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RESEARCH ARTICLE

On the Structured Design Methodology of Effective PRACH Detection: Multi-Stage Thresholding Perspective

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ABSTRACT In this paper, we provide a tutorial on the structured design of effective Physical Random Access CHannel (PRACH) preamble detection based on correlation power. Specifically, the main contribution of this paper is to provide the design methodology leveraging multi-stage thresholds by which Preamble ID and PRACH-related time information (Timing Advance) for identifying the transmitted PRACH preamble signal are obtained. For enhancing the effectiveness of the designed PRACH preamble detector, we also consider joint optimization of multi-stage thresholds beyond the individual optimization of each threshold based on the Power Delay Profile. Consequently, the designed PRACH preamble detector is shown to have a reasonable performance in the sense of detection and false alarm probabilities, which is validated through numerical simulations considering the 3rd Generation Partnership Project conformance test.

INDEX TERMS Detection probability, false alarm probability, multi-stage threshold, power delay profile, Physical Random Access CHannel (PRACH), preamble ID, timing advance.

I. INTRODUCTION

Air interfaces such as Long Term Evolution (LTE) and New Radio (NR) require a joint process of downlink and uplink for mobile communications between the base station (BS) and User Equipment (UE). For that, key information such as radio frequency, cell ID, frequency offset, and timing offset is to be obtained through the downlink and uplink synchronizations [1], [2]. Here, the uplink synchronization is relatively more challenging due to the interferences from simultaneous multi-UEs. For the uplink synchronization, the Physical Random Access CHannel (PRACH) preamble is an upward synchronization signal transmitted by the UE during the initial RACH process and is an essential signal to be detected for establishing the initial communication between the UE and the BS.

From the transmission perspective of the physical layer, the success of the RACH process is achieved mainly by the successful transmission of the NR PRACH preamble signal. In terms of effective PRACH preamble transmission, the NR provides a stable signal transmission by leveraging the Zadoff-Chu (ZC) sequence, repetition of preambles, and Cyclic Prefix (CP) according to a diverse PRACH preamble format [3] with enhanced RA procedures[1] [4].

In conjunction with the stable transmission of the uplink synchronization signal with good correlation properties, the design of highly reliable detection for the NR PRACH preamble is crucial for achieving a successful initial RACH process beyond LTE PRACH preamble detection [5].. For this purpose, the PRACH preamble detector typically makes use of a Power Delay Profile (PDP) which is a consecutive series of correlation power according to timing offset [6], [7]. Therefore, PDP refinement is one of the critical ingredients for effective PRACH preamble detection. It is noteworthy that the PDP refinement is closely related to the sophisticated

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[1] The NR system provides an efficient RA procedure called 2-step RACH beyond existing 4-step RACH in the perspective of model protocol. In this paper, we focus on modem algorithmic design. For a specific understanding of the 2-step RACH procedure, you can refer to [4]

TABLE 1. A concise comparison of our work with the existing PDP-based detection schemes.

Papers	Roles of thresholds	Contents
[6], [7]	· No PDP refinement · PRACH signal detection	· The use of one threshold for deciding the presence of signal
[8], [9]	· PDP refinement with signal threshold · PRACH signal detection	· PDP refinement in the sense of keeping only those that are more likely to be signal · The use of one threshold for deciding the presence of signal
[8], [11]–[13]	· PDP refinement with average power threshold · PRACH signal detection	· PDP refinement in the sense of eliminating only those that are more likely to be noise · The use of one threshold for deciding the presence of signal
[8]–[10]	· PDP refinement based on noise threshold · PRACH signal detection	· PDP refinement in the sense of eliminating only those that are more likely to be noise · The use of one threshold for deciding the presence of signal
[9], [13]	· PDP refinement with multi-stage threshold · PRACH signal detection	· Use of multiple consecutive thresholds for refining PDP · The use of one threshold for deciding the presence of signal
Our work	· PDP refinement based on guided threshold design methodology · PRACH signal detection to be further enhanced	· Enhanced multi-stage threshold by leveraging a novel timing-based threshold · Provision of joint optimization methodology for better validity of multi-stage threshold · Performance enhancements with SNR gain satisfying 3GPP conformance test requirements

threshold design for the PDP refinement, which leads to the ultimate attainment of the highly reliable PRACH preamble detection. Table 1 describes a concise summary of the existing PDP-based detection schemes in comparison with our work.[2]

As described in Table 1, the role of the threshold is primarily divided into two purposes: One is for PDP refinement, which processes and optimizes the PDP. The other is for subsequent detection of the PRACH preamble to decide whether the PRACH preamble signal with the specific Preamble ID (PID) and the Timing Advance (TA) exists or not. There have been researches on the sophisticated threshold design focusing mainly on PDP refinement. Specifically, the signal threshold to filter PDP above the predetermined signal threshold derived from a peak PDP value has been used in [8] and [9]. On the other hand, the noise threshold has been used to identify the entire noise and to eliminate the identified noise [8], [9], [10]. The average power threshold has also been used to refine the PDP in the sense of removing things that are likely to be noise [8], [11], [12], [13]. The main difference between the average and noise thresholds is whether the whole PDP is considered or not for determining the threshold value. Specifically, the noise threshold is obtained by averaging the values other than peak values, reflecting what is likely to be noise. In contrast, the average power threshold reflects the overall PDP values. There have been studies on preamble detection based on a single threshold or consecutive use of multiple thresholds [9], [13].

