Spectral Shape Impact of Nonlinear Compensator Signal in LTE RoF System

Kanesan, T. , Mitani, S. M. , Mohamad, R. , Hizan, H. M. , Ng, W. P. , Ghassemlooy, Z. , Rajbhandari, S. , Haigh, P. A. and Chang, G.-K.

Author post-print (accepted) deposited in CURVE February 2016

Original citation & hyperlink:
Kanesan, T. , Mitani, S. M. , Mohamad, R. , Hizan, H. M. , Ng, W. P. , Ghassemlooy, Z. , Rajbhandari, S. , Haigh, P. A. and Chang, G.-K. (2015) Spectral Shape Impact of Nonlinear Compensator Signal in LTE RoF System. IEEE Photonics Technology Letters, volume 27 (23): 2481 – 2484
http://dx.doi.org/10.1109/LPT.2015.2462122

ISSN 1041-1135
DOI 10.1109/LPT.2015.2462122

“© 2015 IEEE. Personal use of this material is permitted. Permission from IEEE must be obtained for all other uses, in any current or future media, including reprinting/republishing this material for advertising or promotional purposes, creating new collective works, for resale or redistribution to servers or lists, or reuse of any copyrighted component of this work in other works.”

Copyright © and Moral Rights are retained by the author(s) and/ or other copyright owners. A copy can be downloaded for personal non-commercial research or study, without prior permission or charge. This item cannot be reproduced or quoted extensively from without first obtaining permission in writing from the copyright holder(s). The content must not be changed in any way or sold commercially in any format or medium without the formal permission of the copyright holders.

This document is the author’s post-print version, incorporating any revisions agreed during the peer-review process. Some differences between the published version and this version may remain and you are advised to consult the published version if you wish to cite from it.

CURVE is the Institutional Repository for Coventry University

Spectral Shape Impact of Nonlinear Compensator Signal in LTE RoF system

T. Kanesan, *Member, IEEE,* S. M. Mitani, R. Mohamad, H. M. Hizan, W. P. Ng, Z. Ghassemlooy, S. Rajbhandari, P. A. Haigh and Gee-Kung Chang, *Fellow IEEE*

***Abstract*—A large scale investigation is carried out, utilizing several spectral shapes as the source for the direct modulation based frequency dithering (DMFD) method for mitigating the nonlinear effect of long term evolution (LTE) radio-over-fiber (RoF) systems. The dithering signal types include sine, square, saw, sinc and Gaussian waves, whereby all of the signals have different characteristics in terms of the spectral width with a sine wave having the smallest width. We have shown that by varying the dithering signal type with larger spectral widths, no additional distortion is introduced in the linear and optimum optical launch power regions, which are driven by the frequency chirp and chromatic dispersion (CD). Additionally, it is revealed herein that introducing dithering signals with varying spectral widths (i.e larger or smaller) does not change the nonlinear compensator characteristic towards suppression of nonlinearity. The reason for this is that as long as the optical source linewidth is larger than stimulated Brillouin scattering (SBS) linewidth, the proposed method completely suppresses SBS. Finally, the degree of freedom for the dithering signal is infinite with improvement of up to 8 dB of an optical power budget at 10 dBm optical launch power, which can be used towards connecting multiple relay nodes (RNs).**

***Index Terms*— Long Term Evolution (LTE); Radio-over-fibre (RoF); Nonlinear Compensation; Optical OFDM (OOFDM)**

I. INTRODUCTION

Enormous growth in mobile broadband end users is driving the mobile communications market towards the requirement of a consistently progressing technology. Such immense demand resulted in the 3rd generation partnership program (3GPP) introducing the 4th generation LTE technology as the development path for future mobile broadband services [1].

The evolved NodeB (eNB) is a highly complex and costly LTE base station, due to its operating structure as a standalone unit without the need for a central controller. Furthermore, the spectral allocation for LTE is moving towards a higher frequency region, typically at 2.6 GHz (subject to spectrum availability in individual countries). Wireless propagation at such frequency experiences higher path loss, especially in non-line-of-sight connectivity, thus severely affecting high mobility user equipments (UEs). Such a scenario limits the cell radius to 1 km as a result of degradation in the signal-to-noise ratio (SNR) performance at the cell edge [2]. For instance, in [3], a 2.6 GHz based LTE system with 100 Mb/s capacity could only deliver < 20 Mb/s throughput to UE located at the edge of the 1 km radius due to the deterioration in SNR [3].

