Enabling Uncoordinated Spectrum Sharing in Millimeter Wave Networks Using Carrier Sensing

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Abstract—We propose using carrier sensing for distributed, interference management in a millimeter-wave (mmWave) cellular network where spectrum and base station sites are shared by multiple operators that do not coordinate among themselves. We describe important challenges in using traditional carrier sensing (CS) in this setting and propose enhanced protocols to address these challenges. We evaluate the coverage probability of our shared mmWave network using simulations and find that our enhancements lead to significant performance improvements over no CS as well as naive use of CS, for higher values of signal-to-interference and noise ratio (SINR). Interestingly, our evaluations also reveal that for lower values of SINR, not using any CS is the best strategy.

I. INTRODUCTION

The abundance of available spectrum beyond 24 GHz, commonly known as the millimeter wave (mmWave) band [1], is a major contributor to the significant bandwidth improvements that 5G brings. Importantly, the necessity of beam-based transmissions for mmWave, instead of the traditional sector-based transmissions, engenders the opportunity of spatial spectrum sharing [2]. In this paper, we consider the general problem of unlicensed mmWave spectrum sharing among different operators of the same radio access technology (RAT), e.g., 5G.

The very nature of unlicensed usage of the spectrum creates new opportunities for uncoordinated sharing, that has two important advantages. First, uncoordinated spectrum sharing has the flexibility of ad hoc spectrum usage without going through an extensive and time-consuming process via any central coordination. Second, there is no vulnerable central point of attack. An uncoordinated, unlicensed spectrum sharing can facilitate private cellular networks [3] without any centralized control or authorization.

However, along with the advantages, uncoordinated spectrum sharing brings in the significant challenge of distributed interference management. In our shared mmWave network, interference management is essential because, in the absence of coordination, different operators may simultaneously use the same portions of the unlicensed spectrum. Furthermore, different operators may share the same, strategically important, base station (BS) sites/towers [4]. Sharing of the BS sites by operators increases the possibility of strong interferers.

In this paper, we specifically investigate different carrier sensing (CS) schemes for distributed interference management in a mmWave network, with the spectrum and BS sites shared among operators having no inter-operator coordination. Intuitively, CS should improve the performance of a shared spectrum network by avoiding interference. However, we find that CS may not result in optimal behavior under all circumstances because it avoids interference at the cost of reduced transmission activities. CS is advantageous only when the benefit of avoiding interference outweighs the disadvantage of reduced transmissions. Importantly, we determine that the choice regarding whether the CS is incorporated at the transmitter or the receiver is of prime importance. Specifically, we observe that CS at the transmitter (CST) has a significant drawback in our shared mmWave network. Hence, we propose using CS at the receiver (CSR) to overcome the limitation of CST. Due to the lack of coordination among BSs of different operators, the time slots of different BSs may not be in sync. Consequently, CST and CSR cannot prevent interference that may start during the data transmission phase, right after the CS phase is over. To categorize this interference, we introduce the notion of deaf interferers. We propose an enhanced version of CSR, which we call directional CSR with announcements (dCSRA), to tackle the interference from deaf interferers.

Using simulations, we compare the different CS protocols with the coverage probability of a User Equipment (UE) as the comparison metric. Our evaluations show that CSR schemes are always better than CST. For higher values of signal-to-interference and noise ratio (SINR), our proposed dCSRA is advantageous over other CS protocols, and it provides a 3-fold performance improvement over not using any CS. However, our evaluations also reveal that for lower values of SINR, not using any CS is the best strategy.

II. RELATED WORK

Research around mmWave spectrum sharing has progressed primarily in two directions: spectrum sharing between same RATs and spectrum sharing across different RATs. We briefly summarize the existing works in each of these categories.

Spectrum sharing between same RATs: The idea of mmWave spectrum pooling among mobile operators has been explored in various works [2], [4], [5]. These works have demonstrated that spectrum pooling among mobile operators can significantly boost their downlink capacity. In fact, the advantage of spectrum pooling can be achieved even without coordination among the mobile operators, as long as the individual operator networks have comparable BS density [5].

