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# An Adaptive Coverage Enhancement Scheme Based on mmWave RoF for Future HetNets

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**ABSTRACT** For future heterogeneous networks, network coverage is identified as one of the main challenges. This paper focuses on the spectrum sharing and energy consumption problems with millimeter wave radio over fiber (mmWave RoF) utilized to enhance the coverage of the system. The proposed adaptive scheme includes the following steps. First, the system identifies the users as licensed users that primarily own the specific spectrum and unlicensed users that have to purchase the spectrum. Based on the game theory, the spectrum resource is shared among the eNB and low power nodes (LPNs) with a relatively high benefit. Second, an adaptive sleep schedule scheme is performed to reduce the power cost of some LPNs that are scored under the threshold. Third, an adaptive power allocation scheme is utilized to further reduce the power assumption of the system and does not affect the system demand satisfaction. The simulation results finally show that the proposed resource allocation scheme can achieve improved coverage of the network.

**INDEX TERMS** Future HetNet, mmWave, resource allocation, RoF.

## I. INTRODUCTION

The upcoming modern communication system, such as 5G, is expected to realize seamless access with small cells, supporting high data rate up to 10-20 Gbps [1]–[3]. To achieve the demands, the applications of millimeter wave (mmWave) are extended [4], [5]. Radio over fiber (RoF) is one of the solutions to provide high bitrate mmWave signals with optical multi-level modulation techniques [6]–[11]. However, for RoF systems, there is still an tough issue on the resource and coverage shortage of the network [12]–[14].

This paper focuses on the coverage enhancement in a mmWave RoF heterogeneous network (HetNet) by adaptive spectrum sharing and power allocation. The large bandwidth makes mmWave promising to provide high data rates for small cells [3], [15], [16]. And the physical character of the short wavelength makes mmWave highly directional with narrow beams and sensitive to blockage [17]. This results in lower interference and an effective usage of the spectrum. However, within a relatively small area, the conflict still exists and lowers the quality of service (QoS) [18]. Meanwhile, power consumption is one of the major challenges for the multiple demands of services in the future HetNets [19]–[22]. So the spectrum sharing as well as power control should be feasible for this scenario.

To perform the upcoming communication system, there are several key contributors such as the network architecture, base station (BS) deployment, air-interface, spectrum usage, etc [23]. As the network will be dense both for data traffic and users, the multi-layer HetNet will provide a solution with seamless coverage, and the system is capable for technologies such as mmWave and massive multiple-input multiple-output (MIMO) [3]. The high frequency and space-time multiplexing will lead to higher spectral and energy efficiency and resolve many technical challenges for the future system [5], [24], [25].

To further support the future system and reduce the pressure of the service demands, considerable attention is focused on the convergence of wireless communication and optical fiber technologies. The RoF system is capable for distributing mmWave signal and of low power consumption [6], [26], [27]. People notice there is a great potential of the RoF system for a secure and effective transmission for multiple future HetNet application scenarios, such as vehicular (high mobility), multimedia, and interactive services. And the resource allocation is researched by many outstanding works.

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We summarize several related works as follows. Reference [17] proposed an optimized scheme by setting the interference threshold for the secondary licensed network. Reference [28] proposed a full-duplex quasi-gapless carrier aggregation scheme for RoF HetNets. Reference [29] focused on the seamless integration of the RoF system and evaluated 5 Gbps signal transmission. Browning *et al.* [30] researched on the optical frequency combs as a promising solution for the efficient mmWave generation method. References [31] and [32] proposed multi-scale approaches to spectrum sensing and information exchange in mmWave cognitive cellular networks with small cells.

Based on some previous work [33], [34], the main contributions of this paper are as follows.

We first formulate an improved Stackelberg game spectrum sharing scheme to improve the spectrum efficiency. Then, the eNB of the licensed network price the shared spectrum. If the LPNs would like to transmit on some extra band, they need to purchase the corresponding spectrum by paying the price. However, there exists the original spectrum hole ratio of the eNB coverage. By identifying the spectrum hole, the LPN can decide whether to purchase extra band and the number of licensed nodes to offload. By deploying the dynamic scheme, balance is achieved with the most suitable parameters generated by the algorithm.

Then, the system identifies the utility function of the LPNs and finds out the LPNs with relatively low effects, for example, with few users within their coverage. For the LPNs scored less than the threshold, the LPNs will turn on their sleep mode to save power. And when the system thinks the LPN can wake up to serve more users, it wakes and turns off the sleep mode.

