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Simulation and Analysis of Phase Noise Distortion in RF Transceiver of IEEE 802.11a WLAN Bridge System

N. A. Shairi, T. A. Rahman

Abstract— In this paper, simulation and analysis of phase noise distortion in radio frequency (RF) transceiver of Wireless Local Area Network (WLAN) bridge system are presented. It is focused on the oscillator in RF transmitter and RF receiver in the transceiver. The effect of phase noise on the constellation error of RF transmitter and the receiver sensitivity of RF receiver is analysed based on IEEE 802.11a standard. By this way, these analyses can be applied in early stage of oscillator design for RF transceiver of IEEE 802.11a WLAN system. RF behavioural models and Agilent Ptolemy simulator are used in Advanced Design System (ADS) software to perform simulation of constellation error and receiver sensitivity. As a result, it is found that the phase noise of oscillator should not be higher than -120 dbc/Hz at 1 MHz offset in order to optimise the receiver sensitivity and also to minimising constellation error in RF transceiver of IEEE 802.11a standard.

Index Terms—Phase noise, transceiver, transmitter, receiver, constellation error, sensitivity, packet error rate, IEEE 802.11a, WLAN.

I. INTRODUCTION

In designing any RF transceiver system for wireless data communication, RF designers have to really understand several RF distortions in the system that requires full understanding of RF theories. The distortions that must be addressed by RF designers are noises and non-linearities. They must be determined and reduced so that, the best performance of RF transceiver system design can be achieved according to IEEE standards such as IEEE 802.11a [1] and IEEE 802.16 [2]. These standards use Orthogonal Frequency Division Multiplexing (OFDM) technology for broadband data communication [3], [4].

As shown in Fig. 1, WLAN bridge system is an inter-building communication of LAN either connected in point to point or point to multi point configuration. Fig. 2 illustrates an example of transceiver architecture of WLAN bridge system. It is divided into two parts; indoor unit (IDU) and outdoor unit (ODU). In Time Division Duplex (TDD) communication scheme, the transmitter and receiver part are connected to transmit and receive switch (Tx/Rx switch) [5] to the antenna [6]-[9]. The TTD scheme is specified in physical layer (PHY) of IEEE 802.11a standard. Oscillator [10], filters [11]-[13], amplifiers [14],[15], low noise amplifiers (LNA) [16]-[18] and mixers [19] are also the other sub-components in the ODU system of PHY.

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Noor Azwan Shairi, Center for Telecommunication Research & Innovation (CeTRI), Faculty of Electronics and Computer Engineering, Universiti Teknikal Malaysia Melaka (UTeM), Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia.
Tharek Abdul Rahman, Wireless Communication Center, Faculty of Electrical Engineering, Universiti Teknologi Malaysia (UTM), 81300 Skudai, Johor, Malaysia.

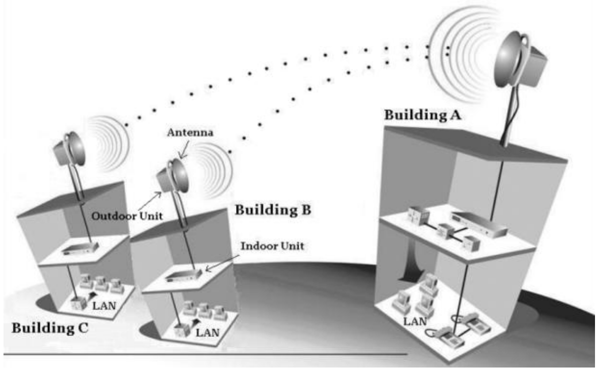

Fig. 1. WLAN bridge system for inter-building communication of LAN.

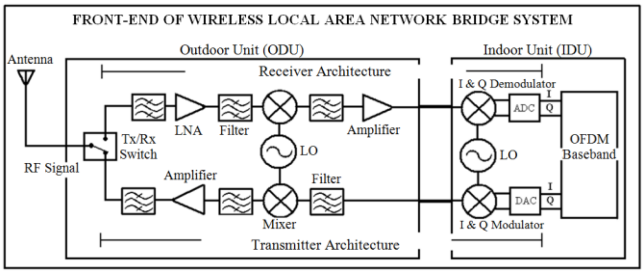

Fig. 2. Typical sub-components in transceiver of WLAN bridge system.

