Millimeter Wave Cell Search for Initial Access: Analysis, Design, and Implementation

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***Abstract*—Millimeter wave (mmWave) technology is gaining momentum because of its ability to provide high data rates. However, in addition to other challenges in the operation of mmWave systems, developing cell search algorithms is a challenge due to high path loss, directional transmission, and excessive sensitivity to blockage at mmWave frequencies. Thus, the cell search schemes of long term evolution (LTE) cannot be used with mmWave networks. Exhaustive and iterative search algorithms have been proposed in literature for carrying out cell search in mmWave systems. The exhaustive search offers high probability of detection with high discovery delay while the iterative approach offers low probability of detection with low discovery delay. In this paper, we propose a *hybrid* algorithm that combines the strengths of exhaustive and iterative methods. We compare the three algorithms in terms of misdetection probability and discovery delay and show that hybrid search is a smarter algorithm that achieves a desired balance between probability of detection performance and discovery delay.**

***Index Terms*—Cell Search, discovery delay, UE orientation, beamforming gain, search sectors.**

I. Introduction

Researchers in communication system design are excited about the dawn of fifth generation (5G) technology for mobile communications because it facilitates the concept of Internet of Things (IoT) whereby almost every device will be interconnected through the Internet [1]. The traditional cellular systems operate in the range of 1 – 30 GHz. However, if we move up in the frequency spectrum, i.e., 30 – 300 GHz, then there is the potential to have channels that can provide much higher bandwidths, capacity, and data rates [2]. This band of carrier frequencies that ranges from 30 – 300 GHz is referred to as the millimeter wave (mmWave) band.

MmWave technology operates at very high carrier frequencies. Because of that, they experience high path loss, which is in accordance with Friis free space path loss equation [2]. Also, increased carrier frequency and consequently, small wavelength makes it very difficult for the signal to penetrate through solid materials. Hence, directional transmission is typically used to provide high gain and compensate for the high path loss and absorption attenuation while beamforming and precoding are the key techniques used for carrying out directional transmissions [3]. Thus, initial access (IA) is a key concern with mmWave systems and is the focus of our study in this paper.

IA is a process by which a base station (BS) and user equipment (UE) establish a physical connection with each other, after which the formal communication starts. The process of IA consists of three steps: cell search, extraction of system information, and random access. *Cell search* is the method during which UE searches for the BSs and associates with the one from which it receives the strongest signal. Once the connection has been established, the BS and UE exchange important system information such as cell configurations, downlink and uplink bandwidth, frequency band, number of transmit antennas, cell identity, etc in a process called *extraction of system information*. UE, having searched for an appropriate BS and extracted system information, next obtains a channel for communicating with the BS by sending channel reservation request to BS using contention-based or contention-free protocols, a scheme referred to as *random access*. At the conclusion of IA process, the user is connected to the data plane and able to transmit/receive actual data.

The process of cell search gets complicated with mmWave systems due to their hallmarks of high path loss, directional transmission, and sensitivity to obstacles. Cell search in LTE is done using a two step synchronization procedure. The BS first omnidirectionally transmits pilot signals; once a link with the UE has been established, formal communication takes place using directional transmission. This cell search scheme of LTE cannot be used with mmWave cellular networks due to range mismatch (a problem that arises due to a difference in the range that can be covered using directional and omnidirectional transmission; also referred to as asymmetry in gain problem [4]) and additional sensitivity to blockage.

Realizing the need for new cell search schemes, researchers have proposed three key algorithms, i.e., exhaustive, iterative, and context-information (CI) based cell search [5]. While studying these algorithms, detection probability (the probability that a UE has been detected) and discovery delay (time required to discover a UE) are the two key parameters that need to be taken into account. Note that we study only down-

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link transmission in this paper. Thus, CI-based search scheme, which uses exhaustive search in downlink, is investigated under exhaustive search [6], [7].

