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Characterizing RF Wireless Receivers Performance in UVM Environment

Salwa Elqassas,Si-Vision, Cairo, Egypt (*salwa.elqassas@si-vision.com*)

Ahmed Nasr,Si-Vision, Cairo, Egypt (*ahmed.adel@si-vision.com*)

Mohammed T. Abdel-Hafez ,Si-Vision, Cairo, Egypt (*mohamed.tawfik@si-vision.com*)

Abstract*—Wireless telecommunication technologies grow rapidly, such as Wi-Fi, 2G/3G/4G cellular technologies, and various Internet of Things (IoT) networks which are all involved in many applications nowadays. Wireless communication has many advantages over its wired counterpart like mobility, easier configuration, easier setup and lower installation cost. On the other hand it has other many difficulties to handle, such as interference and noise. This led to developing various receiver architectures and modulation techniques. The main key metrics to characterize the receiver performance are the sensitivity and the interference tolerance. In this paper we show how we quantify these metrics in UVM verification environment for a complete receiver system composed of analog models and digital demodulator RTL.

Keywords*— UVM(Universal Verification Methodology);BER(Bit Error Rate);PER(Packet Error Rate);TX (Transmitter);RX (Receiver); AWGN(Additive White Gaussian Noise); ADC(Analog to Digital); DAC(Digital to Analog); OOP(Object Oriented Programming); DPI(Direct Programming Interface); LNA (Low Noise Amplifier); RF (Radio Frequency)

I. BACKGROUND

A wireless system is the system providing the service to the user using electro-magnetic waves. The range and performance of wireless communication systems are governed by signal strength and noise level (expressed as the signal-to-noise ratio).

Most of the wireless devices adjust their transmission rate according to the channel conditions. Radio signals weaken with distance. Obstructions in the signal path compound the problem further by absorbing and scattering radio signals. Radio signals can also be reflected by physical objects, resulting in multiple paths between the transmission end-points. Reflected signals arrive at the receiver out of phase with the line-of-sight signal and combine destructively. This is known as multi-path fading.

Systems operating in open or unlicensed bands have to contend with radio devices in co-channels and adjacent channels. Undesired signals with frequencies in or near the receiver's bandpass get processed by the same circuitry as desired signals. Interference can also result from undesired signals that are far outside the receiver's bandpass frequencies. If the signal levels are high enough, local oscillator harmonics can produce anomalies in the receiver [1].

Wireless communication channels are noisy due to enumerated factors above and the receiver must be able to cope with various levels of noise. In that sense the performance of a receiver is determined by its sensitivity, which in turn can be translated into metrics such as BER or PER.

Wireless system consists of three basic subsystems, RF, ADCs/DACs converters and Baseband.

RF subsystem makes possible transmission and reception of analog signals over the wireless communication channel. ADC/DACs interface between analog signal domain and digital (i.e. baseband) domain. Baseband subsystem processes data streams, preparing them for transmission or recovering them from the received signals.

As the digital communication systems become more complex every day, there is a need to use a verification methodology such as UVM [5] that is enriched with features like reusability, extensibility and co-simulation with various libraries/software components which make it efficient to verify such complex systems. One strategic importance of using UVM is the direction for it to be standardized and adopted methodology between most of IP and chip maker entities. UVM is SystemVerilog based library [6] so it makes use of its capabilities to implement unified framework for verification environment development.

In addition to these advantages that UVM can give during digital system verification in general, another feature in SystemVerilog is giving an edge for digital communication system which is DPI.

DPI make it possible to use another languages such as SystemC [7] and make use of its capabilities in the verification environment. SystemC language has the constructs to make analog calculation which can bring analog world calculations to digital verification domain while verifying Analog Mixed Signals systems.

II. SYSTEM MODELLING

Figure 1 shows the main blocks for any communication system. It is consisted of Transmitter (TX) and Receiver (RX) connected through communication channel. The digital part of TX consists of input transducer, source encoder, channel encoder and digital modulator. The input transducer is a sensor that changes energy from one form to another. Transducers can be used at the input (e.g. a microphone) or the output (e.g. a speaker) of a system.

