Performance Analysis of Correlated Multi-Channels in Cognitive Radio Sensor Network based Smart Grid

Emmanuel U. Ogbodo and David G. Dorrell
Discipline of Electrical, Electronic and Computer Engineering, University of KwaZulu-Natal
Durban, South Africa
(e-mail: ogbodoeu@gmail.com and dorrelld@ukzn.ac.za)

Adnan M. Abu-Mahfouz
Meraka Institute
Council for Scientific and Industrial Research (CSIR)
Pretoria, South Africa
(e-mail: a.abumahfouz@ieee.org)

Abstract*—Recently, cognitive radio based sensor network (CRSN) has been introduced into Smart Grids (SG) in order to address the problems of spectrum inefficiency and interferences. CRSN has the capability of opportunistic spectrum access (OSA) to dynamically allocate radio resources to the sensor nodes. However, one of the CRSN challenges is the problem of dual/multi correlation fading channels due to dual/multi antenna channels of the sensor nodes as well as very close spacing of sensor nodes deployment in a SG environment. This correlation can lead to degradation of the signals as well as co-channels interference. In addition, the signal-interference-noise-ratio (SINR), multipath fading, and shadowing peculiar to SG harsh environmental condition including interference from SG equipment also pose great challenges to CRSN based SG. All these problems have attracted research attentions; however, research regarding the problem of correlated signals in SG has not been considered. Hence, this paper aims to address the problem of correlation in multi fading channels. Consequently, an MGF based performance analysis of M-QAM error probability over Nakagami-q dual correlated fading channels with maximum ratio combiner (MRC) receiver technique has been derived using analytical method of trapezoidal numerical integration. An algorithmic approach which is based on a proposed transformation technique has been introduced. The error probability performance analysis is then carried out in MATLAB simulation, the simulations result agrees with the analytical/theoretical result with overlapping curves. Finally, the produced results show that dual correlated channels degrade the signal performance.

Keywords*— *Opportunistic spectrum access (OSA), maximum ratio combiner (MRC), symbol error probability (SEP), correlation fading channels, correlated coefficients, CRSN, Smart Grid.

I. INTRODUCTION

Cognitive Radio based sensor network (CRSN) in Smart Grid enables Power Generation, Transmission, Distribution Companies (Utilities) and Customers to transfer, monitor, predict, control and manage energy usage effectively and in cost efficient manner. CRSN is a component of Communication Network Infrastructure. Hence, reliable communication systems are keys to achieve the benefits of Smart Grid (SG) [1]. This will help to address the problems in the existing power grid such as metering issues, demand-side management (DSM), distributed energy resources (DER), issues of proper penetration of electricity in the rural areas, ageing infrastructure, increase demand, environmental impact of energy resource extraction, poor performance and power quality issues including transmission loss, which invariably will lead to poor utilization and lack of full benefits of smart grid.

Currently, the traditional power grid is on top-down layer approach where the communication flow is only in one direction from the utility to the consumers. A SG has a bidirectional communication flow between utility and consumer. In the SG scenario, the consumer can benefit from real-time energy management and pricing through Demand Response management, thereby enabling energy conservation and cost-effectiveness [2]-[6]. Traditionally, wireless networks are regulated by a spectrum assignment and management policy which makes fixed assignments of spectrum to license holders for a long time within large geographical regions. This fixed assignment under-utilizes spectrum with utilization levels that ranges from 15% to 85% [7]. Cognitive Radio which has the capability of Dynamic Spectrum Access (DSA) is a promising option to solve these spectrum inefficiencies. Hence, Integration of CRSNs (a combination of Cognitive Radios and Wireless Sensor Networks (WSNs)) in Smart Grids will help to address the spectrum issue. A network of CRSN devices can exploit these licensed bands opportunistically through opportunistic spectrum access (OSA) as secondary users (SUs), whereas the licensed users, or the primary users (PUs), have precedence over the spectrum band.

