.e., $\rho(x) = \sum_{y \neq x}\lambda(x, y)$. Let Q be the infinitesimal generator matrix of the MC; the $(x,\ y)$ entry of Q equals $\lambda(x, y)$ if $x \neq y$, and equals $-\rho(x)$ if $x = y$. CTMC models have been previously used to characterize wireless channels [13] [14], and techniques have been proposed to determine the parameters of the MC based on level-crossing rate (LCR) analysis [15]. The LCR at level z_j, denoted by $N_{z_j}, j = 1, 2, \cdots n-1$, and the corresponding steady-state distribution, $\pi_j, j = 1, 2, \cdots n$, are provided below.

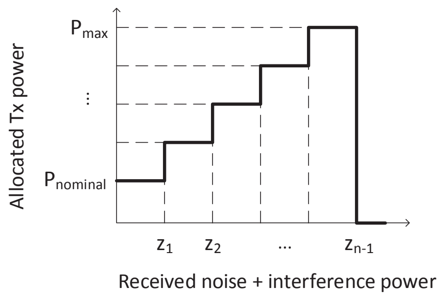


Fig. 3: Allocated Tx power vs. measured interference and noise power.

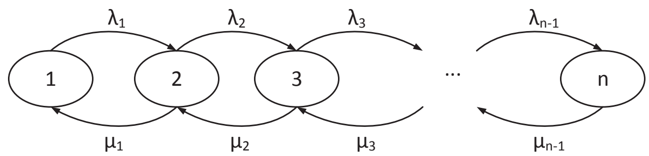


Fig. 4: n-state Markov chain.

Next, we determine the parameters of the generator matrix Q based on the stationary distribution of the system and the LCRs. To simplify the notation, we let $\lambda(j, j+1) = \lambda_j$, and $\lambda(j+1, j) = \mu_j$. Our proposed n-state birth-and-death process is positive recurrent, and has an invariant probability distribution π_j, given by:

$$\pi_j = \frac{\lambda_1 \dots \lambda_{j-1}}{\mu_1 \dots \mu_{j-1}} \pi_1, \quad j = 2, \cdots, n \tag{3}$$

where π_1 is given by:

$$\pi_1 \triangleq \left(1 + \sum_{j=1}^{n-1} \frac{\prod_{i=1}^{j} \lambda_i}{\prod_{i=1}^{j} \mu_i}\right)^{-1}. \tag{4}$$

The additional relations necessary to uniquely determine Q are provided by the LCRs. From [15][16], $N_{z_j}, j = 1, 2, \cdots, n-1$, can be expressed in terms of λ_j and π_j as:

$$N_{z_i} \;=\; \lambda_i \pi_i, \quad i = 1, \cdots, n-1. \tag{5}$$

Here, z_1 and z_{n-1} are computed using the selected P_{nom} and $P_{\max}$ values. To compute $P_{\max}$ and P_{nom}, we need to consider the SINR, which is expressed in dB as [17, Section 12.6]:

$$\text{SINR} = P_T + G_T + G_R - \text{Losses} - P_{N+I} \tag{6}$$

where P_T and P_{N+I} are the transmitted power and the noise-plus-interference power, respectively; G_T and G_R are the transmitter and the receiver antenna gains, respectively; and Losses are the losses experienced by the signal while propagating over the wireless channel. Then, z_1 is computed by setting the SINR to SINR_{th} and P_T to P_{nom}, in dB. The corresponding P_{N+I} is the value of z_1. Similarly, z_{n-1} is computed by setting the SINR to SINR_{th} and P_T to $P_{\max}$. The corresponding P_{N+I} is the value of $z_n - 1$.

Clearly, the current and future states are dependent on the sensing results. However, as the time between the measurements and predictions, K, increases, the freshness of information decreases, which affects the predictions negatively. One way of incorporating that effect is to choose the transition rates, λ_i, μ_i, from a probability distribution and increasing the variance of that distribution as K increases. That way, we account for the uncertainty in the predictions.

After the channel enters state j, it stays in the given state for an exponentially distributed amount of time with parameter λ_1 for $j = 1$, μ_{n-1} for $j = n$, and $(\lambda_j + \mu_{j-1})$, otherwise. Leaving state j, the channel either enters state $j+1$ with probability $\lambda_j/(\lambda_j + \mu_{j-1})$ or $j-1$ with probability $\mu_{j-1}/(\lambda_j + \mu_{j-1})$ for $j = 2, \cdots, n-1$. Obviously, predicting the channel state to be i, where the actual state is j, with $i > j$, would not impact correct reception, since the Tx power for state i is larger than the Tx power for state j. As the channel conditions are not expected to change during the channel coherence time, T_c, we assume that $\lambda_j + \mu_{j-1}$ is normally distributed with mean $1/T_c$ and variance σ^2. T_c can be calculated as [15]:

$$T_c = \sqrt{\frac{9}{16\pi f_d^2}} \tag{7}$$

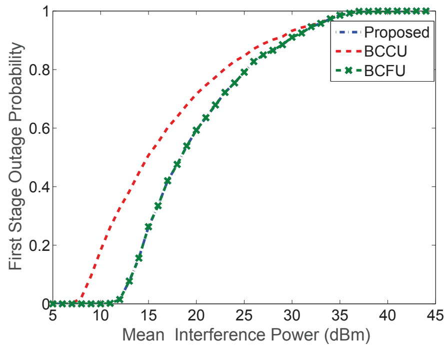
where f_d is the maximum Doppler frequency. This way, we make sure that the holding time in state j is a random variable, with expected value T_c. Increasing σ (to simulate the effect of a larger K) would allow $\lambda_j + \mu_{j-1}$ to be selected from a wider range, and in return, makes it harder to predict the future state.