The first well established cell search algorithm proposed in literature, namely, exhaustive search provides a very good detection probability but takes a longer duration to discover the UE in comparison to iterative search approach [5], [8]. Iterative search [9], because of iteratively narrowing down search beams outperforms exhaustive search in terms of discovery delay but has a low detection probability. Thus, there is an inevitable trade-off between these two algorithms. We can either achieve high detection probability, at the expense of a high discovery delay (exhaustive search) or low discovery delay at the expense of low detection probability (iterative search).

A desirable balance between detection probability and discovery delay is indeed possible and is the main idea of this paper. In particular, we make the following specific contributions:

1) We develop a mathematical framework in order to study the existing cell search solutions.
2) Using that theoretical framework, we enhance the existing study by proposing a new algorithm called *hybrid* search, which is based on the idea of combining the strengths of the two well-established schemes (i.e., exhaustive and iterative) in the cell search literature.
3) We perform a comparative analysis by analyzing the misdetection probability and discovery delay of the three cell search algorithms along three aspects that are: signal-to-noise ratio (SNR) threshold, separation distance between BS and UE, and UE orientation with respect to the BS.

It is important to mention the noticeable work of Giordani *et al*. [5] that served as a foundation for our work. Nevertheless, their work lacks a mathematical foundation for deeply investigating the algorithms. We enhance the existing study by first proposing a theoretical framework for studying the already proposed cell search schemes (i.e., exhaustive and iterative). This mathematical framework serves as the building block for hybrid algorithm, which achieves a desirable balance between detection probability and discovery delay. In addition to that, this is the first work to also consider the effect of UE orientation on discovery delay; a parameter that has not been explored in detail before.

II. The Cell Search Schemes

In this section, we describe our system model and discuss the well established cell search algorithms in literature, i.e., exhaustive search and iterative search.

A. Exhaustive Search

In this method, the BS starts its search for UE by transmitting the synchronization signal, T_{syn}, with a search beamwidth BW°_{EX}, for T_{sig} seconds (s) in a particular sector. Let N_{EX} be a positive integer that denotes the total number of search sectors, then we have

$$N_{EX} = \frac{360^{\circ}}{BW^{\circ}_{EX}} \tag{1}$$

For example, if BW°_{EX} = 10°, then N_{EX} = 36. Let $I = \{1, 2, ...N_{EX}\}$ be a set that represents the index of sectors. Note that we have assumed sectored approximation, i.e., the gain provided by search beam is constant throughout the sector $i \in I$.[1] The search region spanned by the beam for a particular $i \in I$ is found as

$$\begin{aligned} \theta^{\circ}_{S} &= (i-1)BW^{\circ}_{EX}, \\ \theta^{\circ}_{E} &= (i)BW^{\circ}_{EX}, \end{aligned} \tag{2}$$

where θ°_{S} marks the start of the beam and θ°_{E} identifies the end of a beam. Hence, in the above example, for $i = 1$, the search beam spans the region, 0° to 10°.
If $G(\theta)$ is the total antenna gain, then

$$G(\theta) = G_{Tx} + G_{Rx} + BFGain_{Tx} + BFGain_{Rx}, \tag{3}$$

where G_{Tx} and G_{Rx} are the antenna gains due to omnidirectional transmission at the transmitter and receiver, respectively, while $BFGain_{Tx}$ and $BFGain_{Rx}$ are gains due to beamforming at the transmitter and receiver, respectively. $BFGain$ at either the BS or UE is defined as

$$BFGain = E * D, \tag{4}$$

where E is the antenna efficiency and the directivity, D is given as

$$D = \frac{4\pi}{BW^{\circ}}, \tag{5}$$

Now, the synchronization signal, represented by T_{syn}, passes through a channel that can be line-of-sight (LoS) or non-line-of-sight (NLoS). Let the path loss experienced by the signal be

$$L_{mm}(r) = \begin{cases} \rho + 10\alpha_L log(r) + \chi_L & \text{if link is LoS} \\ \rho + 10\alpha_N log(r) + \chi_N & \text{otherwise} \end{cases} \tag{6}$$