Beyond the research on PRACH preamble detection, there have been studies on the RACH process in various layer perspectives. Specifically, a sequence design and joint consideration on PRACH detection and beamforming from a physical layer perspective [14], [15], resource allocation from a higher layer perspective [16], and extension to multi-user and Internet of Things service have been considered [17], [18].

In this paper, we provide the design methodology for PRACH preamble detection based on multi-stage thresholding, which means the consecutive use of multiple thresholds. As a by-product, we obtain a valid individual threshold for improving PDP refinement, based on which we introduce an enhanced multi-stage threshold based PRACH preamble detector. The remainder of this paper is organized as follows: Section II describes the system model for generating and transmitting the PRACH preamble. In Section III, we provide preliminaries on PRACH preamble detection. In Section IV, we describe not only existing individual thresholds but also a novel threshold, which can be considered in the multi-stage thresholding methodology, and in Section V, we consider the design of the PRACH preamble detection from the perspective of PDP refinement and provide a novel multi-stage threshold based PRACH preamble detection as a by-product. In Section VI, we analyze the performance of the designed PRACH preamble detection through numerical simulations, which validate the multi-stage thresholding methodology. Finally, in Section VII, we conclude this paper with a provision for further work.

[2]There exists a trade-off between computational complexity and detection performance for considering thresholding methodologies in the existing PDP-based detection schemes along with our enhanced one.

II. SYSTEM MODEL

In the NR system, the PRACH preamble signal is generated based on a ZC sequence. Specifically, based on the PRACH preamble format from the higher layer signaling, a ZC sequence with a length (L_{RA}) of 839, 139, 1151, or 571 is generated at the transmitter (Tx).

$$s_{u,v}(n) = s_u((n + C_v) \bmod L_{\mathrm{RA}}), \tag{1}$$

where

$$s_u(i) = e^{-j\frac{\pi u i(i+1)}{L_{\mathrm{RA}}}}, \ i = 0,\ 1,\ \cdots,\ , L_{\mathrm{RA}} - 1 \tag{2}$$

and

$$C_v = vN_{CS}, v = 0, \ldots, \left\lfloor \frac{L_{\mathrm{RA}}}{N_{\mathrm{CS}}} \right\rfloor. \tag{3}$$

Here, $\lfloor C \rfloor$ indicates the greatest integer that is less than or equal to C, and $\lceil D \rceil$ represents the smallest integer that is greater than or equal to D for real numbers C and D. and u is the root sequence number obtained from the logical root sequence index by higher layer signaling, A mod B represents the remainder when A is divided by B, $x_u(i)$ is a ZC sequence, C_v is a value obtained from of Cyclic Shifts (N_{CS}) in (3), and frequency-domain representation $x_{u,v}(n)$ of a PRACH preamble is given by a ZC sequence in (1).

$$x_{u,v}(n) = \sum_{m=1}^{L_{RA}-1} S_{u,v}(m) * e^{-j\frac{2\pi mn}{L_{RA}}}. \tag{4}$$

In the perspective of the RACH process, a total of 64 PRACH preambles exist, which is feasible by generating the cyclically shifted PRACH preambles using the values of u and C_v. One u generates $\lfloor L_{RA}/N_{CS} \rfloor$preambles, and if the number is less than 64, the u is increased by 1 until 64 preambles are generated. In addition, when the number of required u's is strictly greater than one, the number of resulting PDPs is equal to the number of u's in the detection process.

Finally, the Tx randomly determines one of the 64 preamble candidates which is given by

$$X_{u,v}(k) = \sum_{n=0}^{L_{RA}-1} x_{u,v}(n) e^{-j\frac{2\pi nk}{L_{RA}}} \tag{5}$$

for $k = 0, \ldots, L_{RA} - 1$ according to DFT with the length of the L_{RA}. The randomly chosen PRACH preamble is zero-padded according to the length of the N_{FFT} and mapped to each subcarrier, and IDFT is applied with the length of the N_{FFT} as

$$z_{u,v}(n) = \sum_{n=0}^{N_{FFT}-1} Z_{u,v}(k) e^{\frac{j2\pi nk}{N_{FFT}}}, \quad n = 0, \ldots, N_{FFT} - 1, \tag{6}$$

where, $Z_{u,v}(k)$ is the one-to-one mapped sequence from $X_{u,v}(k)$ in (5) by the predetermined resource allocation. In addition, a signal is generated as many times as the number of repetitions. Then, CP and Guard Period (GP) for each PRACH preamble format are applied [3].

