NEIGHBORING CELL SEARCH FOR A-LTE SYSTEMS TO FUTURE GENERATION OF CELLULAR TELECOMMUNICATION

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Abstract

Advanced-Long term evolution (A-LTE) is considered to be a key technology for the next generation of cellular telecommunications. In A-LTE systems, each user-equipment detects the surrounding cells by searching their IDs in the synchronization channels of the received waveform. Searching and tracking neighboring cells is important for cellular network management, such as handover and base station cooperation. In this paper, we establish a general framework for neighboring cell search (NCS) in A-LTE systems. In particular, we derive sufficient signal metrics (SSMs) for NCS under various channel conditions, and develop NCS algorithms based on the SSMs, which optimally combine multiple observations over space and/or time. Moreover, we develop a statistical model for NCS using probability analysis. The performance of NCS algorithms is characterized in terms of the number of detected cells and the cell detection probability, and simulation results validate the effectiveness of the proposed algorithms. We establish a general framework for NCS in A-LTE systems, and derive the SSMs for NCS, which optimally combine multiple observations over space and/or time, under various channel conditions and mobility models; We develop a statistical model to analyze the NCS performance in both flat-fading and multipath channels; We design NCS algorithms based on the SSMs, implement the algorithms on a link-level simulator, and characterize their performance for different scenarios.

Keywords—Advanced Long Term Evolution (A-LTE), Multiuser Detection (MUD), Neighboring Cell Search (NCS), Orthogonal Frequency-Division Multiplexing (OFDM), Successive Interference Cancellation.

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I. INTRODUCTION

As a part of the evolving universal mobile telecommunications system (UMTS) beyond high speed packet access (HSPA), long term evolution (LTE) is considered to be a key technology for the next generation of cellular telecommunications. LTE is a standard for wireless communication of high-speed data for mobile phones and data terminals. It is based on the GSM/EDGE and UMTS/HSPA network technologies, increasing the capacity and speed using a different radio interface together with core network improvements. Cell identity (ID) information in LTE systems is carried by the signals in both the primary and secondary synchronization channels (P-SCH and S-SCH), called primary and secondary synchronization signals (PSS and SSS), respectively. While the PSS is mainly dedicated for synchronization, the SSS provides complete information about the cell ID.

The main contributions of this paper are as follows: We establish a general framework for NCS in LTE systems, and derive the sufficient signal metrics (SSMs) for NCS, which optimally combine multiple observations over space and/or time, under various channel conditions and mobility models; We develop a statistical model to analyze the NCS performance in both flat-fading and multipath channels; We design NCS algorithms based on the SSMs, implement the algorithms on a link-level simulator, and characterize their performance for different scenarios.

The rest of the paper is organized as follows. Section II presents the system model and formulates the NCS problem. The SSM for single-cell detection is given in Section III, and the results are then extended to the multi-cell case in Section I V. Section V presents a statistical model for NCS analysis. Simulation results are provided n Section VI, and conclusions are drawn in the last section.

II. PROBLEM FORMULATION

In this section, we describe the network and channel models, as well as formulate the NCS problem.

A. System Model

Consider an inter-cell synchronous LTE network consisting of N_t different cells with distinct cell IDs denoted by the set$N_T = \{1,2,\ldots,N_t\}$, and a UE surrounded by N_e cells, denoted by the set N_E where $N_E \subseteq N_T$ and $|N_E| = N_e$. The SSS of the k^{th} cell is given by the normalized vector $s_k \epsilon \mathbb{R}^{Nsc}$ composed of interleaved scrambled m-sequences defined in [1]. We consider two channel models: flat-fading and multipath channels. In flat-fading channels, the received S-SCH symbol in frequency domain is

$$\mathbf{r} = \sum_{m \epsilon Ne} \alpha_m \mathbf{G}(\tau_m)\, s_m + \mathbf{z} \qquad (1)$$

Where α_m and τ_m are the amplitude and relative delay (withrespect to the initial synchronization) of the signal from that cell, respectively. In multipath channels, the received S-SCH symbol in frequency domain is

$$\sum_{m \epsilon Ne} \sum_{l=1}^{Lm} \alpha_m^{(l)}\, G\left(\tau_m^{(l)}\right) s_m + z \qquad (2)$$

Where L_m is the number of multipath components (MPCs), and $\alpha_m^{(l)}$ and $\tau_m^{(l)}$ are the amplitude and relative delay of the l^{th} path, respectively.