Here, ρ denotes a fixed path loss factor, α_L & α_N are the path loss exponents for LoS and NLoS mmWave links respectively, and χ_L & χ_N are the zero mean log normal random variables for LoS and NLoS mmWave links, respectively, which represent shadowing or blockage [10].
If UE receives a signal from the BS, then the power received, P_r, is expressed as

$$P_r = \frac{P_t G(\theta)\mu}{L_{mm}(r)}, \tag{7}$$

where P_t is the transmit power and μ is the squared envelope of multipath fading where the envelope follows a Rayleigh or Rician distribution depending on whether the UE-BS link is NLoS or LoS, respectively [10]. We are assuming a single BS and a single UE, thus there is no interference due to other users. This assumption is consistent with [9]. The SNR, τ, is thus calculated as

$$\tau = \frac{P_r}{\sigma^2}, \tag{8}$$

[1]Note that for a real world mmWave link, channel inaccuracies (such as fading, angular spread, power delay, scattering, diffraction, etc) affect propagation and lower the gain from its ideal values. For simplicity, these limiting factors have not been included in our analysis. Also, we are considering an ideal rectangular beamforming gain and not taking into account the effect of side lobes.

where σ^2 represents the noise power. A decision regarding the establishment of a BS-UE link is made, such that

$$\begin{cases} \tau \geq \alpha_{th} & \text{Link established} \\ \tau < \alpha_{th} & \text{Link not established} \end{cases} \tag{9}$$

where α_{th} is the SNR threshold.

If UE is not present in a particular search sector, then the BS waits for T_{per} (s) and repeats the entire process for the next sector. This process continues until the BS has found UE, or the BS has searched in all sectors, i.e., $i = N_{EX}$, but could not find a UE.

Assuming a UE has been detected with probability P_d, we now define the discovery delay, which is the time required to discover the user. For the sake of simplicity, we are considering only the effect of UE orientation and search beamwidth on discovery delay. Let UE be located at x° with respect to the BS, then the discovery delay for exhaustive search, DD_{EX}, is computed as

$$\begin{aligned} &DD_{EX} = (i)T_{sig} + (i-1)T_{per}, \ (\text{for } i \in I) \\ &\text{subject to:} \\ &\tau \geq \alpha_{th} \end{aligned} \tag{10}$$

As an example, consider a UE located at 3° with respect to BS. Given that UE has been detected for $i = 1$ by using a $BW^\circ_{EX} = 10^\circ$ that covers the search space from $\theta^\circ_S = 0^\circ$ to $\theta^\circ_E = 10^\circ$; discovery delay for UE calculated using (10) is DD_{EX} = 10μs (where $T_{sig} = 10\mu$s and $T_{per} = 200\mu$s [5]).

B. Iterative Search

Consider a BS searching for UE by deploying iterative search. Iterative search successively narrows down search beam until a suitable link with UE has been established. Let N_{IT} be a positive integer that denotes the number of search sectors, then

$$N_{IT} = m, \tag{11}$$

where m is a positive integer that can take on values that are greater than 1. For example, if the bisection method is used then $m = 2$ and the entire search area is divided into two beams, each having a beamwidth of 180°.

To understand iterative search, let us introduce the concept of $Stages$. Iterative search successively narrows down search beams; this narrowing down of search beam occurs in a particular stage, S. Let $Stages$ be the upper bound on the number of stages, i.e., $S \leq Stages$.[2]

If $BW^\circ_{IT_S}$ is the search beamwidth for a particular stage S, then

$$BW^\circ_{IT_S} = \frac{360^\circ}{m^S}, \tag{12}$$

A similar process to that of exhaustive search follows here. Let $I = \{1, ..., N_{IT}\}$, then the search space spanned by the beam for a particular $i \in I$ at a certain stage S is given by

$$\begin{aligned} \theta^\circ_S(S) &= (i-1)BW^\circ_{IT_S} + \theta^\circ_S(S-1), \\ \theta^\circ_E(S) &= (i)BW^\circ_{IT_S} + \theta^\circ_S(S-1), \end{aligned} \tag{13}$$