In the previous works, we analysed the effect of noise figure on RF receiver's sensitivity [20],[21] and adjacent channel rejection (ACR) [22] in RF receiver of WLAN IEEE 802.11a. We also analysed the effect of third order inter-modulation distortion (IMD) on spectrum mask [23] and constellation error [24] in RF transmitter of WLAN IEEE 802.11a.

From literature, several authors have published different aspects of analysis of phase noise on OFDM system [25]-[31]. For examples, paper in [31] analysed phase noise of LO with and without Phase-locked-loop (PLL), paper in [29] proposed a composition scheme to mitigate the common phase error and inter-carrier interference (ICI) caused by phase noise and paper in [27] analysed the combined effects of phase noise and Doppler spread.

In this paper, simulation and analysis of phase noise distortion of oscillator in RF transceiver are presented; focusing on the oscillator in RF transmitter and RF receiver in the ODU. The effect of phase noise on the constellation error of RF transmitter and the receiver sensitivity of RF receiver is investigated based on IEEE 802.11a standard. By this way, these analyses can be applied in early stage of oscillator design for RF transceiver of IEEE 802.11a WLAN system. This paper is organised as follows. The phase noise theory and the IEEE 802.11a standard of constellation error and receiver sensitivity are presented in section II. Then, RF transceiver modeling and simulation method are presented in section III. The simulation results and its analysis are reported in section IV. Concluding remarks are given in section V.

II. PHASE NOISE DISTORTION AND IEEE 802.11A

In IEEE 802.11a standard, specifications of constellation error and receiver sensitivity are important to ensure that any WLAN system can transmit and receive any information and data with minimum distortions such as oscillator's phase noise and other non-linearity of RF components.

A. *Phase Noise Distortion*

Phase noise can be caused by a number of conditions, but mostly affected by oscillator frequency stability (phase fluctuations) due to the random frequency fluctuations of a signal [32]. Noise sources in oscillator circuit can be divided into two groups, namely device noise (such as thermal, shot, and flicker noise) and interference [25]. Modeling and analysis of phase noise can be found in different approach such as harmonic balance (HB) formulations [33],[34], time-domain (TD) formulations [35], [36] and envelope transient (ET) formulations [37],[34].

As shown in Fig. 3, the phase noise of an oscillator is best described in a frequency domain where the spectral density is characterised by measuring the noise "sidebands" on either side of the output signal center frequency, known as single-side-band (SSB) phase noise [32].

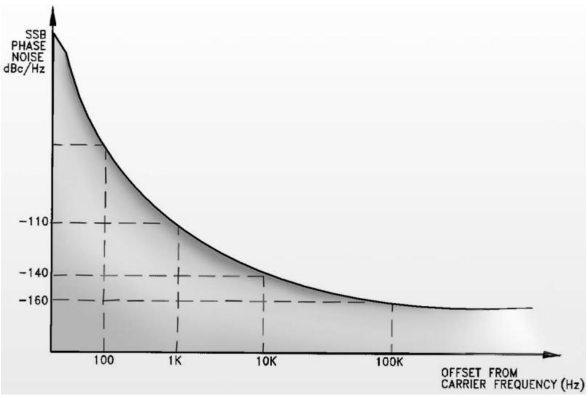

Fig. 3. Single side band phase noise representation [32].

Therefore, phase noise is defined as the ratio of power in one phase modulation sideband to the total signal power per unit bandwidth (1 Hz) at a given offset from the signal frequency [32],

$$S_c(f) = \frac{P_s}{P_{ssb}} \tag{1}$$

where P_s is the carrier power and P_{ssb} is the sideband power in 1 Hz bandwidth at an offset frequency f from the center. In logarithmic term,

$$S_c(f) \text{ in dB} = 10 \log\left(\frac{P_s}{P_{ssb}}\right) . \tag{2}$$

B. *IEEE 802.11a: Constellation Error*

Constellation error is a measure of modulation quality of data communication and has been implemented as a standard in IEEE 802.11a [1] and IEEE 802.16 [2]. References in [38]–[42] reported constellation error simulations or measurements of transmitter and wireless data communication based on these standards.