With electronic-measuring systems, the input transducer converts a quantity to be measured (temperature, humidity, flow rate, weight) into an electrical parameter (voltage, current, resistance, capacitance) that can be processed by an electronic instrument or system. The signal produced by transducer is converted into a digital signal consisting of 1's and 0's.For this we need source encoder and also to use the less possible binary digits to represent the digital signal. In such a way this efficient representation of the source output results in little or no redundancy. The sequence of binary digits is called information sequence.

The information sequence is passed through the channel encoder. The purpose of the channel encoder is to introduce in controlled manner some redundancy in the binary information sequence that can be used at the receiver to overcome the effects of noise and interference encountered in the transmission on the signal through the channel. The binary sequence is passed to the digital modulator which in turn converts the sequence into electric signals so that we can transmit them on channel. The digital modulator maps the binary sequences into signal wave forms, for example if we represent 1 by $\sin(\omega_c t)$ and 0 by $\cos(\omega_c t)$ then we will transmit $\sin(\omega_c t)$ for 1 and $\cos(\omega_c t)$ for 0 where ω_c the angular carrier frequency. After the TX blocks there is the communication channel which is the physical medium that is used for transmitting signals from transmitter to receiver. This channel can be modeled as channel affected by white noise.

This change could be guessed statistically by using Gaussian distribution, which has zero mean in all value. This noise could destroy the signal in additive manner so this noise is called Additive White Gaussian Noise. The channel can also model blocking devices which transmit at the same time with the TX device.

After the channel there are the Rx blocks which start with the digital demodulator that processes the channel corrupted transmitted waveform and reduces the waveform to the sequence of numbers that represents estimates of the transmitted data symbols. This sequence of numbers then passed through the channel decoder which attempts to reconstruct the original information sequence based on the knowledge of the code used by the channel encoder and the redundancy contained in the received data.

The average probability of a bit error at the output of the decoder is a measure of the performance of the demodulator – decoder combination. Source decoder decodes the sequence by reversing the encoding algorithm. After decoding the received data, an approximate replica of the transmitted data is obtained.

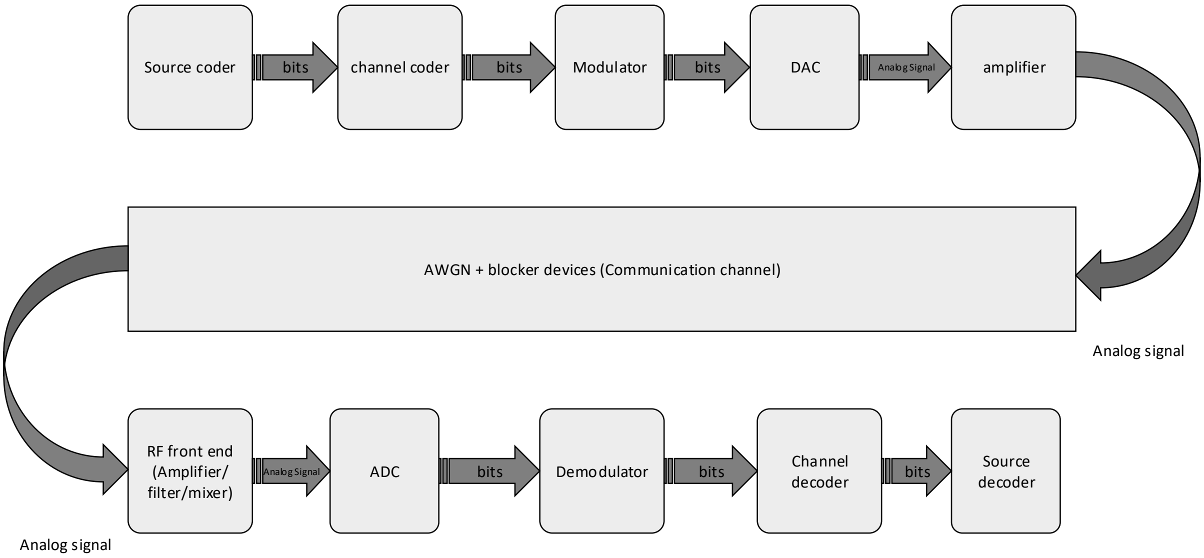

Figure 1: Basic elements of digital communication system

III. METHODOLOGY OF AWGN INSERTION IN UVM ENVIRONMENT

A. *Noise modelling*

Each wireless communication standard provides a specification on the sensitivity of its demodulator, this sensitivity is measured by PER after adding AWGN noise in its channel and the PER value differs depending on the packet length sent from the TX. This PER is measured by sending specific numbers of packets most probable this number is high in most of the standards to have a meaningful PER.