where $\theta^\circ_S(S)$ and $\theta^\circ_E(S)$ mark the beginning and end of the search beam at a certain level S for a particular $i \in I$ while $\theta^\circ_S(S-1)$ is the angular offset from the previous stage.
If UE has received signal from the BS, it measures τ by using Eqs. (3 – 8). Subsequently, we define the following scheme for link establishment

$$\begin{cases} \tau \geq \alpha_{th}, & \text{Link established} \\ \tau \geq \alpha_S, & \text{Narrow down search in this sector} \\ \tau < \alpha_S, & \text{UE is not present in this sector} \end{cases} \tag{14}$$

where α_{th} is the desired threshold at which a decision regarding the establishment of a link is made and α_S is a loose threshold that identifies the region that should be narrowed down to locate UE.

The discovery delay for iterative algorithm is the sum of the delay incurred at a stage, DD_S, at which the UE has been tracked (i.e., $\tau \geq \alpha_S$) and the stage at which UE has been found (i.e., $\tau \geq \alpha_{th}$). Mathematically

$$\begin{aligned} &DD_S = (i)T_{sig} + (i-1)T_{per}, \\ &\text{subject to:} \\ &\quad \tau \geq \alpha_{th} \\ &\text{and} \\ &DD_S = (N_{IT})T_{sig} + (N_{IT}-1)T_{per}, \\ &\text{subject to:} \\ &\quad \tau \geq \alpha_S \end{aligned} \tag{15}$$

Hence, the total delay for iterative search, DD_{IT}, is defined as

$$DD_{IT} = \sum_{S=1}^{Stages} DD_S, \tag{16}$$

subject to the constraint that UE has been detected.

Example: Assume the use of bisection method, i.e., $m = 2$; bisection method bisects the search space and selects the region where UE lies for further processing. The process continues until UE has been found or $S > Stages$. Consider a UE located at 3° with respect to the BS. Let $Stages = 4$, and initial condition $\theta^\circ_S(0) = 0^\circ$, then search starts with

$$\begin{cases} S = 1, \\ BW^\circ_{IT_1} = 180^\circ, \ (\text{using (12)}) \\ i = 1, \\ \theta^\circ_S(1) = 0^\circ, \ (\text{using (13)}) \\ \theta^\circ_E(1) = 180^\circ, \\ i = 2, \\ \theta^\circ_S(1) = 180^\circ, \\ \theta^\circ_E(1) = 360^\circ, \end{cases}$$

Let $\tau \geq \alpha_S$ for $i = 1$, then discovery delay calculated using (15) is $DD_1 = 220\mu$s. Since $S \leq Stages$ and $\tau < \alpha_{th}$, we proceed to the next step.

[2]Note that $Stages$ is a design parameter. Its value depends on the narrowest allowable search beam that antenna arrays at the transmitter and receiver can support.

$$\begin{cases} S = 2, \\ BW^{\circ}_{IT_2} = 90^{\circ}, \\ i = 1, \\ \theta^{\circ}_S(2) = 0^{\circ} + \theta^{\circ}_S(1), \text{ (since } \theta^{\circ}_S(1) = 0^{\circ}) \\ \theta^{\circ}_E(2) = 90^{\circ} + \theta^{\circ}_S(1), \\ i = 2, \\ \theta^{\circ}_S(2) = 90^{\circ} + \theta^{\circ}_S(1), \\ \theta^{\circ}_E(2) = 180^{\circ} + \theta^{\circ}_S(1), \end{cases}$$

Similarly, if $\tau \geq \alpha_S$ for $i = 1$, then DD_2, using (15), is 220μs and next stage begins.

$$\begin{cases} S = 3, \\ BW^{\circ}_{IT_3} = 45^{\circ}, \\ i = 1, \\ \theta^{\circ}_S(3) = 0^{\circ} + \theta^{\circ}_S(2), \text{ (since } \theta^{\circ}_S(2) = 0^{\circ}) \\ \theta^{\circ}_E(3) = 45^{\circ} + \theta^{\circ}_S(2), \\ i = 2, \\ \theta^{\circ}_S(3) = 45^{\circ} + \theta^{\circ}_S(2), \\ \theta^{\circ}_E(3) = 90^{\circ} + \theta^{\circ}_S(2), \end{cases}$$