At last, the system allocates the power to the active nodes adaptively. In order to achieve a demanded minimum power, the system considers the interference among other LPNs and then performs an optimal result.

The rest of the paper is organized as follows. We introduce the system model and presents the basic idea of the system in Section II. In Section III, we propose and analyze the adaptive scheme. Section IV presents the simulation setup as well as the numerical results, then discusses the system performance. Finally, in Section V, the paper is concluded.

## II. SYSTEM MODEL

We consider the mmWave RoF system as is shown in Fig. 1. The central station (CS) generates optical signals, which is transmitted to the eNB serving the primary users (PUs). Within the macro cells, there are multiple small cells including secondary users (SUs) served by low power nodes (LPNs).

Suppose there are $J$ co-channel LPNs in a single macro cell. The indices of the eNB and LPNs are denoted by the set $\mathcal{B} = \{0, 1, \ldots, J\}$, where the index $j = 0$ represents the eNB and $j \geq 1$ stands for the $j$-th LPN. And the set of $I$ external interference nodes are denoted by $i \in \mathcal{B}_I = \{1, 2, \ldots, I\}$. $N_0$ and $N_j$ represent the numbers of PUs and SUs in the $j$-th LPN, respectively.

Assume the nodes in the network transmit and receive signals in the mmWave band. The channel condition is supposed to be block-fading and the zero mean additive noises are independent circularly symmetric complex Gaussian (CSCG) with variance $\sigma^2$.

## III. PROPOSED SCHEME

In this section, we address the proposed scheme as the followings. Firstly, we formulate the Stackelberg game to allocate the spectrum and enable the unlicensed users to access to the network. Then, perform a sleep scheme to deactivate the LPN that contributes little to the system utility function. Moreover, we allocate the power to fulfill the communication demands. At last we analyze the performance of the scheme.

### A. STACKELBERG GAME FORMULATION

Let $r^0$ be the minimum data rate demanded for a random power node, while $r$ is the true minimum user data rate defined for the licensed network. As for a node among $N$ attached nodes, we have $U = N \ln\left(\frac{r}{r^0}\right)$ as the general utility function.

The LPNs aim to obtain maximum data rates with the least cost, their utility function is defined as

$$U_j = CN_j \ln\left(\frac{r_j}{r^0}\right) - (1-\gamma)AF_j, \tag{1}$$

where $C$ is a positive constant, and $A$ is the unit price of the frequency band. To optimize the LPN $j$, we have

$$\max_{F_j} \; U_j \quad st. 0 \leq F_j \leq F. \tag{2}$$

The utility function $U_M$ for the licensed network is expressed in (3), as shown at the bottom of the next page. Following with the transformed $U_M$ into the form $F_j^*(\gamma)$ for the backward induction.

Here

$$Q_0(\vec{\beta}) = \frac{F}{f_0(\vec{\beta})r^0} \log\left(1 + SINR_{0,min}^{(0)}\right) \tag{4}$$

$$Q_j(\beta_j) = \frac{N_j C}{Af_j(\beta_j)r^0} \log\left(1 + \frac{SINR_{j,min}^{(1)}}{\beta_j}\right) \tag{5}$$

