Resource Allocation Using Filtennas in the Presence of Leakage

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***Abstract*—The utilization of newer spectrum bands such as in 5G and 6G networks, has the potential to inadvertently cause interference to passive sensing applications operating in the adjacent portions of spectrum. One such application that has received a lot of attention has been passive weather sensing where leakage from 5G mmWave band transmissions in the 26 GHz spectrum could potentially impact the observations of passive sensors on weather prediction satellites. To mitigate problems such as the above, we present a design framework that can be employed in mmWave networks by using filtennas (or filtering antennas) at the transmitter along with integrated resource allocation to minimize leakage into adjacent channels. Specifically, we propose an Iterative Leakage Aware Water Filling solution to allocate power and bandwidth in a system employing filtennas that guarantees performance requirements while reducing the leakage. In addition, a key contribution of this work is the characterization of the leakage function based on the order of filtennas which is incorporated in our resource allocation framework.**

***Index Terms*—Leakage, mmWave, 5G, 6G, Filtennas, Water Filling, Weather Prediction.**

I. Introduction

The development of 5G and beyond 5G systems has led to the utilization of newer and newer spectrum that has not been previously allocated for commercial wireless applications. These new spectrum opportunities for 5G have led to concerns and apprehensions regarding impacting adjacent portions of the spectrum which are used for other services. A recent example of critical consequence has been the impact of 5G services and radio transmissions on weather forecasting. Specifically, the allocation of 5G band in the 26 GHz spectrum referred to as 3GPP band n258 has been a cause of serious concern in the meteorological data forecasting community because the 5G transmissions in n258 band have been witnessed to impact the observations of passive sensors on weather satellites used to detect the amount of water in the atmosphere which have been known to adversely affect weather forecasting and predictions [1] [2]. A very recent work [4] on numerical characterization of the impact of 5G leakage on the well-known Super Tuesday Tornado Outbreak data set, has received a lot of attention from the 5G and meteorological communities besides the popular press [5] [6]. Another recent example of widespread attention and controversy is the impact of 5G transmissions on the aviation services [3]. This problem of spectrum coexistence has led to an impasse in the rollout of 5G cellphone services and renewed debates between the Federal Communications Commission (FCC) and Federal Aviation Administration (FAA).

In this paper, we investigate power and bandwidth allocation among adjacent channels in the presence of leakage. While we do not consider passive sensors or the effect of leakage on them, we employ filtering antennas or filtennas with varactor diodes as tuning elements [7] [8] at the transmitter towards the objective of mitigating leakage among the adjacent channels. We begin by formulating an optimization problem which is aimed at minimizing the total power transmitted by the base station subject to bandwidth, power, rate and filtenna constraints and devise a solution methodology to arrive at the optimal bandwidth and power allocations in the presence of leakage between adjacent channels. A novel contribution of this work is an Iterative Leakage Aware Water Filling solution to allocate power and bandwidth in a system employing filtennas that guarantees performance requirements while reducing the leakage. In order to account for the leakage, we propose a filtenna model and characterize the leakage using a leakage function which we further employ in the numerical evaluations of the resource allocation strategy.

The remainder of the paper is organized as follows. Section II describes the system model. Section III explains the formulation of the resource allocation problem that we propose to investigate and the subsequent subsection describes the proposed methodology to solve the optimization problem. Section IV provides the formulation of the leakage function which is incorporated in our proposed optimization framework. This is followed by Section V which presents numerical results that show how various parameters such as filtenna order and channel conditions impact resource allocation. We finally conclude in Section VI.

