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MGF-Based Analysis of Spectrum Sensing Over $K-\mu$ Fading Channels for 5G Cognitive Networks

GUANGQIAN CHU [1,2], KAI NIU [1], (Member, IEEE), WEILING WU [1], AND FANGLIAO YANG [1]
[1] Key of Universal Wireless Communications, Ministry of Education, Beijing University of Posts and Telecommunications, Beijing 100876, China
[2] School of Information Science and Electrical Engineering, Shandong Jiaotong University, Jinan 250357, China

Corresponding author: Guangqian Chu (chugq2003@bupt.edu.cn)

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ABSTRACT With the development of wireless communication techniques, higher spectrum efficiency is being pursued for the fifth generation (5G) mobile communication. Cognitive radio (CR) has attracted much attention from industry and academia due to its ability to improve spectrum efficiency. In 5G CR networks, the most important function is spectrum sensing (SS). However, SS performance deteriorates seriously for single-antenna signal detection. To improve spectrum efficiency, multiple-antenna (MA) signal-detection techniques have been proposed to improve SS performance by taking advantage of MA diversity reception. In this paper, we propose an MGF-based method for performance analysis of SS over $k-\mu$ channels for 5G CR networks. The expressions of the average detection probabilities are derived in closed form for cases of SA signal detection and MA signal detection. For MA signal detection, we mainly consider maximal ratio combining (MRC) and square law combining (SLC) diversity reception scheme over the $k-\mu$ fading channel. The improvement in detection performance is quantified for the MRC and SLC schemes. The simulation results show that the MRC and SLC diversity reception ($L > 1$) schemes achieve significant sensing diversity gains compared with that in the SA case.

INDEX TERMS MGF-based method, $k-\mu$ fading channels, spectrum sensing, multiple antennas.

I. INTRODUCTION

As wireless communication services grow rapidly, especially the fifth generation (5G) mobile communication systems, the shortage of spectrum resources is an urgent problem to be overcome. Cognitive radio (CR) is a key technology for exploiting the underutilized spectrum to deal with limited spectrum resources and the low utilization of the licensed spectrum [1], [2]. Spectrum sensing (SS) is the first step in cognitive networks. However, due to multi-path fading, shadow fading, low signal-to-noise ratio (SNR), noise level uncertainty and hidden terminal problems, a cognitive user (CU) with a single antenna (SA) may not reliably discriminate the action of the primary user (PU); namely, spectrum bands may remain vacant or occupied [3]. Motivated by the above factors, we consider multiple-antenna (MA) signal detection.

MA signal detection can improve SS performance significantly by making full use of MA cooperation. Over Rayleigh fading channels, maximal ratio combining (MRC), selection combining (SC), and switch and stay combining (SSC) were investigated in [4] and [5]. Diversity reception schemes of square law selection (SLS) and square law combining (SLC) were analyzed over fading channels such as Rayleigh, Rician and log-normal shadowing in [6]. Over Nakagami-m fading channels, based on an equal gain combining (EGC) MA signal-detection scheme, closed-form expressions for the average detection probabilities were derived in [7] and [8].

Recently, the $k-\mu$ distribution and $\eta-\mu$ distribution were proposed [9]. The $k-\mu$ distribution can be used to represent classic fading models such as Rayleigh, Rician, and Nakagami- m when the parameters k and μ change [10]. The $k-\mu$ distribution can be used to represent the small-scale variation of the fading signal in a line-of-sight (LOS) condition. The $\eta-\mu$ distribution can provide accurate characterization of small-scale variation of the fading signal in a non-line-of-sight (NLOS) condition [11], [12]. Saman, Tellambura and Jiang have discussed the spectrum sensing performance of the $\eta-\mu$ channel.

There are a few studies on the detection of unknown signals over the $k-\mu$ fading channel [13], [14]. Aloqlah [13] analyzed the performance of SS over the $k-\mu$ fading based on infinite series summation of Fox H-functions. However, an MA signal-detection scenario was not considered in [13]. In [14], signal detection in a single CR network was investigated over the $k-\mu$ fading based on a Gauss hypergeometric function, and the authors analyzed OR logic and AND logic. The motivation of this paper is to derive the closed-form expressions of the average detection probabilities for cases of SA signal detection and MA signal detection over the $k-\mu$ channel.

Probability density function (PDF)-based methods and moment generating function (MGF)-based methods are two basic method types for deriving the closed-form expression of the average detection probability of SS [10]. Compared with the former, the latter does not require direct integration of the Marcum-Q function [7], which will result in difficulties in finding the closed-form solution. Herath *et al.* [8] proposed an MGF-based method for the performance evaluation of SS. However, this MGF-based method has not been studied over $k-\mu$ channels.

The main contributions of this work are summarized as follows.

1) We propose an MGF-based method for performance analysis of SS over $k-\mu$ channels, which avoids some difficulties of the PDF method and uses a contour integral to represent the Marcum-Q function.

2) Based on the MGF method, the closed form $\bar{P}^{SA}_{d,k-\mu}$ is derived for SA signal detection over the $k-\mu$ fading for 5G cognitive networks.

3) Based on the MGF method, the closed form $\bar{P}^{MRC}_{d,k-\mu}$ is derived for MA signal-detection schemes using MRC over $k-\mu$ channels for 5G cognitive networks.

4) Based on the MGF method, the closed form $\bar{P}^{SLC}_{d,k-\mu}$ is derived for MA signal-detection schemes using SLC over $k-\mu$ channels for 5G cognitive networks.

5) The detection performance is verified by analysis and simulations using different parameters.

The rest of the paper is organized as follows. Section II describes the $k-\mu$ fading model and problem formulation. Section III derives $\bar{P}^{SA}_{d,k-\mu}$ over $k-\mu$ fading channels. Section IV investigates MA diversity reception schemes (MRC and SLC) over $k-\mu$ fading channels. Section V presents the simulation results and analysis, and section VI gives concluding remarks.

II. CHANNEL MODEL AND PROBLEM FORMULATION

A. THE $K-\mu$ FADING CHANNEL MODEL

For a LOS propagation scenario, a general multi-path fading model can be represented by the $k-\mu$ fading distribution [15]. Two physical parameters, $k>0$ and $\mu>0$, are used to describe the $k-\mu$ distribution.