The first approach in adding AWGN noise is to add it on the input of the LNA (see Fig. 2), the place where it is already exist in the real world. But as the RF front-end operating frequency is very high, the simulation becomes very slow. So this approach was not efficient to measure the PER in different SNR values to catch the sensitivity of the demodulator. The second approach is to add the AWGN to the input of the baseband filter after the down-conversion mixer as in figure 2. As the frequency in this stage is not very high which will minimize the time of the simulation to be able to run the simulation efficiently for huge number of packets and get accurate results for PER.

The implementation of the AWGN within the digital verification environment is done using SystemC language, then imported by DPI objects generating two AWGN sources having no correlation between these sources. These two AWGN sources (*S1*, *S2*) are added on the input of the filter stage marked in red color as shown in figure (2) that precedes the demodulator stage. In order to make sure that the in-phase and quadrature phase components have no relation with each other, we have made the following up-conversion. If the input positive pin and negative pin of the differential pair of the in-phase component of the filter is current, the value that will be added to each pin is:

$$(\cos(2\pi f t) * S1) - (\sin(2\pi f t) * S2))$$

And if the input of the filter was voltage, the value that will be added to each pin of the differential pair is:

$$(\cos(2\pi f t) * S1) - (\sin(2\pi f t) * S2))/2$$

Where f is the intermediate frequency.

If the input positive pin and negative pin of the differential pair of the quadrature component of the filter is current, the value that will be added to each pin is:

$$((\sin 2\pi f t * S1) + (\cos 2\pi f t \ * S2))$$

And if the input of the filter was voltage, the value that will be added to each pin of the differential pair is:

$$((\sin 2\pi f t * S1) + (\cos 2\pi f t \ * S2))/2$$

This relation results from transformation from low pass filtering to band pass filtering. If we assume that the first AWGN source S1 is the in-phase component and the second AWGN source S2 is the quadrature-phase component so the AWGN will be (S1+jS2) and according to Hilbert transform [13]:

$$\mathrm{x}(t) = (\mathrm{S1} + \mathrm{jS2})\, e^{2j\pi f t} \qquad (1)$$

$$\mathrm{x}(t) = (\mathrm{S1} + \mathrm{jS2}) * (\cos(2\pi f t) + \mathrm{j} * \sin(2\pi f t)) \qquad (2)$$

$$\mathrm{x}(t) = (S1 * \cos(2\pi f t) - S2\ \sin(2\pi f t)) + j(S2 \cos(2\pi f t) + S1 \sin(2\pi f t)) \qquad (3)$$

Where $\mathrm{x}(t)$ is the injected up converted AWGN to the input of the baseband filter.