However, there are some challenges that need to be overcome in the deployment of this CRSN paradigm in SG [8]-[14], such as link reliability, co-channel interference, bandwidth, and latency [15]-[18]. In addition, irregular channel conditions and electromagnetic signal-to-noise-ratio-interference from the SG equipment caused by harsh environmental conditions of the SG adversely affects the overall network performance [19]. Hence, one of the non-optimal ways to attain a better throughput-received -signal of the sensed data at the sensor nodes is by deploying sensor nodes with multi channels in close ranges. Nevertheless, there exist a multi co-channels in CRSN paradigm due to the closeness of sensor nodes with multi channels deployed in CRSN based SG environment. These result to dual/multi correlated channels including co-channel interference which adversely affects the received signal of the communication network performance. Thus, leading to high symbol error probability (SEP) or high bit error rate (BER) with poor signal to noise ratio (SNR). Also, other factors such as multipath fading and shadowing do impair the received signal network performances. Consequently, these problems of correlation of signals can typically be addressed by introducing algorithmic transformation approach and reception diversity technique; such that, a performance analysis will be carried out in order to obtain an improved average signal-to-noise-ratio (SNR) by combining two or more desired signal of the multiple channels. This performance improvement by maximization of the average SNR will give rise to interference mitigation and optimal throughput of transfer of the sensed data in the SG network.

Before we look at the performance improvement, we shall first of all look at the approach of the related works in the literature. Hence, the rest of this paper is organized as follows: section II related works are highlighted, in section III we present moment generating function (MGF) based performance analysis of error probability of dual/multi correlated channels in CRSN based SG including the use of algorithmic approach and transformation technique for converting correlated channels into non-identical and independent signal under Nakagami-q distribution. In section IV we present simulation results and discussion. Finally, we conclude the paper in section V.

II. RELATED WORKS

Numerous works that relates to performance improvements in cognitive radio network (CRN)/CRSN based smart grids have been published [20]-[26]. Most of these works aim at improving communication in SG without the consideration of neither correlation multipath fading channels nor diversity reception technique. Few works that consider correlation multipath fading channels in CRN though neither in CRSN nor in CRSN based SG includes the work by Shaikh *et al.* [27]. They carried out detection performance in correlated multiple antenna elements using linear test statistic which confirmed that the performance is severely degraded due to the correlation among the sensors antennas. Hence, they proposed a modest hard decision fusion strategy by exploiting collaborative gain to improve the performance. Another work in CRN was carried out by Al-Juboori *et al.* [28] in which they consider a multichannel spectrum sensing and presented a closed-form expression for average detection probabilities derived while considering dual and triple correlated channels using Selection Combining (SC) technique under multipath Nakagami-m fading channels with different fading severities. Also, Digham *et al.* [29] conducted performance evaluation in CRN using selection combining (SC) diversity techniques in independent and identically distributed L-number channel branches under Rayleigh fading distributions. In addition, Adebola *et al.* [30] investigated performance on Independent but non-identically distributed channel branches over generalized fading environment based on MGF using SC, Square-Law Selection (SLS) and Maximal Ratio Combining (MRC) diversity schemes. Kim *et al.* [31] carried out sensing performance of energy detector with Correlated multiple antennas and verified that the amount of correlation among antenna channels is directly proportional to degradation of performance. Zhang *et al.* [32] conducted Performance investigation in CRN for spectrum underlay single input multiple output multi access channels while considering PUs interference constraints and SUs peak power constraints. In [33] the authors evaluated bit error rate (BER) performance of Cognitive Radio Physical layer under Rayleigh channel using different channel encoding techniques, digital modulation and channel conditions.

Furthermore, works that are purely on wireless systems that is neither based on CRN/CRSN nor in SG but involves performance analysis of signals including correlation multiple antenna channels and receiver diversity are found in [34]-[38]. So far, it is obvious from the literatures that works on performance analysis of multi correlated channels and receiver diversity technique in CRN/CRSN based SG are not predominant or has not been considered, considering the fact that SG has severe harsh environmental conditions and electromagnetic interference from the SG equipment. Hence, the focus of this paper is to conduct performance analysis on CRSN communication signal under dual correlated Nakagami-q fading channels conditions in SG environment.