In order to avoid continuous deployment of eNB at every 1 km to accommodate the highest throughput of LTE, we designed and developed a relaying system. The principle of operation is based on simple amplifying and forwarding RNs with RoF acting as the interface between the eNB and RN [4-8]. In other words, instead of eNB, the RN delivers the LTE signal to the UE at the cell edge. The initial LTE-RoF design was carried out as a half duplex link [8], subsequently evolving into a full duplex frequency division duplex (FDD) system [4].

For commercial deployment, it would be preferable that a single eNB supports multiple RNs in a similar manner to a passive optical network, where a single optical line terminal supports multiple optical network units via optical splitters. However, there is a limitation in supporting multiple RNs due to the limitation on the optical launch power. A higher optical launch power will provoke nonlinearity in optical fiber, which in our case is limited to only self phase modulation (SPM) and SBS due to single wavelength operation. As a solution, we recently proposed a direct modulation based frequency dithering (DMFD) method for nonlinear compensation specifically designed for the LTE RoF system [5], which enabled the use of higher optical launch powers. Further optimizations of this method were carried out in the perspective of optical modulators [6] and dithering frequency f_d with higher order modulations [7]. In [6], it is shown that DMFD method introduces an additional ~3 dB optical power penalty in comparison to external modulation while imposing a lower cost. It is also shown in [7] that f_d has to meet the condition of $\{f_L < f_d < f_{RF}\}$, where f_L and f_{RF} are the dithering boundary limit and the LTE carrier frequency, respectively. Ref. [7] also revealed that increasing the dithering signal power further improves the LTE RoF system. Since the DMFD method solely thrives on the characteristics of the dithering signal, it is important to analyze the dithering signal from various perspectives. Based on this type of analysis one is able to find the condition of $\{f_L < f_d < f_{RF}\}$ and provide further understanding in the execution of this method. The final degree of freedom that has not been exploited is the dithering signal shape itself, simply because the dithering signal broadens the linewidth of the laser in order to compensate for the optical fiber nonlinearity. Therefore the spectral shape

---

Manuscript received [].T Kanesan, S. M. Mitani, R. Mohamad, and H. M. Hizan are with the Telekom Malaysia R&D, 63000 Cyberjaya, Selangor, Malaysia (e-mail: thavamaran.kanesan@ieee.org).

Wai Pang Ng and Zabih Ghassemlooy are with the Optical Communications Research Group, NCRLab, Northumbria University, Newcastle upon Tyne, NE1 8ST, U.K.

Sujan Rajbhandari is with the Department of Engineering Science, University of Oxford, Parks Road, Oxford OX1 3PJ, U.K.

Paul Anthony Haigh is with the High Performance Networks Group, University of Bristol, BS8 1TR, U.K.

Gee-Kung Chang is with the School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA 30332 USA.

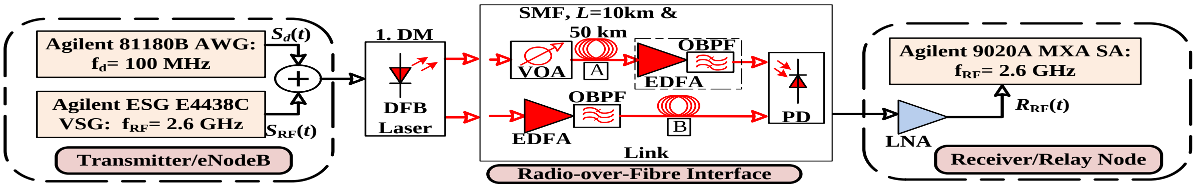

Fig 1: Experimental setup to investigate the spectral shape impact on the DMFD method for LTE RoF system. AWG: arbitrary waveform generator, VSG: vector signal generator, DM: direct modulation, DFB: distributed feedback laser, SMF: single mode fiber, VOA: variable optical attenuator, EDFA: erbium doped fiber amplifier, OBPF: optical bandpass filter, PD: photodetector, LNA: low noise amplifier, SA: signal analyzer.

might play an inherent role for this application. All the prior arts only utilized a simple sine wave as the dithering signal [5-7].