II. System Model

The scenario considered in this paper is the downlink of a single-input-single-output (SISO) system where each of the transmitters is equipped with filtennas. Moreover, we have considered a channelized system wherein each transmission

2770-7679/22/$31.00 ©2022 IEEE
DOI 10.1109/FNWF55208.2022.00109

is on an orthogonal channel. Despite the transmissions being orthogonal, there is leakage from these transmissions which interfere with the adjacent channels. In order to mitigate the leakage from these transmissions, reconfigurable filtennas, a unique integration of a filter and an antenna, are incorporated into the transmitter design [9]–[11]. A simplistic model depicted by Fig. 1 considers a base station equipped with filtennas transmitting to n receivers. There is a filtenna associated with each channel for transmission. We denote the transmit powers to the n receivers by $P_1, P_2, \cdots, P_n$ and the channel bandwidths for the transmissions to each of these receivers by $W_1, W_2, \cdots, W_n$. We assume each of the n channels are Gaussian with channel gains denoted by $h_{1b}, h_{2b}, \cdots, h_{nb}$. The background noise variance is denoted by σ^2.

We have considered the the total transmit power from the base station to comprise of four components with the principal component being the actual transmit power and the remaining three being fractions of the actual transmit power. Firstly, we have an increasing function α of channel bandwidth which denotes the fraction of the transmit power consumed by the ADCs and DACs at the transceivers. The second function is β which is increasing in the number of varactor stages l of a filtenna. While having an infinitely large l results in complete suppression of leakage, practical processing power considerations require that l be finite. Hence, the leakage reduction comes at the expense of power consumed by filtennas and we account for the power consumption of filtennas by a function β of varactor stages l. Finally, we have a term for leakage denoted by a function δ which depends on the number of varactor stages of filtennas besides the channel bandwidth. The number of varactor stages controls the roll-off of a filtenna which in turn determines the leakage reduction, i.e., the larger the number of varactor stages, the sharper is the roll-off of the filtennas resulting in a reduction of the leakage power contribution from the transmission in a given channel. Thus, we define the leakage function δ to be non-decreasing in the channel bandwidth and decreasing in the number of varactor stages l. We have assumed α, β and δ to be the same for all the n transmissions. Moreover, the model imposes rate constraints that need to be met as part of the quality of service requirements of each of the transmissions.

III. Leakage Aware Power and Bandwidth Optimization

We consider an optimization problem which aims to find transmit powers and bandwidths which minimize the total power consumed at the base station.

$$f_i(P_i, W_i, l) = P_i + \alpha(W_i)P_i + \beta(l)P_i + \delta(W_i, l)P_i \tag{1}$$

$$f(P_1, P_2, \cdots, P_n, W_1, W_2, \cdots, W_n, l) = \sum_{i=1}^{n} f_i(P_i, W_i, l) \tag{2}$$

$$\min_{P_1, P_2, \cdots, P_n, W_1, W_2, \cdots, W_n, l} f(P_1, P_2, \cdots, P_n, W_1, W_2, \cdots, W_n, l) \tag{3}$$

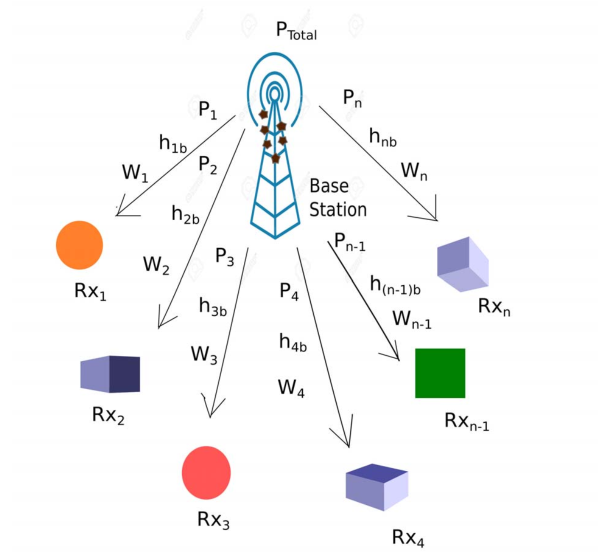

Fig. 1: System Model

$$\text{s.t.} \quad W_1 + W_2 + \cdots + W_n \leq W \qquad \text{(Total bandwidth constraint)} \tag{4}$$