As depicted in Fig. 4, constellation error is measured under error vector magnitude (EVM) where it is defined as the differences between a measured signal (measured symbol) and its ideal error-free point (ideal symbol) in the signal constellation [43]. IEEE 802.11a specifies modulation quality in term of relative constellation error (dB) instead of EVM (rms) by the given equation,

$$\textit{Constellation Error} = 20 \log EVM . \tag{3}$$

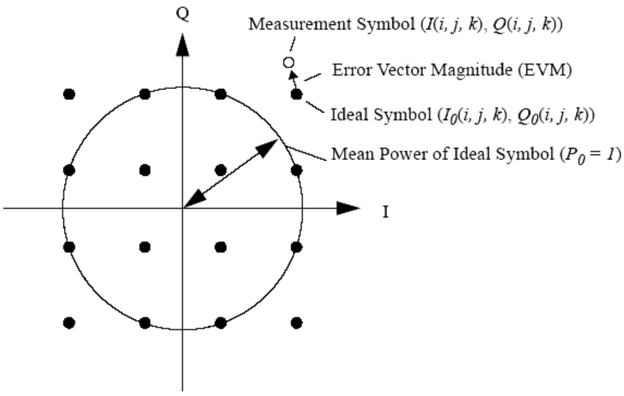

Fig. 4. Constellation error and related parameters [1].

As listed in Table I, the relative constellation error shall not exceed a data-rate dependent value where the better the signal quality, the lower the EVM value. As discussed in [43], constellation error or EVM is signal impairments due to I/Q imbalances (amplitude, phase, group delay), effects of signal compression, phase noise, spurious signals and transient effects.

TABLE I. Allowed relative constellation error and EVM equivalent.

Data rate (Mbps)	Relative constellation error (dB) [1]	EVM (% rms)
6	-5	56.2
9	-8	39.8
12	-10	31.6
18	-13	22.3
24	-16	15.8
36	-19	11.2
48	-22	7.9
54	-25	5.6

C. *IEEE 802.11a: Receiver Sensitivity*

Receiver sensitivity which is also known as minimum detectable signal (MDS) [44], is defined as a minimum signal level that a system can detect with acceptable signal-to-noise ratio [45]. In wireless data communication, sensitivity is the minimum received signal level that produces a specified bit error rate (BER) when the signal is modulated with a bit sequence of data.

Sensitivity equation is derived from noise figure equation in [44], [45] where the sensitivity of input signal level is written as,

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$$S_{i\,\min}(dBm) = -174 dBm/Hz + 10\log B + NF_{sys}(dB) + 10\log SNR_{o_{\min}} \quad (4)$$

where,

B = receiver bandwidth in Hertz (Hz)

NF_{sys} = receiver's system noise figure (dB)

$SNR_{o\ min}$ = required minimum signal to noise ratio (SNR) at receiver output (linear)

From literature, phase noise can reduce the effective of SNR in OFDM wireless system as reported in [26], [28], [29], [31], thus effecting the receiver sensitivity of RF receiver. Besides, the receiver sensitivity also depends on the type of modulation (i.e. QPSK, BPSK and16-QAM) [46] because SNR is related with bit energy to noise power spectral density, *Eb/no* of the modulation [44].

A frame-based receiver performance test called packet error rate (PER) is used in IEEE802.11a standard rather than BER as a parameter test to specify the requirement of sensitivity performance. Therefore, the PER shall be less than 10% at a Physical Sublayer Service Data Units (PSDU) length of 1000 bytes for rate-dependent input levels (minimum sensitivity) as listed in Table II [1]. In other words, the receiver sensitivity shall be equal or less than the specified input levels (minimum sensitivity) at 10% PER.

TABLE II. Allowed minimum sensitivity versus data rate [1]

Data rate (Mbps)	Modulation format	Minimum sensitivity (dBm)
6	BPSK	-82
9	BPSK	-81
12	QPSK	-79
18	QPSK	-77
24	16-QAM	-74
36	16-QAM	-70
48	64-QAM	-66
54	64-QAM	-65

III. MODELING AND SIMULATION METHOD

Analysis on the RF transceiver of wireless data communication that involves with RF distortions could not be achieved with just simply compute using simple mathematical equations. Therefore, Advanced Design System (ADS) software has been chosen due to its ability in performing an advanced simulation. In simulation, RF behavioural models and Agilent Ptolemy simulator are used to perform constellation error and receiver sensitivity based on IEEE 802.11a.

The RF behavioural models are referred to as parameter-based behavioural models. The parameter-based behavioural models typically provide superior speed relative to the circuit-level simulation where it can be classified as tops-down system models that support a tops-down system design flow. They are characterised by a small number of independent parameters such as frequency, gain, bandwidth, noise figure, phase noise and etc.

