Receiver Characteristic Aware Optimal Resource Allocation in Multi-RAT Wireless Networks

Amr Nabil, Aditya V. Padaki, Mohammad J. Abdel-Rahman, Allen B. MacKenzie, and Jeffrey H. Reed
Wireless @ VT, Department of Electrical & Computer Engineering, Virginia Tech, Blacksburg, VA
{anabil, avpadaki, mo7ammad, mackenab, reedjh}@vt.edu

Abstract—To cope with increasing demand on wireless services, next-generation wireless systems are expected to use multiple radio access technologies, with different receive and transmit characteristics, operating over the same band of spectrum in a spatial-temporal neighborhood. This will make the RF front-ends susceptible to unprecedented adjacent-channel interference (ACI), which can jeopardize communication performance. In this paper, we propose a novel ACI-aware joint channel and power allocation framework that takes into account the receiver imperfections arising due to (i) imperfect image frequency rejection, and (ii) analog-to-digital converter aliasing. The proposed resource allocation framework aims at minimizing the number of allocated channels and the aggregate power transmitted while satisfying the rate demands of different links in a multi-RAT environment. The results demonstrate the criticality of receiver-characteristic awareness when designing resource allocation schemes for different types of networks. Also, the trade-off between channel allocation and power assignment is explained.

I. INTRODUCTION

Rapid increases in data transfer volume and number of wireless devices connected to wireless networks are expected to continue [1]. This places enormous demands on the radio frequency (RF) spectrum. To cope with this increasing demand, several researchers have proposed improving the spectrum utilization by replacing the static and exclusive spectrum allocation model with a dynamic allocation model. This provides the way for network sharing and coexistence (see, for example, [2], [3]).

To ensure harmonious coexistence, several frameworks based on sensing, beacons, and databases have been proposed [2]. Such frameworks will allow many radio access technologies (RATs) to operate in the same band while avoiding harmful interference to each other. However, realizing such frameworks imposes an onerous task of managing wireless networks with diverse technologies and optimizing several parameters to maximize spectral efficiency. The Spectrum Access System (SAS) is one database-driven framework in which a centralized entity manages spectrum in real time. SAS has been recently adopted by the FCC to enable spectrum sharing in the 3.5 GHz band [4].

Interference can be broadly categorized into two types—co-channel and adjacent channel interference (ACI). The former is due to radio signals in overlapping frequencies with the desired signal. ACI is again of two types: One caused by transmitters on adjacent channels due to spectral leakage into the desired channel. The other type of ACI is due to the nonlinear response of the receiver front-end which causes the radio signals in adjacent channels to mix-up with the intended signal in the desired channel. There has been much literature detailing the management of co-channel interference and ACI due to spectral leakage between coexisting systems [5], [6], [7]. However, management of ACI due to the nonlinear response of the receiver front-end has received less attention. This type of ACI primarily arises due to receiver imperfections and inherent non-linearity in their operation. Conventionally, receivers were protected from ACI during band planning and allocation by carefully-crafted guard bands customized to the technologies and receiver RF front-ends. This prevented adjacent channel signals from entering the receiver circuits. However, next-generation wireless networks will witness an unprecedented diversity in RATs and front-ends, accessing the same band of spectrum in a spatial-temporal neighborhood. Thus, the framework of allocating customized static guard bands collapses when exceedingly diverse RATs need to be managed dynamically. Managing ACI due to the nonlinear response of the receiver front-end adds to the challenges for coexistence of wireless networks on a dynamic basis.

It is imperative for next-generation wireless networks (with coexistence and sharing) to consider the impact of receiver front end imperfections on the desired channels while performing network-wide spectrum allocation. The ill effects of allocating spectrum oblivious to receiver sensitivities is exemplified by the recent LightSquared (LS) controversy. A company, called LS, obtained a license to deploy LTE repeaters in a band adjacent to the civilian GPS downlink. The planned deployments were worth close to $3B. However, ex-post testing and analysis demonstrated that the LTE repeaters compromised the performance of GPS receivers because the latter poorly
tolerated ACI. This resulted in the FCC suspending the license for LS. We note that FCC was dealing with allocation of static bands in this case. If channel allocations remain oblivious to receiver characteristics, such an issue would be significantly amplified when disparate systems want to coexist dynamically.