III. PRELIMINARIES ON PRACH PREAMBLE DETECTION

When a receiver (Rx) with N_{RX} antennas receives PRACH preamble signals through an Additive White Gaussian Noise (AWGN) channel, the received signal at the j-th Rx antenna is described as

$$r^j_{u,v}(n) = z_{u,v}(n) + w^j(n) \tag{7}$$

considering the removal of the CP and GP. Here, $w^j(n)$ represents the AWGN at the j-th Rx antenna, where the noise follows complex Gaussian distribution with mean and variance of 0 and σ^2, respectively. As the first step for acquiring correlated power according to timing shift, the N_{zc} point DFT for $r^j_{u,v}(n)$ proceeds, which is given by

$$R^j_{u,v}(k) = \sum_{n=0}^{N_{FFT}-1} r^j_{u,v}(n) e^{-j\frac{2\pi nk}{N_{FFT}}} \tag{8}$$

for $k = 0, \ldots, N_{FFT} - 1$. Subsequently, after removing the zero-padding part of $R^j_{u,v}(k)$, the Rx gets the effective frequency-domain signal $Y^j_{u,v}(n)$ with a length of L_{RA}. At the same time, the Rx locally generates a ZC sequence $x^{j,\alpha}_{u,v}(k)$ to the root sequence number of the generated 64 preamble candidates. Here, α represents the index of u used for generating 64 PRACH preamble signals and must create as many PDPs as $\lceil 64/\lfloor L_{RA}/N_{CS} \rfloor \rceil$. Where, $x^{j,\alpha}_{u,v}(k)$ is subjected to a DFT according to the length of LRA to obtain $X^{j,\alpha}_{u,v}(k)$. A conjugate complex signal $X^{j,\alpha*}_{u,v}(k)$ of the self-produced $X^{j,\alpha}_{u,v}(k)$ is obtained. The components of $Y^j_{u,v}(n)$ and each component of the complex signal $X^{j,\alpha*}_{u,v}(k)$ are multiplied.

$$A^{j,\alpha}_{u,v} = \begin{cases} Y^j_{u,v}(k) * X^{j,\alpha*}_{u,v}, & \text{if } 0 \le k \le L_{RA} - 1. \\ 0, & \text{else.} \end{cases} \tag{9}$$

Subsequently zero padding is applied to have $A^{j,\alpha}_{u,v}(k)$ with N_{FFT} a length of, and IFFT with a size of N_{FFT} to obtain $a^{j,\alpha}_{u,v}(k)$. Then, the PDP is operated as follows:

$$\text{PDP}^{j,\alpha}(k) = \frac{1}{N_{FFT}} \left| a^{j,\alpha}_{u,v} \right|^2 \tag{10}$$

The whole process of generating the PRACH preamble and PDP is shown in Fig.1.

After obtaining the $\text{PDP}^{j,\alpha}(k)$ of the signal obtained from each antenna, the PDPs generated by the number of antennas N_{RX} are averaged using

$$\text{PDP}^{\alpha} = \frac{1}{N_{RX}} \sum_{j=1}^{N_{RX}} \text{PDP}^{j,\alpha}(k), \quad k = 0, \ldots, N_{FFT} - 1. \tag{11}$$

Finally, through Multi-Stage Thresholding (MST), the PDP is refined, through which the PRACH preamble is detected, and the values of the PDP are analyzed for each SW to determine the location of the highest peak. The length of the SW is defined as follows:

$$N_{SW} = \left\lfloor \frac{N_{CS} N_{FFT}}{L_{RA}} \right\rfloor. \tag{12}$$

Therefore, in the detector, $\lfloor L_{RA}/N_{cs} \rfloor$ SWs with a length equal to N_{SW} are divided for each PDP, and a total of 64 SW areas are divided to determine the location of the peak. Here the SW areas $\text{SW}^{\alpha}_n(k)$'s are defined as follows:

$$\begin{cases} \text{PDP}^{\alpha}(k), & \text{if } n = 0. \\ \text{PDP}^{\alpha}(N_{FFT} - n * N_{SW} + k), & \text{if } 1 \le n \le \left\lfloor \frac{L_{RA}}{N_{cs}} \right\rfloor. \end{cases} \tag{13}$$

for $k = 1, \ldots, N_{sw} - 1$. n is the index of SW in one PDP. If we create all the SW in one PDP, we add one to the root sequence index u and create the SW until we create 64 SW. Each SW uses thresholding to determine the existence and location of the peak and to estimate u and its TA transmitted according to the location for detecting the preamble and for synchronizing with the transmitter.