$$P_1 + P_2 + \cdots + P_n \leq P \qquad \text{(Total power constraint)} \tag{5}$$

$$W_1 \ln\left(1 + \frac{h_{1b}P_1}{\sigma^2 + \sum_{i \neq 1} \delta(W_i, l)P_i}\right) \geq R_1^{\min}, \cdots,$$

$$W_n \ln\left(1 + \frac{h_{nb}P_n}{\sigma^2 + \sum_{i \neq n} \delta(W_i, l)P_i}\right) \geq R_n^{\min} \quad \text{(Rate constraints)} \tag{6}$$

$$l \geq 1 \qquad \text{(constraint on varactor stages)} \tag{7}$$

Theorem 1: The resource allocation problem (1-7) has solutions $\{P_i^*\}_{i=1}^n$, $\{W_i^*\}_{i=1}^n$ and l^* which meet the rate constraints (6) with equality.

Proof: Let us consider that not all rate constraints are met with equality at the optimum transmit powers, channel bandwidths and number of varactor stages of a filtenna. Let us consider the constraint inequality for $j = 1$ where $j = 1, 2, \cdots, n$.

$$W_1^* \ln\left(1 + \frac{h_{1b}P_1^*}{\sigma^2 + \sum_{i \neq 1} \delta(W_i^*, l^*)P_i^*}\right) > R_1^{\min} \tag{8}$$

We assume that the rate constraints are met with equality for $j = 2, \cdots, n$ and only for $j = 1$ the equality of the rate constraint is not met as shown by (8). However, when we lower P_1^* to $P_1^* - \epsilon$, the leakage contribution of link 1 to the remaining links $j = 2, \cdots, n$ is lowered, which implies that the achieved rates of the links $j = 2, \cdots, n$ are strictly greater than the threshold rates R_j, $j = 2, \cdots, n$. This is a contradiction to our assumption that the rate constraints are met with equality for $j = 2, \cdots, n$. In addition, as a result of lowering P_1^* to $P_1^* - \epsilon$, the solution P_1^* no longer holds true because $P_1^* - \epsilon$ further minimizes the objective function (3). This is a contradiction to our claim that P_1^* is a solution. Thus, our assumption that the rate constraints are met with equality at the solutions for all links except one is invalidated. Henceforth, we conclude that a blanket equality of rate constraints is achieved at the solutions $\{P_i^*\}_{i=1}^n$, $\{W_i^*\}_{i=1}^n$ and l^* for the given optimization problem. Mathematically,

$$W_1^* \ln\left(1 + \frac{h_{1b}P_1^*}{\sigma^2 + \sum\limits_{i\neq 1}\delta(W_i^*, l^*)P_i^*}\right) = R_1^{\min}, \cdots,$$
$$W_n^* \ln\left(1 + \frac{h_{nb}P_n^*}{\sigma^2 + \sum\limits_{i\neq n}\delta(W_i^*, l^*)P_i^*}\right) = R_n^{\min} \tag{9}$$

Corollary 1.1: The solutions $\left\{\{P_i^*\}_{i=1}^n, \{W_i^*\}_{i=1}^n, l^*\right\}$ are obtained by solving the underdetermined system of equations (9) together with the total bandwidth constraint (4) and the total power constraint (5).

Corollary 1.2: The constraint on the stages of a filtenna is not necessarily met with equality at the solutions. Alternatively, $l^* = 1$ is not necessarily the only solution.