In Agilent Ptolemy simulator, the main Agilent Ptolemy controller is Data Flow controller. This controller, together with the data sources and measurement components provide the various analyses of modern communication systems such as transmit spectrum mask, constellation error, sensitivity and adjacent channel rejection.

A. RF Transmitter and Constellation Error

Depicted in Fig. 5 is the proposed RF transmitter block diagram for WLAN bridge system. From the IF input port, the IF filter attenuates any unwanted frequencies generated by output signal of IDU and it is then converted to 5.725-5.825 GHz by mixer. The first RF filter (RF1 filter) selects the desired RF band while rejecting spurious frequencies generated by the mixer including LO and IF feed-through. The RF signal is amplified to the desired level by two power amplifiers. Again, the RF signal is filtered by the second RF filter (RF2 filter) to attenuate out of band frequencies that amplified by the amplifiers and finally radiated through the antenna. All these components are modelled in ADS using parameter-based behavioural models.

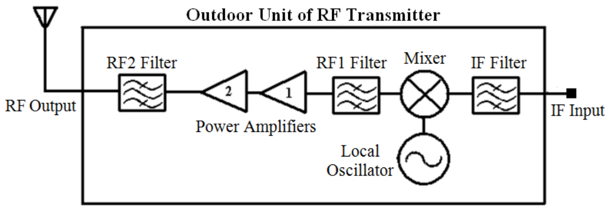

Fig. 5. RF transmitter model of WLAN bridge system.

A simulation setup of constellation error of RF transmitter is shown in Fig. 6 where the RF transmitter's constellation error is analysed by measuring the EVM value. The simulation is based on IEEE 802.11a standard, section 17.3.9.7. The EVM test component (*WLAN_IEEE80211a_RF_EVM*) used in the simulation has to sample the received signal in a manner similar to an actual receiver [1]. The transmitted frame is set to 30 frames. Take note that the constellation error test should be performed over at least 20 frames as required in the standard. Since the EVM test component only measures EVM value, the relative constellation error (dB) has to be calculated using (3).

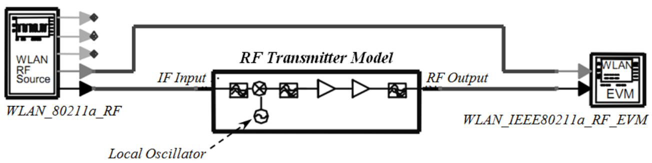

Fig. 6. Simulation setup for constellation error of RF transmitter.

B. RF Receiver and Receiver Sensitivity

Depicted in Fig. 7 is the proposed RF receiver block diagram for WLAN bridge system. From the RF input port, a band select filter (BS filter) attenuates out-of-band signals received by the antenna. Two low-noise amplifiers (LNA) boost the desired signal level while minimally adding the noise of RF signal. Image reject filter (IR filter) is used to eliminate the image frequency before down conversion. The mixer down-converts the RF signal to a lower IF by mixing the RF signal with a LO signal. Then, the channel select filter (CS filter) attenuates all unwanted frequency components generated by the mixer and any signal in the adjacent channels. To boost the IF signal to the desired level, the cascaded power amplifiers are used so that the IDU can detect the signal.

All these components are modelled in ADS using parameter-based behavioural models.

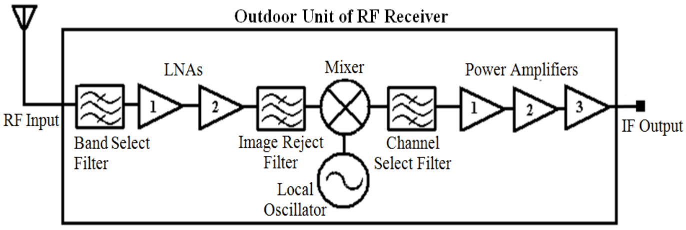

Fig. 7. RF receiver model of WLAN bridge system.

The simulation setup of receiver sensitivity of RF receiver is shown in Fig. 8 where it is performed according to IEEE 802.11 standard, section 17.3.10.1. The standard uses PER parameter as a frame-based receiver performance test. PER parameter test is a frame check sequence after the user data, by which the receiver determines if the data was corrupted. Therefore, the signal output from the RF receiver model is processed using *WLAN_80211a_RF_RxFSync* component in getting actual data and the PER is then measured by using *WLAN_80211a_BERPER* component.