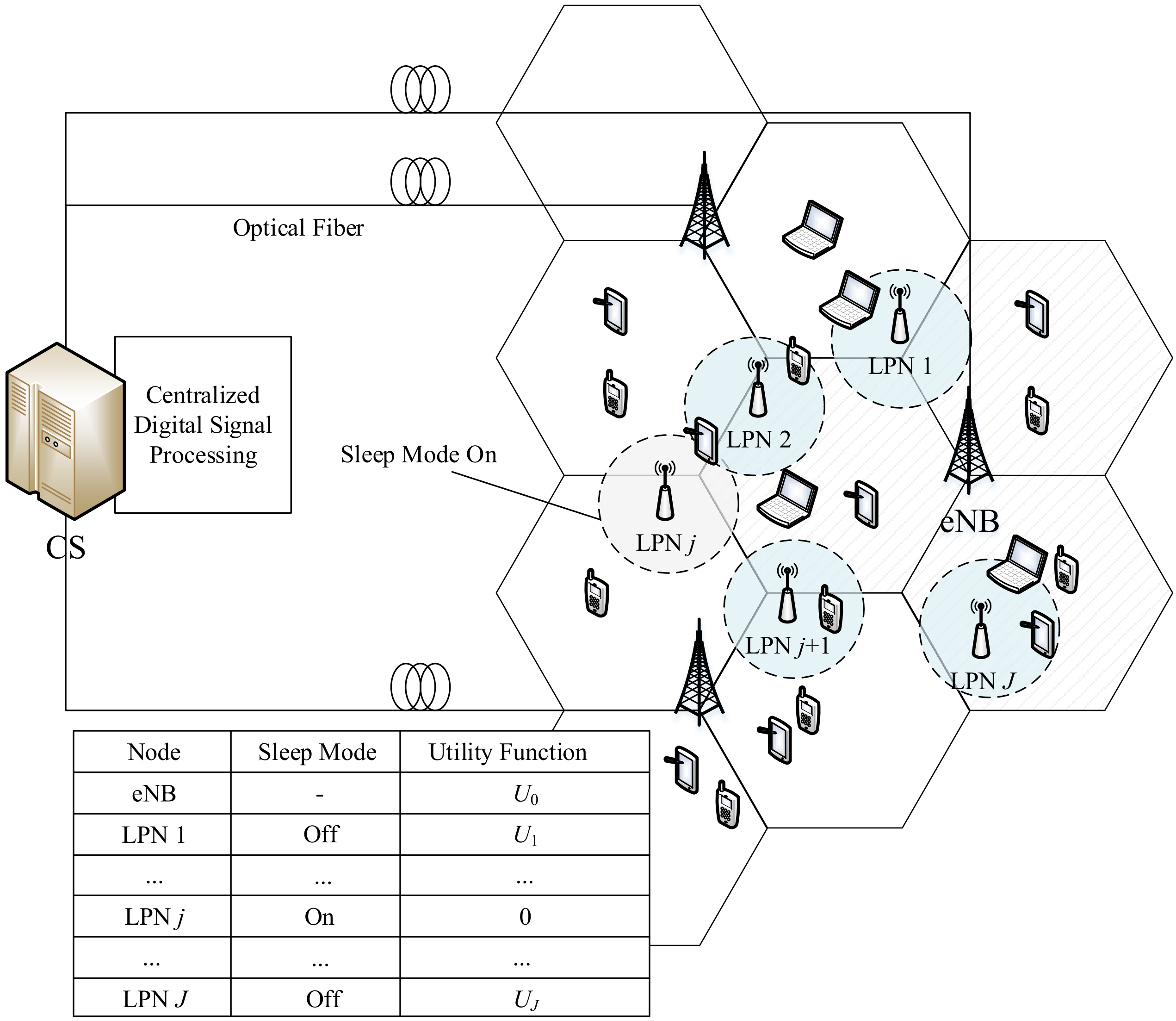
$$\vec{\beta} = (\beta_1, \beta_2, \beta_3 \ldots \beta_F). \tag{6}$$

For the licensed network, formulate the optimization problem as

$$\max_{\gamma, \vec{\beta}} \; U_M \; st. \, 0 \leq \gamma \leq 1 \; \beta_j \geq 1, \quad j = 1, 2, \ldots, J,$$

where $\vec{\beta} = (\beta_1, \beta_2, \beta_3 \ldots \beta_F)$.

The eNB of the licensed network randomly initializes its parameters $\gamma$ and $\vec{\beta}$. LPNs decide to purchase how much bandwidth after solving the optimization problem. For new $\gamma$ and $\vec{\beta}$, LPNs purchase some bandwidth. The eNB performs a backward induction to achieve the balance.




| Node | Sleep Mode | Utility Function |
|---|---|---|
| eNB | - | $U_0$ |
| LPN 1 | Off | $U_1$ |
| ... | ... | ... |
| LPN $j$ | On | 0 |
| ... | ... | ... |
| LPN $J$ | Off | $U_J$ |

**FIGURE 1.** **The mmWave RoF HetNet structure.**

Here we have $U_j$ as a function of $F_j$, with second derivative formulated as

$$\frac{\partial^2 U_j}{\partial {F_j}^2} = \frac{-N_j C}{{F_j}^2} < 0. \tag{7}$$

Then solve the maximal $F_j$ with the given $\gamma$

$$\frac{\partial U_j\left(F_j\right)}{\partial F_j} = \frac{N_j C}{F_j} - (1-\gamma)A, \tag{8}$$