A. Iterative Leakage Aware Water Filling

We now solve for the optimization variables, transmit powers and bandwidths assuming that the solution l^* supposes any integer between 1 and 5 which are the typical values for the number of varactor stages of a filtenna. In our solution methodology, we begin by assuming a set of initial bandwidths allocated according to the total power constraint (5). Thereafter, we solve for the transmit powers using waterfilling power allocation. Conventionally, the power allocation is chosen so as to maximize the rate of reliable communication. We formulate the waterfilling optimization problem for our framework keeping this convention into consideration. We consider the optimization problem which serves to maximize the communication rate takes a special account of the channel leakage in addition to noise. Hence, we designate this optimization problem as the Leakage Aware Waterfilling Power Allocation. Henceforward, we apply the transmit powers thus obtained in the system of equations (9) to acquire bandwidths and designate this component of the complete procedure as the Leakage Aware Bandwidth Allocation. We iterate this complete procedure several times until convergence is achieved. Thus, we term this algorithmic methodology as the Iterative Leakage Aware Power and Bandwidth Allocation.

We assume $W_1^{(0)}, \cdots, W_n^{(0)}$ be the initial set of bandwidths which satisfy the total bandwidth constraint (4). We use these initial bandwidths in the waterfilling power allocation described in the sequel. We discuss the leakage aware waterfilling power allocation for the first iteration $i = 1$.

$$\tilde{C}_n^{(1)} = \max_{P_1^{(1)}, \cdots, P_n^{(1)}} \sum_{m=1}^{n} \ln\left(1 + \frac{h_{mb}P_m^{(1)}}{\sigma^2 + \sum\limits_{j\neq m}\delta(W_j^{(0)}, l^*)P_j^{(1)}}\right)$$
$$\text{s.t.} \quad \sum_{m=1}^{n} P_m^{(1)} = P, \quad P_m^{(1)} \geq 0, \quad m = 1, \cdots, n \tag{10}$$

This optimization problem can be solved by Lagrangian methods. Consider the Lagrangian

$$\mathcal{L}(\lambda^{(1)}, P_1^{(1)}, \cdots, P_n^{(1)}) =$$
$$\sum_{m=1}^{n} \ln\left(1 + \frac{h_{mb}P_m^{(1)}}{\sigma^2 + \sum\limits_{j\neq m}\delta(W_j^{(0)}, l^*)P_j^{(1)}}\right) - \lambda^{(1)}\sum_{m=1}^{n} P_m^{(1)}$$

where $\lambda^{(1)}$ denotes the Lagrange multiplier. The Kuhn-Tucker condition for the optimality of a power allocation is

$$\frac{\partial \mathcal{L}}{\partial P_m^{(1)}} = \begin{cases} 0 & \text{if } P_m^{(1)} > 0 \\ \leq 0 & \text{if } P_m^{(1)} = 0 \end{cases} \tag{11}$$

The power allocation which satisfies the Kuhn-Tucker condition (11) is

$$P_m^{(1)} = \left(\frac{1}{\lambda^{(1)}} - \frac{\sigma^2 + \sum\limits_{i\neq m}\delta(W_i^{(0)}, l^*)P_i^{(1)}}{|h_{mb}|^2}\right)^+ \tag{12}$$

where the $+$ in the superscript indicates that the allocated power is non-negative.

Here, we underscore the fact that the ratio $|h_{mb}|^2/(\sigma^2 + \sum_{j\neq m}\delta(W_j^{(0)}, l^*)P_j^{(1)})$ is the normalized Signal to Leakage plus Noise Ratio (SLNR). We can easily observe from (12) that the transmit power $P_m^{(1)}$ is an increasing function of the normalized SLNR for channel m. Claim: As the normalized SLNR for channel m increases, the transmit power $P_m^{(1)}$ for channel m increases. The Lagrange multiplier $\lambda^{(1)}$ for the optimal power allocation (12) is chosen such that the power constraint (10) is met

$$\sum_{m=1}^{n}\left(\frac{1}{\lambda^{(1)}} - \frac{\sigma^2 + \sum\limits_{j\neq m}\delta(W_j^{(0)}, l^*)P_j^{(1)}}{|h_{mb}|^2}\right)^+ = P \tag{13}$$

