Phenomenology of Signals Degraded by Phase Noise

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Abstract— **This paper presents an overview of phase noise sources and propagation along with the impact component-level phase noise has on observable characteristics of radio frequency (RF) signals. Phase noise is typically a design parameter that is specified to meet RF system performance requirements. This paper describes how differences in component-level phase noise properties can degrade transmitted signals. Phase noise is a controllable characteristic only during the component and system design stage; its attributes typically cannot be changed after implementation. This implies that there is some amount of transmitter uniqueness due to component and system architecture, which can enable differentiation of transmitters that are intended to generate nominally identical waveforms. In this paper we demonstrate that multiple transmitters producing nominally identical signals can be discriminated based on their underlying component variations, via phase noise measurements of their transmitted signals.**

I. INTRODUCTION

Phase noise non-idealities due to imperfect components or component design, such as frequency-dependent curvature, slope, absolute as well as relative levels, and spurs, result in the transmission of non-ideal signals. Components contributing to phase noise include reference oscillators, digital to analog converters (DACs), amplifiers, power supplies, and phase locked synthesizers. For example, the jitter on a clock for a DAC directly impacts signal quality, which affects communications systems' data rates. An increase in clock jitter results in lower data rates while a decrease in jitter yields higher data rates. Systems that can be affected by phase noise include, *e.g.*, cellular, Bluetooth, and WiFi systems. In analog transmitters reference oscillators and phase locked loops (PLL) impact performance. Therefore signals with identical analytic characteristics (frequency, modulation, *etc.*) produced by different hardware architectures will not be identical upon transmission. How a system is designed, including the choice of components listed above, define its over-the-air radio frequency (RF) performance.

In addition to having an impact on traditional RF system performance metrics, signals degraded by imperfect phase noise can be differentiated from each other. Transmitter discrimination has been described extensively in the literature [1]. There are several classic methods that attempt to leverage differences in transmitter hardware. These include examining the characteristics of the rising edge of a pulse [2–4] and analyzing imperfections in I/Q constellations [5]. Recently, Polak and Goeckel described how phase noise performance at the PLL component level can be used as a unique identifier [6]. Polak and Goeckel's effort does not take into account the full system architecture, and thus in this paper we will discuss the characteristics of observable signals transmitted by realistic RF systems, both with and without modulation. The discrimination method we discuss in this paper involves measurement of phase noise, which has an advantage over other methods [2–5], it requires neither *a priori* information about the signal's modulation nor high-speed digitization hardware needed to measure pulse edges.

II. TRANSMITTER ARCHITECTURE

A transmitter is commonly composed of several core elements: a reference oscillator, signal source, mixer(s), amplifier(s), and antenna(s). These elements all contribute to the overall phase noise. In certain cases, components with poor phase noise performance will dominate the overall performance, regardless of other higher-performing components or subsystems. For example, the system's reference oscillator will dictate the jitter of the transmitted waveform. The combination of the reference oscillator and the signal source can introduce spurious content and spectral power spreading beyond a waveforms design.

III. SIGNAL COMPARISON

As a baseline, we will compare three signal generators producing the same continuous wave (CW) signal. The generators are an Agilent N5172B signal generator, an Ettus Research B205mini, and an Ettus Research N210, the latter two of which are software defined radios (SDRs). Each source is configured to produce the same RF output power. We first compare CW signals, and measure their phase noise using a spectrum analyzer with a phase noise measurement option.

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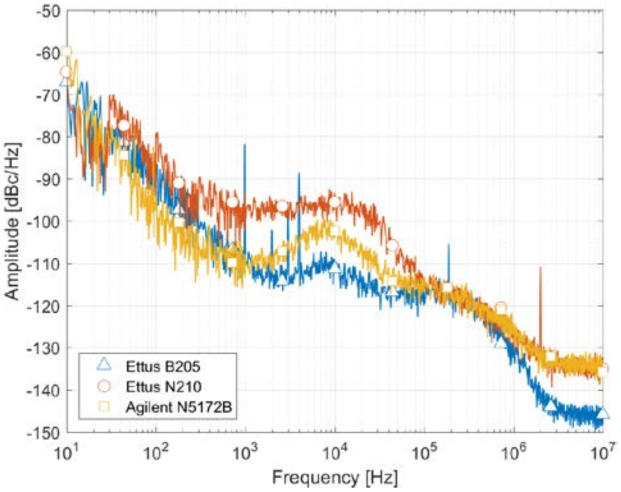

Fig. 1. Comparison of phase noise of transmitted CW signals from an Agilent N5172B, Ettus B205mini, and Ettus N210. These measurements show the unique characteristics (spurious content and noise floor amplitude and curvature) that are the result of a system's hardware configuration.