Spectrum sharing across different RATs: Unlicensed mmWave bands can be shared by WiFi and mobile operators [6]–[8]. In general, unlicensed spectrum sharing among different RATs requires distributed interference management because coordination between operators of different RATs...
is unlikely. The interference can be managed by running distributed algorithms on the BSs, for scheduling the downlink time slots of the associated UEs [6]. Alternately, distributed interference management can be performed by adding intelligence/adaptability in the CS protocol [7], [8].

In our work, we draw insights from these existing works and build upon their contributions. However, our work is the first to investigate CS in a mmWave network with shared BS sites that allows spectrum sharing without any coordination among the operators.

III. SYSTEM MODEL

We consider an unlicensed mmWave band of $W$ Hz that is shared by $M$ operators. A UE is served only by its subscribed operator. A UE associates with a BS, among all the BSs of its subscribed operator, that provides maximum signal power, averaged over the fading randomness. There is no coordination among the BSs of different operators as well as between different BSs of the same operator. Some of the BS sites are shared by multiple operators. We use $X_{j,m}$ to denote the location of the $j^{th}$ BS of network $m$. All the BSs transmit at a fixed power of $P_r$, and the UEs’ transmit power is $P_t$.

We assume that the blocking of each link is independent and identically distributed as: a link is in line-of-sight (LoS) with probability $p_L(r) = e^{-\beta r}$ and in non line-of-sight (NLoS) with probability $p_N(r) = 1 - p_L(r)$, where $r$ is the link distance in meters [9]. Free space path loss at a distance of $r$ meters from the transmitter is modeled as: $PL(r) = C_r r^{-\alpha_r}$, where $C_r$ is the path loss at a reference distance of 1 meter, $\alpha_r$ is the path loss exponent of mmWave signals [1], and $\tau \in \{L (\text{LoS}), N (\text{NLoS})\}$. We assume that each link undergoes independent Rayleigh fading [4]. Thus, the loss in received power due to small scale fading is modeled by an exponential random variable with unit mean.

We consider uniform linear antenna arrays [9] with $n_{BS}$ and $n_{UE}$ antenna elements at each of the BSs and UEs, respectively. Beam steering is done only in the horizontal direction while the vertical steering angle is always fixed. We consider codebook based analog beamforming [9], and single stream downlink transmissions. We assume that an antenna array’s radiation pattern follows a step function with a constant gain, $M_{BS}$ (for BS), $M_{UE}$ (for UE), in the main lobe, and a constant gain, $m_{BS}$ (for BS), $m_{UE}$ (for UE), in the side lobe [9]. For the values of $M_{BS}$, $M_{UE}$, $m_{BS}$, and $m_{UE}$ we use the expressions given in [10]. From a UE’s viewpoint, the misalignment between its main lobe and an interfering BS’s main lobe is uniformly random in $[0^\circ, 360^\circ]$. Thus, the combined antenna gain from an interfering BS to a UE is modeled as a random variable, $G$, whose possible values are $M_{BS}M_{UE}, M_{BS}m_{UE}, m_{BS}M_{UE},$ and $m_{BS}m_{UE}$ with probability $(\theta_{BS})^2/2\pi \times (\theta_{UE})^2/2\pi, (\theta_{BS})^2/2\pi \times (1 - \theta_{UE})/2\pi, (1 - \theta_{BS})^2/2\pi \times (\theta_{UE})^2/2\pi), \text{ and } (1 - \theta_{BS})^2/2\pi \times (1 - \theta_{UE})/2\pi$, respectively. Here $\theta_{BS}$ and $\theta_{UE}$ are the main lobe beamwidth (in radians) for the BSs and the UEs, respectively. While computing the downlink SINR, we assume that a UE and its associated BS have gone through the beam training phase and their antennas are aligned for maximum gain, which is $M_{BS}M_{UE}$.