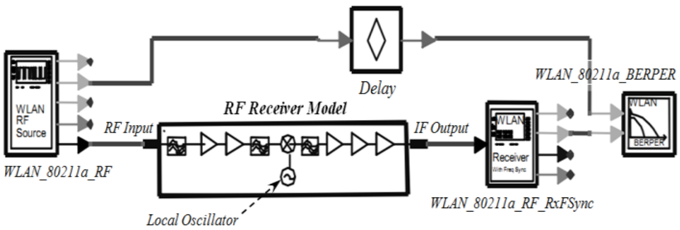

Fig. 8. Simulation setup for receiver sensitivity of RF receiver.

IV. RESULTS AND ANALYSES

A. Constellation Error of RF Transmitter due to Phase Noise

The constellation error of RF transmitter is simulated at data rate of 54 Mbps and 6 Mbps (at higher and lower data rate) with different phase noise values as listed in Table III. Phase Noise 1 is taken from manufacturer's data sheet. Phase Noise 2 and 3 is self-defined value by adding 20 dB and 40 dB respectively according to the Phase Noise 1 value.

TABLE III. List of phase noise values for simulation of constellation error of RF transmitter.

SSB Phase Noise (Offset)	Phase Noise 1 (dBc/Hz)	Phase Noise 2 (dBc/Hz)	Phase Noise 3 (dBc/Hz)
10 kHz Offset	-99	-79	-59
100 kHz Offset	-124	-104	-84
1 MHz Offset	-144	-124	-104

The simulated results of constellation error of RF transmitter are shown in Fig. 9. The graphs show the same constellation error over the input power swept with different phase noise values. For overall performance, the constellation error is degraded as the input signal in RF transmitter is increased. Phase Noise 1 and 2 have shown a good constellation error at low input signal (less than - 30 dB from -10 to -5 dBm of input signal). However, the constellation error for Phase Noise 3 is very poor although the input signal is very low. Therefore, in order to meet the IEEE 802.11a standard; for 54 Mbps data rate, the input power has to be approximately lower than -5.25 dBm (for Phase Noise 3) compared to –3 dBm (for Phase Noise 1 and 2). Thus, the constellation error is lower than –25 dB as required in the standard (see Table I). For 6 Mbps data rate, the input power can be theoretically higher than 10 dBm as plotted in Fig. 9 (b) but may limited by maximum transmit output power and transmit spectrum mask requirement due to gain compression [23].

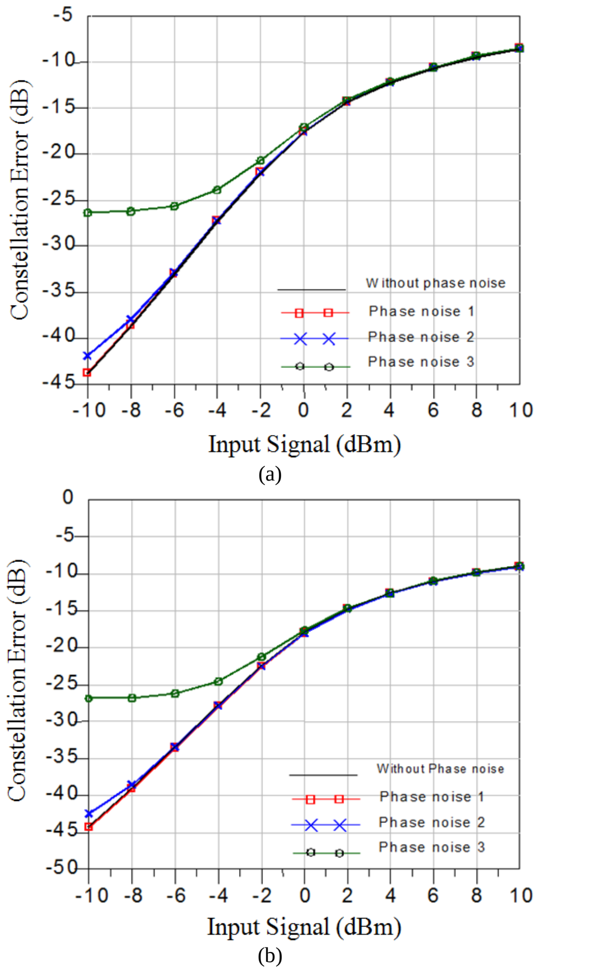

Fig. 9. Simulated results of constellation error (in dB) versus IF input signal (dBm) of RF transmitter at (a) 54 Mbps and (b) 6 Mbps.