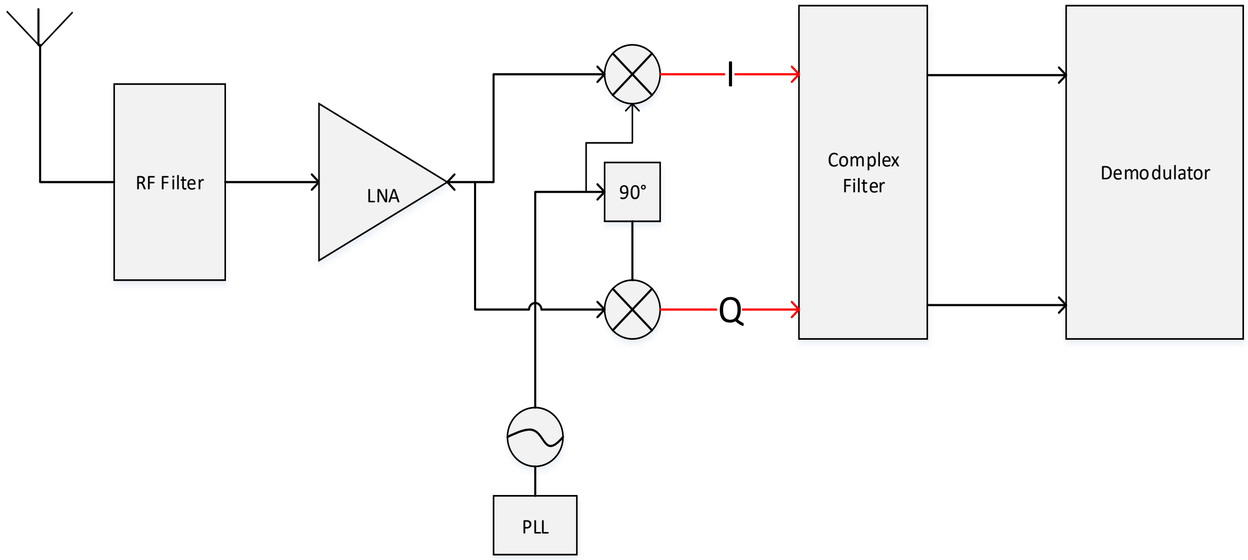

Figure 2: Receiver architecture

So the in-phase component will be:

$$S1 * \cos(2\pi f t) - S2\ \sin(2\pi f t)$$

And the quadrature-phase component is:

$$S2\cos(2\pi f t) + \ S1\sin(2\pi f t).$$

For each source of the AWGN there is a sigma which controls the power of the AWGN added to be able to change this power and sweep it on different SNR .To calculate this power there are two methods depending on the input of the filter. If the input of the filter is voltage then the output noise power is as following:

$$output\ noise\ power\ = (BW * \sigma^2)/fs$$

Where BW is the filter noise bandwidth, σ is the sigma of the AWGN sources and fs is the sampling frequency. And if the input of the filter is current then the output noise power is as following:

$output\ noise\ power = (BW * \sigma^2 * R)/fs$ where R is the transimpedance.

This relation in case of voltage input is derived from the output of the following integration:

Considering $H(f)$ is the filter transfer function and No is the Noise Power Density

$$output\ noise\ power\ = \int_{-\infty}^{\infty} No\ * |H(f)|^2 df \quad (1)$$

$$output\ noise\ power\ =\ No *\ BW \quad (2)$$

After taking into consideration that $No\ =\ \sigma^2/fs$ where σ is the sigma of the AWGN sources and fs is the sampling frequency

So the $output\ noise\ power\ = \frac{\sigma^2}{fs}\ .BW \quad (3)$

And the signal power when there is no noise added is a constant value for the same analog models ,so to calculate SNR it will be the signal power calculated from simulation divided by the noise power calculated from previous relation.

The number of packets needed for calculating BER and PER for most of the wireless standards are usually huge for the simulation environment. So in order to speed-up the simulation process we divided the packets into smaller number of packets that were simulated in number of parallel jobs and launched these jobs on a grid. After making that there was a need to add a tasks to the environment to calculate the packets were received with error and the packets which are not received and how many errored bits were received. Then a script is written to gather the data from the simulation log based and generate a final report with the BER and PER for each SNR.

B. UVM environment

Figure 3 shows the UVM verification environment that is used. An UVM agent is instantiated to inject the AWGN to the input of the filters as described in the previous section. This Agent is implemented using UVM/SystemVerilog libraries with DPI to make use of SystemC functions in calculating the inserted AWGN. The agent’s virtual interface is connected to the input of the baseband filter using bind statements.