Likewise, $\tau \geq \alpha_S$ for $i = 1$, discovery delay for $S = 3$ is $DD_3 = 220\mu$s.

$$\begin{cases} S = 4, \\ BW^{\circ}_{IT_4} = 22.5^{\circ}, \\ i = 1, \\ \theta^{\circ}_S(4) = 0^{\circ} + \theta^{\circ}_S(3), \text{ (since } \theta^{\circ}_S(3) = 0^{\circ}) \\ \theta^{\circ}_E(4) = 22.5^{\circ} + \theta^{\circ}_S(3), \\ i = 2, \\ \theta^{\circ}_S(4) = 22.5^{\circ} + \theta^{\circ}_S(3), \\ \theta^{\circ}_E(4) = 45^{\circ} + \theta^{\circ}_S(3), \end{cases}$$

If $\tau \geq \alpha_{th}$, then a link between BS-UE has been established. The total discovery delay in the view of above example is

$$DD_{IT} = DD_1 + DD_2 + DD_3 + DD_4 = 670\mu s,$$

Otherwise, if $\tau < \alpha_{th}$ at $S = 4$, the search process terminates and this becomes a case of misdetection.

III. Proposed Algorithm

We aim to combine the strengths of exhaustive search and iterative search and propose a *hybrid* algorithm that outperforms iterative in terms of misdetection probability and exhaustive in terms of discovery delay.

To be precise, the BS first implements iterative search after which exhaustive search begins. Let N_{HY} be a positive integer that defines the number of search sectors, such that

$$N_{HY} = \begin{cases} N_{IT} = m, \\ \text{subject to:} \\ \quad S \leq Stages,\ \tau < \alpha_{th} \\ \\ N_{EX} = \frac{BW^{\circ}_{IT_S}}{BW^{\circ}_{EX}}, \\ \text{subject to:} \\ \quad S > Stages,\ \tau < \alpha_{th} \end{cases} \tag{17}$$

Iterative search tracks down UE by using wide beams. Following that, exhaustive search exhaustively scans the targeted region in order to establish a suitable link. Let us define BW°_{HY} as the search beam for hybrid scheme, then

$$BW^{\circ}_{HY} = \begin{cases} BW^{\circ}_{IT_S} = \frac{360^{\circ}}{m^S} \\ \text{subject to:} \\ \quad S \leq Stages,\ \tau < \alpha_{th} \\ \\ BW^{\circ}_{EX} \\ \text{subject to:} \\ \quad S > Stages,\ \tau < \alpha_{th} \end{cases} \tag{18}$$

Following the footsteps of exhaustive and iterative search, let us define $I = \{1, ..., N_{HY}\}$. The region spanned by the beam for a particular $i \in I$ at a specific stage, S, is given as

$$\begin{aligned} \theta^{\circ}_S(S) &= (i-1)BW^{\circ}_{HY} + \theta^{\circ}_S(S-1), \\ \theta^{\circ}_E(S) &= (i)BW^{\circ}_{HY} + \theta^{\circ}_S(S-1), \end{aligned} \tag{19}$$

If UE is present in the current sector of search, then τ is measured using Eqs. (3 – 8). The decision regarding the establishment of a UE-BS link is made using (14). Discovery delay for hybrid search, DD_{HY}, is

$$DD_{HY} = DD_{IT} + DD_{EX}, \tag{20}$$

where DD_{EX} is calculated using (10) and DD_{IT} is given by (15, 16).

Example: Consider an example wherein UE is situated 3° with respect to the BS. Let $m = 2$, $Stages = 3$, $BW^{\circ}_{EX} = 10^{\circ}$, and initial condition $\theta^{\circ}_S(0) = 0^{\circ}$. The search begins with

$$\begin{cases} N_{HY} = N_{IT} = 2, \\ S = 1, \\ BW^{\circ}_{HY} = BW^{\circ}_{IT_1} = 180^{\circ}, \\ i = 1, \\ \theta^{\circ}_S(1) = 0^{\circ}, \\ \theta^{\circ}_E(1) = 180^{\circ}, \\ i = 2, \\ \theta^{\circ}_S(1) = 180^{\circ}, \\ \theta^{\circ}_E(1) = 360^{\circ}, \end{cases}$$

Let $\tau \geq \alpha_S$ for $i = 1$. The delay incurred at $S = 1$, using (15), is 220μs. Since a suitable link has not been established, so the next stages begins.