IV. CARRIER SENSING FOR INTERFERENCE MANAGEMENT

Among the well known random access protocols, we choose CS over ALOHA and slotted ALOHA because ALOHA suffers from low throughput and slotted ALOHA requires synchronization of time slots among all the BSs. Traditionally (in WiFi and LTE-LAA), CS is done at the transmitter (CST), where the transmitter listens for any ongoing transmission. If the transmitter identifies the channel to be occupied, it postpones its transmission; otherwise, it transmits its signal. We explain in Section IV-B that CST has a drawback when multiple operators share BS sites. Thus, we propose using carrier sensing at the receiver (CSR). CSR has been investigated for mmWave networks in [7]; however, the problem of co-located BSs is not considered there. Both CST and CSR can be performed omnidirectionally or directionally. With omnidirectional CS, the sensing node listens for any ongoing transmission. In contrast, with directional CS, the sensing node measures the channel power only in the direction of its main lobe. Considering both the choices of sensing location and direction, we have four possibilities: omnidirectional CST, directional CST, omnidirectional CSR, and directional CSR. We assume that all the BSs in the shared mmWave network use the same variant of CS, with the same sensing threshold.

A. Interference in spite of carrier sensing

While the purpose of CS is to avoid interference, it cannot eliminate interference completely. To characterize this unavoidable interference, we use the notion of hidden interferers and deaf interferers. Our characterization of the interferers is defined with respect to a UE. For this purpose, we consider a typical UE, located at the center of the considered region, $(0,0)$, as the reference UE. The difference between hidden and deaf interferers arises due to the timing characteristics of our mmWave network. We first explain these timing characteristics and then present the ideas of hidden and deaf interferers.

1) Timing characteristics: Since the BSs use single-stream downlink channels, they serve their associated UEs using a time division multiple access (TDMA) scheme with round-robin scheduling. We assume that all the BSs use the same duration for their downlink time slots, say $t_s$. However, the time slots of different BSs may not be aligned. At the beginning of the time slots, the sensing nodes perform CS, with sensing time negligible compared to $t_s$. If a sensing node measures the channel power (time-averaged over fading randomness) to be below a threshold, say $P_{th}$, then it initiates downlink transmission; otherwise, the transmission is deferred. The sensing node senses the channel again after a duration of $t_s$, at the beginning of the next time slot.

Now, consider a downlink time slot of the typical UE, where the sensing node, the typical UE itself (performing CSR) or its associated BS (performing CST), has assessed the channel to be free, and the typical UE is receiving downlink signals from its associated BS, located at $X_{b,n}$. At any point of time, say $t$,
during this downlink time slot of the typical UE, all the BSs (except the typical UE’s associated BS) can be divided into two classes: $\mathcal{B}_b$ and $\mathcal{B}_a$. $\mathcal{B}_b$ and $\mathcal{B}_a$ are the set of BSs whose last CS phase, prior to $t$, precedes and succeeds, respectively, the CS of the BS at $X_{b,n}$. Note, in the context of downlink transmissions, the CS is performed by the BS itself or its UE depending on whether CST or CSR is used; however, that distinction is unimportant for distinguishing $\mathcal{B}_b$ from $\mathcal{B}_a$. Figure 1 shows an example, where the top two rows are time slots of BSs belonging to $\mathcal{B}_b$, and the bottom two rows are time slots of BSs belonging to $\mathcal{B}_a$. Next, we use $\mathcal{B}_b$ and $\mathcal{B}_a$ to define hidden and deaf interferers, respectively.

2) Hidden interferers: Among the set of BSs in $\mathcal{B}_a$, a subset of it would be silent due to their own respective CS, and the remaining ones would be transmitting downlink signals. Among these active ones, a BS is a hidden interferer if it causes interference to the typical UE. Thus, a BS at $X_{j,m}$ is a hidden interferer to the typical UE, if:

\begin{equation}
\text{CST: } \begin{aligned}
P_T C_{\tau(b,n)} f_{j,m} A_{j,m} ||X_{b,n} - X_{j,m}||^{-\alpha_{b,n}} < P_{th} \\
\text{and } P_T C_{\tau(0,0)} f_{j,m} G_{j,m} ||X_{j,m}||^{-\tau_{(0,0)} (j,m)} > N_f
\end{aligned}
\end{equation}

\begin{equation}
\text{CSR: } \begin{aligned}
P_T C_{\tau(b,n)} f_{j,m} A_{j,m} ||X_{b,n} - (x,y)||^{-\alpha_{b,n}} < P_{th} \\
\text{and } P_T C_{\tau(0,0)} f_{j,m} G_{j,m} ||X_{j,m}||^{-\tau_{(0,0)} (j,m)} > N_f
\end{aligned}
\end{equation}

where $\{x, y\}$ is the location of the scheduled UE of the BS at $X_{j,m}$. Both for CST and CSR, the first inequality is based on the fact that the BSs at $X_{j,m}$ could not sense the ongoing downlink transmission from the BS at $X_{b,n}$ to the typical UE.