In this paper, for the first time, we investigate the impact of the spectral shape of the dithering signal on fibre nonlinear compensation and its relative impact on the LTE RoF system. The spectral shapes under investigation are comprised of both baseband and passband dithering signals. Furthermore, dithering causes linewidth broadening and a wider linewidth is known to introduce additional distortion. Therefore, as part of the findings, we investigate whether varying the spectral shape of the dithering signal limits the system performance due to the increased phase modulation/linewidth broadening. The rest of the paper is organized as follows, Section II introduces the experimental system, Section III presents and discusses the findings and Section IV draws conclusions on the new findings.

II. Experimental Setup for Nonlinear Compensation Analysis with Varying Spectral Shapes

The proposed setup of the DMFD method for the LTE RoF system is depicted in Fig. 1. The vector signal generator, Agilent ESG E4438C is preprogrammed to generate the LTE signal, which is composed of quadrature phase shift keying (QPSK), 16-quadrature amplitude modulation (QAM), and 64-QAM mapping schemes. These schemes are then multiplexed with the inverse fast Fourier transform to generate an orthogonal frequency division multiplexing (OFDM) signal. The transmission rate of the LTE signals are 33, 66 and 100 Mb/s for QPSK, 16-QAM and 64-QAM, respectively, configured according to the LTE standard [9]. The baseband OFDM signal is then up-converted to 2.6 GHz $S_{RF}(t)$.

Agilent 81180B arbitrary waveform generator (AWG) is used for the generation of various dithering signals $S_d(t)$ at 100 MHz, namely sine, square, sawtooth, sinc and Gaussian waves as mentioned. Among these signals, sine, square, sawtooth, and Gaussian are passband waveforms, while sinc is a baseband waveform. For further information on the selection of 100 MHz, refer to [7]. The ideal spectral shapes of the waveforms are shown in Fig. 2. As depicted in Fig. 2(a), the sine wave is ideally composed of a single frequency signal, although in practical system some harmonics will arise. However, the square and sawtooth waves, shown in Fig. 2(b) and 2(c), respectively, exhibit harmonics. Therefore, square and sawtooth waves operating at non-ideal conditions such as for the DMFD method, have the potential of further broadening the laser linewidth and potentially more rigorously compensate the nonlinearity. The sinc baseband waveform (Fig. 2(d)) covers the entire baseband segment with a cutoff at 100 MHz. Finally, the Gaussian wave (Fig. 2(e)) acting as a passband signal, has similar characteristics to a sine wave, while having a larger spectral width, translating into a wider linewidth.

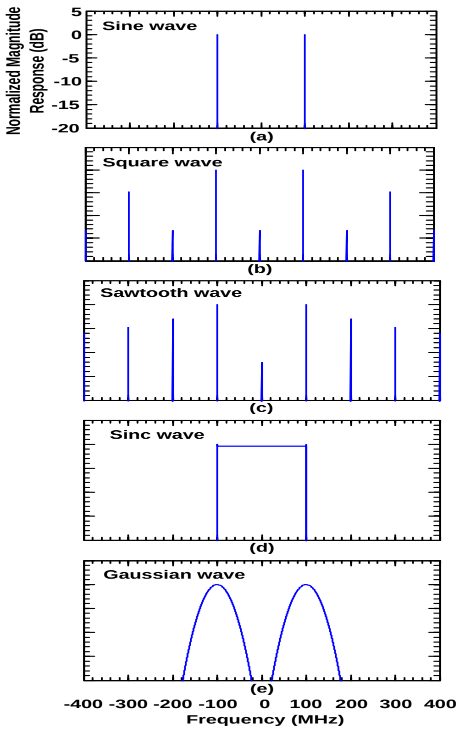

Fig. 2: Spectral shapes of dithering signals, namely (a) Sine, (b) Square, (c) Sawtooth, (d) Sinc, and (e) Gaussian waves. Note that the x- and y-axes are the same for the five graphs.

The LTE and dithering signals are passively combined to directly modulate the distributed feedback laser (DFB) operating at the wavelength of 1551.11 nm. As a result, the DFB laser is frequency chirped and its linewidth broadened with the dithering signal. The frequency chirping phenomena in a direct modulation condition will conventionally induce additional distortion due to its inherent phase modulation and linewidth broadening. However, in our prior work, we found that using a sine wave as a dithering signal to induce frequency chirp does not further distort the LTE signal. Here, we will unveil if varying the spectral shape of the dithering signal might prove otherwise due to the increased phase modulation.