Feedback protocol: After each transmission slot, the GEO sends feedback messages to LEOs to notify them about the required Tx powers for the upcoming slot. These messages are not ACKed. If a LEO does not receive a feedback packet, it transmits over a predefined channel at power $P_{\max}$ in order to increase the probability of successful delivery. In that case, the difference between the required power and $P_{\max}$ is wasted. However, if the GEO switched to a different channel assuming LEO would get the control packet, the whole Tx power would be wasted and data packet would be lost.

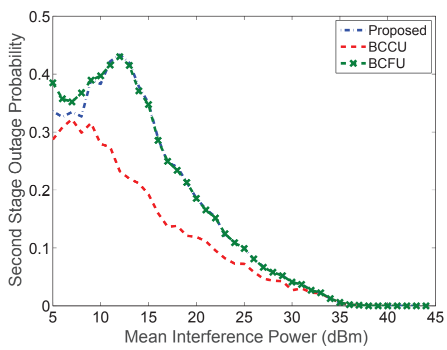
IV. Performance Evaluation

We compare our proposed DFH algorithm with two algorithms, namely, the best-channel-to-closest-user (BCCU) and the best-channel-to-farthest-user (BCFU). In BCCU, the receiver allocates the channels to satellite links starting with the best channel (channel with lowest interference) and closest LEO. In contrast, in BCFU the receiver allocates the channels to satellites starting with the best channel and farthest LEO. If the best channel cannot serve the farthest LEO, the receiver tries the next farthest LEO and so on. In all algorithms, the receiver allocates the best T channels among all possible channels, since the remaining $L - T$ channels would require higher Tx powers. For the proposed algorithm, we set β to 1 for a fair comparison. The values of some of the key simulation parameters are as follows: distances between LEOs and the GEO range from 1000 to 11000 km, carrier frequency $f_c = 10$ GHz, $T = 20$, $L = 100$, $P_{\max} = 40$ dBm, $\text{SINR}_{th} = 10$ dB, and the Tx and Rx antenna gains $G_T = G_R = 55$ dBi.

We compare the performances of the three algorithms in terms of the number of feasible links and the average power



(a) First-stage outage probability



(b) Second-stage outage probability

Fig. 5: First- and second-stage outage probabilities vs. mean interference powers

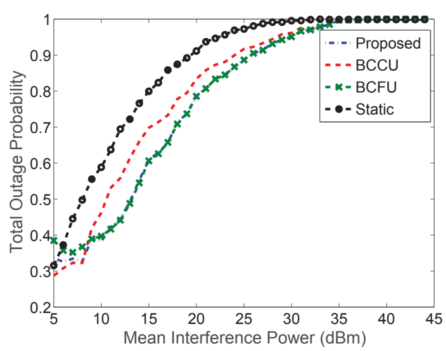
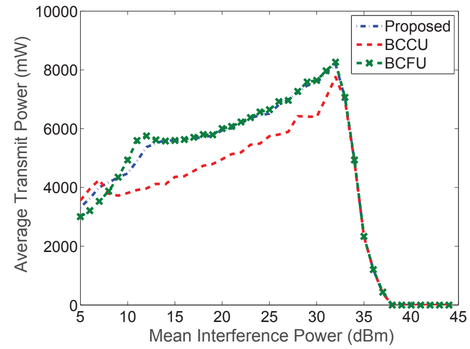


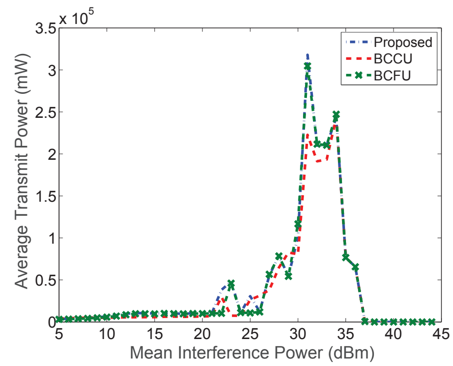
Fig. 6: Total outage probability vs. mean interference power.

per feasible link. We consider two types of feasible links, first- and second-stage. First-stage feasible links are those that can be supported without exceeding the maximum Tx power. In other words, number of first-stage feasible links can be found by subtracting the number of outages from the total number of links. Second-stage feasible links, on the other hand, correspond to links that require less than or equal amount of the *predicted* Tx power. Links that experience outage in the first stage are not assigned any Tx power. However, links that are feasible in the first stage but infeasible in the second stage (due to varying channel conditions) are assigned Tx powers that are less than or equal to $P_{\max}$, and that power is wasted since the required SINR cannot be achieved at the receiver under the current channel conditions.