We can easily see that $\lambda^{(1)}$ is a linear function of $\left\{P_m^{(1)}\right\}_{m=1}^n$. We substitute the $\lambda^{(1)}$ in (12). Consequently we can observe that the $P_m^{(1)}$ in (12) is a linear combination of $\left\{P_m^{(1)}\right\}_{m=1}^n$. Thus, we have n linear equations in n variables $\{P_m^*\}_{m=1}^n$ to solve assuming all the other quantities in these equations to be constants. It should be noted here that in the absence of leakage the optimization problem (III-A-10) and its solutions (12) reduce to those of the classical waterfilling power allocation scheme. We subsequently substitute $\left\{P_m^{(1)}\right\}_{m=1}^n$ in (9) to

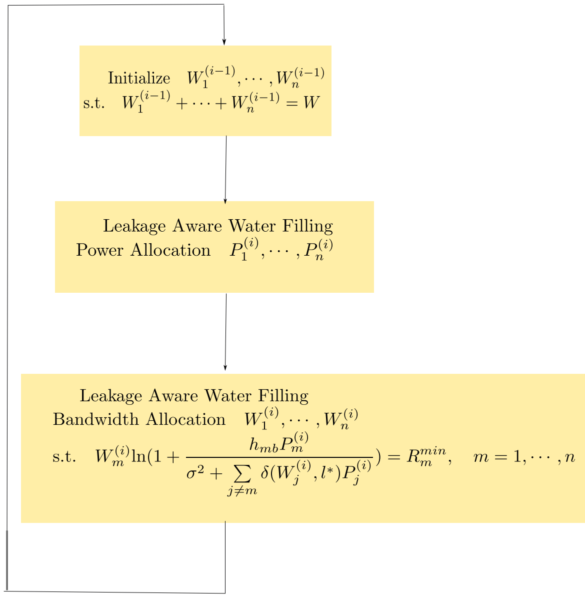

Fig. 2: Iterative leakage aware power and bandwidth allocation. The i in the parantheses stands for the iteration number.

solve for $\left\{W_m^{(1)}\right\}_{i=1}^{n}$. Thus, we have n non-linear equations in $\left\{W_m^{(1)}\right\}_{m=1}^{n}$ to solve. Hereafter, we have $\left\{W_m^{(1)}\right\}_{m=1}^{n}$ as the initial set of bandwidths for the second iteration $i = 2$ and the rest of the procedure in the sequence follows. This complete procedure is iterated multiple times until the powers and the bandwidths converge. We have depicted the iterative leakage aware power and bandwidth allocation in the form of a block diagram shown as Fig. 2.

IV. Modeling the Leakage Function

To suppress leakage from the 5G band in the wireless communication links, reconfigurable filtennas, a unique integration of a filter and an antenna, are incorporated into the system design. Here, we consider a tunable radiating resonator as the building block of the proposed reconfigurable filtenna which integrates varactor diodes to adjust the operating frequency. A schematic of this configuration is shown in Fig. 3. Assuming there are 30 channels distributed over 24.5 to 27.5 GHz band, each channel has 100 MHz bandwidth, and thus it is desired to have a filtenna with 100 MHz bandwidth and tunable center frequency. The tunability can be achieved by integrating a varactor in each resonator of the filtenna, where the order of the reconfigurable filtenna is considered as equal to the number of varactors. Based on the circuit simulation, the frequency response of a Chebyshev filtenna with 100 MHz bandwidth and center frequency of 26 GHz with 0.2 dB ripple for different filter orders can be obtained as shown in Fig. 4 [12]. As can be seen, by increasing the filter order, the roll-off of the bandpass filtering response becomes sharper, thereby reducing the leakage to the adjacent channels. Based on Fig. 4, we can obtain the power leakage from this reference channel