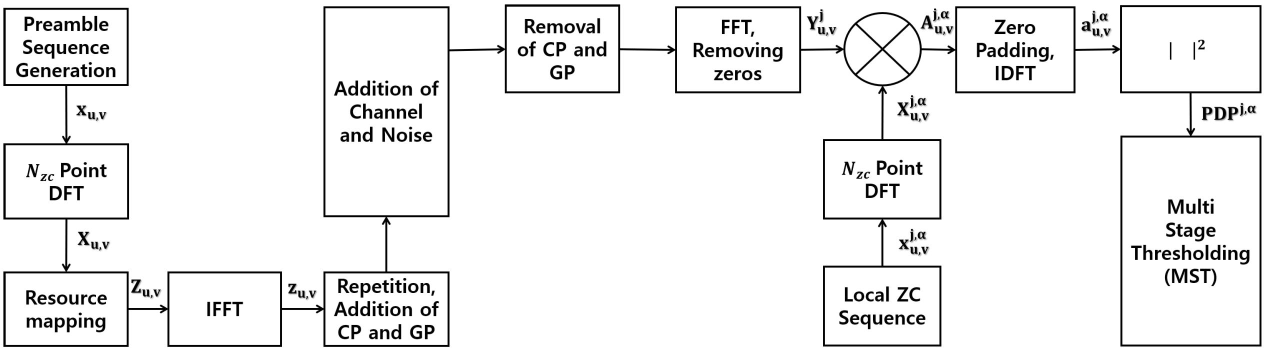

FIGURE 1. **Overall structure for generating PRACH preamble and acquiring refined PDP.**

IV. SINGLE-STAGE THRESHOLDING METHODOLOGY FOR PDF REFINEMENT

Beyond the typical use of the maximum correlated power and pre-determined thresholding for identifying PRACH PID and TA, it has been shown that performance enhancement can be feasible by refining PDP, which is a sort of sufficient information rather than the maximum correlated power itself. In this Section, we consider those beneficial individual ingredients for the PDP refinement in the sense of maximizing detection probability or minimizing false alarm probability.

A. NOISE THRESHOLDING BASED PDP REFINEMENT

The noise thresholding methodology is to remove only those that are likely to be noise from the original PDP, which is achieved by filtering out PDP above the finely designed noise threshold. Specifically, the noise threshold is specified by using the highest value of PDP and N_N values on both sides adjacent to the highest one. The intuition behind leveraging the noise threshold is that the relatively low PDP values are more likely to be caused by noise rather than the PRACH preamble signal. For this reason, we can use the following quantity to consider reasonable value for specifying representative PDP value.

$$\mathrm{PA}_N^{\alpha}(i, N) = \sum_{k=k^*-N}^{k^*+N} \mathrm{SW}_n^{\alpha}(k), \tag{14}$$

where i denotes the index indicating SW ranging from 1 to 64, and k^* denotes the position of the peak in the SW. Based on the representative quantity (14) for PDP values caused by the PRACH preamble signal, the ultimate noise threshold can be derived as

$$T_n^{\alpha}(i) = K_N \frac{\sum_{k=1}^{L_{\mathrm{SW}}} \mathrm{SW}_n^{\alpha}(k) - \mathrm{PA}_N(i, N_N)}{L_{\mathrm{SW}}}, \tag{15}$$

where the averaging over each SW and the scaling factor K_N are considered to alleviate the uncertainty caused by noise, which is significant at an especially low Signal to Noise (SNR) environment.

The utility of noise thresholding methodology and its major design issues are as follows:

- Consideration only PDP values greater than or equal to the noise threshold decreases false alarm probability.
- Reasonable determination of N_N is to be considered, which is feasible by numerical approach.
- The optimization for the scaling factor K_N should be accomplished, which is realized by offline searching beforehand.

B. AVERAGE POWER THRESHOLDING BASED PDP REFINEMENT

The role of average power thresholding itself is essentially the same as that of noise thresholding in that the methodology can remove only those that are likely to be noise from the original PDP. The difference is that the average power thresholding considers all the values of PDP. Specifically, the average power threshold is defined according to each SW and is obtained by multiplying the averaged PDF value within each SW by the scaling factor K_A.

Similar to the use of noise thresholding methodology, all the PDP values below the average power threshold are removed to have the refined PDP, which can be expressed as follows:

$$T_A^{\alpha}(i) = K_A \left(\frac{1}{L_{\mathrm{SW}}} \sum_{k=0}^{L_{\mathrm{SW}}-1} \mathrm{SW}_n^{\alpha}(k) \right). \tag{16}$$

The utility of average thresholding methodology and its major design issues are as follows:

- Consideration of PDP values greater than or equal to the average threshold decreases false alarm probability.
- The optimization for the scaling factor K_A should be accomplished, which is realized by offline searching in advance.

It is noteworthy that the average power threshold utilizes more information than the noise threshold in that the average power threshold does not exclude the representative PDP value in (14). Thus, it is expected that the performance in terms of false alarm probability can be enhanced by leveraging the average power threshold, which will be validated via numerical results in Section VI.

C. SIGNAL THRESHOLDING BASED PDP REFINEMENT

The signal threshold methodology is to refine PDP in that the refined PDP has only those that are likely to be signals from the original PDP, which is a complementary role with the noise thresholding or average power thresholding. Thus, only the PDP value above the signal threshold is interpreted as a signal component.