TABLE I
Simulation Parameters

f_c	73 GHz
P_t	30dBm
E	Assuming 100%
G_{Tx}	24.5 dBi
G_{Rx}	24.5 dBi
UE position	Randomly generated (unless stated otherwise)
BF	Analog beamforming.
T_{sig}	10 μs
T_{per}	200 μs
α_S	20 dB
α_{th}	40 dB (unless stated otherwise)
NF	10dB

$$\begin{cases} N_{HY} = N_{IT} = 2, \\ S = 2, \\ BW^{\circ}_{HY} = BW^{\circ}_{IT_2} = 90^{\circ}, \\ i = 1, \\ \theta^{\circ}_{S}(2) = 0^{\circ} + \theta^{\circ}_{S}(1),\ (\text{since } \theta^{\circ}_{S}(1) = 0^{\circ}) \\ \theta^{\circ}_{E}(2) = 90^{\circ} + \theta^{\circ}_{S}(1), \\ i = 2, \\ \theta^{\circ}_{S}(2) = 90^{\circ} + \theta^{\circ}_{S}(1), \\ \theta^{\circ}_{E}(2) = 180^{\circ} + \theta^{\circ}_{S}(1), \end{cases}$$

Assume $\tau \geq \alpha_S$ for $i = 1$, the delay incurred at $S = 2$ is 220μs (using Eq. 15). Since $S \leq Stages$, the next stage begins.

$$\begin{cases} N_{HY} = N_{IT} = 2, \\ S = 3, \\ BW^{\circ}_{HY} = BW^{\circ}_{IT_3} = 45^{\circ}, \\ i = 1, \\ \theta^{\circ}_{S}(3) = 0^{\circ} + \theta^{\circ}_{S}(2),\ (\text{since } \theta^{\circ}_{S}(2) = 0^{\circ}) \\ \theta^{\circ}_{E}(3) = 45^{\circ} + \theta^{\circ}_{S}(2), \\ i = 2, \\ \theta^{\circ}_{S}(3) = 45^{\circ} + \theta^{\circ}_{S}(2), \\ \theta^{\circ}_{E}(3) = 90^{\circ} + \theta^{\circ}_{S}(2), \end{cases}$$

Suppose $\tau \geq \alpha_S$ for $i = 1$, but link has not been established. Since $S = Stages$, exhaustive search starts. Note that delay incurred at $S = 3$ is 220μs.

$$\begin{cases} N_{HY} = N_{EX} \approx 5, \\ BW^{\circ}_{HY} = BW^{\circ}_{EX} = 10^{\circ}, \\ i = 1, \\ \theta^{\circ}_{S}(4) = 0^{\circ} + \theta^{\circ}_{S}(3),\ (\text{since } \theta^{\circ}_{S}(3) = 0^{\circ}) \\ \theta^{\circ}_{E}(4) = 10^{\circ} + \theta^{\circ}_{S}(3), \\ i = 2, \\ \theta^{\circ}_{S}(4) = 10^{\circ} + \theta^{\circ}_{S}(3), \\ \theta^{\circ}_{E}(4) = 20^{\circ} + \theta^{\circ}_{S}(3), \\ i = 3, \\ \theta^{\circ}_{S}(4) = 20^{\circ} + \theta^{\circ}_{S}(3), \\ \theta^{\circ}_{E}(4) = 30^{\circ} + \theta^{\circ}_{S}(3), \\ i = 4, \\ \theta^{\circ}_{S}(4) = 30^{\circ} + \theta^{\circ}_{S}(3), \\ \theta^{\circ}_{E}(4) = 40^{\circ} + \theta^{\circ}_{S}(3), \\ i = 5, \\ \theta^{\circ}_{S}(4) = 40^{\circ} + \theta^{\circ}_{S}(3), \\ \theta^{\circ}_{E}(4) = 45^{\circ} + \theta^{\circ}_{S}(3), \end{cases}$$

Assuming $\tau \geq \alpha_{th}$ for $i = 1$, a suitable link between BS and UE has been established. The delay experienced at this level is 10μs (using Eq. 10). The total delay is the sum of the delays experienced during both iterative and exhaustive search, and is found to be 670μs (using (20)).