As mentioned earlier, efficient utilization of RF spectrum is of paramount importance. Frameworks which minimize the number of allocated channels and total transmit power whilst ensuring minimum data rate requirements are of immense interest for next-generation spectrum management systems (e.g., SAS). The significance of considering receiver performance in frameworks for efficient spectral utilization was first shown in [8]. Such frameworks are complete only upon the inclusion of receiver characteristics and accounting for their impact on spectrum utilization in dynamic and heterogeneous radio environments.

In this paper, we propose a comprehensive framework to account for receiver imperfections arising due to image frequency rejection and analog-to-digital converter (ADC) aliasing for informed channel allocations. We describe the receiver architecture considered and outline the methodology for accounting for the impact of these parameters on the communication link for the specified operating region of the receiver. To the best of our knowledge, this is the first attempt to include the impact of aforementioned receiver parameters for channel allocation and power assignment optimization.

Main contributions:

- We develop a receiver-characteristics-aware optimization framework for resource allocation in multi-RAT wireless networks.
- We provide insights on how to set the problem parameters under the proposed framework to control the trade-off between the number of allocated channels and the total power transmitted in the network.
- We show the effect of heterogeneous receiver characteristics on the overall utilization of network resources.

The rest of the paper is organized as follows. In Section II, preliminaries on the sources of wireless receiver imperfections are provided. In Section III, we introduce the system model and state our problem. In Section IV, we develop the proposed optimization framework. Section V shows numerical results and gives insights on how to set the configuration parameters of the proposed framework. In Section VI, we conclude our work and indicate directions for future research.

II. PRELIMINARIES

In this section, we briefly outline the receiver architecture considered and the phenomena that cause ACI. Throughout the discussion of this paper, we assume a Direct Conversion Receiver (DCR) architecture as shown in Fig. 1, which is increasingly common in next-generation wireless systems [9]. The front end Band Pass Filter (BPF) typically spans the entire range of RF frequencies in which the receiver is designed to operate. Thus, the desired signal bandwidth is typically a small fraction of the front end BPF. Moreover, since this is an RF filter, it generally exhibits poor selectivity. Consequently, unwanted signals from adjacent bands enter the receiver front end.

The receiver transfer characteristics can be divided into three regions as shown in Fig. 2: Linear, weak nonlinear, and strong nonlinear. The impact of distortions when the receiver operates in the nonlinear region was previously considered in [10]. However, accounting for ACI due to receiver impairments in the linear region is missing in the existing literature. In this paper, we introduce a receiver-characteristics-aware resource allocation framework which takes into consideration receiver impairments occurring in the linear region of operation.

We consider two major receiver impairments that lead to ACI namely, incomplete image frequency rejection and imperfect sampling leading to ADC aliasing. Due to these effects, components of signals from adjacent channels appear in the desired channel at the output of the RF front end.

A. Impact of Receiver Impairments

In this section, we describe the quantitative formulation of the impact of the two receiver impairments based on the models developed in [9], [11], [12]. We describe the framework specific to our use case and direct readers keen on elaborate analysis to those references.

Consider a receiver front end band pass filter spanning a set of contiguous channels $C = \{1, 2, \ldots, C\}$ of equal
TABLE I: Matrix representation example of receiver impairments for \( C = 4 \) and \( B = 2 \) [12].

<table>
<thead>
<tr>
<th>Mixer</th>
<th>( P_{\text{mix}} )</th>
</tr>
</thead>
</table>
|       | \[
\begin{bmatrix}
0 & 1 & 0 & 1 \\
0 & 0 & 1 & 0 \\
1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0
\end{bmatrix}
\] |

| ADC | \( P_{\text{ADC}} = \begin{bmatrix}
|G|^2 & |G|^2 & |G|^2 & |G|^2 \\
|G|^2 & |G|^2 & |G|^2 & |G|^2 \\
|G|^2 & |G|^2 & |G|^2 & |G|^2 \\
|G|^2 & |G|^2 & |G|^2 & |G|^2
\end{bmatrix}
\] |

| Receiver Chain | \( P_{R\text{F\_chain}} = Z_{\text{ADC}} Z_{\text{AAF}} Z_{\text{mix}} P \) |

where \( P_{R\text{F\_chain}} \) denotes the power received in channel \( c \in C \). Throughout the discussion in this paper, we assume the receiver is operating in the linear region.