B. Optimal NCS Detector

When prior knowledge of neighboring cells is not available, the optimal NCS detector is the maximum likelihood estimator (MLE),given by

$$\widehat{N}_E = argmax_{N_E \subseteq N_T} \wedge (r|N_E) \qquad (3)$$

Where $\widehat{N}_E$ is the optimal subset of cells based on the observation '**r**'. On the other hand, when prior knowledge of neighboring cells is available, the optimal NCS detector becomes the maximum a posterior (MAP) estimator. We will focus on the case without prior knowledge of neighboring cells in this paper, and the analysis applies analogously to the latter case. Note that the MLE for NCS detection is computationally prohibitive due to a large number of hypotheses and parameters. Hence, we first investigate the optimal detection algorithm for a single cell and then sub-optimal detection algorithms for multiple cells.

III. SINGLE-CELL DETECTION

In this section, we derive the SSM for single-cell detection in both flat-fading and multipath channels, followed by a discussion on detection with multiple observations over time(multiple radio frames) and/or space (multiple antennas).

A. Detection in Flat-Fading Channels

We first consider optimal single-cell detection, where the hypothesis for cell $k \epsilon N_t$ is given by

$$H_k:\ r = \alpha_k G(\tau_k) s_k + z$$

And the optimal detection follows likelihood-ratio test (LRT) with the decision rule

$$\hat{k} = \arg max_{k \in N_T} \wedge (r|H_k).$$

Note that given α_k and τ_k, the conditional likelihood of **r** can be written as [8], [9].

$$\wedge (r|H_k, \alpha_k, \tau_k) \propto exp\left\{\frac{2Re\{\langle \alpha_k G(\tau_k) s_k, r\rangle\}}{2\sigma_z^2} - \frac{\|\alpha_k G(\tau_k) s_k\|^2}{2\sigma_z^2}\right\} \quad (4)$$

We proceed to derive the SSM for the cases with and without statistical channel knowledge (SCK) in the following.

1) *Case without SCK:* When SCK is not available, i.e., α_k and τ_k are deterministic unknown parameters, the likelihood of each hypothesis by joint detection and estimation is the maximum likelihood (ML) over the unknown channel parameters, as shown in the following proposition.

Proposition 1: When SCK is not available, the likelihood $\wedge_{NSCK}(r|H_k)$ is

$$\wedge_{NSCK} (r|H_k) \propto max_{\tau_k} exp\left\{\frac{|F(\tau_k; s_k, r)|^2}{2\sigma_z^2}\right\} \quad (5)$$

Where $F(\tau_k; s_k, r) = \langle G(\tau_k)s_k, r\rangle$is the discrete-time Fourier transform (DTFT) of vector $r^*\otimes s_k$evaluated atτ_k. Moreover, the ML estimate for the amplitude is given by

$$\hat{\alpha} = argmax_{N_E \subseteq N_T} \wedge (r|H_k, \alpha_k, \tau_k) = \langle G(\tau_k)s_k, r\rangle$$

Remark 1: The optimal single-cell detection for this case is to find the largest$\wedge_{NSCK}$ $(r|H_k)$, or equivalently the largest $max_{\tau_k}|F(\tau_k; s_k, r)|^2$as follows:

$$\hat{k}_{NSCK} = argmax_{k\in N_t} max_{\tau_k}|F(\tau_k; s_k, r)|^2 \quad (6)$$

Note that the sufficient statistic forH_k in single-cell detection is$max_{\tau_k}|F(\tau_k; s_k, r)|^2$ which we refer to as the SSM. Therefore, for implementation one first calculates the DTFT of the point-wise multiplication$r^*\otimes s_k$ for differentτ_k, assigns the maximum overτ_k to be the SSM for hypothesisH_k, and then chooses the cell with the maximum SSM as the detected cell.

2) *Case with SCK:* Consider that the parameters $\alpha_k$andτ_k are mutually independent and have prior distribution $f\,(\alpha_k)$ and $f\,(\tau_k)$, respectively. The generalized likelihood of hypothesisH_k is given by

$$\wedge_{SCK}\ (r|H_k) = E_{\alpha_k,\tau_k}\{\wedge\ (r|H_k, \alpha_k, \tau_k)\} \quad (7)$$

This likelihood depends on the specific distribution of channel parameters, and we can simplify (7) for the case of Rayleigh fading in the following proposition.