The Van-der-Pol model can be used to describe the laser noise arising from linewidth broadening given by [10]:

$$\Delta\phi(t)^2 = \frac{\zeta(1+\alpha^2)(t)}{2n\tau_{\mathrm{p}}} = \frac{2(t)}{\tau_{\mathrm{coh}}} \qquad (1)$$

where α is the linewidth enhancement factor, n is the number of photons in the laser resonator, τ_p is the photon lifetime, ξ is the fraction of spontaneous emission, and τ_{coh} is the coherence time of the laser, which is related to the full width at half maximum (FWHM) of the DFB laser linewidth by:

$$\Delta\nu_{FWHM} = \frac{2}{\tau_{coh}} \tag{2}$$

Frequency dithering with a dithering signal is approximately equivalent to producing multiple random spontaneous emission events, leading to a Wiener process in the phase of the DFB laser defined as [11]:

$$\Delta S_d(t)^2 = \frac{2(t)}{\tau_{cohd}} \tag{3}$$

where τ_{cohd} is the coherence time of the dithering signal at the optical layer. It is important to note that the original coherence time of the DFB laser is τ_{coh}. Applying the random phase modulation with the dithering signal reduces the coherence time of the laser with FWHM of:

$$\frac{1}{T_{coh}} = \frac{1}{\tau_{coh}} + \frac{1}{\tau_{cohd}} \tag{4}$$

where the reduced coherence time is equivalent to a broaden linewidth. As shown in (4), co-modulating a dithering signal broadens the linewidth of LTE signal, which is capable of blocking the formation of an SBS grating, thus resulting in reduced back-reflected power.

A detailed investigation of the DMFD method is conducted among the linear, optimum and nonlinear optical launch power regions by varying the optical launch power over the range of -8 to 10 dBm [5]. In Fig. 1 the LTE signal is directed towards Link A for lower optical launch power, while Link B is used for higher optical launch power in order to induce nonlinearity.

Single mode fibers (SMFs) are employed as the RoF medium with the transmission range fixed to 10 km and 50 km. After propagating through SMFs, signals are detected via a photodetector with the direct detection (DD) method. Following photodetection, the received radio frequency LTE signal $R_{RF}(t)$ is passed through a low noise amplifier for amplification and subsequently demodulated via the electrical signal analyzer (SA), Agilent 9020A MXA.

III. RESULTS AND DISCUSSION

The quality of the received signals are characterized both in analogue and digital domains by means of measurement metrics, namely the electrical power penalty and error vector magnitude (EVM), respectively. The power penalty as a function of optical launch power measurements are shown in Figs. 3(a), (b), and (c) for QPSK, 16-QAM and 64-QAM systems, respectively. The measurements are performed for uncompensated and compensated links with transmission distances of 10 and 50 km. The power penalty is measured as a function of back-to-back SNR. Fig. 3 is categorized into three regions: I) linear region – frequency chirp and chromatic dispersion (CD) induced distortion, II) intermixing region – reduced distortion achieved by the interaction between CD and frequency chirp with SPM and SBS, and III) nonlinear region – nonlinearity based distortion from SPM and SBS effects. For further details on the fundamental nonlinear response within region III, refer to [8].

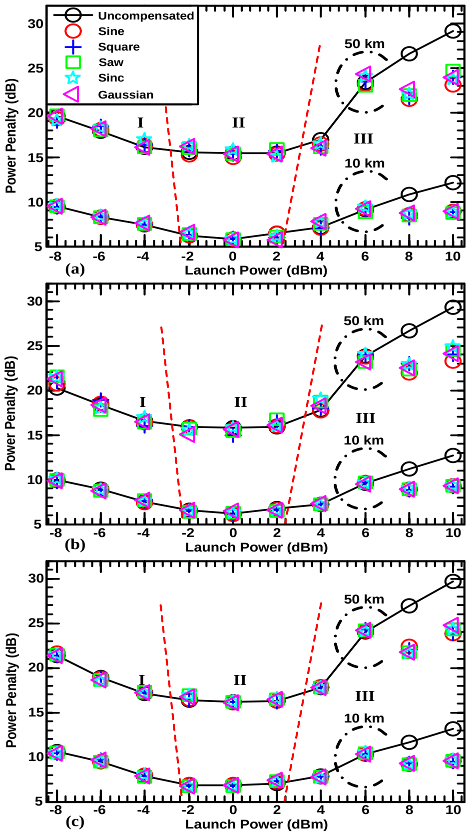

Fig. 3: Optical launch power against power penalty for (a) QPSK, (b) 16-QAM, and (c) 64-QAM, with uncompensated (no dithering) and dithering with signals shaped as sine, square, saw, sinc, and gaussian.