The solution $F_j^*$ is obtained as

$$F_j^* = \begin{cases} F, & 1 - \frac{N_j C}{AJ} \le \gamma \le 1 \\ \frac{N_j C}{A(1-\gamma)}, & 0 \le \gamma < 1 - \frac{N_j C}{AJ} \end{cases} \tag{9}$$

Generally, the LPN cannot occupy all the spectrum usage of the licensed network, so $\gamma < 1 - \frac{N_j C}{AJ}$ is feasible in

$$U_M = \sum_{j\ge 1}(1-\gamma)AF_j + C\left(N_M \ln\left(\frac{r_M}{r^0}\right) + \sum_{j\ge 1} N_j^{offload} \ln\left(\frac{r_j^{offload}}{r^0}\right)\right).$$

$$U_M\left(\gamma, \vec{\beta}\right) = C\sum_{j\ge 1} N_j + Cf_0(\vec{\beta}) \ln\left((1-\gamma)\, Q_0(\vec{\beta})\right) + C\sum_{j\ge 1} f_j(\beta_j) \ln\left(\frac{\gamma Q_j\left(\beta_j\right)}{1-\gamma}\right). \tag{3}$$

most situation. It is helpful to assume that $F_j^*(\gamma)$ equals to $\frac{N_j C}{A(1-\gamma)}$ to further simplify the problem.

To solve the above-mentioned problem, $\vec{\beta}$ needs to be dependent. We consider the following two cases: (i) $\vec{\beta}$ is predetermined; (ii) for each LPN, change $\vec{\beta}$ until achieving the maximum access data rate. In [33], we gave the detailed solution for $\vec{\beta}$.

### B. SLEEP SCHEME

If the utility function achieved by a specific LPN is too low, we define the LPN turns to the sleep mode. We set a Boolean type identifier of sleep mode **s**. The details are described in Alg.1.

**Algorithm 1** Sleep Scheme

**Initialization:**

Utility function values, $\mathbf{U} = [U_1, ..., U_J]$; Identifier of sleep mode **s**; Threshold for sleep mode on, $T_S$; Threshold for coverage, $T_C$.

**Main loop:**

- (j=1,2,...,J)
- At time $t$, we have the utility function value $U_j$ of the LPN $j$.
- If $U_j \geq T_S$, keep the LPN $j$ active. $s_j = 1$.
- If $U_j < T_S$, the LPN $j$ turns on sleep mode. $s_j = 0$.
- If the system cannot fulfill the demand of some user within some area (i.e., users located at the area where coverage is less than $T_C$), check if there are sleeping LPN nearby. If so, turn off the sleep mode of the LPN.

For simplicity, the sleep scheme does not feed back to the game algorithm. The game algorithm processes without considering whether the sleep mode is on for the LPNs. The sleep mode may change according to the value of the utility function of the specific LPN. In this work, we assume a system that does not vary too fast, so there is no big problem. But for the system that varies fast, for example, with high mobility, further consideration shall be made.

### C. POWER ALLOCATION

To achieve the optimal performance, radio resource management one of the most critical issues in taking the advantage of the network, mitigating inter-cell and inter-user interference and guaranteeing acceptable QoS for active users. Considering the fact that users with better CSI would contribute more capacity to the system but consumes less power, so the users with better channel condition should have a higher priority over the users with worse CSI [20]. The power allocation problem can be formulated as the follows to maximize the sum rate,

$$\max_{\rho} \left\{ R_{sum} = \sum_i \sum_k R_{i,k} \right\}, \tag{10}$$

Here $R_{i,k}$ is the data rate for user $k$ within the coverage of power node $i$.

Proofed by [20], the power allocation can be expressed as

$$\rho_{i,k} = \begin{cases} \left[ \frac{1}{2} \left( \frac{P_{diff}}{\tilde{P}_i g_{i,k-1}} + 1 - \sum_{u=k+1}^{|\mathcal{U}_i|} \rho_{i,u} \right) \right]^+, & k \in \Phi \\ \left[ \frac{I_{i,u}^{th}}{1 + I_{i,u}^{th}} \left( 1 - \sum_{u=k+1}^{|\mathcal{U}_i|} \rho_{i,u} + \frac{1}{\tilde{P}_i g_{i,k-1}} \right) \right]^+, & k \in \Phi' \\ \left[ \frac{I_{i,u}^{th}}{1 + I_{i,u}^{th}} \left( 1 - \sum_{u=k+1}^{|\mathcal{U}_i|} \rho_{i,u} \right) \right]^+, & k = 1 \end{cases} \tag{11}$$