Proposition 2: In Rayleigh fading channels, the likelihood$\wedge\ (r|H_k)$is given by

$$\wedge_{SCK}\ (r|H_k) = E_{\alpha_{k,\tau_k}}\left\{exp\left(\frac{|F(\tau_k; s_k, r)|^2}{2\sigma_z^2(1+\frac{\sigma_z^2}{\sigma_k^2})}\right)\right\} \quad (8)$$

Where the amplitude $|\alpha_k|$ follows the Rayleigh distribution with parameterσ_k.

Remark 2: In the case of Rayleigh fading channels, Proposition 2 provides a simplified formula of the likelihood (equivalently, the SSM) in (7) for single-cell detection, reducing the computation from double integrals into a single one in (8). Note that the captured SSS is of duration $1/\Delta f$, and hence $\tau_k$can only range from 0 to $1//\Delta f$. We then consider a specialcase where the delay $\tau_k$is uniform on $[0, 1//\Delta f)$, and$\sigma_k^2 = \sigma_0^2$for all k N_E. Then, the likelihood ofH_k in (8) becomes

$$\wedge_{Rayl_{Unif}} (r|H_k) \propto \int_0^{1/\Delta f} exp\left\{\frac{|F(\tau_k;s_k,r)|^2}{2\sigma_z^2\left(1+\frac{\sigma_z^2}{\sigma_k^2}\right)}\right\} d\tau_k \quad (9)$$

In high signal-to-noise ratio (SNR) regimes, we can approximate the DTFT as

$$|F(\tau_k;s_k,r)|^2 \approx |\alpha_m|^2|F(\tau_k;s_k,G(\tau_m)s_m)|^2 + |F(\tau_k;s_k,z)|^2$$
$$\approx |\alpha_m|^2|F(\tau_k;s_k,G(\tau_m)s_m)|^2 + \sigma_z^2 \quad (10)$$

This approximation implies that the DTFT$|F(\tau_k;s_k,r)|^2$has a spiky peak at$\tau_k = \tau_m$for hypothesisH_m, while it is flat over $\tau_k \epsilon [\,0, 1/\Delta f)$ for all other hypotheses. By convexity of the exponential function, decision using (9) can be approximated by using (6), i.e.

$$\arg max_{k\epsilon N_\tau} \wedge_{Rayl_{Unif(r|H_k)}} \sim$$
$$\arg max_{k\epsilon N_\tau} max_{\tau_k} |F(\tau_k;s_k,r)|^2$$

Remark 3: Proposition 1 obtains the SSM for single-cell detection when the channel parameters are unknown but deterministic. On the other hand, when SCK is available, though SSMs for general cases in (7) cannot be written in a closed form, Proposition 2 obtains the SSM for Rayleigh fading channels. We also showed that the two SSMs in Proposition 1 and 2 are approximately the same under condition (10), and thus we can use (6) for implementation in practical systems with the detailed procedure described in Remark 1.

B. Detection in Multipath Channels

We then consider NCS in multipath channels, where the conditional likelihood is

$$\wedge\,(r|H_k,\alpha_k,\tau_k) \propto exp\left\{\frac{2Re\{\langle\sum_{i=1}^{L_k}\alpha_k^{(l)}G(\tau_k^{(l)})s_k,r\rangle\}}{2\sigma_z^2}-\frac{\left\|\sum_{l=1}^{L_k}\alpha_k^{(l)}G(\tau_k^{(l)})s_k\right\|^2}{2\sigma_z^2}\right\} \quad (11)$$

Whereα_k= $\{\alpha^{(l)}k{:}l$ = 1, 2. . .$L_k\}$ and τ_k= $\{\tau^{(l)}$

$k{:}l$ = 1, 2, . . ., $L_k\}$. For general multipath channels, it is difficult to further simplify the likelihood $\Lambda(\mathbf{r}\ |H_k)$ obtained from (11). To gain some insights, we consider discrete-time channels where inter-arrival times of the MPCs are multiples of$1/N_{sc}\Delta f$, i.e., all the arrival times can be expressed as

$$\tau_k^{(l)}\epsilon\left\{\frac{j}{N_{sc}\Delta f}\right\}+\tau^*{:}\,j\epsilon\mathbb{Z}^+\cup\{0\} \quad (12)$$