IV. Performance Analysis

The objective of this work is to compare the performance of the three algorithms by analyzing the misdetection probability and discovery delay. Note that in Fig. 2, Fig. 3, and Fig. 4, solid lines show the misdetection probability while dotted lines are used to represent discovery delay. Misdetection probability depends on a number of factors, such as distance, received SNR, search beam width, and LoS or NLoS channel. Without loss of generality, we have fixed the narrowest allowable search

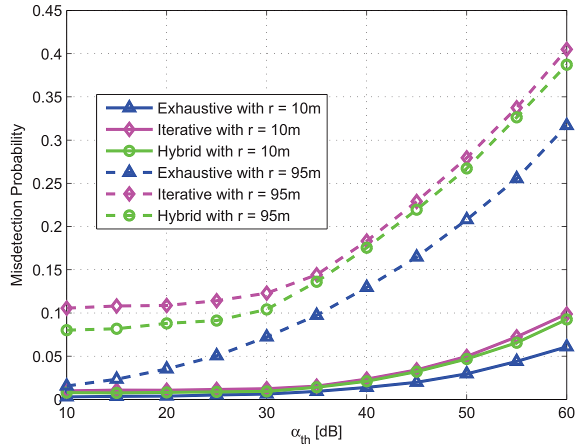

Fig. 1. Misdetection probability for the three algorithms at r = 10m and r = 95m.

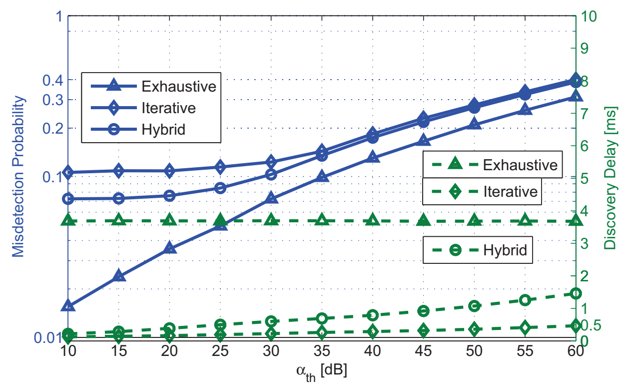

Fig. 2. SNR threshold vs misdetection probability and discovery delay.

beam at 10° in order to have a fair comparison [11]. Thus, $BW^{\circ}_{EX} = 10^{\circ}$ for exhaustive search, which is equivalent to $m = 2$, $Stages = 5$ for iterative search. Similarly, $BW^{\circ}_{EX} = 10^{\circ}$, $m = 2$, and $Stages = 3$ for hybrid search. Channel is generated as LoS or NLoS by following a uniform random distribution and is approximated using Monte Carlo simulations (10^5 times). The simulation parameters are summarized in Table I.

We first compare the performance of the three algorithms in terms of misdetection probability. For this purpose, we vary α_{th}, and plot misdetection probability for the three algorithms. We assume that the UE can be located anywhere in the cell at a fixed radius r. Fig. 1 shows two sets of results; one set is plotted at $r = 10$m and the second at $r = 95$m (to see the performance for edge users). It can be seen that misdetection probability is low at 10m as compared to 95m, which is intuitive because of a decrease in SNR for the latter case. Each simulation point on the graph is estimated using Monte Carlo simulation with 10^5 iterations. Exhaustive search provides the lowest misdetection probability. On the other hand, the proposed hybrid algorithm lies in between exhaustive and iterative in terms of performance.