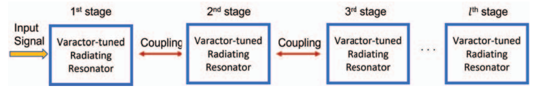

Fig. 3: Filtenna schematic

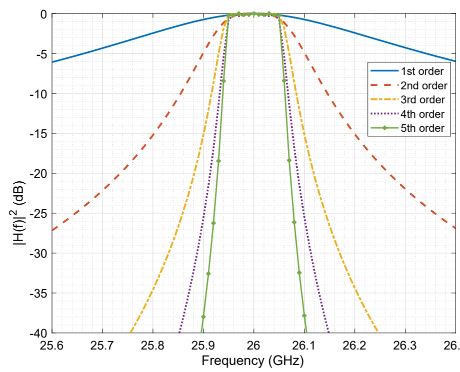

Fig. 4: Frequency response of the Chebyshev filter for different orders

to other channels by using

$$S_y^l(f) = S_x(f)|H^l(f)|^2, \quad S_x(f) = \frac{P_{total}}{BW_{total}} \tag{14}$$

$$P_{leaked}^l = \int_{f_1}^{f_2} S_y^l(f) \tag{15}$$

$$P_n^l = \frac{P_{leaked}^l}{P_r}, \quad P_r = \frac{P_{total}}{N} \tag{16}$$

where $H^l(f)$ is the frequency response of the filtenna and $S_x(f)$ and $S_y^l(f)$ are the power spectral densities of the input and output signals, respectively. P_{total} is the total power distributed over the total bandwidth (BW_{total}). f_1 and f_2 are the lower and upper frequency bounds of the channels that we use to obtain the leakage from the reference channel to the corresponding channels. It is noted that P_{leaked}^l is the leaked power from reference channel to the other adjacent channels which can be calculated numerically. In addition, P_n^l is the normalized leaked power, which is plotted in Fig. 5. P_r is the reference channel power, where N denotes the number of channels equal to 30. In this case, Channel 1 denotes the reference channel with a center frequency of 26 GHz and 100 MHz bandwidth, while the adjacent channels are numbered in order from 2 to 9. A polynomial can be fitted to the marker points corresponding to the leaked power from the reference to each adjacent channel.

In order to account for the leakage in the calculation of signal to leakage plus noise ratio (SLNR), we have chosen the following function,

$$\delta(l) = \begin{cases} 0.0026l^4 - 0.0441l^3 + 0.3179l^2 - 1.1338l + 1.6951 & l = 1, 2 \\ \frac{0.3152}{l^2} & l = 3, 4, 5 \end{cases} \tag{17}$$

in which the first function considers the leakage from the reference channel to the closest channel for $l = 1, 2$, whereas the second function in the form of $\frac{k}{l^2}$ assumes for $l = 3, 4, 5$ and k is obtained by minimizing the sum of squared error between the assumed function and the leakage functions representing the leakage from the reference channel to the eight adjacent channels.

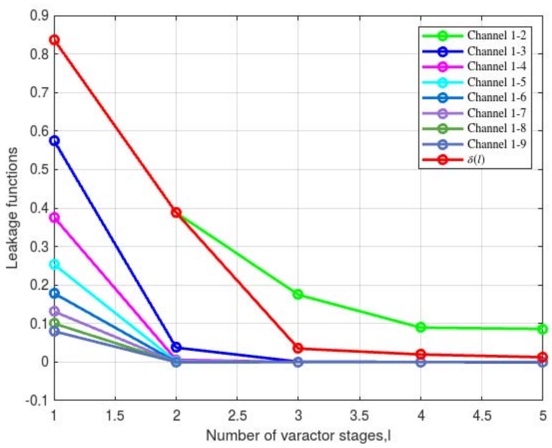

Fig. 5: Normalized leaked power P_n^l from the reference channel (Channel 1) to the other eight adjacent channels along with the proposed leakage function $\delta(l)$.

V. Numerical Results

This section presents an analysis of the numerical results for power and bandwidth allocation obtained based on the Iterative Leakage Aware Waterfilling Power and Bandwidth Allocation algorithm for a setting with $n = 2$ users and provides a basic understanding of the resource allocation problem for the 5G mmWave band transmission in the 26 GHz spectrum. We consider a scenario which entails different channel gains but same achievable rates of communication for the two users.