Where$\tau^*$is a constant that can be tuned to better capture the MPCs. In such cases, the MPCs are orthogonal to each other in the sense that

$$\langle G\left(\tau_k^{(l)}\right)s_k,G\left(\tau_k^{(l')}\right)s_k\rangle=\delta_{l,l'}$$

Following similar derivations of Propositions 1 and 2, we derive the SSMs for multipath cases in the next propositions. The detailed proof is omitted due to space constraints.

Proposition 3: Under the condition (12), when SCK is not available, the likelihood $\wedge_{NSCK}\,(r|H_k)$for multipath channels is given by

$$\wedge_{NSCK}\,(r|H_k)\propto max_{\tau_k}exp\left\{\frac{\sum_{l=1}^{L_k}|F(\tau_k;s_k,r)|^2}{2\sigma_z^2}\right\} \quad (13)$$

Proposition 4: Under the condition (12), for independent Rayleigh fading channels with$\left|\alpha_k^{(l)}\right|\sim Rayleigh(\sigma_k^{(l)})$, the likelihood$\wedge_{Rayl}\,(r|H_k)$ for multipath channels is given by

$$\wedge_{Rayl}\,(r|H_k)\propto\prod_{l=1}^{L_k}\frac{1}{1+\sigma_k^{(l)\,2}/\sigma_z^2}\times E_{\tau_k}\left\{exp\left(\sum_{l=1}^{L_k}\frac{|F(\tau_k;s_k,r)|^2}{2\sigma_z^2\left(1+\sigma_z^2/\sigma_k^{(l)\,2}\right)}\right)\right\} \quad (14)$$

In particular, if (i)$\tau_k^{(l)}$'s are independent and uniform on $[0, 1//\Delta f)$ and (ii) $\sigma_k^{(l)} = \sigma_0^2$for all k and l, the cell detection algorithm can employ (13) instead of (14).

Remark 4: Propositions 3 and 4 derive the likelihood functions for multipath channels without and with SCK, respectively, under the condition (12). For the former case, the SSM of cell k is the sum of the largest $L_k$taps of$|F(\tau_k; s_k, r)|^2$; while for the latter case with Rayleigh fading, the likelihood isgiven by (14) if the amplitude $\alpha_k^{(l)}$'s are mutually independent. We also showed that under some channel conditions the cell detection algorithm can employ (13) instead of (14).

IV. MULTI-CELL DETECTION

In this section, we develop algorithms for multi-cell detection based on successive interference cancellation (SIC) for the case without SCK. The result can be extended to the case with SCK as shown in Section III-B.

A. Optimal Detection

The optimal multi-cell detection uses the MLE given in (3). For a given number of neighboring cells$|N_E| = N_e$, there are $\binom{N_t}{N_e}$possible subsets of cells, and each corresponds to a hypothesis $\widehat{H}_n$for $n = 1, 2. . . ,\binom{N_t}{N_e}$Let $\wedge^* N_e$denote the maximum likelihood of these hypotheses.

$$\wedge^* (N_e) \triangleq max_n \wedge \left(r|\widehat{H}_n\right) \qquad (15)$$

The subset of cells corresponding to$\wedge^* (N_e)$ is the ML estimate of the neighboring cells for a given *N*e. Hence, in order to avoid over-fitting, we need to impose constraints on the search process.

B. System Diagram

The system diagram of the proposed NCS algorithm is depicted in Fig. 1, and a description of the search process is given as follows:

1) Extract the S-SCH symbol in the received waveform and calculate the element-wise products of the S-SCH symbol with each candidate SSS;

2) Calculate the norm of the DTFT of these element-wise products, and combine the MPCs with largest energy as the SSM for each cell;

3) Select the cell with the largest SSM and corresponding time delay taps (largest accumulated SSM when multiple observations are available);

4) Estimate the multipath channel of the detected cell using MMSE or ML, and cancel the signal of the detected cell from the received signal;

5) Go back to 2 to detect the next cell based on the residual signal until the constraints are met;

6) Joint channel estimation (optional): at each step, channels of all detected cells can be jointly estimated, preventing false detection or estimation in previous steps. Note that this step may require high dimensional matrix inversion as the number of detected cell increases.