Here $[\cdot]^+ = max\{0, \cdot\}$, $P_{diff}$ denotes the demanded minimum power difference between the decoded and undetectable signals, $g_{i,k}$ is the normalized channel gain, $I_{i,u}^{th}$ represents the desired minimum SINR, $\tilde{P}_i$ is the total power consumption of power node $i$, $\Phi$ stands for the set of user conforming Eq. 12, and $\Phi'$ is the complementary set of $\Phi$.

Then we have

$$I_{i,u}^{th} \leq \frac{\left( \frac{P_{diff}}{\tilde{P}_i g_{i,k-1}} + 1 - \sum_{u=k+1}^{|\mathcal{U}_i|} \rho_{i,u} \right)}{\left( \frac{2}{\tilde{P}_i g_{i,k-1}} + 1 - \sum_{u=k+1}^{|\mathcal{U}_i|} \rho_{i,u} - \frac{P_{diff}}{\tilde{P}_i g_{i,k-1}} \right)}. \tag{12}$$

### D. PERFORMANCE ANALYSIS

According to previous assumptions, the signal to interference plus noise ratio (SINR) of the user $k$ served by the node $j$ in the non-spectrum hole period is denoted by

$$SINR_{j,k}^{(0)} = \frac{P_j h_{j,k}}{\sum_{s \in \mathcal{B}/j} P_s h_{s,k} + \sum_{i \in \mathcal{B}_I} P_i' h_{i,k}' + \sigma^2}. \tag{13}$$

Meanwhile, the SINR during the spectrum hole period can be expressed as

$$SINR_{j,k}^{(1)} = \frac{P_j h_{j,k}}{\sum_{s \in \mathcal{B}/\{0,j\}} P_s h_{s,k} + \sum_{i \in \mathcal{B}_I} P_i' h_{i,k}' + \sigma^2}. \tag{14}$$

In the Eq.(13,14), $P_j$ and $P_i'$ represent the transmit power of LPN $j$ and external power node $i$, respectively. The path gain between the user $k$ and LPN $j$ is expressed by $h_{j,k}$, and $h_{i,k}'$ indicates the path gain between the user $k$ and external power node $i$. We also assume that the LPNs are sparsely located in the licensed network and the interference between them is ignored for simplicity.

For LPN $j$, the minimum user data rate before offloading licensed users is

$$r_j = \frac{F_j(1-\gamma)}{N_j} \log(1 + SINR_{j,min}^{(0)}), \tag{15}$$

where $\gamma$ and $F_j$ express the spectrum hole ratio and the relay $j$'s bandwidth, respectively, and $SINR_{j,min}^{(0)}$ denotes the minimum SINR among $N_j$ users served by LPN $j$ in the non-spectrum-hole period. Similarly, the minimum user data rate of LPN $j$ after offloading the licensed users can be expressed as

$$r_j^{offload} = \frac{F_j\gamma}{N_j^{offload}} \log(1 + \frac{SINR_{j,min}^{(1)}}{\beta_j}), \tag{16}$$

where $\beta_j$ is the offloading factor, $SINR_{j,min}^{(1)}$ is the minimum SINR obtained among $N_j$ in spectrum holes. Here $N_j^{offload} = f_j(\beta_j)$ is an increasing function with the variable $\beta_j$, and in practice, we obtain the $f_j(\cdot)$ by analyzing long term statistic with particular distributions of users and LPNs. Hence, the minimum user data rate of the licensed network is denoted by

$$r_M = \frac{F(1-\gamma)}{N_M} \log(1 + SINR_{0,min}^{(0)}), \tag{17}$$

where $F$ represents the total bandwidth of the eNB, $N_M = f_0(\beta_1, \beta_2, \ldots, \beta_J)$ is a non-increasing function with offloading factors as its variable, and $SINR_{0,min}^{(0)}$ denotes the minimum SINR of the $N_M$ users. Then the relationship between $N_M$ and $N_j^{offload}$ satisfies

$$N_M + \sum_{j=0}^{J} N_j^{offload} = N_0. \tag{18}$$

## IV. SIMULATION RESULTS

We setup the numerical simulation and the corresponding results are presented in this section, then evaluate the performance of several schemes including the one proposed. Table 1 lists the main parameters for the simulation.