Under $k-\mu$ fading channels, the received instantaneous SNR is γ, and its PDF can be expressed as [16]

$$f_\gamma(\gamma)=\frac{\mu(1+k)^{\frac{\mu+1}{2}}\gamma^{\frac{\mu-1}{2}}}{k^{\frac{\mu-1}{2}}\exp(\mu k)\bar{\gamma}^{\frac{\mu+1}{2}}}\exp(-\frac{\mu(1+k)\gamma}{\bar{\gamma}})\times I_{\mu-1}(2\mu\sqrt{\frac{k(1+k)\gamma}{\bar{\gamma}}}),\quad (1)$$

where k is defined as $k=E_{domi}/E_{scatt}$, E_{domi} denotes the total power of the dominant elements, E_{scatt} describes the total power of the scattered waves, and μ is the number of multi-path clusters. In (1), $\bar{\gamma}$ is the average of γ, and $I_v(\cdot)$ is the v-th modified Bessel function of the first kind.

B. MGF OF THE $K-\mu$ CHANNEL

Over $k-\mu$ fading channels, the MGF of the γ is given by [17]:

$$\begin{aligned}M_\gamma(s)&=E(-s\gamma)=\int_0^\infty\exp(-s\gamma)f_\gamma(\gamma)d\gamma\\&=(\frac{\mu(1+k)}{\mu(1+k)+s\bar{\gamma}})^\mu\exp(\frac{\mu^2(1+k)}{\mu(1+k)+s\bar{\gamma}}-\mu k)\\&=(\frac{\mu(1+k)}{\mu(1+k)+s\bar{\gamma}})^\mu\exp(-\frac{s\mu k\bar{\gamma}}{\mu(1+k)+s\bar{\gamma}})\\&=(\frac{B}{1+B})^\mu\frac{z^\mu}{(z-\frac{1}{1+B})^\mu}\exp(\frac{(1-z)\mu k}{(B+1)z-1}),\end{aligned}\quad (2)$$

where $1-\frac{1}{z}=s$, $A=\mu(1+k)$ and $B=A/\bar{\gamma}$.

III. MGF-BASED ANALYSIS OF SINGLE ANTENNA SIGNAL DETECTION OVER THE $K-\mu$ Fading

A. BINARY HYPOTHESIS TEST

At an energy detector, the detection of the PU signal $s(t)$ can be regarded as [18]

$$r(t)=\begin{cases}n(t), & H_0\\ h\,s(t)+n(t), & H_1,\end{cases}\quad (3)$$

where $r(t)$ is the received signal, $n(t)$ is an additive signal, and h denotes the channel gain. The received signal energy Y is measured over an observation time of T and compared with a predetermined threshold λ to decide whether the signal is present or not. H_1 denotes primary signal presence, and H_0 denotes primary signal absence. Under H_0 and H_1, the test statistic Y can be modeled as a central and noncentral chi-square distribution [19].

$$Y\sim\begin{cases}x^2_{2u}, & H_0\\ x^2_{2u}(2\gamma), & H_1,\end{cases}\quad (4)$$

where $u=TW$ is the time bandwidth product and W is the bandwidth of the channel. γ is the SNR. Thus, under H_0 and H_1, the PDF of Y can be given by [5]

$$f_Y(y)=\begin{cases}\frac{1}{2^u\Gamma(u)}y^{u-1}e^{-\frac{y}{2}}, & H_0\\ \frac{1}{2}(\frac{y}{2\gamma})^{-\frac{u-1}{2}}-\frac{2\gamma+y}{2}I_{u-1}(\sqrt{2\gamma y}), & H_1,\end{cases}\quad (5)$$

where $\Gamma(.)$ is the gamma function.

Over AWGN channels, the probabilities of detection and false alarm are given by [18]

$$P_d = P_r\ (Y > \lambda | H_1) = Q_u(\sqrt{2\gamma}, \sqrt{\lambda}), \tag{6}$$
$$P_f = P_r\ (Y > \lambda | H_0) = \frac{\Gamma(u, \lambda/2)}{\Gamma(u)}, \tag{7}$$

where $\Gamma(\cdot,\cdot)$ denotes the incomplete gamma function [20] and $Q_u(a, b)$ is the generalized Marcum-Q function, which is defined by [21]

$$Q_u(a,b) = \frac{1}{a^{u-1}} \int_b^\infty x^u e^{-\frac{x^2+a^2}{2}} I_{u-1}(ax)dx.$$

B. AVERAGE DETECTION PROBABILITY FOR SINGLE ANTENNA SIGNAL DETECTION OVER THE $K-\mu$ FADING CHANNEL

In this subsection, $\bar{P}^{SA}_{d,k-\mu}$ is derived based on the MGF method over the $k-\mu$ fading channel.

By calculating the expectation of P_d in (6) over the PDF of the channel [5], $\bar{P}^{SA}_{d,k-\mu}$ can be expressed as.

$$\bar{P}^{SA}_{d,k-\mu} = \int_0^\infty P_d f_\gamma(\gamma) d\gamma\ . \tag{8}$$

To calculate $\bar{P}^{SA}_{d,k-\mu}$, using the circular contour integral to represent the generalized Marcum-Q function, (6) can be written as [22]

$$P_d = \frac{e^{-\frac{\lambda}{2}}}{j2\pi} \oint_\Delta \frac{e^{(\frac{1}{z}-1)\gamma + \frac{\lambda}{2}z}}{z^u(1-z)} dz, \tag{9}$$

where Δ is a circular contour, the radius is r, and $0 \le r \prec 1$. Therefore, $\bar{P}^{SA}_{d,k-\mu}$ over the $k-\mu$ fading channel is calculated by

$$\begin{aligned}\bar{P}^{SA}_{d,k-\mu} &= \int_0^\infty P_d f_\gamma(\gamma) d\gamma \\ &= \frac{e^{-\frac{\lambda}{2}}}{j2\pi} \oint_\Delta \left(\int_0^\infty e^{(\frac{1}{z}-1)\gamma} f_\gamma(\gamma) d\gamma\right) \frac{e^{\frac{\lambda}{2}z}}{z^u(1-z)} dz \\ &= \frac{e^{-\frac{\lambda}{2}}}{j2\pi} \oint_\Delta M_\gamma(1-\frac{1}{z}) \frac{e^{\frac{\lambda}{2}z}}{z^u(1-z)} dz,\end{aligned} \tag{10}$$