The proposed NCS algorithm employs the derived SSM combined with SIC, and can be used as a basis for the design of practical systems under performance-complexity trade-off.

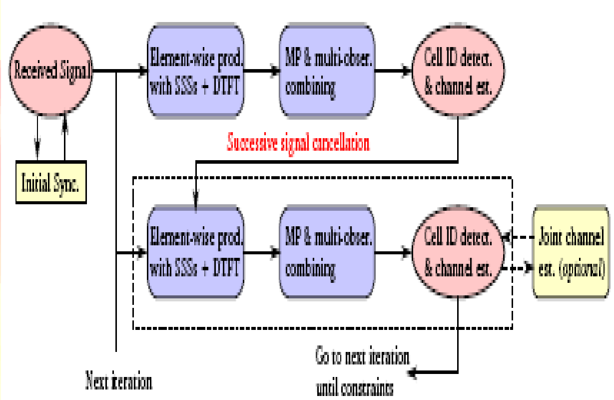

Fig1. System diagram

V. STATISTICAL MODEL FOR NCS ANALYSIS

A. Flat-Fading Channel

We first consider the case of flat-fading channels given by (1), where the UE is surrounded by the set of neighboring cells *N*E. Since the received signal power from the m^{th}cell is equal to$|\alpha_m|^2$, the SINR of the signal from the m^{th} cell is

$$SINR_m = \frac{|\alpha_m|^2}{P - |\alpha_m|^2 + N_{sc}\sigma_z^2}$$

Where$P \triangleq P - |\alpha_m|^2$the total signal power.The statistical property of is$\langle G\left(\tau_k^{(l)}\right)s_k, G\left(\tau_k^{(l')}\right)s_k\rangle$ is obtained via simulation in [12].Miss detection for the first cell occurs when the SSM of any cells in *N*E is less than the maximum SSM of cells in *N*T*N*E. Hence, the detection probability is

$$P_D(N_E) = 1 - \prod_{k_1 \epsilon N_E}\left(1 - \prod_{k_1 \epsilon N_T/N_E} P\{Y_{k_1} > Y_{k_2}\}\right) \quad (16)$$

C. Multipath Channel

The corresponding probability of detection can then be obtained similarly as in (16). Moreover, we can obtain the maximum number of detectable cells for a given detection probability as in the flat fading case.

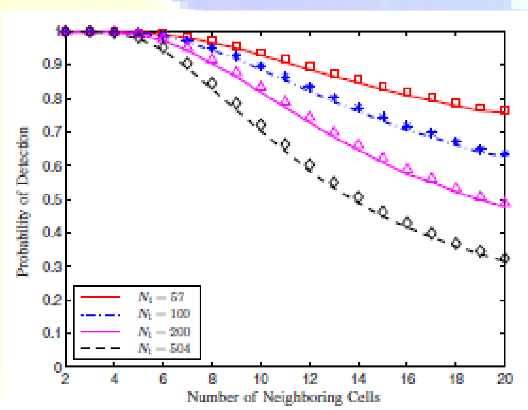

Fig.2 Flat-fading &Multipath channel Prop

VI. SIMULATION RESULTS

In this section, we evaluate the performance of the proposed NCS algorithms in terms of the number of detected cells and the cell detection probability by simulations. In particular, we use a link-level simulator that models multiple cell transmission with deployment assumptions based on the agreed macro-cell system simulation parameters. We consider the deployment of 57 cells (19 locations) with wrap-around structure and inter-cell distance equal to 1.732 km. We focus on the NCS process after initial synchronization with frequency error correction.

NCS Performance for Different SNR

We first examine the NCS performance for different SNR in GSM TU 3 channels (i.e., UE's speed is 3 km/h) for N_t= 57. Figure 3 shows the number of detected cells at various locations, and Fig. 4 shows the detection probability of the first four cells at cell edge, which is of most interest for handover.

First of all, both the number of detected cells and detection probability increase with the SNR, Second, the performance improvement diminishes in high SNR regimes (approximately over 15 dB), since the performance is limited by multi-cell interference in those regimes. Third, Fig. 3 shows that the UE can detect most cells at the cell edge and least at the cell center in high SNR regimes, which agrees with intuition that the UE at cell edge has a better overall signal reception from its neighboring cell.