In Fig. 3, signals in regions I and II with sine wave dithered shows no variation compared to the uncompensated LTE RoF signal, which conforms with our prior findings [5-7]. Additionally, dithering with square, saw, sinc and Gaussian waves shows no changes as well when compared to the uncompensated LTE RoF signal. Concentrating on nonlinear propagation, region III depicts that the DMFD method is only effective for an optical launch power of > ~6 dBm and successfully compensates SBS induced distortion. Optical launch powers < ~6 dBm within region III are dominated by SPM and hence the DMFD method does not suppress the distortion. In principal, SPM introduces nonlinearity in the form of harmonics and intermodulation products arising from the refractive index based random phase modulation, while SBS is a nonlinearity that induces scattering and back-reflection with a strong dependency on the linewidth with a threshold limit. Therefore, the DMFD method broadens the linewidth of an optical source and only effectively compensates SBS. For an optical launch power of > 6 dBm, it is clear that with the changes in dithering spectral shapes, the system improvements at 8 dBm and 10 dBm are approximately uniform. The uniformity is because all spectral shapes have successfully broadened the linewidth and suppressed the SBS up to the fundamental limit.

The findings herein are twofold, first showing that the DMFD method with varying dithering signals do not introduce

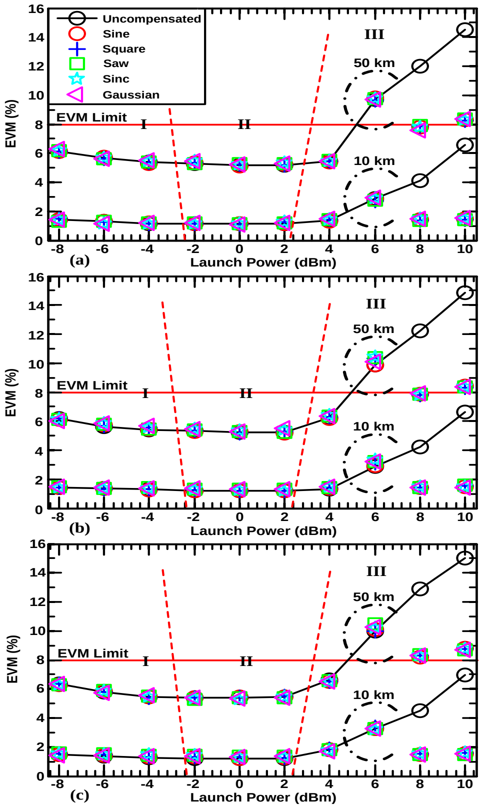

Fig. 4: Optical launch power against EVM for (a) QPSK, (b) 16-QAM, and (c) 64-QAM, with uncompensated (no dithering) and dithering with signals shaped as sine, square, saw, sinc, and gaussian.

additional distortion in regions I and II, despite the increase/decrease in the linewidth due to varying spectral shapes in the dithering signal introducing an additional frequency chirp. Fundamentally this is because the DMFD method with a DFB laser does not initiate optical mode re-growth similar to a Fabry-Perot laser, thus regions I and II remain more or less unchanged. Secondly, our thorough investigations show that as long as the broadened linewidth is larger than the SBS linewidth, then SBS is successfully suppressed, and therefore the investigation has revealed that the dithering signal can be of any shape, as long as it has a spectral width that is larger than a sine wave, which is achievable by any waveform.

Since the power penalty describes the system performance in terms of the out-of-band distortion, we conducted a detailed qualitative analysis based on EVM. Figs. 4(a), (b) and (c) illustrate the measured EVM of the QPSK, 16-QAM and 64-QAM systems, respectively. It is of paramount importance to achieve an EVM close to 8% in the system design according to the 3GPP LTE requirement [12]. The categorization of regions in Fig. 4 is similar to Fig. 3. At 10 km transmission span, the uncompensated link for 8 dBm and 10 dBm optical launch powers still falls below 8% EVM. However, with varying dithering signals, LTE RoF signals across QPSK, 16-QAM and 64-QAM at 8 dBm and 10 dBm achieved EVMs similar to region II.