due to $M_\gamma(1-\frac{1}{z}) = \int_0^\infty e^{(\frac{1}{z}-1)\gamma} f_\gamma(\gamma) d\gamma = M_\gamma(s)$, $\bar{P}^{SA}_{d,k-\mu}$ can be written as

$$\begin{aligned}&\bar{P}^{SA}_{d,k-\mu} \\ &= (\frac{B}{1+B})^\mu \frac{e^{-\frac{\lambda}{2}}}{j2\pi} \oint_\Delta \left(\int_0^\infty e^{(\frac{1}{z}-1)\gamma} f_\gamma(\gamma) d\gamma\right) \frac{e^{\frac{\lambda}{2}z}}{z^u(1-z)} dz \\ &= (\frac{B}{1+B})^\mu \frac{e^{-\frac{\lambda}{2}}}{j2\pi} \oint_\Delta p(z) dz,\end{aligned} \tag{11}$$

where

$$p(z) = \frac{e^{\left(\frac{\lambda}{2}z + \frac{(1-z)\mu k}{(B+1)z-1}\right)}}{z^{u-\mu}(1-z)(z-\frac{1}{1+B})^\mu} = g(z)\cdot h(z), \tag{12}$$

with

$$g(z) = \frac{e^{\frac{(1-z)\mu k}{(B+1)z-1}}}{\left(z-\frac{1}{1+B}\right)^\mu} = \frac{e^{\left(\frac{(1-z)\mu k}{(B+1)(z-1/(1+B))}\right)}}{\left(z-\frac{1}{1+B}\right)^\mu}, \tag{13}$$

and

$$h(z) = \frac{e^{\frac{\lambda}{2}z}}{z^{u-\mu}(1-z)}. \tag{14}$$

Applying Laurent series expansion to $g(z)$[7], we have

$$\begin{aligned}g(z) &= \frac{\exp\left(\frac{(1-z)\mu k}{(1+B)(z-1/(1+B))}\right)}{\left(z-\frac{1}{1+B}\right)^\mu} \\ &= \sum_{n=1}^\infty \frac{(\mu k)^{n-1}(1-z)^{n-1}}{(n-1)!(1+B)^{n-1}\left(z-\frac{1}{1+B}\right)^{\mu+n-1}}.\end{aligned} \tag{15}$$

Therefore, $p(z)$ can be derived as

$$\begin{aligned}&p(z) \\ &= \frac{e^{\left(\frac{\lambda}{2}z + \frac{(1-z)\mu k}{(B+1)z-1}\right)}}{z^{u-\mu}(1-z)\left(z-\frac{1}{1+B}\right)^\mu} = g(z)h(z) \\ &= \sum_{n=1}^\infty \frac{(\mu k)^{n-1}(1-z)^{n-1}}{(n-1)!(1+B)^{n-1}\left(z-\frac{1}{1+B}\right)^{\mu+n-1}} \frac{e^{\frac{\lambda}{2}z}}{z^{u-\mu}(1-z)} \\ &= \sum_{n=1}^\infty \frac{(\mu k)^{n-1}}{(n-1)!(1+B)^{n-1}} \frac{(1-z)^{n-1}e^{\frac{\lambda}{2}z}}{\left(z-\frac{1}{1+B}\right)^{\mu+n-1} z^{u-\mu}(1-z)}.\end{aligned} \tag{16}$$

To calculate the contour integral in (11), the residue theorem is introduced [23]. According to the theorem, (11) can be evaluated by calculating the residues of $p(z)$.

Case I: $u > \mu$

In the case, (16) contains $u-\mu$ order poles at the origin and $\mu+n-1$ order poles at $1/(1+B)$. Thus, $\bar{P}^{SA}_{d,k-\mu}$ can be given by

$$\bar{P}^{SA}_{d,k-\mu} = e^{-\frac{\lambda}{2}}(\frac{B}{1+B})^\mu \times [Res(p;0) + (Res(p;\frac{1}{1+B})], \tag{17}$$

where the residue of $p(z)$ are $Res(p;0)$, $Res(p;\frac{1}{1+B})$ at the origin and at $1/(1+B)$, respectively. The residues can be found as

$$\begin{aligned}Res(p;0) &= \sum_{n=1}^\infty \frac{(\mu k)^{n-1}}{(n-1)!(1+B)^{n-1}}\Big[\frac{1}{(u-\mu-1)!} \\ &\quad\times \frac{d^{u-\mu-1}}{dz^{u-\mu-1}} \frac{e^{\frac{\lambda}{2}z}(1-z)^{n-1}}{(1-z)(z-\frac{1}{1+B})^\mu}\Big]\Big|_{z=0},\end{aligned} \tag{18}$$

$$\begin{aligned}Res(p;\frac{1}{1+B}) &= \sum_{n=1}^\infty \frac{(\mu k)^{n-1}}{(n-1)!(1+B)^{n-1}}\Big[\frac{1}{(\mu+n-2)!} \\ &\quad\times\Big[\frac{d^{\mu+n-2}}{dz^{\mu+n-2}} \frac{e^{\frac{\lambda}{2}z}(1-z)^{n-1}}{z^{u-\mu}(1-z)}\Big]\Big|_{z=\frac{1}{1+B}}.\end{aligned} \tag{19}$$

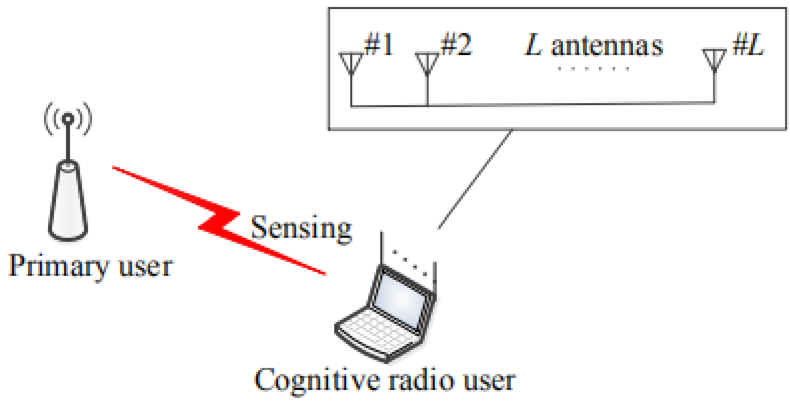

FIGURE 1. Multiple-antenna signal detection system model.