III. MGF BASED PERFORMANCE ANALYSIS UNDER DUAL CORRELATED CHANNELS

A. System Model

CRSN based SG is a typical scenario where channel conditions fluctuate dynamically, hence CRSN systems employs an adaptive modulation schemes so as to take into account the difference in channel conditions. The adaptive modulation adjusts transmission parameters such as power, data rate, modulation technique, etc. Consequently, a CRSN with adaptive modulation can be equipped with M-ary PSK, M-QAM, DSSS, etc.

However, in this paper, we are using M-ary quadrature amplitude modulation (M-QAM) modulation scheme because it is widely used in communication systems due to its high benefits of bandwidth efficiency as well as power efficiency. In this case, during transmission, the SG sensed data is modulated using M-QAM under correlated fading channels distribution conditions such that the signals are received at the various sensor nodes. We consider a dual-branch single-input multiple-output (SIMO) system. The received signal at the receiver can be modelled as:

$$y_i(t) = \sqrt{E_s} h_i(t) x(t) + n_i(t) \quad i = 1,2 \tag{1}$$

where $yi(t)$ is the received signal, E_s is the transmit signal power, *x* is the transmitted symbol (signal), $h_i(t)$ is Nakagami-q fading channels impulse response which is describes as: $h_i = h_i^I + jh_i^Q$ and has a zero mean with complex Gaussian variables represented as $(0, \sigma_x^2)$ and $(0, \sigma_y^2)$, i ∈ [1,2], *i* is the i-number of branches of fading channels, $n_i(t)$ is the noise with complex Gaussian distribution $CN\ (0, N_0)$, where N_0 is the noise power spectral density of one-sided branch channel, and i ∈ [1,2]. But

$$q = \sigma_y / \sigma_x \tag{2}$$

where $0 \leq q < 1$.

Also, based on the assumption that,

$$E[(h_i^I)^2] = E[(h_i^Q)^2] = \sigma^2 \tag{3}$$

Then the covariance of the h_1 and h_2 branches can be represented as,

$$Ch_i^I h_2^I = E[h_1^I \, h_2^I] = \rho\sigma^2 \tag{4a}$$

$$Ch_i^Q h_2^Q = E[h_1^Q \, h_2^Q] = \rho\sigma^2 \tag{4b}$$

For the noise components we have,

$$E[n_i h_k^I] = E[n_i h_k^Q] = 0, \quad \mathrm{i} = 1,2;\ \mathrm{k} = 1,2 \tag{4c}$$

We define the instantaneous signal-to-noise ratio (SNR) as

$$\gamma = E_s/N_0 \tag{5}$$

Then the moment generating function (MGF) of the received SNR over Nakagami-q channels can be written as,

$$M_{\gamma_q}(s) = \left(1 - 2s\bar{\gamma} + \frac{(2S\bar{\gamma})^2 \; q^2}{(1+q^2)^2}\right)^{-1/2} \tag{6}$$

where $0 \leq q < 1$ and $\bar{\gamma}$ is the average received SNR for each symbol and is expressed as, $\bar{\gamma} = 2\sigma^2 E_s/N_0$.

B. MGF based Performance Analysis of M-QAM over Single Nakagami-q Fading Channel.

In AWGN the symbol error rate probability (SEP) of detection of M-QAM is given by [34]

$$P_{MQAM} = a/n \left\{ \frac{e^{-b.\frac{\gamma}{2}}}{2} - \frac{ae^{-b\gamma}}{2} + (1-a)\sum_{i=1}^{n-1} e^{-\frac{b\gamma}{si}} + \sum_{i=n}^{2n-1} e^{-b\gamma/si} \right\} \tag{7}$$

Where $= 1 - \frac{1}{\sqrt{M}}$; $= \frac{3}{M-1}$;$si = 2sini\pi/4n$; M is the constellation order which may be 4, 16, 32, etc.; n is the number of iteration.