1) Mixer – image frequency rejection: We assume the local oscillator frequency to be the center of the front-end band pass filter. Imperfect mixing results in the image frequency signal component appearing at the desired channel \( c \). Using the developments in [12], we re-formulate the mixer output at the desired channel \( c \in C \) specific to our use case as,

\[
P_{\text{mix}}[c] = P_R[c] + \lambda P_R[C - c + 1],
\]

where \( P_{\text{mix}}[c] \) is the mixer output at channel \( c \), and \( \lambda \) denotes the image frequency rejection ratio of the receiver.

2) ADC aliasing: The input signal to the ADC spans \( C \) channels. However, if there are only a set \( B = \{1, 2, \ldots, B\} \) of channels in the first Nyquist zone of the ADC, where \( B \subset C, B < C \), there will be aliasing. Assuming that an anti-aliasing-channel-select filter before the ADC filters out the unwanted frequencies, the output of this filter for channel \( c \) can be written as, \( P_{\text{AAF}}[c] = |G|^2 P_{\text{mix}}[c] \), where \( P_{\text{AAF}}[c] \) is the anti-aliasing filter output at channel \( c \), and \( G \) is the linear gain of the filter. We now re-formulate the analysis in [12] to obtain the ADC output for channel \( c \in B \) of the first Nyquist zone as:

\[
P_{\text{ADC}}[c] = \sum_{k=-\left\lfloor \frac{c}{2B} \right\rfloor}^{\left\lfloor \frac{c}{2B} \right\rfloor} P_{\text{AAF}} \left( \left( \frac{C - B}{2} \right) + c - k B \right).
\]

3) Entire receiver chain: The output power of the channel \( c \) in the first Nyquist zone post sampling for the receiver chain can be expressed as:

\[
P_{R\text{F\_chain}}[c] = \sum_{k=-\left\lfloor \frac{c}{2B} \right\rfloor}^{\left\lfloor \frac{c}{2B} \right\rfloor} \left( P_R[i - k B] + \lambda P_R[C - i + k B + 1] \right),
\]

where \( i = \left( \frac{C - B}{2} \right) + c \). The example matrix representation is shown in Table I. In general, the output of each channel of the first Nyquist zone is:

\[
P_{R\text{F\_chain}} = Z P,
\]

where \( Z = Z_{\text{ADC}} Z_{\text{AAF}} Z_{\text{mix}} P \). Let \( \mu_{cc} \) represent the element of row \( c \) and column \( \hat{c} \) of the matrix \( Z \). Post digitization, if the desired channel in the first Nyquist zone, then \( \mu_{cc} \) captures the impact of the signals in an adjacent channel \( \hat{c} \in C \setminus \{c\} \) on the desired channel \( c \).

III. SYSTEM MODEL AND PROBLEM STATEMENT

We consider a set \( M = \{1, 2, \ldots, M\} \) of links belong to different networks in a multi-RAT environment. Each link \( m \in M \) can be assigned a transmission power on channel \( c \) (denoted by \( \gamma^m_c \)), where \( 0 \leq \gamma^m_c \leq \gamma_{\text{max}} \) and \( \gamma_{\text{max}} \) is the maximum total power that can be assigned to any link. We assume that the front end band pass filter of each link’s receiver spans the whole \( C \). The channels allocated to link \( m \in M \) need to be contiguous. \( C_m \) represents a subset of channels so that a signal transmitted on channel \( \hat{c} \in C_m \) causes ACI to channel \( c \) at the receiver of link \( m \) with amount of \( \mu^m_{\hat{c}c} \) of the signal power. Denote \( I = \{1, 2, \ldots, I\} \) as the set of data rates with which data transfer can be performed on any channel. The chosen data rate from this set depends on the received signal-to-interference-plus-noise (SINR) value on the corresponding channel taking into consideration intended signal’s power and ACI.