**TABLE 1. Main parameters.**

| Parameters | Values |
|---|---|
| Simulation scenario | ITU-UMa/UMi |
| Macro cell radius | 500m |
| eNB TX power | 46 dBm |
| Small cell radius | 50m |
| LPN TX power | 30 dBm |
| Carrier frequency | 60GHz |
| System bandwidth | 100Mhz |
| Distribution of users | Uniform |
| Therminal noise density | -174 dBm/Hz |

As is shown in Fig.2, we compare the coverage probability of the different groups of users. As the SINR threshold increases, the coverage probability decreases. We can observe that the coverage probability is higher for PUs than that of SUs at relatively lower SINR threshold, but the ratio becomes lower at higher SINR threshold. One of the possible reasons is that PU is closer to the eNB and may be interfered by LPNs when the SINR threshold becomes higher.

The SINR distribution before and after the schemes is shown in Fig.3 and Fig.4, respectively. As we can see, the SINR increases globally, which shows that the proposed scheme is helpful for the system performance on the overall SINR.

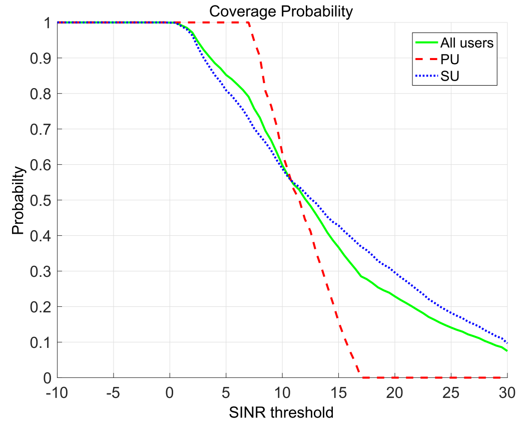



**FIGURE 2. The coverage probability v.s. the SINR threshold.**

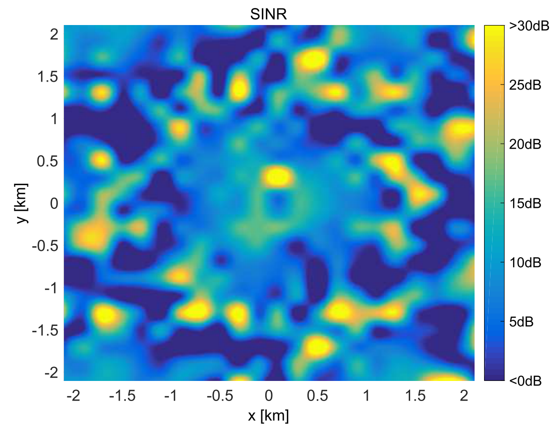



**FIGURE 3. SINR distribution without deploying the proposed scheme.**

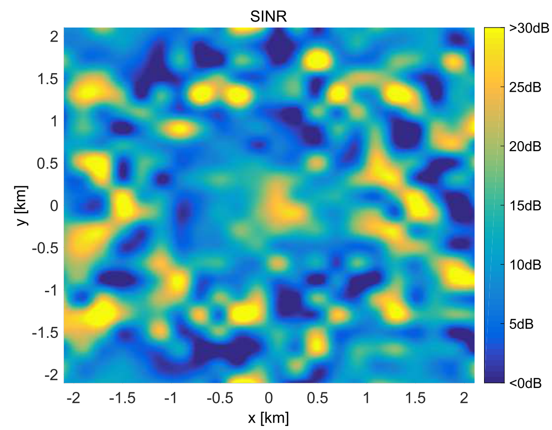



**FIGURE 4. The coverage probability v.s. the SINR threshold.**

## V. CONCLUSIONS

In this paper, we focused on the coverage problem in the mmWave RoF HetNet system and proposed an adaptive spectrum sharing and power allocation scheme. We setup the framework of Stackelberg game algorithm to serve for the users in the network. Then we performed the sleep scheme and power allocation method, and analyzed the performance of the scheme. Finally, we simulated the scheme and it is capable to improve the overall coverage of the system.

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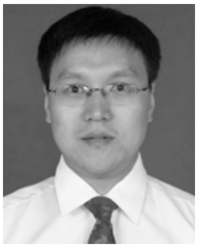

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