Figure 1 shows the difference between hidden and deaf interferers with the help of an example. Both hidden interferers and deaf interferers fall under the general class of hidden terminals. In our context, the distinction between hidden and deaf interferers is crucial because neither CST nor CSR can prevent interference from the deaf interferers, as explained in the next section.

B. Tackling hidden and deaf interferers

In this section, we investigate the capability of CS protocols in tackling hidden and deaf interferers.

1) CS at transmitter (CST): CST can neither eliminate hidden interferers, nor deaf interferers, irrespective of whether the sensing is done omnidirectionally ($\alpha$CST) or directionally ($d$CST), as shown with the help of an example in Figure 2. For both the cases in Figure 2, UE 1 is within the main lobe of BS 2, but still BS 1 transmits downlink signals to UE 1, because BS 1 cannot sense the ongoing transmissions of BS 2. Thus, the downlink signals of both the UEs experience interference. In this example, BS 2 is a hidden interferer to UE 1, and BS 1 is a deaf interferer to UE 2.

When multiple BSs are at different heights on the same tower, they cannot sense each other’s ongoing transmission via $\alpha$CST or $d$CST. When these undetectable co-located BSs act as hidden interferers, they may produce interference as strong as the desired signal at a UE. We show an example scenario in Figure 3 with two co-located BSs. In this figure, BS 1 is unable to sense the ongoing transmissions from BS 2.

2) CS at receiver (CSR): Due to the above problem with CST, we explore the option of carrier sensing at the receivers, i.e., at the UEs, in the context of downlink transmissions. If a scheduled UE senses the channel to be free, it informs its associated BS. Only then, the associated BS transmits downlink signals to the UE. Similar to CST, CSR can be direction (dCSR) or omnidirectional (oCSR). Now, let us...
revisit the scenario of Figure 3. If UE 1 performs CS while BS 2 is transmitting downlink signals to UE 2, UE 1 will measure a significant amount of power in the channel. Hence, it would not inform BS 1 that the channel is free, and BS 1 will not transmit any signal. Thus, CSR can resolve the problem of co-located BSs acting as hidden interferers. More generally, CSR can eliminate interference from (almost) all the hidden interferers, as long as the sensing threshold, $P_{th}$, is not significantly above the noise floor, $N_f$.

CSR can tackle the hidden interferers, but it cannot prevent deaf interference, as shown in Figure 4(a). In this figure, BS 2 is transmitting downlink signals to UE 2, which has assessed the channel to be free via CSR. During the timeslot of downlink transmission to UE 2, UE 1 performs CSR (Figure 4(a) is for dCSR, but a similar figure can be drawn for oCSR) and fails to sense the ongoing transmissions from BS 2. Hence, UE 1 informs its associated BS, BS 1, to transmit downlink signals. This results in BS 1 becoming a deaf interferer to UE 2.

3) dCSR with announcements (dCSRA): To resolve the problem of deaf interference, we propose dCSR with announcements and explain its working using Figure 4(b). Tackling deaf interferers requires interference protection beyond CS. Thus, in dCSRA, if a UE (UE 2 in Figure 4(b)) assesses the channel to be unoccupied via dCSR, it sends out a few broadcast announcements. If a BS (BS 1 in Figure 4(b)) hears this announcement, it would detect the presence of a UE in its vicinity. Now, even if this BS’s scheduled UE (UE 1 in Figure 4(b)) incorrectly assesses the channel to be free, this BS would refrain from transmission and prevent being a deaf interferer to the UE that had made the announcement previously. There are a few important points to note about dCSRA. First, we use dCSRA instead of oCSRA to reduce the problem of exposed terminals [8]. Second, for a BS to hear the announcements, it must be silent (not transmitting). The BSs that are close to an announcing UE are assured to be silent; otherwise, the UE would not have assessed the channel to be free in the first place. In contrast, the BSs that are farther away from an announcing UE may not hear the announcements and may cause deaf interference. However, such interference would not be as severe as the interferers are farther away from the UE. Third, the announcements by a UE are sent out omnidirectionally, as shown in Figure 4(b), because a deaf interferer can be anywhere around a UE. Hence, it is also logical for the BSs to use omnidirectional sensing when listening for the announcements.