Case II: $u \le \mu$

In this case, there is no poles at the origin. There are $\mu + n - 1$ order poles at $1/(1+B)$. Therefore, $\bar{P}^{SA}_{d,k-\mu}$ is given by

$$\bar{P}^{SA}_{d,k-\mu} = e^{-\frac{\lambda}{2}}(\frac{B}{1+B})^{\mu} \times [(Res(p; \frac{1}{1+B})]. \tag{20}$$

IV. MULTI-ANTENNA SIGNAL DETECTION OVER THE $K-\mu$ CHANNEL

The MA signal-detection system model is given in Fig. 1. As shown in Fig. 1, the PU has one antenna, and the CU has L antennas. Assuming that the channel between the PU antenna and the l-th antenna of the CU is the $k-\mu$ fading channel, the received signal $r_l(t)$ of the CU can be expressed as

$$r_l(t) = h_l \cdot s(t) + n(t), \tag{21}$$

where $n(t)$ is the additive signal and h_l is the gain of the l-th fading channel. The CU receives the PU signal. Then, the signals from each antenna are processed according to the MA diversity schemes. After binary hypothesis judgment, the spectrum detection result can be obtained.

In the following section, the average detection probabilities are derived based on the MRC and SLC MA signal-detection schemes with the MGF-based method over the $k-\mu$ channel.

A. MRC-BASED MULTI-ANTENNA SIGNAL DETECTION OVER THE $K-\mu$ FADING CHANNEL

In the MRC diversity reception, we assume that channel state information (CSI) is available at the receiver. The main aim of the assumption is to derive the uniform standard of achievable performance. The diversity reception performance of other MA can then be compared with a uniform standard. Furthermore, in CR applications, the CSI is available to the CU [7].

Under the MRC diversity reception scheme, over AWGN channels, the average detection probability and the false alarm probability can be expressed as [24], [25], [27].

$$\bar{P}^{MRC}_{d,AWGN} = Q_u(\sqrt{2\gamma_{MRC}}, \sqrt{\lambda}), \tag{22}$$

$$P^{MRC}_{f,AWGN} = \frac{\Gamma(u, \lambda/2)}{\Gamma(u)}, \tag{23}$$

where $\gamma_{MRC} = \sum_{i=1}^{L} \gamma_i$ is the SNR of the MRC combiner. For independent identically distributed $k-\mu$ fading channels, the MGF of γ_{MRC} can be written as

$$\begin{aligned} M_{\gamma_{MRC}}(s) &= [M_{\gamma}(s)]^L \\ &= [(\frac{\mu(1+k)}{\mu(1+k)+s\bar{\gamma}})^{\mu} \times \exp(\frac{-s\mu k\bar{\gamma}}{\mu(1+k)+s\bar{\gamma}}]^L \\ &= (\frac{\mu(1+k)}{\mu(1+k)+s\bar{\gamma}})^{L\mu} \exp(\frac{-Ls\mu k\bar{\gamma}}{\mu(1+k)+s\bar{\gamma}}). \end{aligned} \tag{24}$$

According to (10) and (22), under the MRC scheme, $\bar{P}^{MRC}_{d,k-\mu}$ can be computed as

$$\begin{aligned} \bar{P}^{MRC}_{d,\,k-\mu} &= \frac{e^{-\frac{\lambda}{2}}}{j2\pi} \oint_{\Delta} [M_{\gamma}(s)]^L \frac{e^{\frac{\lambda}{2}z}}{z^u(1-z)} dz \\ &= \frac{e^{-\frac{\lambda}{2}}}{j2\pi} \oint_{\Delta} (\frac{B}{1+B})^{L\mu} \frac{z^{L\mu}}{(z-\frac{1}{1+B})^{L\mu}} \\ &\quad \times \exp(\frac{(1-z)L\mu k}{(B+1)z-1}) \\ &\quad \times \frac{e^{\frac{\lambda}{2}z}}{z^u(1-z)} dz = (\frac{B}{1+B})^{L\mu} \frac{e^{-\frac{\lambda}{2}}}{j2\pi} \oint_{\Delta} p_{MRC}(z) dz. \end{aligned} \tag{25}$$

Proposition 1: Under the MRC MA signal-detection scheme, for independent identically distributed $k-\mu$ fading channels, the average detection probabilities $\bar{P}^{MRC}_{d,k-\mu}$ can be shown as follows.

Case I: $u > L\mu$,

$$\begin{aligned} \bar{P}_{d,MRC} = e^{-\frac{\lambda}{2}}(\frac{B}{1+B})^{L\mu} &\times [Res(p_{MRC}; 0) \\ &+ (Res(p_{MRC}; \frac{1}{1+B})]. \end{aligned} \tag{26}$$

Case II: $u \le L\mu$,

$$\bar{P}^{MRC}_{d,\,k-\mu} = e^{-\frac{\lambda}{2}}(\frac{B}{1+B})^{L\mu} \times [(Res(p_{MRC}; \frac{1}{1+B})]. \tag{27}$$

For proof of Proposition 1, see Appendix A.

B. SLC-BASED MULTI-ANTENNA SIGNAL DETECTION OVER THE $K-\mu$ CHANNEL

Under the SLC diversity reception scheme, over AWGN channels, the detection probability and the false alarm probability can be denoted by [25], [26], [28].

$$P_{d,AWGN}^{SLC} = P\{Y_{SLC} > \lambda \,|\, H_1\} = Q_{Lu}(\sqrt{2\gamma_{SLC}}, \sqrt{\lambda}), \quad (28)$$

$$P_{f,AWGN}^{SLC} = P\{Y_{SLC} > \lambda \,|\, H_0\} = \frac{\Gamma(Lu, \lambda/2)}{\Gamma(Lu)}, \quad (29)$$

where $\gamma_{SLC} = \sum_{i=1}^{L} \gamma_i$ is the SNR of the SLC combiner. For independent identically distributed $k-\mu$ channels, the MGF of γ_{SLC} can be represented by

$$\begin{aligned} M_{\gamma_{SLC}}(s) &= [M_\gamma(s)]^L \\ &= [(\frac{\mu(1+k)}{\mu(1+k)+s\bar{\gamma}})^{L\mu} \exp(\frac{-s\mu k\bar{\gamma}}{\mu(1+k)+s\bar{\gamma}})]^L \\ &= (\frac{\mu(1+k)}{\mu(1+k)+s\bar{\gamma}})^{L\mu} \exp(\frac{-Ls\mu k\bar{\gamma}}{\mu(1+k)+s\bar{\gamma}}). \quad (30) \end{aligned}$$