Consequently, the signal thresholding mainly uses the signal component, which is basically the highest PDP value in each SW, by considering a scaling factor K_S simultaneously. Therefore, the signal threshold is expressed as follows:

$$T_S^{\alpha}(i) = K_S * \mathrm{PA}_N^{\alpha}(i, N_S). \tag{17}$$

The utility of average thresholding methodology and its major design issues are as follows:

- Consideration of PDP values greater than or equal to the signal threshold increases detection probability.
- A numerical approach should be considered to determine the value of N_S reasonably.
- The optimization for the scaling factor K_S should be accomplished, which is feasible by offline searching in advance.

From the perspective of detector performance, while noise or average power thresholding contributes to decreasing the false alarm probability, signal thresholding contributes to increasing the detection probability.

V. UNIFIED MULTI-STAGE THRESHOLDING FOR PDP REFINEMENT

This Section provides a unified MST methodology consisting of consecutive series of Single-Stage Thresholding (SST). Here, each individual thresholding for SST belongs to one of two roles of thresholding. One is to filter out the appropriate signal power. The other is to remove correlated powers which come from noise power.

Based on a non-trivial combination of primary individual thresholds, a multi-stage thresholding-based PRACH detection framework is derived, whose enhanced performance becomes feasible in comparison with the conventional detection scheme (without no PDP refinement) to maximize detection probability and minimize false alarm probability.

The SST constituting the existing MST exhibits the following two characteristics.

- Signal thresholding filters out the correlation powers considered as signal.
- Noise or average power thresholding removes all the corresponding powers of PDP regarded as noise.

A. PERSPECTIVE OF REMOVING CORRELATED POWER FROM NOISE

Intuitively, the average power is more than noise power in considering all PDP components. It is more reasonable to assume the average thresholding as a role of removing noise-like powers in PDP. By leveraging effective ways of eliminating noise-like PDP components, the false alarm probability could be minimized further.

B. PERSPECTIVE OF SELECTING CORRELATED POWER FROM SIGNAL

For maximizing detection probability, it is critical to determine the representative correlated power value from the refined PDP. This is because we decide that signal exists when the representative value is greater than or equal to the predetermined threshold value, which is also used in the conventional detection scheme without PDP refinement. Thus, the essence is determining reasonably minimized representative correlated power, Which becomes more effective, especially at low SNR regions.

For achieving this, two approaches are feasible. One is to use averaged correlated powers considering both maximum correlated power and correlated powers around the maximum one. The other is to use the output of signal thresholding as an input for selecting a reasonable minimized representative value among PDP components. Specifically, depending on the sign of the expected TA, we choose the final representative value of correlated power instead of a naive selection of maximum correlated power, which corresponds to the conventional detection scheme.

The algorithmic implementation of the two approaches can be written as follows:

- (First approach: Use of more information of correlated powers) For the feasible PDP, the following $2m + 1$ correlated powers are to be considered.

  $$\sum_{k=k^*-m}^{k^*+m} \mathrm{SW}_n^{\alpha}(k), \tag{18}$$

  where k^* is the position corresponding to the maximum correlated power in the PDP.
- (Second approach: Use of timing information) Given the i-th SW, the final selected value of correlated power is determined by considering the following rule.
  - If the value of TA is greater than or equal to 0, the representative correlated power is determined to be the l-th largest one among correlated powers corresponding to a positive valued TA.
  - Else, the representative correlated power is determined to be the l-th largest one among correlated powers corresponding to a negative valued TA.
  - Here, the value of l is a factor to be optimized, where we assume $l = 2$.

VI. NUMERICAL ANALYSIS

In this Section, we carry out performance evaluation in terms of detection probability (P_d) and false alarm probability (P_f), where if only a PRACH preamble other than the transmitted PRACH preamble is detected, no PRACH preamble is detected, or correct PRACH preamble is detected but is out of the transmitted timing range, we consider it as miss detection, whose corresponding probability is $1 - P_d$. In addition, if a

TABLE 2. Simulation environments.

Frequency Range	FR1	Zero correlation zone configuration	11
Spectrum type	Unpaired	PRACH root sequence configuration	0
PUSCH subcarrier spacing	30 kHz	Restricted set configuration	unrestricted
PRACH subcarrier spacing	15 kHz	msg FDM	2
PRACH configuration index	172	SNR	-12 dB ~ -1 dB
Number of Rx antennas	2	Channel model	AWGN

TABLE 3. Performance of Single-Stage Thresholding and Multi-Stage Thresholding with scaling factor optimized at SNR=−10 dB.