B. Receiver Sensitivity of RF Receiver due to Phase Noise

Table IV is the phase noise values used in the simulation of receiver sensitivity performance of RF receiver. Phase Noise 1 is taken from manufacturer's data sheet. Phase Noise 2 and 3 are self-defined value by adding 40 dB and 60 dB respectively according to the Phase Noise 1 value.

TABLE IV. List of phase noise values for simulation of

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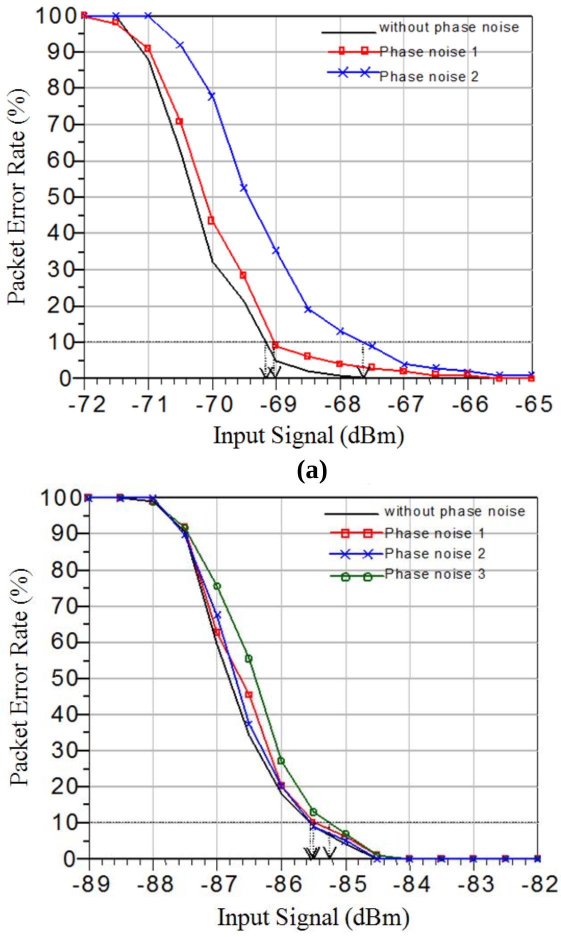
receiver sensitivity of RF receiver.

SSB Phase Noise (Offset)	Phase Noise 1 (dBc/Hz)	Phase Noise 2 (dBc/Hz)	Phase Noise 3 (dBc/Hz)
10 kHz Offset	-99	-59	-39
100 kHz Offset	-124	-84	-64
1 MHz Offset	-144	-104	-84

Depicted in Fig. 10, a high sensitivity performance can be seen at Phase Noise 1 at data rate of 54 Mbps and 6 Mbps. However, the sensitivity performance starts to degrade as the phase noise of oscillator is increased (for Phase Noise 2 and 3). However, there is a significant degradation of sensitivity performance at data rate of 54 Mbps compared with data rate of 6 Mbps. This is because the modulation format used for high data rate (54 Mbps) is more sensitive to phase noise than the lower data (6 Mbps). This is due to minimum SNR for specified data rate which is related with bit energy to noise power spectral density, *Eb/no* of the modulation format [44].



(b)

Fig. 10. Simulated results of PER (%) versus RF input signal (dBm) of RF receiver at (a) 54 Mbps and (b) 6 Mbps.

V. CONCLUSION

The simulation of phase noise distortion and its analysis in RF transceiver of IEEE 802.11a WLAN bridge system have been discussed. The RF behavioural models and Agilent Ptolemy simulator are used to perform constellation error and receiver sensitivity simulation based on IEEE 802.11a standard. The behavioural models are referred to as parameter-based behavioural models. The constellation error and receiver sensitivity of RF transceiver are simulated at data rate of 54 Mbps and 6 Mbps (at higher and lower data rate) with different phase noise values. It is found that the phase noise of oscillator should not be higher than -120 dbc/Hz at 1 MHz offset in order to optimise the receiver sensitivity and also to minimising constellation error in the RF transceiver. Therefore, these analyses can be applied in early stage of oscillator design for RF transceiver of IEEE 802.11a WLAN system.

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