According to (10) and (28), under the SLC scheme, $\bar{P}_{d,k-\mu}^{SLC}$ is derived as

$$\begin{aligned} \bar{P}_{d,k-\mu}^{SLC} &= \frac{e^{-\frac{\lambda}{2}}}{j2\pi} \oint_\Delta [M_\gamma(s)]^L \frac{e^{\frac{\lambda}{2}z}}{z^{Lu}(1-z)} dz \\ &= \frac{e^{-\frac{\lambda}{2}}}{j2\pi} \oint_\Delta (\frac{B}{1+B})^{L\mu} \frac{z^{L\mu}}{(z-\frac{1}{1+B})^{L\mu}} \\ &\quad \times \exp(\frac{(1-z)L\mu k}{(B+1)z-1}) \frac{e^{\frac{\lambda}{2}z}}{z^{Lu}(1-z)} dz \\ &= (\frac{B}{1+B})^{L\mu} \frac{e^{-\frac{\lambda}{2}}}{j2\pi} \oint_\Delta p_{SLC}(z) dz. \quad (31) \end{aligned}$$

Proposition 2: Under the SLC MA signal-detection scheme, for independent identically distributed $k-\mu$ fading channels, the average detection probabilities $\bar{P}_{d,k-\mu}^{SLC}$ may be shown as follows.

Case I: $Lu > L\mu$,

$$\begin{aligned} \bar{P}_{d,k-\mu}^{SLC} = e^{-\frac{\lambda}{2}} (\frac{B}{1+B})^{L\mu} \times [Res(p_{SLC}; 0) \\ + (Res(p_{SLC}; \frac{1}{1+B})]. \quad (32) \end{aligned}$$

Case II: $Lu \le L\mu$,

$$\bar{P}_{d,k-\mu}^{SLC} = e^{-\frac{\lambda}{2}} (\frac{B}{1+B})^{L\mu} \times [(Res(p_{SLC}; \frac{1}{1+B})]. \quad (33)$$

For proof of Proposition 2, see Appendix B.

V. SIMULATION RESULTS AND ANALYSIS

The detection performance of the average detection probabilities is evaluated for cases of SA signal detection and MA signal detection (MRC and SLC) with the MGF-based method over $k-\mu$ fading. Based on the average detection probabilities, the simulation results and analysis can be shown as follows.

Fig. 2 illustrates the behavior of $\bar{P}_{d,k-\mu}^{SA}$ versus k fluctuations for $P_f = 0.1$, $u = 2$, $\mu = 1$ and different values of $\bar{\gamma}$

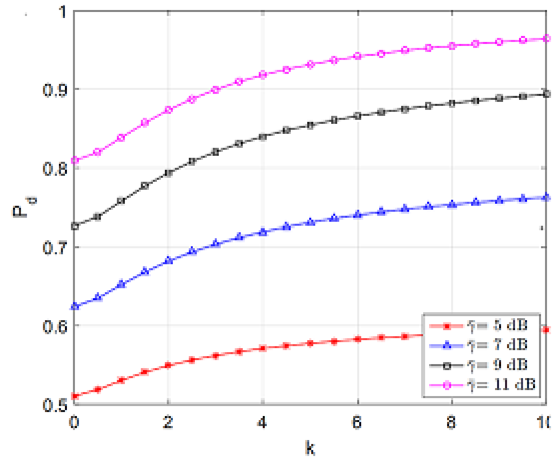

FIGURE 2. Average detection probabilities versus k over $k-\mu$ channels for $P_f = 0.1$, $u = 2$, $\mu = 1$, and different $\bar{\gamma}$.

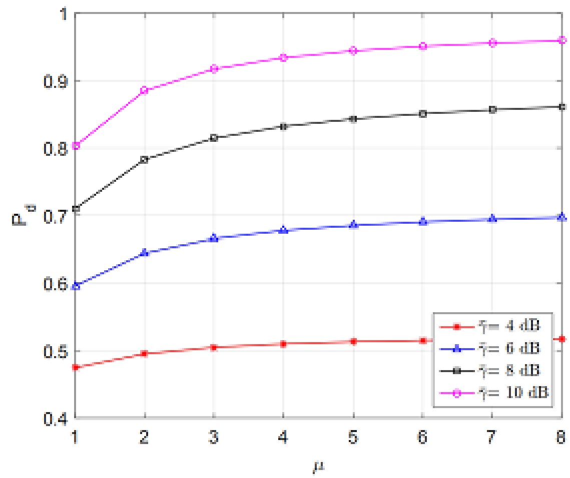

FIGURE 3. Average detection probabilities versus μ over $k-\mu$ channels for $P_f = 0.1$, $u = 1$, $k = 1$, and different $\bar{\gamma}$.

over $k-\mu$ fading channels. There is a significant deviation of $\bar{P}_{d,k-\mu}^{SA}$ when k increases from 0 to 8 or $\bar{\gamma}$ increases from 5 dB to 11 dB. As an example, for the case of $\bar{\gamma} = 9$ dB, Fig. 2 shows that $\bar{P}_{d,k-\mu}^{SA} = 0.73$ for $k = 0$ and $\bar{P}_{d,k-\mu}^{SA} = 0.86$ for $k = 6$. Likewise, Fig. 2 also shows that $\bar{P}_{d,k-\mu}^{SA} = 0.58$ and $\bar{P}_{d,k-\mu}^{SA} = 0.73$ when $k = 6$ and $\bar{\gamma} = 5$ dB and when $k = 6$ and $\bar{\gamma} = 7$ dB, respectively.

Fig. 3 demonstrates the performance of $\bar{P}_{d,k-\mu}^{SA}$ versus μ for $P_f = 0.1$, $u = 1$, $k = 1$, and different values of $\bar{\gamma}$ over $k-\mu$ fading channels. There are obvious variations of $\bar{P}_{d,k-\mu}^{SA}$ as μ increases from 1 to 8 or $\bar{\gamma}$ increases from 4 dB to 10 dB. For example, for the case of $\bar{\gamma} = 8$ dB, $\bar{P}_{d,k-\mu}^{SA} = 0.71$ for $\mu = 1$ and $\bar{P}_{d,k-\mu}^{SA} = 0.84$ for $\mu = 5$. That is, $\bar{P}_{d,k-\mu}^{SA}$ increases by 18% for $\mu = 5$ compared with that for $\mu = 1$.