	K_N	K_S	K_A	N_N	N_S	P_d	P_f
Signal Threshold Based SST	-	0	-	-	-	0.6864	0.1408
Noise Threshold Based SST	9	-	-	24	-	0.8638	0.0347
Noise and Signal Threshold Based MST	9	0	-	24	-	0.8638	0.0347
Average Power Threshold Based SST	-	-	6.8	-	-	0.9331	0.0080
Average power, Signal Power, and Timing information Based MST	0	0.6	9	6	4	**0.9760**	**0.0043**

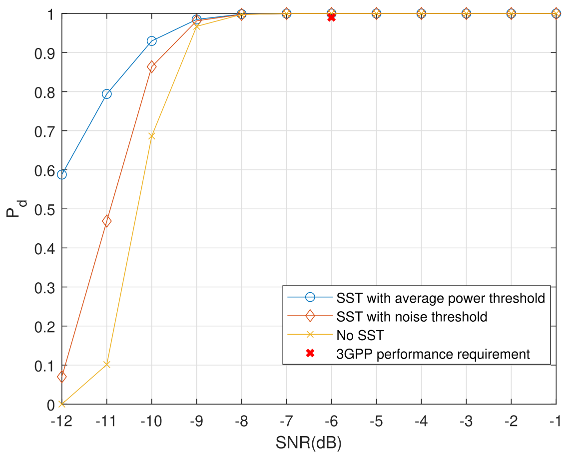

FIGURE 2. Detection probability of SSTs according to SNR.

signal consisting of only noise is incorrectly determined as a PRACH preamble, it is considered false alarm, whose probability corresponds to P_f. For the performance evaluation, the simulation environment specified in [19] and [20] is described in Table 2. Note that the target SNR is specified as -6dB for the requirement of

$$P_d \geq 0.99 \text{ and } P_f \leq 0.001. \tag{19}$$

A. EFFECT OF MULTI-STAGE THRESHOLDING TO PRACH PREAMBLE DETECTOR PERFORMANCE

Since the conventional detection scheme (with no PDP refinement) satisfies the above requirements at the SNR of -6 dB, which is a target SNR as specified in the 3GPP standard. We evaluate the performance of SSTs and MSTs in the range of SNR varying from -12 dB ~ -1 dB to identify the performance difference among SSTs and MSTs, including the conventional detection scheme (No SST). For designing such SSTs and MSTs, the scaling factors were optimized, which is described in Table 3.

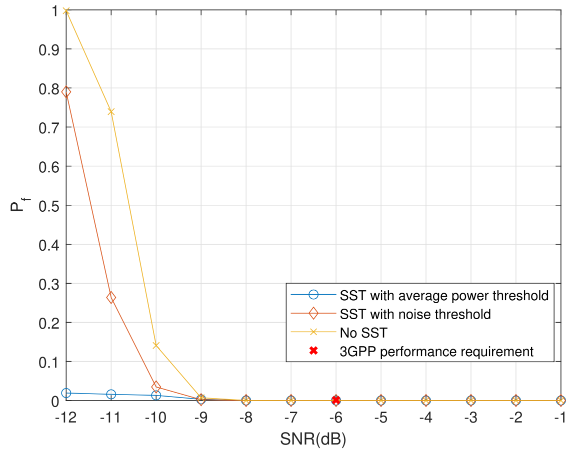

FIGURE 3. False alarm probability of SSTs according to SNR.

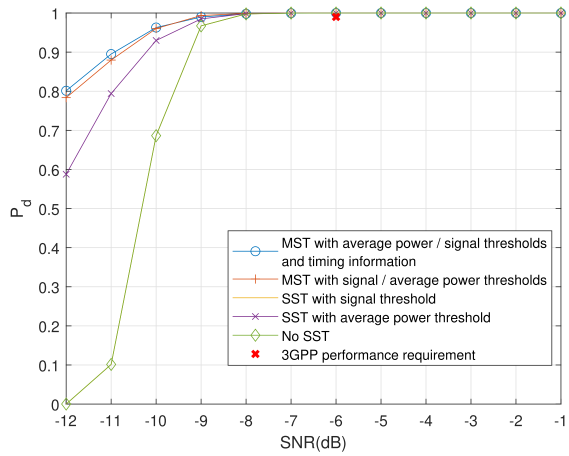

FIGURE 4. Detection probability of SSTs and MSTs according to SNR.

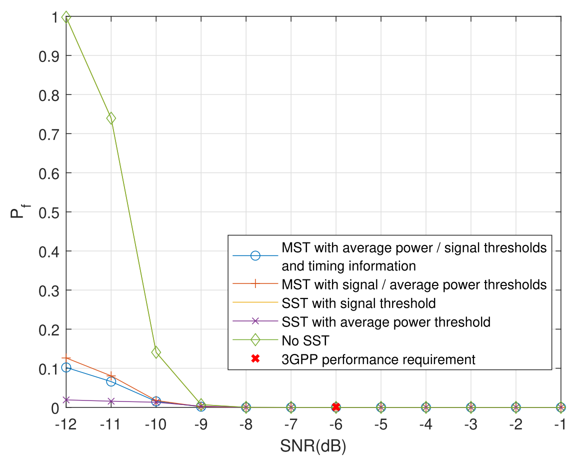

FIGURE 5. False alarm probability of SSTs and MSTs according to SNR.

To elaborate the performances of SSTs and MSTs, we give shape to the guided principles on the MST methodology including the following optimization, which is described in Table 3.

- Joint optimization of scaling factors for signal, average, and noise thresholds.
- Determination of optimal values of l_N and l_S for maximizing the effect of noise averaging and the amount of signal information.