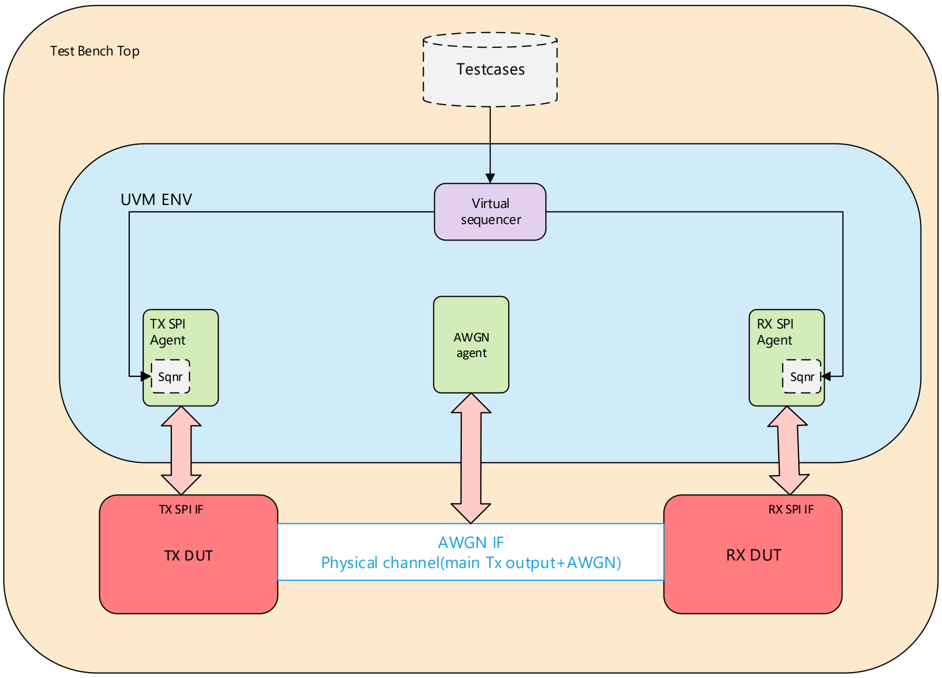

Figure 3: UVM environment used for AWGN insertion

IV. METHODOLOGY OF INTERFERERS INSERTION IN UVM ENVIRONMENT

A. *Interferer adding*

Each wireless communication standard provides a specification for the Carrier to Interferer power ratio (C/I) in which the demodulator will be able to receive at it with a reference PER value. C/I is measured for different interferer signal at different offsets either in band with possible frequency offset of the communication standard or out of band. This C/I is measured by making the Interferer sends the data along time before the main TX starts sending its own data.

The approach to add the interferer signal is injecting it on the input of the Low Noise Amplifier (LNA) of the receiver by instantiating another DUT instance that is sending this interferer signal on the frequency band we want to measure the C/I at.

B. *UVM environment*

Figure 4 shows the UVM environment that is used to simulate the TX and RX DUT instances communicating with each other , and another instance of the DUT transmits the interferer signal on the same band at which both TX and RX are communicating with different values of C/I, then calculate the output PER for each C/I.

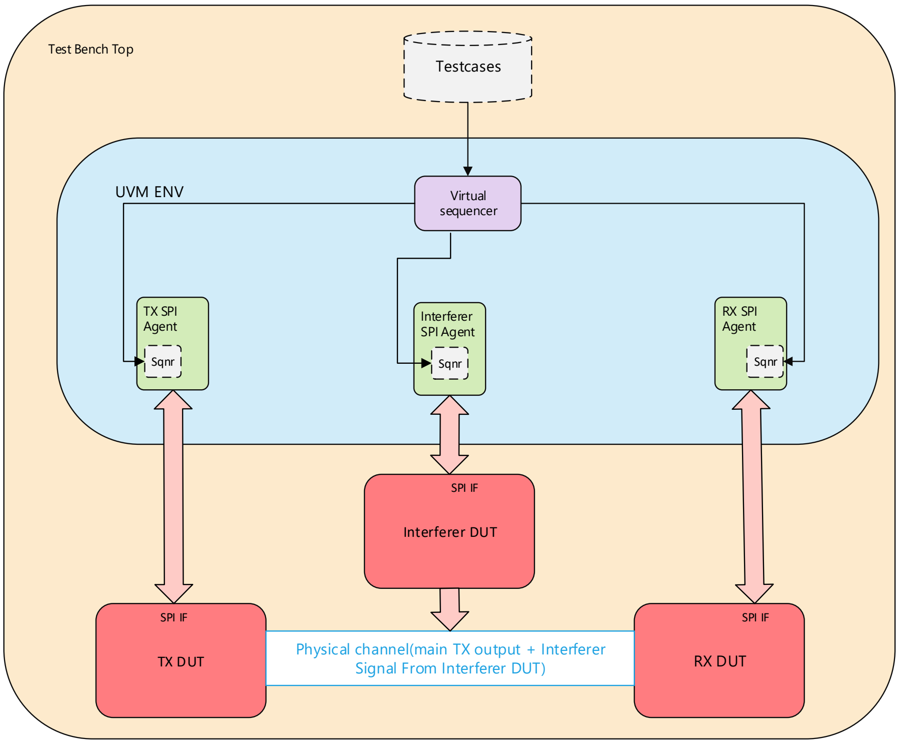

Figure 4: the UVM environment in case of Interferer existence

VI. RESULTS

To validate our results we compared the measurements in the lab with the measurements in the simulation. It’s found that for the same BER value the SNR introduced in the simulation environment is close to the one that is measured in the lab in two systems with the values shown in Table 1. This mismatch is due to the inaccuracy in some analog models due to its complexity to model it in the simulation environment.