Fig. 4 depicts the impact of the average SNR $\bar{\gamma}$ on $\bar{P}_{d,k-\mu}^{SA}$ with $u = 3$, $\mu = 2$, $k = 4$ over $k-\mu$ fading channels for 5G cognitive radio network. Fig. 4 shows that $\bar{P}_{d,k-\mu}^{SA}$ increases with increasing $\bar{\gamma}$. For example, when $P_f = 0.2$ and

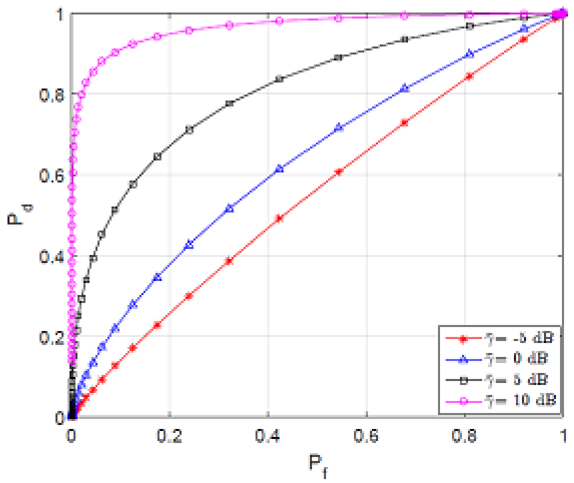

FIGURE 4. **Average detection probabilities versus P_f over $k-\mu$ channels with different $\bar{\gamma}$.**

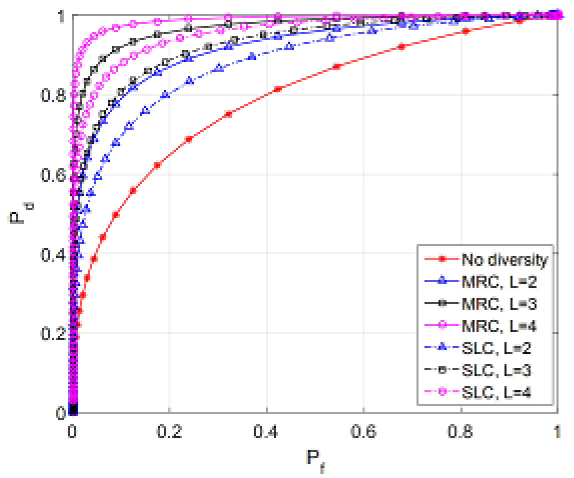

FIGURE 5. **Average detection probabilities versus P_f over $k-\mu$ channels based on the MRC and SLC MA signal detection schemes with $L = 1, 2, 3, 4$.**

γ is -5 dB, 0 dB, 5 dB, and 10 dB, $\bar{P}^{SA}_{d,k-\mu}$ is 0.26, 0.39, 0.67, and 0.96, respectively. As anticipated, the detection performance continues to improve as $\bar{\gamma}$ increases over the $k-\mu$ channel.

Finally, Fig. 5 shows the effect of different antenna numbers on the average detection probabilities for $u = 3$, $\mu = 1$, $k = 4$, and $L = 1, 2, 3, 4$ over $k-\mu$ fading channels. $\bar{\gamma}$ is set to 5 dB. As shown in Fig. 5, the MRC and SLC MA signal-detection schemes can achieve great sensing diversity gains compared with the SA case over $k-\mu$ channels. Furthermore, an increase in L results in better detection performance. The MRC scheme offers better performance at the cost of higher complexity compared with the SLC scheme.

VI. CONCLUSION

In this paper, an MGF-based method of performance analysis of SS is investigated over $k-\mu$ fading channels for 5G CR networks. The average detection probabilities in closed form are derived for cases of SA and MA signal-detection schemes including MRC and SLC. The detection performance improves as k or μ or $\bar{\gamma}$ increases. The simulation results demonstrate the significant detection performance gain of the MRC and SLC diversity reception schemes over the SA case. Furthermore, the MRC diversity scheme always performs better than the SLC scheme.

APPENDIX A
PROOF OF PROPOSITION 1

Rewrite (25),

$$\begin{aligned}\bar{P}^{MRC}_{d,\,k-\mu} &= \frac{e^{-\frac{\lambda}{2}}}{j2\pi}\oint_{\Delta}[M_{\gamma}(s)]^{L}\frac{e^{\frac{\lambda}{2}z}}{z^{u}(1-z)}dz\\ &= \frac{e^{-\frac{\lambda}{2}}}{j2\pi}\oint_{\Delta}\left(\frac{B}{1+B}\right)^{L\mu}\frac{z^{L\mu}}{(z-\frac{1}{1+B})^{L\mu}}\\ &\quad\times\exp\left(\frac{(1-z)L\mu k}{(B+1)z-1}\right)\\ &\quad\times\frac{e^{\frac{\lambda}{2}z}}{z^{u}(1-z)}dz = \left(\frac{B}{1+B}\right)^{L\mu}\frac{e^{-\frac{\lambda}{2}}}{j2\pi}\oint_{\Delta}p_{MRC}(z)dz\end{aligned}$$

where

$$p_{MRC}(z) = \frac{e^{(\frac{\lambda}{2}z+\frac{(1-z)L\mu k}{(B+1)z-1})}}{z^{u-L\mu}(1-z)(z-\frac{1}{1+B})^{L\mu}} = g_1(z)h_1(z) \tag{34}$$

with

$$g_1(z) = \frac{e^{\frac{(1-z)L\mu k}{(B+1)z-1}}}{(z-\frac{1}{1+B})^{L\mu}} = \frac{e^{\frac{(1-z)L\mu k}{(B+1)(z-\frac{1}{1+B})}}}{(z-\frac{1}{1+B})^{L\mu}} \tag{35}$$

and

$$h_1(z) = \frac{e^{\frac{\lambda}{2}z}}{z^{u-L\mu}(1-z)} \tag{36}$$

Applying Laurent series expansion to $g_1(z)$ [7] gives the following

$$\begin{aligned}g_1(z) &= \frac{e^{\frac{(1-z)L\mu k}{(B+1)z-1}}}{(z-\frac{1}{1+B})^{L\mu}} = \frac{e^{\frac{(1-z)L\mu k}{(B+1)(z-\frac{1}{1+B})}}}{(z-\frac{1}{1+B})^{L\mu}}\\ &= \sum_{n=1}^{\infty}\frac{[L\mu k]^{n-1}(1-z)^{n-1}}{(n-1)!(1+B)^{n-1}(z-\frac{1}{1+B})^{L\mu+n-1}}\end{aligned} \tag{37}$$