B. COMPARISON BETWEEN NOISE THRESHOLDING AND AVERAGE POWER THRESHOLDING

Intuitively, the average thresholding utilizes more information in PDP than the noise thresholding. Consequently, the higher detection performance of the detection with average thresholding based PDP is observed than that with noise thresholding based PDP, which is confirmed in Figs. 2 and 3. Considering the effectiveness of the average power thresholding, we can reach the MST design principle that the average power thresholding should be a component of MST, which will be used afterward.

In general, it is expected that the performance of MST is higher than that of SST. To maximize the higher performance of MST, numerical results are obtained by considering each thresholding methodology from no SST to SST to MST, which are shown in Figs. 4 and 5. Specifically, for fair comparison between SSTs and MSTs, scaling factor optimization has been extensively for each thresholding methodology, which is illustrated in Table 3.

The main characteristics of the MSTs over SSTs in the sense of PRACH preamble detector performance are as follows:

- Even though signal thresholding can be no beneficial, the signal thresholding can be advantageous in MST, which is confirmed by Table 3 and 4 and 5.
- The individual thresholding using timing information can contribute to enhancing the PRACH preamble detector performance based on MST, which was observed from Table 3 and 4 and 5.

From the feasible individual thresholding methodology, it is observed that the MST such that signal thresholding, average power thresholding, and use of timing information is considered shows the highest performance in view of detection and false alarm probabilities. Thus, the higher performance of MST in comparison with that of SST has been seen, which becomes more significant, especially in a low SNR regime.

C. SNR SATISFYING 3GPP REQUIREMENTS FOR EACH THRESHOLD COMBINATION

Regardless of the pattern of the Receiver Operating Characteristic (ROC) curve which characterizes detection and false alarm probabilities jointly, one important point is whether the 3GPP requirements of $P_d \geq 0.99$ and $P_f \leq 0.001$ are satisfied or not. Based on the overall tendency of ROC curve, we can derive the minimum value of SNR such that the 3GPP requirements are satisfied, which is evaluated in the numerical simulations as described in Table 4. From the Table 4, we see that the MST results in large SNR gain than SST. Therefore, the following design principle still holds. *The PRACH preamble detector with MST guarantees higher detector performance than SST in the sense of detection and false alarm probabilities.*

TABLE 4. Description of minimum SNR satisfying 3GPP requirements for each thresholding methodology.

Thresholding methodology for PDP refinement	SNR
No SST with no PDP refinement	−9.0 dB
SST with Average thresholding	−9.0 dB
MST with T_A and Timing information	−9.1 dB
MST with T_S and T_A	−9.4 dB
MST with T_S and Timing information	−9.6 dB
MST with T_S, T_A, and Timing information	−9.2 dB

D. DISCUSSION

The channel models considered in the 3GPP performance requirements [19] are AWGN and Tapped Delay Line (TDL) fading channels. Extensive numerical simulations have been done in AWGN, but the robustness of SSTs and MSTs in the TDL is sufficiently expected for the following reasons.

- By leveraging MST methodology, there exists SNR margin coming from algorithmic gain, which is validated from Table 4.
- From the perspective of the performance requirement in [19], there exists a time tolerance that is recognized as the correct answer even if a certain error and TA information exist at the correct timing. Therefore, robust detector performance is expected to be obtained even if a timing shift caused by the TDL channel occurs.

On the other hand, a fundamental limit exists for obtaining additional performance improvements while refining PDP with an algorithmic approach. Beyond the algorithmic approach, a Machine Learning (ML) based approach to feasible PDP information can be more beneficial, and various ML models can be utilized to achieve higher performance beyond the existing (algorithmic) detection schemes based on the PDP components, which is one of the meaningful directions for further research.

VII. CONCLUSION

In this paper, we provided the structured design methodology on the PRACH preamble detection based on the feasible PDP. It was observed that the evolution from SST to MST is natural to refine the PDP and to achieve high detectability of the PRACH preamble detector. From the perspective of individual thresholding, average thresholding was more appropriate than noise thresholding due to use of leveraging more information of PDP. For further enhancement of PDP refinement, the joint use of timing information was observed to be more beneficial than the use of signal thresholding only, which showed the validity of MST in the design of PRACH detection. It was validated from numerical simulations that MST contributes to refining the PDP resulting in higher detection probability and lower false alarm probability than the conventional detection scheme without PDP refinement, whose is more prominent in low SNR regime even less than target SNR in [19]. However, a fundamental limit exists for obtaining additional performance improvements while refining PDP with an algorithmic approach. Beyond the algorithmic approach, ML based approach to feasible PDP information can be more beneficial, and various ML models can be utilized to achieve higher performance than the existing detection schemes based on the PDP components, which is one of the meaningful directions of further research. For example, It appears feasible to conduct research on PDP refinement using ML instead of a multi-stage threshold, as well as exploring the detection of TA and PID.