A. Channel Effect on the Received Signal Strength

The received signal strength is affected by the channel between the transmitter and the receiver. Channel effects are mainly due to path loss and small scale fading. We assume that each link’s transmitter and receiver is independently positioned according to a Binomial Point Process (BPP) [13]. The path loss coefficient, denoted by \( PL^{mn} \), is a function of the distance \( d^{mn} \) between transmitter \( n \) and receiver \( m \), and path loss exponent \( \alpha \) (i.e. \( PL^{mn} = (d^{mn})^{-\alpha} \)). Small scale propagation is modeled using a Rayleigh fading model. We denote the overall channel coefficient between transmitter \( n \) and receiver \( m \) on channel \( c \) as \( h^{mn}_c \), and \( h^{mn}_c \) can be obtained by multiplying the path loss coefficient by the Rayleigh fading coefficient.

B. Problem Statement

Each link \( m \in M \) has a rate demand (denoted by \( D^m \)) to be met through aggregating data rates on its allocated channels. The main objective is to minimize the total number of utilized channels. Also, minimizing the total amount of power transmission from all links is desired. The overall objective is a linear combination of aforementioned two objectives while meeting the data rate demands of all links. Table II summarizes the important notation used in this paper.
TABLE II: Notation.

<table>
<thead>
<tr>
<th>Set and Indices</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \mathcal{M} )</td>
<td>Set of links in the network</td>
</tr>
<tr>
<td>( \mathcal{C} )</td>
<td>Set of available contiguous channels in the network</td>
</tr>
<tr>
<td>( \mathcal{C}^m )</td>
<td>Subset of channels so that a signal transmitted on channel ( c \in \mathcal{C}^m ) causes ACI to channel ( c \in \mathcal{C} ) at the receiver of link ( m \in \mathcal{M} )</td>
</tr>
<tr>
<td>( I )</td>
<td>Set of data rates that can be supported on any channel</td>
</tr>
</tbody>
</table>

Data:

- \( B^m \): Maximum number of channels that can be allocated to link \( m \in \mathcal{M} \) which corresponds to the bandwidth of the ADC filter.
- \( \gamma_{\text{max}} \): Maximum total power that can be assigned any link.
- \( \eta_i \): SINR threshold level \( i \).
- \( \mu_{c,c'} \): ACI effect on the receiver of link \( m \in \mathcal{M} \) caused by channel \( c' \) signal on channel \( c \in \mathcal{C} \).
- \( h_{c,m}^{\text{in}} \): Channel coefficient between the transmitter of link \( n \in \mathcal{M} \) and the receiver of link \( m \in \mathcal{M} \) on channel \( c \in \mathcal{C} \).
- \( \sigma^2 \): Average power of the background noise.
- \( D^m \): Data rate demand on link \( m \in \mathcal{M} \).

Decision Variables:

- \( x_c^m \): Binary variable to indicate whether or not channel \( c \in \mathcal{C} \) is allocated to link \( m \in \mathcal{M} \).
- \( \gamma_m \): Assigned power to link \( m \in \mathcal{M} \) on channel \( c \in \mathcal{C} \).
- \( R_c^m \): Achievable rate on channel \( c \in \mathcal{C} \) if allocated to link \( m \in \mathcal{M} \).

IV. OPTIMIZATION FRAMEWORK

In this section, we present the proposed optimization framework which accounts for the unique characteristic of each link’s receiver. We start with the problem constraints, then we introduce the objective function.

A. Optimization Constraints

1) Avoiding co-channel interference between links: Denote \( x_c^m \) as a binary variable to indicate whether or not channel \( c \in \mathcal{C} \) is allocated to link \( m \). Two links cannot utilize the same channel. This can be represented using the following set of constraints:

\[
\sum_{m \in \mathcal{M}} x_c^m \leq 1, \quad \forall c \in \mathcal{C}. \tag{5}
\]

2) Restricting maximum number of channels per link: The maximum number of channels, denoted as \( B^m \), that can be allocated to link \( m \) is proportional to the bandwidth of the ADC filter.

\[
\sum_{c \in \mathcal{C}} x_c^m \leq B^m, \quad \forall m \in \mathcal{M}. \tag{6}
\]