Thus, $p_{MRC}(z)$ can be written as

$$\begin{aligned}&p_{MRC}(z)\\ &= \frac{e^{(\frac{\lambda}{2}z+\frac{(1-z)L\mu k}{(B+1)z-1})}}{z^{u-L\mu}(1-z)(z-\frac{1}{1+B})^{L\mu}} = g_1(z)h_1(z)\\ &= \sum_{n=1}^{\infty}\frac{[L\mu k]^{n-1}(1-z)^{n-1}}{(n-1)!(1+B)^{n-1}(z-\frac{1}{1+B})^{L\mu+n-1}}\times\frac{e^{\frac{\lambda}{2}z}}{z^{u-L\mu}(1-z)}\\ &= \sum_{n=1}^{\infty}\frac{[L\mu k]^{n-1}}{(n-1)!(1+B)^{n-1}}\frac{e^{\frac{\lambda}{2}z}(1-z)^{n-1}}{(z-\frac{1}{1+B})^{L\mu+n-1}z^{u-L\mu}(1-z)}\end{aligned} \tag{38}$$

Therefore, $\bar{P}_{d,k-\mu}^{MRC}$ can be calculated using (11) with the following change in parameter: $\mu \to L\mu$ [28].

A. WHEN $u > L\mu$

In this case, the integral (25) contains $u-L\mu$ and $L\mu+n-1$ order poles at $z = 0$ and $z = 1/(1+B)$, respectively. Therefore, $\bar{P}_{d,k-\mu}^{MRC}$ can be represented as

$$\bar{P}_{d,\,k-\mu}^{MRC} = e^{-\frac{\lambda}{2}}(\frac{B}{1+B})^{L\mu} \times [Res(p_{MRC};0) + (Res(p_{MRC};\frac{1}{1+B})]$$

where $Res(p_{MRC};0)$ is the residue of the function $p_{MRC}(z)$ at the origin and $Res(p_{MRC};\frac{1}{1+B})$ is the residue of the function $p_{MRC}(z)$ at $1/(1+B)$. The residues can be calculated as

$$Res(p_{MRC};0) = \sum_{n=1}^{\infty}\frac{[L\mu k]^{n-1}}{(n-1)!(1+B)^{n-1}} \times[\frac{1}{(u-L\mu-1)!}\frac{d^{u-L\mu-1}}{dz^{u-L\mu-1}} \times\frac{e^{\frac{\lambda}{2}z}(1-z)^{n-1}}{(1-z)(z-\frac{1}{1+B})^{L\mu}}]\,|_{z=0} \tag{39}$$

$$Res(p_{MRC};\frac{1}{1+B}) = \sum_{n=1}^{\infty}\frac{[L\mu k]^{n-1}}{(n-1)!(1+B)^{n-1}} \times[\frac{1}{(L\mu+n-2)!} \times[\frac{d^{L\mu+n-2}}{dz^{L\mu+n-2}}\frac{e^{\frac{\lambda}{2}z}(1-z)^{n-1}}{z^{u-L\mu}(1-z)}]\,\Big|_{z=\frac{1}{1+B}} \tag{40}$$

(26) has been verified.

B. WHEN $u \le L\mu$

In this case, there is no pole at $z = 0$. There are only $L\mu+n-1$ order poles at $z = 1/(1+B)$. Thus, $\bar{P}_{d,k-\mu}^{MRC}$ can be computed as

$$\bar{P}_{d,\,k-\mu}^{MRC} = e^{-\frac{\lambda}{2}}(\frac{B}{1+B})^{L\mu} \times [(Res(p_{MRC};\frac{1}{1+B})]$$

(27) has been verified. Therefore, proposition 1 has already been verified.

APPENDIX B
PROOF OF PROPOSITION 2

Rewrite (31)

$$\begin{aligned}\bar{P}_{d,k-\mu}^{SLC} &= \frac{e^{-\frac{\lambda}{2}}}{j2\pi}\oint_{\Delta}[M_{\gamma}(s)]^{L}\frac{e^{\frac{\lambda}{2}z}}{z^{Lu}(1-z)}dz\\ &= \frac{e^{-\frac{\lambda}{2}}}{j2\pi}\oint_{\Delta}(\frac{B}{1+B})^{L\mu}\frac{z^{L\mu}}{(z-\frac{1}{1+B})^{L\mu}} \times\exp(\frac{(1-z)L\mu k}{(B+1)z-1})\frac{e^{\frac{\lambda}{2}z}}{z^{Lu}(1-z)}dz\\ &= (\frac{B}{1+B})^{L\mu}\frac{e^{-\frac{\lambda}{2}}}{j2\pi}\oint_{\Delta}p_{SLC}(z)dz\end{aligned}$$

where

$$p_{SLC}(z) = \frac{e^{(\frac{\lambda}{2}z+\frac{(1-z)L\mu k}{(B+1)z-1})}}{z^{Lu-L\mu}(1-z)(z-\frac{1}{1+B})^{L\mu}} = g_2(z)h_2(z) \tag{41}$$

with

$$g_2(z) = \frac{e^{\frac{(1-z)L\mu k}{(B+1)z-1}}}{(z-\frac{1}{1+B})^{L\mu}} = \frac{e^{\frac{(1-z)L\mu k}{(B+1)(z-\frac{1}{1+B})}}}{(z-\frac{1}{1+B})^{L\mu}} \tag{42}$$

and

$$h_2(z) = \frac{\exp(\lambda z/2)}{z^{Lu-L\mu}(1-z)} \tag{43}$$

Applying Laurent series expansion to $g_2(z)$ [7] gives the following

$$g_2(z) = \frac{e^{\frac{(1-z)L\mu k}{(B+1)z-1}}}{(z-\frac{1}{1+B})^{L\mu}} = \frac{e^{\frac{(1-z)L\mu k}{(B+1)(z-\frac{1}{1+B})}}}{(z-\frac{1}{1+B})^{L\mu}} = \sum_{n=1}^{\infty}\frac{[L\mu k]^{n-1}(1-z)^{n-1}}{(n-1)!(1+B)^{n-1}(z-\frac{1}{1+B})^{L\mu+n-1}} \tag{44}$$