We can then derive MGF based average error probability by simply retaining the M-QAM SEP given in (7) under AWGN to be integrated over Nakagami-q fading distribution with this expression,

$$\bar{P_s} = \int_0^\infty P_s(\gamma)\, f_{\gamma_s}(\gamma)\, d\gamma \tag{8}$$

But the MGF of a nonnegative random variable is given by,

$$M_\gamma(s) = \int_0^\infty f_s(\gamma) e^{s\gamma}\, d\gamma \tag{9}$$

Hence, MGF based average error probability is derive thus,

$$\bar{P}_{MQAM} = \int_0^\infty a/n \left\{ \frac{e^{-b.\frac{\gamma}{2}}}{2} - \frac{ae^{-b\gamma}}{2} + (1-a)\sum_{i=1}^{n-1} e^{-\frac{b\gamma}{si}} + \sum_{i=n}^{2n-1} e^{-b\gamma/si} \right\} \left(1 - 2s\bar{\gamma} + \frac{(2S\bar{\gamma})^2 \; q^2}{(1+q^2)^2}\right)^{-1/2} \tag{10}$$

Applying trapezoidal rule, gives:

$$\bar{P}_{MQAM} = {}^{a}/_{n} \left(\frac{1}{2} M_{\gamma_q}\left(-\frac{b}{2}\right) - \frac{a}{2} M_{\gamma_q}(-b) + (1-a)\sum_{i-1}^{n-1} M_{\gamma_q}\left(\frac{-b}{s_i}\right) + \sum_{i-n}^{2n-1} M_{\gamma_q}\left(\frac{-b}{s_i}\right) \right) \tag{11}$$

Equation (11) is the derived MGF based average SEP of M-QAM over single Nakagami-q fading channel.

C. MGF based Performance Analysis of M-QAM over Dual Correlated Nakagami-q Fading Channel using MRC Diversity Technique

SEP performance analysis is usually being conducted on an independent non-identical fading channel distribution. It is obviously not feasible to conduct performance evaluation on identical dual correlated fading channels. Consequently, a transformation technique was proposed in [37] which is used to transform the identical dual correlated channels into non-identical independent channels. Hence, we introduce an algorithmic approach based on the transformation technique, the algorithmic approach is given as,

$$Cz = \begin{bmatrix} 1 & \rho \\ \rho & 1 \end{bmatrix} \tag{12}$$

Where Cz is the covariance, obtain by assigning correlated coefficient, ρ, and ρ *is* $0 \leq \rho \leq 1$. The transformation technique is given as,

$$\bar{\gamma} = (1 + \rho)\bar{\gamma} \tag{13}$$

$$\bar{\gamma} = (1 - \rho)\bar{\gamma} \tag{14}$$

Equations (13) and (14) are used for converting any two-given identical but correlated fading channels with average SNR, $\bar{\gamma} = \bar{\gamma}_1 = \bar{\gamma}_2$, and correlated coefficient, ρ, into non-identical independent channels. Hence, under Nakagami-q fading conditions, the equivalent non-identical independent fading channels, can then be used to obtain an MGF based expression for maximum ratio combiner (MRC) received SNR, γ, as:

$$M_{\gamma qMRC}(s) = M_{\gamma q1}(s)M_{\gamma q2}(s) \tag{15}$$

Now, we can derive an MGF based expression for performance on SEP of MQAM over Nakagami-q dual correlated fading channels with MRC by substituting (15) with M_{γ_q} in (11), this yield:

$$\begin{aligned}\bar{P}_{MQAM} = {}^{a}/_{n}\Bigg(&\frac{1}{2}M_{\gamma q1}(s)M_{\gamma q2}(s)\left(-\frac{b}{2}\right)\\ &-\frac{a}{2}M_{\gamma q1}(s)M_{\gamma q2}(s)(-b) + (1\\ &-a)\sum_{i-1}^{n-1}M_{\gamma q1}(s)M_{\gamma q2}(s)(\frac{-b}{s_i})\\ &+\sum_{i-n}^{2n-1}M_{\gamma q1}(s)M_{\gamma q2}(s)(\frac{-b}{s_i})\Bigg)\end{aligned} \tag{16}$$

IV. Results and Discussion

Since the transformed independent signals are equivalent to the identical dual correlated signals, we then conduct MGF based MRC diversity receiver technique performance evaluation on the transformed non-identical independent signals. **Error! Reference source not found.** to **Error! Reference source not found.** shows how the variation of correlation coefficient, ρ ($\rho\ = 0, 0.3, 0.6, 0.8\ and\ 1$) affected the received signals respectively. The simulations were conducted in MATLAB environment and the same number of iteration ($n = 10000$) of the transmitted signals was used in all the cases of variation of ρ.