3) Contiguity of link’s allocated channels: All channels allocated to a specific link have to be contiguous. If a link utilizes a channel \( c \) and other channels, the consecutive channel \((c+1)\) or \((c-1)\) has to be allocated to the same link. For example, link \( m \) seizes two channels where one of them is channel 1, the other one has to be channel 2. Considering each channel in the set indexed from 1 to \( C - 1 \), this restriction can be mathematically expressed as follows:

\[
\text{If } \{x_c^m = 1\} \text{ and } \sum_{\ell > c} x_{\ell}^m \geq 1 \Rightarrow \{x_{c+1}^m = 1\}. \tag{7}
\]

We first introduce an indicator variable

\[
y_c^m = \begin{cases} 1 & \text{if } \sum_{\ell > c} x_{\ell}^m \geq 1 \text{ and } x_c^m = 1 \\ 0 & \text{else} \end{cases}
\]

The forward relationship can be expressed as follows:

\[
\sum_{\ell > c} x_{\ell}^m \leq (M_c + 1) y_c^m, \quad \forall c \in \mathcal{C}, m \in \mathcal{M}, \tag{8}
\]

where \( M_c \) is an upper bound on \( \sum_{\ell > c} x_{\ell}^m - 1 \).

The backward relationship can be formulated as:

\[
\sum_{\ell > c} x_{\ell}^m + m_c y_c^m \geq m_c + 1, \quad \forall c \in \mathcal{C} \setminus \{C\}, m \in \mathcal{M}, \tag{9}
\]

where \( m_c \) is a lower bound on \( \sum_{\ell > c} x_{\ell}^m - 1 \). It is easy to see that \( m_c = -1, \forall c \in \mathcal{C} \).

Then, the original expression can be expressed as:

\[
\text{If } \{x_c^m = 1\} \text{ and } \{y_c^m = 1\} \Rightarrow \{x_{c+1}^m = 1\}, \tag{10}
\]

which can be formulated as follows:

\[
x_{c+1}^m \geq x_c^m + y_c^m - 1, \quad \forall c \in \mathcal{C} \setminus \{C\}, m \in \mathcal{M}. \tag{11}
\]

4) Relationship between channel allocation and power transmission: A link is to transmit with a non-zero power level only on its allocated channels. This restriction can be modeled using:

\[
\gamma_c^m \leq \gamma_{\text{max}} x_c^m, \quad \forall c \in \mathcal{C}, m \in \mathcal{M}. \tag{12}
\]

5) Restricting link total power transmission: The total power transmitted from a link across its allocated channels should not exceed a predefined limit \( \gamma_{\text{max}} \). This can be expressed as follows:

\[
\sum_{c \in \mathcal{C}} \gamma_c^m \leq \gamma_{\text{max}}, \quad \forall m \in \mathcal{M}. \tag{13}
\]

6) Link demand constraints: Each link’s data rate demand must be met. Denote \( R_c^m \) as the achievable data rate on channel \( c \) if allocated to link \( m \). This can be expressed as follows:

\[
\begin{cases}
R_c^m = 0 \text{ if } x_c^m = 0 \\
\text{else if } x_c^m = 1 \text{ then } R_c^m \geq 0
\end{cases}
\]

The link demand constraints are:

\[
\sum_{c \in \mathcal{C}} R_c^m \geq D^m, \quad \forall m \in \mathcal{M}. \tag{14}
\]
7) SINR-to-rate mapping constraints: In practical wireless systems, each range of SINR values is mapped to a single Modulation and Coding Scheme (MCS) which defines the resulting date rate. Assume that there are $I$ MCSs which correspond to the same number of supported data rates. Each SINR range is mapped to an achievable date rate value as shown in Fig. 3. In the context of our problem, the SINR at the receiver of link $m$ on channel $c$ can be expressed as:

$$\text{SINR}_c^m = \frac{h_{c,m}^n \gamma^m_{c,m}}{\sigma^2 + \sum_{n \in \mathcal{M}} \mu^m_n \sum_{n \in \mathcal{M}, n \neq m} h_{c,m}^n \gamma^m_{c,n}}, \quad \forall c \in \mathcal{C}, m \in \mathcal{M},$$