However, QPSK, 16-QAM and 64-QAM in Figs. 4(a), (b), and (c), respectively, at 8 dBm (10 dBm) resulted in average EVMs of ~12.5% (~14.8%) for the 50 km transmission span. By introducing the DMFD method with varying dithering signals at 50 km transmission span, the average EVMs improved to ~8% (~9%) for 8 dBm (10 dBm) optical launch powers, respectively whereby showing that 50 km is the transmission limit of the proposed system.

Through EVM measurements, it is shown that with any type of dithering signals, the LTE RoF system can achieve close to 8% even at 10 dBm optical launch power, whereby providing an additional power budget of 8 dB compared to 2 dBm optical launch power that falls within region II.

IV. CONCLUSION

In this paper, we have proposed and thoroughly investigated the DMFD method with varying dithering signals for the nonlinear compensation of the LTE RoF system. Herein, it was revealed that any type of dithering signals can be used for the DMFD method, provided that the spectral width is larger than a sine wave. Finally, it was also shown that despite the fact that DMFD induces frequency chirp, it does not deteriorate the signal propagating in the linear and optimum optical launch power regions even with larger spectral width based dithering signals.

REFERENCES

[1] T. Banham. (2010) Mobile Communications Supplement: The LTE Supplement. *informa telecoms & media*.

[2] Y. Qian, Z. Guo, R. Fan, H. Wang, J. Liu, Y. Yan, *et al.*, "Improving outdoor to indoor coverage by use of TD-LTE in-band relay," in *Personal Indoor and Mobile Radio Communications (PIMRC), 2013 IEEE 24th International Symposium on*, 2013, pp. 2658-2662.

[3] T. Wirth, V. Venkatkumar, T. Haustein, E. Schulz, and R. Halfmann, "LTE-Advanced Relaying for Outdoor Range Extension," in *Vehicular Technology Conference Fall (VTC 2009-Fall), IEEE 70th*, 2009, pp. 1-4.

[4] T. Kanesan, W. P. Ng, Z. Ghassemlooy, and C. Lu, "Experimental full duplex simultaneous transmission of LTE over a DWDM directly modulated RoF system," *Optical Communications and Networking, IEEE/OSA Journal of*, vol. 6, pp. 8-17, 2014.

[5] T. Kanesan, W. P. Ng, Z. Ghassemlooy, and L. Chao, "Experimental demonstration of the compensation of nonlinear propagation in a LTE RoF system with a directly modulated laser," in *Communications (ICC), 2013 IEEE International Conference on*, Budapest, Hungary, 2013, pp. 3884-3888.

[6] T. Kanesan, W. P. Ng, Z. Ghassemlooy, and C. Lu, "Impact of Optical Modulators in LTE RoF System with Nonlinear Compensator for Enhanced Power Budget," in *Optical Fiber Communication Conference/National Fiber Optic Engineers Conference (OFC/NFOEC) 2013*, 2013, pp. 1-3.

[7] T. Kanesan, W. Ng, Z. Ghassemlooy, and C. Lu, "Investigation of Optical Modulators in Optimized Nonlinear Compensated LTE RoF System," *Lightwave Technology, Journal of,* vol. PP, pp. 1-1, 2014 (Early Access).

[8] W. P. Ng, T. Kanesan, Z. Ghassemlooy, and C. Lu, "Theoretical and Experimental Optimum System Design for LTE-RoF Over Varying Transmission Span and Identification of System Nonlinear Limit," *Photonics Journal, IEEE,* vol. 4, pp. 1560-1571, 2012.

[9] 3GPP, "Evolved Universal Terrestrial Radio Access (E-UTRA); Physical channels and modulation (3GPP TS 36.211 V10.4.0 Rel-10)," 2011.

[10] K. Vahala and A. Yariv, "Semiclassical theory of noise in semiconductor lasers - Part I, II," *Quantum Electronics, IEEE Journal of,* vol. 19, pp. 1096-1101, 1983.

[11] S. Karlin and H. M. Taylor, *A First Course in Stochastic Processes*, 2nd ed. New York: Academic Press, 1975.

[12] 3GPP, "EVM for LTE Repeater (3GPP TSG-RAN4 Meeting #52, TS 36.143, Rel-8)," 2009.