In this numerical study, we consider the parameters delineated in the Table I. The simulations have been conducted under the assumption that SNR of user 2 is 3 dB better than that of user 1. Fig. 6(a) and Fig. 6(b) show a comparison in the variation of bandwidth allocation against SNR for different minimum rates with the former assuming $l = 2$ and the latter assuming $l = 3$ varactor stages. The decreasing trend of bandwidth with respect to SNR can be explained by the fact that as SNR increases implying that channel becomes better, the rate requirements are met with lower bandwidth allocation. It can be easily seen that in the former case the bandwidth allocation satisfying the rate constraints is larger compared to the latter as a consequence of larger leakage contribution due to lower number of varactor stages. The specific example shows that the case with $l = 2$ stages results in bandwidth allocation nearly 1.5 times larger than the case with $l = 3$ stages. We can see that consistently through Fig. 6 and Fig. 7 the performance of user 2 is superior to that of user 1 owing to better channel conditions as specified by SNR. Fig. 7(a) shows that the bandwidth allocation reduces with the increase in l as a result of corresponding diminution in the leakage. Alternatively, the increase in l results in increase in the SLNR which is accompanied by lower bandwidth allocation at any given SNR. It is interesting to note that the bandwidth allocation for $l = 3, 4, 5$ coincide with each other as opposed to that for $l = 1, 2$ owing to the behaviour of the leakage function at these l values which entails that the leakage function contributes nearly the same leakage power for $l = 3, 4, 5$ and different leakage powers for $l = 1, 2$. Fig. 7(b) presents a non-monotonically decreasing behaviour of the transmit power plus leakage power contribution of the two users with respect to l stages for different total transmit powers. The increase of total transmit power results in the increase in the actual transmit power and leakage power contribution of a user for a given l accompanied by the fact that user 2 gets a higher power allocation than user 1 for a given total transmit power owing to better channel conditions.

TABLE I: Simulation Parameters

Parameters	Notation	Value
Maximum total bandwidth	W	100 MHz
Maximum total transmit power	P	10 W
Minimum rate for User 1	R_1^{min}	30 Mbps
Minimum rate for User 2	R_2^{min}	30 Mbps
Noise variance	σ^2	1

VI. Conclusions and Future Directions

This paper presented a comprehensive design framework for resource allocation in the presence of leakage into adjacent channels along with the integration of filtennas at the transmitters. A novel Iterative Leakage Aware Waterfilling algorithm was proposed to obtain the optimal resource allocation with performance guarantees. We have characterized leakage as a function of the filtenna order (varactor stages) and studied the impact of leakage on resource allocation. Numerical results using transmissions in the 26 GHz mmWave bands show that bandwidth and power are allocated more efficiently with an increase in the number of varactor stages of a filtenna since it reduces leakage, thereby improving the channel conditions to meet the performance requirements. Numerical results also show that the bandwidth reduction and the actual transmit power plus leakage power contribution of a transmitter is lowered 1.5 times with an increment of a single varactor stage. An important future direction is to incorporate multiple antennas at the transmitter and receiver (MIMO) in studying leakage suppression with filtennas. The design framework presented here can be generalized to other emerging frequencies where unintended leakage from wireless communication systems can be reduced to other passive sensing applications and systems.

Acknowledgment

This work is supported by the NSF SWIFT program under Award No. 2128077, as well as in part by ECCS-2028823.