where $\sigma^2$ is the average power of the background noise, $h_{c,m}^n$ is the channel coefficient between the transmitter of link $n$ and the receiver of link $m$ on channel $c$. When the SINR is below a minimum threshold $\eta_i$, the rate is set to zero. This can be expressed as follows. For each $c \in \mathcal{C}, m \in \mathcal{M}$:

$$\frac{h_{c,m}^n \gamma^m_{c,m}}{\sigma^2 + \sum_{n \in \mathcal{M}} \mu^m_n \sum_{n \in \mathcal{M}, n \neq m} h_{c,m}^n \gamma^m_{c,n}} < \eta_i \Rightarrow R_c^m = 0.$$

The strict inequality can be converted to a non-strict one by adding a small number $\varepsilon$. Rearranging the terms and introducing a new binary variable $t_c^m$, the constraint can be represented as follows:

$$h_{c,m}^n \gamma^m_{c,m} - \eta_i \sum_{n \in \mathcal{M}} \mu^m_n \left( \sum_{n \in \mathcal{M}, n \neq m} h_{c,m}^n \gamma^m_{c,n} \right) + \varepsilon \leq \eta_i \sigma^2 \Rightarrow t_c^m = 1 \Rightarrow R_c^m = 0,$$

which can be modeled using the following two inequalities:

$$h_{c,m}^n \gamma^m_{c,m} - \eta_i \sum_{n \in \mathcal{M}} \mu^m_n \left( \sum_{n \in \mathcal{M}, n \neq m} h_{c,m}^n \gamma^m_{c,n} \right) + \varepsilon - (E_c^m - \epsilon_0) t_c^m \geq \eta_i \sigma^2 + \epsilon_0, \quad \forall c \in \mathcal{C}, m \in \mathcal{M},$$

where $E_c^m = -\eta_i \sum_{n \in \mathcal{M}} \mu^m_n \left( \sum_{n \in \mathcal{M}, n \neq m} h_{c,m}^n \gamma^m_{c,n} \right) - \eta_i \sigma^2$ and $\epsilon_0$ is a small constant.

$$R_c^m \leq (1 - t_c^m) R_{I_1}, \quad \forall c \in \mathcal{C}, m \in \mathcal{M}. \quad (14)$$

When the SINR value exceeds the minimum threshold $\eta_i$, we can represent the relationship between the SINR and the achievable rate as follows. Setting $R_c^m = 0$, for each $c \in \mathcal{C}, m \in \mathcal{M}, i \in \mathcal{I}$:

$$\sigma^2 + \sum_{n \in \mathcal{M}} \mu^m_n \left( \sum_{n \in \mathcal{M}, n \neq m} h_{c,m}^n \gamma^m_{c,n} \right) \geq \eta_i \sigma^2 \Rightarrow R_c^m \geq R_{i-1} + \varepsilon.$$

We introduce a new binary variable $s_{c,i}^m$ to break down the relationship between the two expressions as follows:

$$h_{c,m}^n \gamma^m_{c,m} - \eta_i \sum_{n \in \mathcal{M}} \mu^m_n \left( \sum_{n \in \mathcal{M}, n \neq m} h_{c,m}^n \gamma^m_{c,n} \right) \geq \eta_i \sigma^2 \Rightarrow$$

$$s_{c,i}^m = 1 \quad \text{and} \quad s_{c,i}^m = 1 \Rightarrow R_c^m \geq R_{i-1} + \varepsilon.$$

Focusing on the first relationship, the forward part can be modeled as follows:

$$h_{c,m}^n \gamma^m_{c,m} - \eta_i \sum_{n \in \mathcal{M}} \mu^m_n \left( \sum_{n \in \mathcal{M}, n \neq m} h_{c,m}^n \gamma^m_{c,n} \right) \geq \eta_i \sigma^2$$

$$\leq (J^m_i + \epsilon) s_{c,i}^m - \epsilon, \forall c \in \mathcal{C}, m \in \mathcal{M}, i \in \mathcal{I}, \quad (15)$$

where $J^m_i = h_{c,m}^n \gamma^m_{c,m} - \eta_i \sigma^2$ and $\epsilon$ is a small constant. The backward part can be represented using the following constraint.