The relation between the sensitivity and SNR is as following:

$$SNR = Sensitivity - (KTB + NF)$$

Where KTB is the thermal noise power in the receiver and NF is the noise figure.

And as the NF and KTB values are the same in both lab and analog models, so the difference between the calculated sensitivity in both environments is the same as the difference between the SNR as shown in Table 1.

Table 1 comparison between lab results and verification results

Mode	SNR_{Lab} (dB) – SNR_{Sim} (dB)	$Sensitivity_{Lab}$ (dBm) – $Sensitivity_{Sim}$ (dBm)
System 1	0.4	0.4
System 2	0.2	0.2

Achieved results prove the value of this methodology to measure the wireless receiver sensitivity and its performance against interferer signals.

VII.CONCLUSION

Wireless receiver sensitivity and interference performance are the key metrics for measuring performance of wireless communication system. It's presented in this paper a new approach to measure these two metrics in UVM verification environment that simulating the whole system with both digital part and analog part in a digital simulator. Analog part is modeled with HDL language. The existing of the whole system while measuring these metrics provide the capability to monitor any part of the system that can affect these metrics while measuring it and so it can be enhanced in an earlier stage of the design. This approach was validated by matching its measured results with lab results.

V. RELATED WORK

Presented in [8] a unified methodology for the verification of AMS systems based on SystemC and UVM. The clear separation of the DUT and its verification description has been extended to analog mixed signal ones. Thus the essential unification of analog and digital verification is made possible. It's shown that the components and the scenarios designed for the simulation-based verification can be reused during the validation of the actual hardware prototype measurements. To support the new methodology inspired by UVM, they have introduced new language constructs and generic verification components in SystemC and its AMS extensions to create AMS scenarios consisting of stimuli generation and response checking.

In [9] it's presented that the BER value of simulation and theoretical BER values did not experience a significant difference.

Another example for system level verification is discussed in [10].In wireless communication system, the needs of data rate are increasing day by day which requires more bit rate in same channel bandwidth. Multi-level digital modulation schemes are one of such techniques by which it is possible to increase the bit rate in same channel. In such modulation technique, for k-bits of information, one of the M=2k possible symbols is used to modulate a carrier signal, which results of k-times increment of bit rate in same bandwidth. From simulation results, it is seen that for same values of M the Rician channel exhibits better performance than AWGN and Rayleigh in terms of SNR with constant BER.

Another example of the verification in wireless communication systems is discussed in [11]. The Bluetooth radio system simulation is presented over realistic statistical indoor channels. Excellent agreement was obtained between simulation and experimental measurements that have been reported in the literature. The Bit Error Rate performance of the Bluetooth system was shown to be satisfactory for links, which have no Forward Error Correction. Forward Error Correction is required only in very noisy environments. In contrast, reliable communication between Bluetooth enabled devices requires Forward Error Correction and Automatic Repeat Request schemes for all hut very low noise environments.

Different application of using UVM-SystemC-AMS appeared in [12]. It's presented in it a multi-disciplinary virtual prototyping, verification, and validation framework for MEMS using SystemC AMS, UVM, and Coventor MEMS (micro-electro-mechanical systems). To this end, SystemC AMS has been enhanced to model multi-physical systems using bond graphs and to ensure the consistency of the model via compile-time dimensional analysis. MEMS+ has been enhanced with a SystemC AMS model export feature to integrate reduced-order models of the MEMS into the system-level application model. Finally, UVM-SystemC-AMS allows to realize a unified, structured, configurable, and modular test environment for MEMS design. They applied their framework to a vibration sensor system and successfully achieved its verification.

So to the best of our knowledge there were experiments to model the AWGN using Matlab on system level without modelling it in the functional simulation environment that is simulating the digital and analog parts of the design itself interacting with each other. In this paper we make use of previous works of using SystemC in UVM environments to model AGWN in UVM verification environment and characterize wireless receiver performance.

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