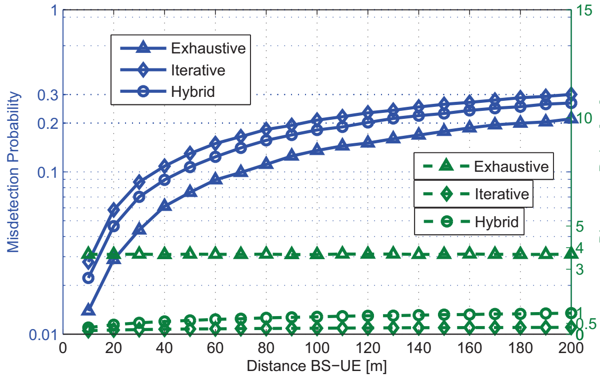

Fig. 3. Distance vs misdetection probability and discovery delay.

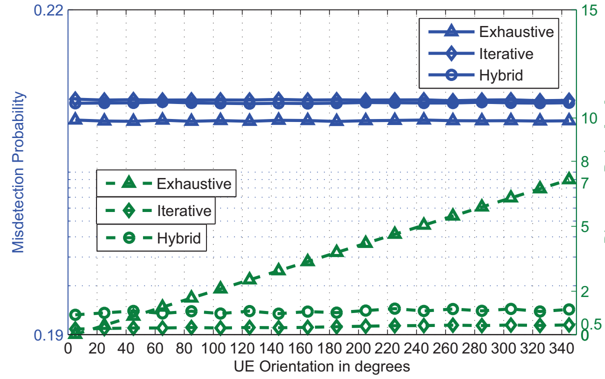

Fig. 4. UE orientation vs misdetection probability and discovery delay.

In order to study discovery delay performance of the three algorithms against α_{th}, we have fixed r at 95m and vary α_{th} from 10dB to 60dB in 5dB increments. The solid lines for misdetection probability in Fig. 2 present the increasing misdetection probability with increasing SNR threshold. It can be seen that hybrid algorithm lies in between exhaustive and iterative in terms of its misdetection probability performance. Discovery delay is computed only when a UE has been detected. Every time a UE has been found, the discovery delay is calculated using Eq. 10, Eq. 15, and Eq. 20 for exhaustive, iterative, and hybrid algorithms, respectively. This discovery time is stored and the discovery delay for a particular α_{th} is computed by taking average over all the stored values (i.e., average over the number of times UE has been discovered in 10^5 trials). Fig. 2 shows that hybrid algorithm lies mid-way between exhaustive and iterative in terms of its discovery delay performance.

Next, we study the effect of distance by increasing the separation distance between BS and UE in 10m increments from 10m to 200m. In this case, we have fixed α_{th} at 40dB. The results are shown in Fig. 3. It can be seen from the figure that misdetection probability increases with increasing distance and hybrid algorithm lies mid-way between exhaustive and iterative in terms of its performance. Same process for computing discovery delay follows here. It can be seen that exhaustive search has high discovery delay in comparison to iterative and hybrid schemes.

Following this, we study the effect of UE orientation on misdetection probability and discovery delay. To do that, we vary the position of UE from 9° to 359° in 20° increments. We have fixed the radius at $r = 95$m to see the algorithm's performance for edge users. Note that we are using $\alpha_{th} = 50$dB since this is a threshold at which all three algorithms give same misdetection probability. With all three algorithms having same misdetection probability, we can easily see an algorithm's robustness to initial UE orientation. The results are plotted in Fig. 4. It can be seen that exhaustive search is most sensitive to initial UE orientation while iterative and hybrid are relatively robust to this parameter. The misdetection probability for all three algorithms lie within acceptable limits (i.e., 0.2).

V. Conclusions and Future Work

In this paper, we have combined the advantages of exhaustive and iterative search schemes and proposed a hybrid algorithm that achieves a higher detection probability than iterative search and lower discovery delay than exhaustive search algorithm. Simulation results show that hybrid scheme attains a good balance between misdetection probability and discovery delay. As part of our future work, we aim to extend our work to the case of multiple users and also investigate into the discrepancy in achievable data rates with the three cell search algorithms.

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