V. EVALUATIONS

In this section, we compare the CS schemes, with the non CS scheme (nonCS), where no CS is performed before the downlink transmissions, as the baseline. We use the coverage probability of the typical UE, $P_c(Z)$, as the evaluation metric. $P_c(Z)$ is the probability that typical UE’s SINR is greater than $Z$, at an instant $t$, during its scheduled downlink timeslot. Thus, $P_c(Z) = Pr[(\text{SINR} > Z) \cap T] = Pr[(\text{SINR} > Z) \cap T] \times P(T)$, where $T$ is the event of downlink transmission to the typical UE from its associated BS at $X_{b,n}$.

We evaluate $Pr[(\text{SINR} > Z) \cap T]$ using simulations, and find $P(T) = p_T$ analytically, as described next. If there are $N_a$contending BSs within the sensing range of a node, then it will find the channel free with probability $(1 - p_T)^{N_a}$. Thus, we obtain $p_T$ by solving: $p_T = 1 - (1 - p_T)^{N_a}$. Now, to obtain a deterministic value of $N_a$, we consider the average sensing region of a node, and assume it to be circular. Then, we find $N_a$ as the number of contenders in this circular region, based on the BS density of the operators. For $Pr[(\text{SINR} > Z)\cap T]$, we use $(C_{r(b,n)} t_{b,n} F_{\text{BS}}^{(1,0)} M_{\text{BS}} M_{\text{UE}}) / (\sigma^2 + I)$, where $r$ is the distance between the typical UE and its associated BS, $\sigma^2 = N_f/P_T$, and $I$ is the aggregate interference. For computing $I$, we find the interference caused by each of the BSs and add up these values to obtain $I$. For a BS at $X_{j,m}$, we assume it belongs to $B_0$ with probability 0.5, and to $B_a$ otherwise. Next, depending on whether it belongs to $B_0$ or $B_a$, we check for the hidden or deaf conditions in Equation 1 or Equation 2. If the BS does not satisfy these criteria, it produces no interference. However, if the BS satisfies the hidden/deaf criteria, its interference is $C_{r(j,m)} G_{j,m} ||X_{j,m}||^{-\alpha_X^{(j,m)}}$ with probability $p_T$, and zero otherwise.

Simulation parameters: We consider a shared band of $W = 600$ MHz. For the path loss model at $37$ GHz, we use $C_L = -60$ dB, $C_N = -70$ dB, $\alpha_L = 2$, and $\alpha_N = 4$ [1]. For transmit power, we use $P_T = 36$ dBm and $P_U = 16$ dBm. For the number of antennas, we use $n_{BS} = 64$ and $n_{UE} = 16$. 

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Fig. 3: Figure showing that CST cannot avoid interference from the co-located BSs.

Fig. 4: Figure demonstrating the problem with deaf interferers and resolution using dCSRA.
We observe that, as the possibility of strong interference from a co-located BS increases. In contrast, the performance of dCSRA improves as \( \rho \) increases because a higher value of \( \rho \) increases \( P(T) \) for dCSRA, without allowing any unwanted interference.

### VI. CONCLUSIONS

We investigated CS for interference management in a mmWave network where multiple non-coordinating operators share spectrum and BS sites. We described that CST cannot prevent interference from co-located BSs, and CSR cannot tackle the deaf interferers. We proposed dCSRA, which can prevent interference from hidden interferers and most of the deaf interferers. We evaluated the coverage probability of our shared mmWave network using simulations and demonstrated the superiority of dCSRA at higher values of SINR. We also showed that, for lower values of SINR, not using any CS is the best strategy.

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