Therefore, $\bar{P}_{d,k-\mu}^{SLC}$ can be denoted

$$\begin{aligned}p_{SLC}(z) &= \frac{e^{(\frac{\lambda}{2}z+\frac{(1-z)L\mu k}{(B+1)z-1})}}{z^{Lu-L\mu}(1-z)(z-\frac{1}{1+B})^{L\mu}} = g_2(z)h_2(z)\\ &= \sum_{n=1}^{\infty}\frac{[L\mu k]^{n-1}(1-z)^{n-1}}{(n-1)!(1+B)^{n-1}(z-\frac{1}{1+B})^{L\mu+n-1}}\times\frac{e^{\frac{\lambda}{2}z}}{z^{Lu-L\mu}(1-z)}\\ &= \sum_{n=1}^{\infty}\frac{[L\mu k]^{n-1}}{(n-1)!(1+B)^{n-1}}\frac{e^{\frac{\lambda}{2}z}(1-z)^{n-1}}{(z-\frac{1}{1+B})^{L\mu+n-1}z^{Lu-L\mu}(1-z)}\end{aligned} \tag{45}$$

Thus, $\bar{P}_{d,k-\mu}^{SLC}$ can be calculated using (11) with the following change in parameters: $u \to Lu$ and $\mu \to L\mu$ [28]

A. WHEN $Lu > L\mu$

In this case, there are $Lu-L\mu$ order poles at the origin and $L\mu+n-1$ order poles at $1/(1+B)$. Thus, $\bar{P}_{d,k-\mu}^{SLC}$ can be expressed as

$$\bar{P}_{d,k-\mu}^{SLC} = e^{-\frac{\lambda}{2}}(\frac{B}{1+B})^{L\mu} \times [Res(p_{SLC};0) + (Res(p_{SLC};\frac{1}{1+B})]$$

where the residue of the function $p_{SLC}(z)$ is $Res\ (p_{SLC};0)$ at the origin and the residue of the function $p_{SLC}(z)$ is $Res\ (p_{SLC};\frac{1}{1+B})$ at $1/(1+B)$. The residues can be derived as

$$Res\ (p_{SLC};0) = \sum_{n=1}^{\infty}\frac{[L\mu k]^{n-1}}{(n-1)!(1+B)^{n-1}}[\frac{1}{(Lu-L\mu-1)!} \times\frac{d^{Lu-L\mu-1}}{dz^{Lu-L\mu-1}}\frac{e^{\frac{\lambda}{2}z}(1-z)^{n-1}}{(1-z)(z-\frac{1}{1+B})^{L\mu+n-1}}]\,|_{z=0} \tag{46}$$

$$
\begin{aligned}
&Res\,(p_{SLC};\frac{1}{1+B})\\
&= \sum_{n=1}^{\infty} \frac{[L\mu k]^{n-1}}{(n-1)!(1+B)^{n-1}} [\frac{1}{(L\mu+n-2)!}\\
&\quad \times [\frac{d^{L\mu+n-2}}{dz^{L\mu+n-2}} \frac{e^{\frac{\lambda}{2}z}(1-z)^{n-1}}{z^{Lu-L\mu}(1-z)}] \Big|_{z=\frac{1}{1+B}}
\end{aligned} \tag{47}
$$

(32) has been verified.

B. WHEN $Lu \leq L\mu$

In this case, there is only $L\mu + n - 1$ order poles at $1/(1+B)$ to be considered in radius $r \in [0, 1)$. There is no pole at the origin. Therefore, $\bar{P}^{SLC}_{d,k-\mu}$ can be given by

$$
\bar{P}^{SLC}_{d,k-\mu} = e^{-\frac{\lambda}{2}} (\frac{B}{1+B})^{L\mu} \times [(Res(p_{SLC};\frac{1}{1+B})]
$$

(33) has been verified. Thus, proposition 2 has already been verified.

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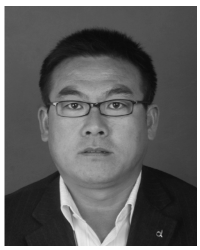

GUANGQIAN CHU was born in 1970. He received the graduate degree from the Department of Electrical and Mechanical Engineering, Tongji University, Shanghai, China, in 1995, and the M.S. degree in signal and information processing from the Chongqing University of Posts and Telecommunications, Chongqing, in 2006. He is currently pursuing the Ph.D. degree in signal and information processing with the Beijing University of Posts and Telecommunications. His current research interests include wireless communication, spectrum sensing, cognitive radio, and digital mobile communication.

KAI NIU was born in 1974. He received the B.S. degree in information engineering and the Ph.D. degree in signal and information processing from the Beijing University of Posts and Telecommunications (BUPT), Beijing, China, in 1998 and 2003, respectively. He is currently an Associate Professor with the School of Information and Communication Engineering, BUPT. His research interests include coding theory and its applications, space-time codes, and broadband wireless communication. Since 2008, he has been a Senior Member of the Chinese Institute of Electronics (CIE) and a Committee Member of the Information Theory Chapter, CIE.

WEILING WU was born in 1938. He is currently a Professor and Doctoral Tutor at the School of Information and Communication Engineering, Beijing University of Posts and Telecommunications. His main research directions are variable channel information transmission, mobile communications, and information theory and coding. He has been involved in teaching and research in the field of information and communication for a long time. As a Project Leader, he has hosted and undertaken more than 10 national-level scientific research projects, such as projects 973 and 863 of the Natural Science Foundation. He has received two national awards and four ministerial awards. In recent years, he has published more than 200 papers, seven patents, and four national textbooks and monographs: *Information Processing and Coding*, *Principles of Mobile Communication*, *Principles of Communication*, and *Key Technologies in Mobile Communications*. He is a former Chairman of the China Electronics Association, the Chairman of the Information Theory Branch, and an Expert Member of the Ministry of Radio, Film, and Television.

FANGLIAO YANG was born in 1991. He received the B.S. degree in electronic engineering from the Beijing University of Posts and Telecommunications, Beijing, China, in 2010, where he is currently pursuing the Ph.D. degree with the School of Information and Communication Engineering. His research interests include information theory, coding theory, and digital signal processing.