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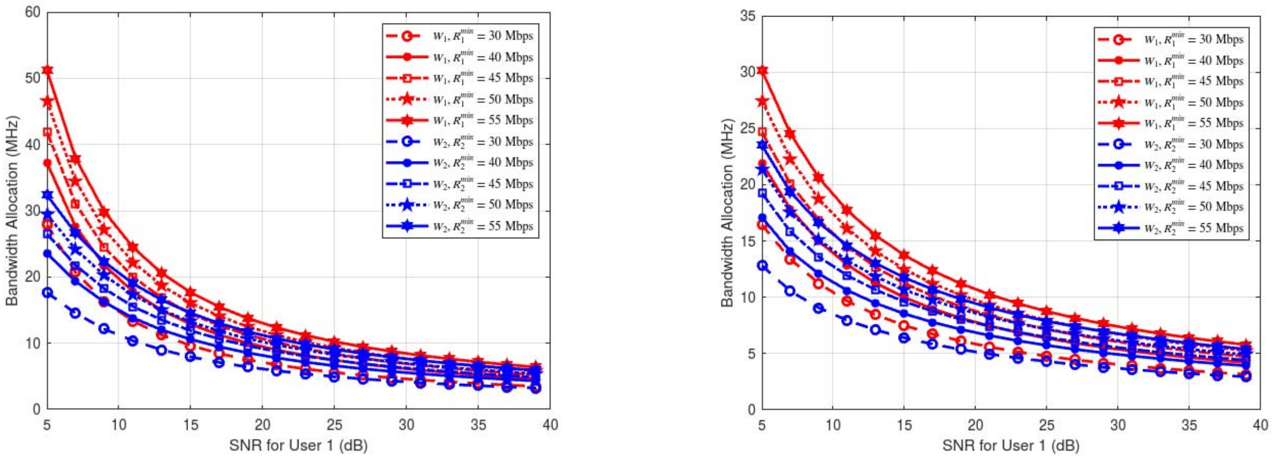
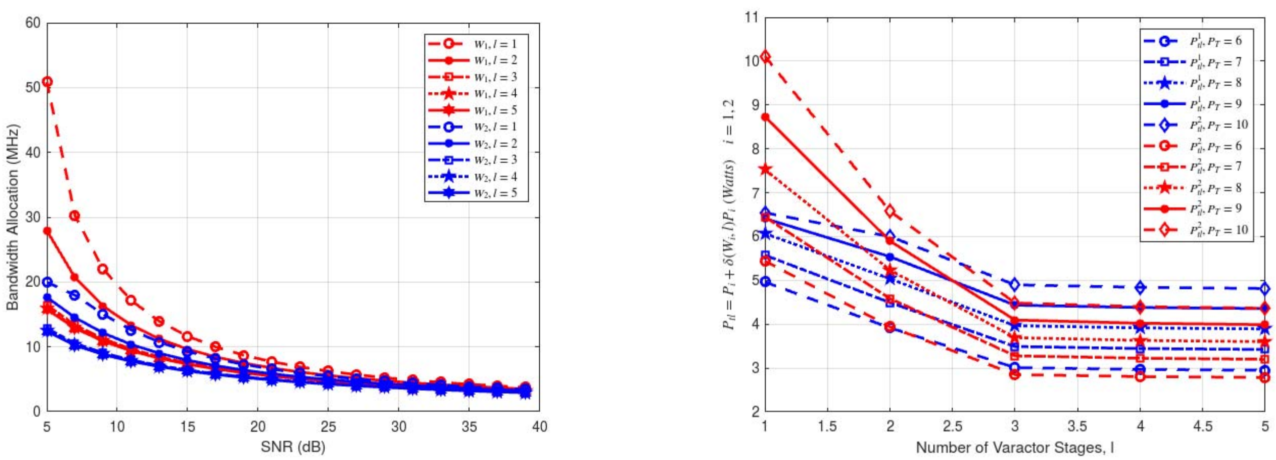


(a) (b)

Fig. 6: Bandwidth allocation for $n = 2$ users versus SNR for different minimum rates for (a) $l = 2$ (b) $l = 3$. The blue lines correspond to user 1 and red lines correspond to user 2.



(a) (b)

Fig. 7: (a) Bandwidth allocation for $n = 2$ users versus SNR for different varactor stages l. (b) Variation of transmit plus leakage power contribution of $n = 2$ users w.r.t varactor stages l with SNR of user 1=5 dB and SNR of user 2=8 dB

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