Fig. 1 shows measurements of three baseline systems. These measurements show the unique characteristics including spurious content, noise floor amplitude, and phase noise curvature. All of these observable characteristics are the result of a system's hardware configuration. The generators are all configured to produce the same waveform at the same frequency, yet the phase noise attributes close to the carrier and the spurious content are not the same. The B205mini, for example, has a spur at 200 kHz offset as opposed to the N210 that has a spur located at a 2 MHz offset. In this case, the combination of the shape and amplitude of the noise floor, in conjunction with the spurious content, is one way to distinguish between the systems.

The same features seen in Fig. 1 can be observed when transmitting a modulated waveform. To show this, a GSM base station signal was generated using the Agilent N5172B and the Ettus Research N210, as shown in Fig. 2. The shape of the noise floor between 100 kHz and 300 kHz are shown to be noticeably different.

The internal differences in the system components determine the variations in the transmitted signal. These differences include reference oscillator stability, power supply noise, phased looked loop characteristics, signal generation methodology, and amplifier characteristics. Note that the real-world GSM measurement is of a complete integrated system, including power amplifiers and other components such as filters. Using the N210 and specific software a software defined GSM base station is used to produce GSM signals at the same carrier frequency as the commercial base station. In Fig. 2, the spurs that appear at 60 Hz and 2 MHz offset reveal that this signal is not produced by the same hardware as the real GSM base station. With noise floor and other spectrum congestion, it would be challenging to see the 2 MHz spur from the N210 in a real-world open-air measurement. However, the phase noise curvature between 100 kHz and 1 MHz is a good indicator of a rogue base station.

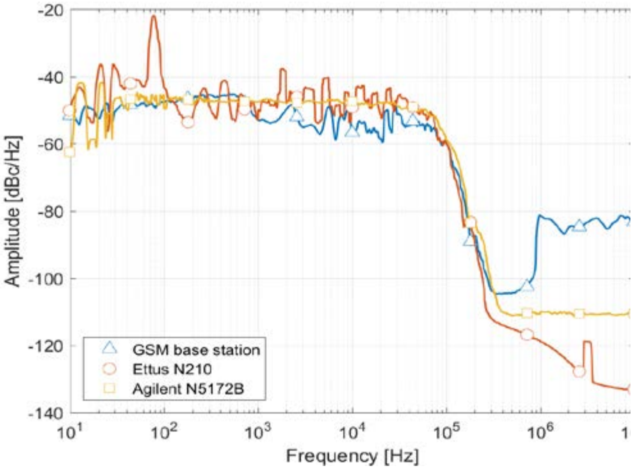

Fig 2. Phase noise measurement of real-world GSM base station, and laboratory-generated GSM waveforms from an Agilent N5172B and an Ettus Research N210 SDR. This comparison shows that phase noise characteristics of each of the signals, including the amplitude of the noise floor and spurious content, can be used to distinguish transmitters.

IV. CONCLUSION

In this paper we demonstrated the impact of fundamental hardware components' phase noise properties on a transmitted signal's phase noise. The combination of components and their particular implementation in a system can result in transmitted signals that can be differentiated by observable characteristics. In other words, there is a deterministic relationship between measurable RF signal properties and the transmitter's hardware components. The phase noise measurement technique we presented is independent of higher-layer protocols or applications. The technique is completely passive, channel-agnostic, and does not require *a priori* information about the modulation or format of the transmitted waveform; another advantage is that the presented technique does not require expensive hardware. This technique can be used to address the proliferation of inexpensive devices that are capable of impersonating, *inter alia*, cell phone base stations.

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