REFERENCES

[1] A. F. Molisch, *Wireless Communications*. Hoboken, NJ, USA: Wiley, 2005.
[2] H. Kim, *Design and Optimization for 5G Wireless Communications*. Hoboken, NJ, USA: Wiley, 2020.
[3] 3GPP, *Tech. Specification Group Radio Access Network, NR, Phys. Channels Modulation*, V.18.0.0, Standard TS 38.211, 2023.
[4] 3GPP, *Tech. Specification Group Radio Access Network, NR, Phys. Layer Procedures for Control*, V.18.0.0 Standard TS 38.213, 2023.
[5] B. Liang, Z. He, K. Niu, B. Tian, and S. Sun, "The research on random access signal detection algorithm in LTE systems," in *Proc. 5th IEEE Int. Symp. Microwave Antenna, Propag. EMC Technol. Wireless Commun.*, Oct. 2013, pp. 115–118, doi: 10.1109/MAPE.2013.6689965.
[6] A. Chakrapani, "On the design details of SS/PBCH, signal generation and PRACH in 5G-NR," *IEEE Access*, vol. 8, pp. 136617–136637, 2020.
[7] Y. Hu, J. Han, S. Tang, H. Gao, Y. Su, and J. Shi, "A method of PRACH detection threshold setting in LTE TDD femtocell system," in *Proc. 7th Int. Conf. Commun. Netw. China*, Aug. 2012, pp. 408–413, doi: 10.1109/ChinaCom.2012.6417517.
[8] T. Li, W. Wang, and T. Peng, "An improved preamble detection method for LTE PRACH in high-speed railway scenario," in *Proc. 10th Int. Conf. Commun. Netw.*, Aug. 2015, pp. 544–549, doi: 10.1109/CHINACOM.2015.7497998.
[9] T. A. Pham and B. T. Le, "A proposed preamble detection algorithm for 5G-PRACH," in *Proc. Int. Conf. Adv. Technol. Commun. (ATC)*, Hanoi, Vietnam, Oct. 2019, pp. 210–214, doi: 10.1109/ATC.2019.8924502.
[10] S. S. Rout, "Enhanced PRACH detection by wavelet de-noising," in *Proc. Int. Conf. Commun. Signal Process. (ICCSP)*, Chennai, India, Apr. 2019, pp. 0195–0199, doi: 10.1109/ICCSP.2019.8697945.
[11] S. Kim, K. Joo, and Y. Lim, "A delay-robust random access preamble detection algorithm for LTE system," in *Proc. IEEE Radio Wireless Symp.*, Jan. 2012, pp. 75–78, doi: 10.1109/RWS.2012.6175341.
[12] Z. Zhang, "Novel PRACH scheme for 5G networks based on analog Bloom filter," in *Proc. IEEE Global Commun. Conf.*, Dec. 2018, pp. 1–7, doi: 10.1109/GLOCOM.2018.8647961.
[13] T. Morohashi, C.-H. Liao, A. Koizuka, M. Suzuki, and H. Morikawa, "A high-performance RACH detection scheme for random access overload in LTE-advanced," in *Proc. IEEE Conf. Standards Commun. Netw. (CSCN)*, Tokyo, Japan, Oct. 2015, pp. 1–6, doi: 10.1109/CSCN.2015.7390422.
[14] S. Huang, L. Zhao, M. Jiang, and W. Liu, "Improved preamble detection and round-trip delay estimation for random access in high-mobility airborne communication systems," in *Proc. IEEE/CIC Int. Conf. Commun.*, Changchun, China, Aug. 2019, pp. 384–388, doi: 10.1109/ICCCHINA.2019.8855820.
[15] S. Mukherjee, A. K. Sinha, and S. K. Mohammed, "Timing advance estimation and beamforming of random access response in crowded TDD massive MIMO systems," *IEEE Trans. Commun.*, vol. 67, no. 6, pp. 4004–4019, Jun. 2019.
[16] N. Zhang, G. Kang, J. Wang, Y. Guo, and F. Labeau, "Resource allocation in a new random access for M2M communications," *IEEE Commun. Lett.*, vol. 19, no. 5, pp. 843–846, May 2015.
[17] M. I. Hossain, A. Azari, J. Markendahl, and J. Zander, "Enhanced random access: Initial access load balance in highly dense LTE—A networks for multiservice (H2H-MTC) traffic," in *Proc. IEEE Int. Conf. Commun. (ICC)*, Paris, France, May 2017, pp. 1–7, doi: 10.1109/ICC.2017.7996622.
[18] T. Kim, I. Bang, and D. K. Sung, "An enhanced PRACH preamble detector for cellular IoT communications," *IEEE Commun. Lett.*, vol. 21, no. 12, pp. 2678–2681, Dec. 2017.
[19] 3GPP, *Tech. Specification Group Radio Access Network; NR; Base Station (BS) Conformance Test. Part 1: Conducted Conformance Test.*, V.18.0.0 Standard TS 38.141-1, 2023.
[20] G.-D. Jo and Y. H. Lee, "Performance evaluation of physical random access channel in 5G new radio," in *Proc. 21st Int. Conf. Adv. Commun. Technol. (ICACT)*, Feb. 2019, pp. 256–259, doi: 10.23919/ICACT.2019.8701919.

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