In Figure 5, we depict the first- and second-stage outage



(a) First-stage feasible links

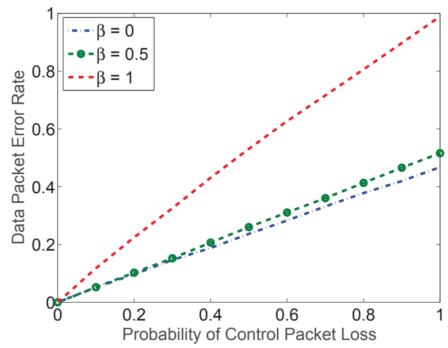


(b) Second-stage feasible links

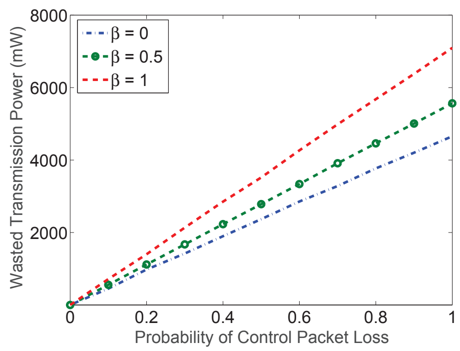
Fig. 7: Mean transmit power per first- and second-stage feasible links vs. mean interference power.

probabilities vs. the mean interference powers. Notice that the first stage outage probability is the same for the proposed algorithm and BCFU. In fact, that is the lowest achievable outage probability, since the outage is a constraint in the optimization problem of the proposed algorithm. BCFU can also achieve this outage probability level, as it starts with assigning the best channel to the farthest link, if possible. The summation of these probabilities, referred to as the total outage probability, is shown in Figure 6. We observe that all algorithms outperform the static approach, where the predefined FH sequence is not altered, as the bad channels cannot be avoided in the static approach. We also observe that the proposed algorithm slightly outperforms BCFU under low interference power levels.

In Figure 7, we depict the average transmit power per link for first- and second-stage feasible links vs. mean interference power. Notice that BCCU has lower average transmit power even though the proposed algorithm tries to minimize the Tx power. The reason is in the proposed algorithm, we ensure that every satellite link is assigned a feasible channel, whereas in BCCU, the farther users may be declared as BHs. Notice that in Figure 7a, the average transmit power per first-stage feasible link approaches $P_{\max}$ as the interference power increases up to a certain point, and then it decreases to zero. This is because all links are declared as BHs and none of them is assigned any power when the mean interference power exceeds 33 dBm. In Figure 7b, we observe that the average transmit power per second-stage feasible link increases up to a certain point.



(a) PER vs. probability of a control packet loss



(b) Wasted Tx power vs. probability of a control packet loss

Fig. 8: Effect of erroneous feedback channel

This is because first-stage feasible links are assigned powers but they become infeasible in the second stage, which takes the average transmit power per second stage feasible link to infinity. We do not plot the average transmit power per feasible link for the static case, since it will go to infinity as the mean interference power keeps increasing. From these figures, we observe that there is a tradeoff between minimizing the outage probability and the average transmit power per feasible link.

We also investigate the effect of an unreliable feedback channel. For this purpose, we vary the probability of control packet loss and plot the packet error rate (PER) and wasted Tx power graphs. In Figure 8a, we see that as the probability of control packet loss increases, the PER also increases, reaching 1 for $\beta = 1$. In Figure 8b, wasted power reaches 7×10^3 mW when $\beta = 1$, which is close to the maximum power of $P_{\max} = 10^4$ mW, since all LEOs that did not receive control packets will transmit with maximum power and that power is likely to be wasted. With $\beta = 1$, the proposed algorithm tries to minimize the Tx powers only, resulting in many changes in the nominal FH sequence. If we set β to 0, the algorithm tries to minimize the changes in the FH sequence only, which results in less PER and wasted power. Finally, if we choose $0 < \beta < 1$, the PER and wasted powers will be in between. Since BCCU and BCFU algorithms do not take the number of changes in the FH sequence into account, their performances behave similar to the proposed algorithm with $\beta = 1$. This makes the proposed algorithm more desirable when the feedback channel is erroneous.

V. Conclusions

In this paper, we investigated three techniques for dynamic channel assignment in multi-user SATCOM. These techniques exploit the sensing capabilities of CRs for detecting channel quality, predicting future channel conditions, and replacing them in real-time when necessary. We advocated an assignment technique whose goal is to ensure that all satellite links are assigned channels such that their SINR requirements are met, while the total Tx power and the communication overhead resulting from altering the FH sequences are minimized. With this definition, we formulated a multi-objective minimization problem and solved it by transforming it into the maximum weighted perfect bipartite matching problem. Then, we showed how future channel conditions can be predicted using current sensing results. Finally, we evaluated the performances of all three assignment techniques, and showed the effect of control packet losses on their performances.

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