Looking at **Error! Reference source not found.** we can see that when ρ = 0, the simulation result and theoretical or analytical result actually matches which is depicted by the overlapping curves in Fig. 1. Another important observation here is that the received signal has a very low symbol error rate, thus, confirming that in a circumstance of uncorrelation (when ρ=0) the received signal will be void of excessive errors. But as the ρ is varied from 0.3 to 1, we noticed that the symbol error rate increases in the received signal; hence, the presence of excess errors causes degradation of the received signal thereby resulting to poor link reliability in the SG ecosystem. It is also important to note that in each of the graphs the simulated results matches with the analytical numerical integration results as depicted by the overlapping curves shown in Fig. 1 to Fig. 5. Also, we notice that in each case, the SNR increases as the SEP reduces; which is a clear confirmation that SNR can be maximized by having a reduced SEP.

For a better analysis, one can use a particular SNR, i.e. the same SNR condition environment in all cases to estimate the approximate error rate of the received signal. Table I helps to illustrate comparisons of the error rate with respect to various ρ under the same SNR condition environment. Consequently, we can see that the error rate increases as the ρ increases, this confirms that correlation of antenna channels degrades the performance of the received signals of the SG sensed data.

TABLE I. ERROR RATE COMPARISONS TABLE WITH RESPECT TO P

Correlated Coefficient (ρ)	**SNR (dB)**	**SEP**
0	18	$4.0 * 10^{-4}$
0.3	18	$6.0 * 10^{-4}$
0.6	18	$7.5 * 10^{-4}$
0.8	18	$9.0 * 10^{-4}$
1	18	$9.0 * 10^{-3}$