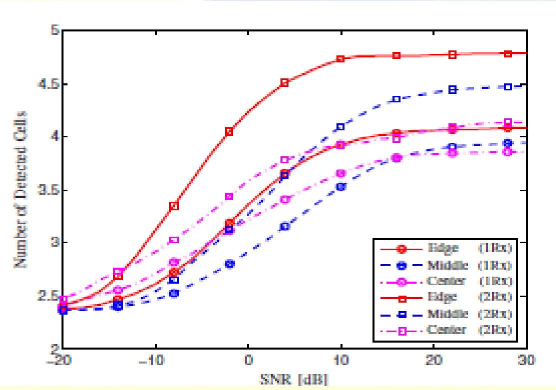

Fig.3.Number of detected cells at different UE locations with respect to the SNR

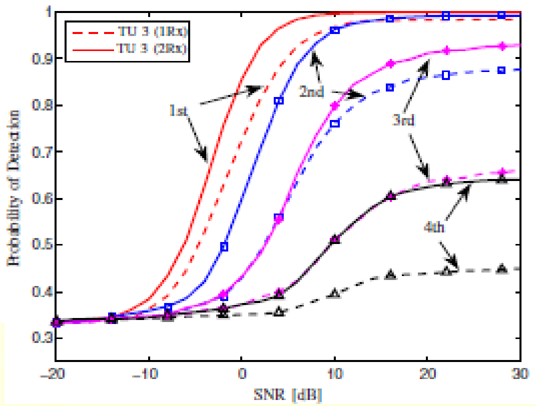

Fig.4. Detection probability of first four cells with respect to the different SNR at cell edge.

VII. CONCLUSION

In this paper, we have established a general framework for NCS in LTE systems and derived the SSMs for NCS under various channel and operation environments. We then developed NCS algorithms based on the SSMs, and characterized their performance in terms of the number of detected cells and the cell detection probability through link-level simulations. Our results showed the NCS performance with different transmission powers and at different UE positions, where roughly one more neighboring cell can be detected at the cell edge than center. Furthermore, we develop a statistical model for NCS performance analysis in both flat-fading and multipath channels. The outcome of the paper provides insights into the essence of NCS problem and can serve as guidelines for algorithm design in LTE systems.

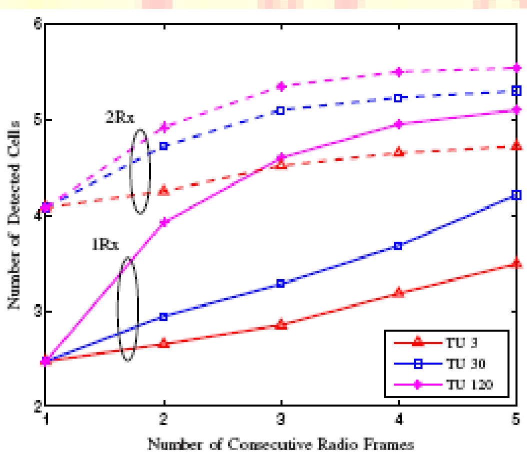

Fig.5.Number of detected cells using observations from multiple radio frames at cell edge. The UE is equipped with single or dual antennas

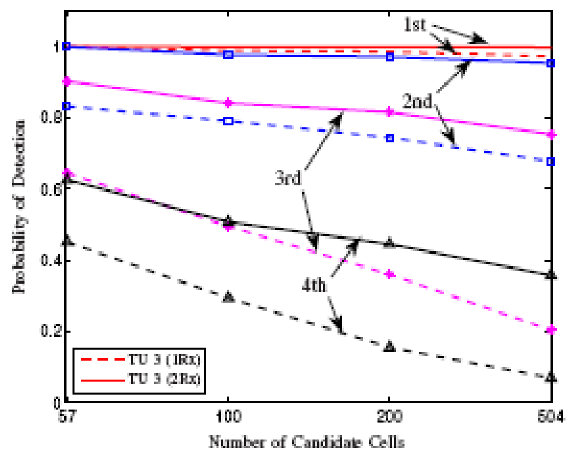

Fig.6.Detection probability of the first four cells with respect to the number of candidate cells at cell edge.

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