$$h_{c,m}^n \gamma^m_{c,m} - \eta_i \sum_{n \in \mathcal{M}} \mu^m_n \left( \sum_{n \in \mathcal{M}, n \neq m} h_{c,m}^n \gamma^m_{c,n} \right) - \eta_i \sigma^2$$

$$\geq q_{c,i}^m (1 - s_{c,i}^m), \forall c \in \mathcal{C}, m \in \mathcal{M}, i \in \mathcal{I}, \quad (16)$$

where $q_{c,i}^m = -\eta_i \sum_{n \in \mathcal{M}} \mu^m_n \left( \sum_{n \in \mathcal{M}, n \neq m} h_{c,m}^n \gamma^m_{c,n} \right) - \eta_i \sigma^2$.

Now, focusing on the second relationship, the forward part can be modeled as follows:

$$R_c^m \geq (R_{i-1} + \varepsilon) s_{c,i}^m, \quad \forall c \in \mathcal{C}, m \in \mathcal{M}, i \in \mathcal{I}. \quad (17)$$
The backward part can be modeled as:

\[
R_c^m \leq R_{i-1} + \varepsilon - \epsilon + (Q_i + \epsilon) s_{c,i},
\]

\[
\forall c \in C, m \in M, \forall i \in I,
\]  

(18)

where \( Q_i = R_i - R_{i-1} - \varepsilon. \)

B. Optimization Objective

Minimizing the spectrum usage allows other networks to operate and coexist with SAS networks. On the other hand, minimizing the network power consumption saves energy costs and prolongs battery life in mobile networks. Also, it facilitates better coexistence with non-SAS networks because this will minimize the ACI caused to those networks. The goal of our problem then is to balance the minimization of the network power consumption and spectrum usage through a controlling parameter \( \beta. \) The objective function can be formulated as:

\[
\min \left\{ \sum_{m \in M} \sum_{c \in C} x_c^m + \beta \sum_{m \in M} \sum_{c \in C} \gamma_c^m \right\}. 
\]

The overall joint power and band allocation problem with receiver characteristics awareness can be expressed as a mixed integer linear program (MILP).

V. PERFORMANCE EVALUATION

In this section, we show the performance of the proposed optimization framework under both homogeneous and heterogenous network setups. Besides, we show how to control the trade-off between channel allocation and power assignment.

A. Evaluation Setup

In our experiments, we consider the network topology shown in Fig. 4. The network consists of five links belonging to different wireless systems where all transmitters and receivers exist within a square area with side length of 100 m. The location of each link’s transmitter is generated using a BPP while each receiver’s location is randomly generated within a distance between 20-50 m from its transmitter’s location. The number of available channels is set to 20. The number of SINR levels are four. \( \gamma_{\text{min}} \) is set to 1 watt. The path loss exponent (\( \alpha \)) is 3.5. Background noise power is \( 10^{-7} \) watts. The demand of each link is a parameter in our simulations. In each experiment, we assume the same demand for all links, i.e. \( D_m \equiv D, \forall m \in M. \) Each receiver’s ADC is assumed to process signals within at most four channels. Also, each of the two receiver characteristics parameters (namely, \( \lambda \) and \( G \)) are the same across all channels for each receiver, and are randomly generated from two sets as follows. If the mixer is marked as ‘good’, \( \lambda \) is selected randomly in the range \( [0.001, 0.01]. \) In case of ‘bad’ mixers, the value is generated in the range \( [0.01, 0.05]. \) On the other hand, \( G \) is generated within the range \( [0.01, 0.1] \) when the receiver’s ADC is ‘good’. For ‘bad’ ADCs, the value is chosen from the range \( [0.1, 0.3]. \) These ranges have been carefully chosen in consistence with the experimental results obtained at Wireless @ VT labs.