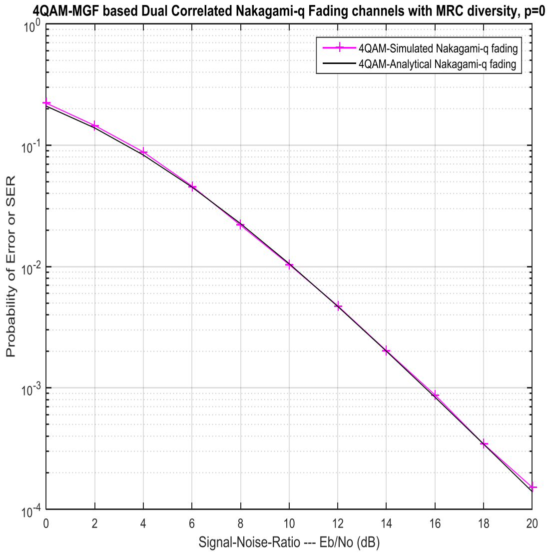

Fig. 1. MGF based MQAM with ρ =0

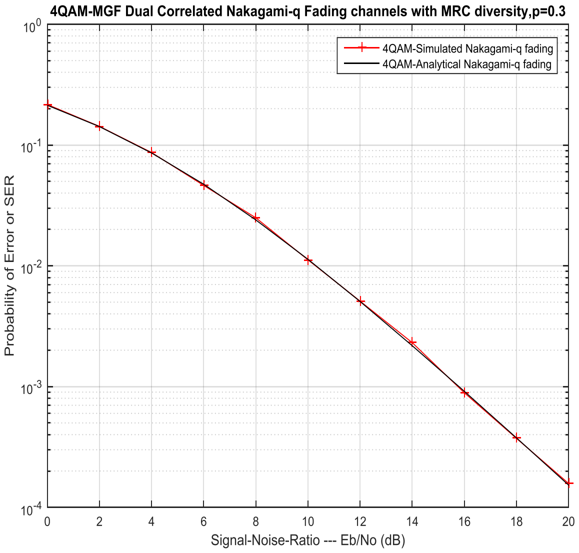

Fig. 2. MGF based MQAM with ρ =0.3

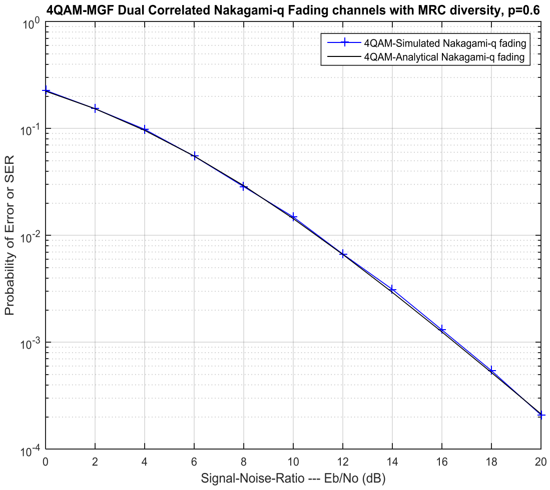

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Fig. 3. MGF based MQAM with ρ =0.6

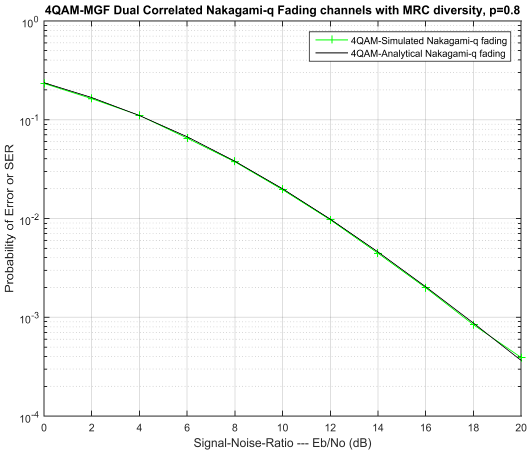

Fig. 4. MGF based MQAM with ρ =0.8

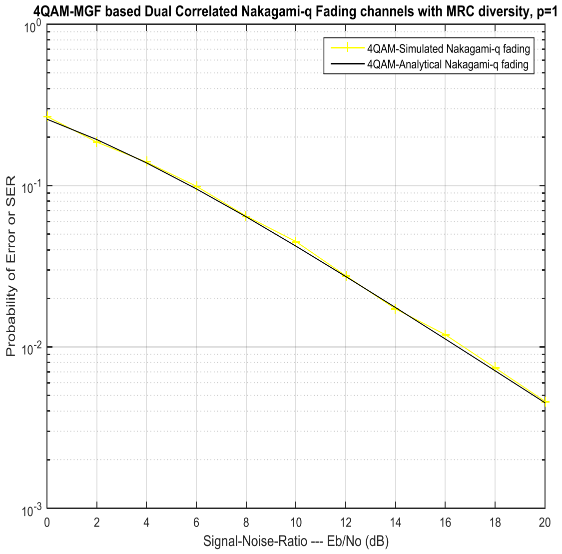

Fig. 5. MGF based MQAM with ρ =1

V. CONCLUSION

In this paper, we provide an overview of CRSN based paradigm in SG and illustrate how performance analysis can be conducted in dual correlated fading channels under Nakagami-q distribution. We derived an expression for (MGF) based performance analysis of error probability of MQAM over single Nakagami-q fading channels using analytical method of trapezoidal numerical integration. Furthermore, MGF based SEP of MQAM over dual/multi correlated Nakagami-q fading channels with MRC diversity receiver technique was also derived using the same analytical method of trapezoidal numerical integration. A transformation technique was used in converting the dual correlated signals into an independent but non-identical signal. The derived error probability expressions are then used in carrying out performance analysis on these independent signals. Overall, our simulation results agree with our analytical solution results. These results will enable performance improvement in the deployment of multi-channels sensor nodes in CRSN based SG. Hence, CRSN based SG designer will make sure that the antenna channels in a multi-channels sensor nodes are substantially spaced apart including adequate spacing of sensor nodes deployment in a SG environment to overcome signal degradation due to dual/multi correlations

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