We used CPLEX to solve our optimization problems. All experiments were run using a cluster at Virginia Tech, called BlueRidge [14]. More specifically, each experiment was executed on a single node of BlueRidge that has 16 processors (utilized by CPLEX when possible) and 64 GB memory. The running time of each experiment ranges from few seconds to few minutes. We use the following metrics to evaluate our proposed allocation scheme: (i) total number of allocated channels \( (C_{\text{total}}), \) and (ii) total amount of power generated collectively by all links \( (P_{\text{total}}). \)

B. The Case of Homogeneous Networks

Here, networks in which all receivers have similar characteristics are referred to as homogeneous networks. Our initial simulations revealed that a naive optimization framework that does not account for the receiver characteristics fails to satisfy link demands in most cases. Under our proposed framework, all demands are satisfied. Due to space limitation, we omitted the part of results that shows the demand satisfaction under the proposed framework, and demand dissatisfaction under the naive approach. Table III shows the channel allocation and power assignment for homogeneous network setup. It is clear that with the same channel allocation and slight increase in the power assignment (compared to the naive approach) under the proposed optimization framework results in satisfying all link demands. For example, the naive approach fails to satisfy a rate demand per link of 20 Mb/s while \( C_{\text{total}} = 5 \) and \( P_{\text{total}} = 0.367. \) Under the proposed framework, the channel allocation stays the same while \( P_{\text{total}} \) increased by only 6.63% to consider the effect of ‘Bad’ ADCs. While \( C_{\text{total}} \) does not change, the percentage of total power increase becomes 9.2% and
TABLE III: Channel allocation and power assignment w/ and w/o RF-characteristics awareness for homogeneous networks (β = 1).

<table>
<thead>
<tr>
<th>D</th>
<th>w/o RF awareness</th>
<th>w/ RF awareness</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>w/ Bad Mixers</td>
<td>w/ Bad ADCs</td>
</tr>
<tr>
<td></td>
<td>c_total</td>
<td>P_total</td>
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<tr>
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<td>0.1851</td>
<td>5</td>
</tr>
<tr>
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<td>0.9218</td>
<td>15</td>
</tr>
<tr>
<td>20</td>
<td>1.4611</td>
<td>20</td>
</tr>
<tr>
<td>25</td>
<td>2.6802</td>
<td>25</td>
</tr>
<tr>
<td>30</td>
<td>3.4031</td>
<td>30</td>
</tr>
<tr>
<td>35</td>
<td>4.1318</td>
<td>35</td>
</tr>
</tbody>
</table>

TABLE IV: The trade-off between channel allocation and power assignment (‘bad’ receivers case).

<table>
<thead>
<tr>
<th>D</th>
<th>β = 1</th>
<th>β = 4</th>
<th>β = 10</th>
<th>β = 100</th>
<th>β = 1000</th>
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</thead>
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<tr>
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<td>P_total</td>
<td>c_total</td>
<td>P_total</td>
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<td>4.1318</td>
<td>35</td>
<td>4.1318</td>
<td>35</td>
<td>4.1318</td>
</tr>
</tbody>
</table>

10.81% when considering the effect of ‘Bad’ mixers and receivers, respectively.

C. Balancing Channel Allocation and Power Assignment

Here, we show the ability of our framework to control the trade-off between C_total and P_total. We consider the setup of ‘bad’ receivers for this set of experiments. As shown in Table IV, when β increases, the proposed framework favors minimizing the total assigned power at the cost of utilizing larger number of channels.

D. The Case of Heterogeneous Networks

Here, we consider a general case where only a subset of the receivers has good characteristics while the others are not. Table V shows the channel allocation and power assignment for heterogeneous networks setup. As expected, the higher the percentage of ‘bad’ receivers, the larger number of channels and total power are required to satisfy all demands.

VI. CONCLUSIONS

In this paper, we proposed a novel receiver-characteristic aware framework in a multi-RAT environment. Besides, the framework allows controlling a trade-off between channel allocation and total power emission by all links in the network. The objective was to minimize the total number of utilized channels and the aggregated power emission while meeting all rate demands of the links. Through extensive simulations, we showed the criticality of the receiver characteristics awareness when designing resource allocation schemes. This work can be extended in several directions. The problem size grows quickly with the number of links and channels. Approximation/heuristic methods are then needed in order to facilitate finding good solutions for bigger network sizes. On the other hand, receiver parameters were assumed to be deterministic in our simulations. In reality, they are stochastic where the values cannot be known for certain. Considering the uncertainty in these parameters is a promising direction to extend our work.

REFERENCES