Keysight Technologies
NB-IoT System Modeling: Simple Doesn't Mean Easy

White Paper

Abstract

This paper presents a method for modeling and evaluating a new NB-IoT (Narrowband Internet of Things) system in a combined multi-domain simulation environment. Due to the complex analog and digital components of the communication system, accurate modeling is crucial to understanding system behavior. Realistic modeling examples are used with a new simulation method for an in-depth study of the RF transceivers, advanced modem technology and non-ideal hardware.

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Unlocking Measurement Insights

Understanding the NB-IoT Standard

Developing a new standard

Once the need for a standard has been established, a group of experts will form a technical committee to discuss and negotiate a preliminary proposal. As soon as this draft has been developed, it is dispersed to a broader group of members for comments and eventually approval. All elements of the proposal are negotiated, including scope, key definitions and content. Increasingly, simulation software is being used to study new technologies to speed the development of standards and cut hardware implementation costs.

The standardization of Narrowband-IoT, a new cellular-based narrowband technology targeted for Internet of Things, began in 2014 as a 3GPP study item. The first version was released in June 2016, as a part of Release 13 of the global 3GPP standard. This standard aims to address:

- Improved indoor coverage
- Increased support for a massive number of low-throughput devices
- Low delay sensitivity
- Low device power consumption
- Ultra-low device cost
- An optimized network architecture on top of LTE air interface and network

The NB-IoT specifications are expected to continue to evolve beyond Release 13, with support for multicasting and positioning towards the new 5G NB-IoT standards.

PHY specification

The 3GPP TS 36.211 Release 13, V13.2.0 (2016-06) provides a physical channel and modulation specification for narrowband IoT. The new device category, Cat-NB1, supports tens of kbps speed and a 200 kHz channel bandwidth. Prior to this release, the eMTC (enhanced Machine Type Communications) data rate supported a variable rate up to 1 Mbps, with a bandwidth of 1.4 MHz with Category M1 (Cat-M1).

The Narrowband Physical Uplink Shared Channel provides two subcarrier spacing options: 15 kHz and 3.75 kHz. The additional option of using 3.75 kHz provides deeper coverage to reach challenging locations, such as deep inside buildings, where there is limited signal strength. The data subcarriers are modulated using binary phase shift keying (BPSK) and quadrature phase shift keying (QPSK) with a phase rotation of π/2 and π /4 respectively. Selection of the number of subcarriers for a resource unit can be 1, 3, 6 or 12 to support both single tone and multi-tone transmission.

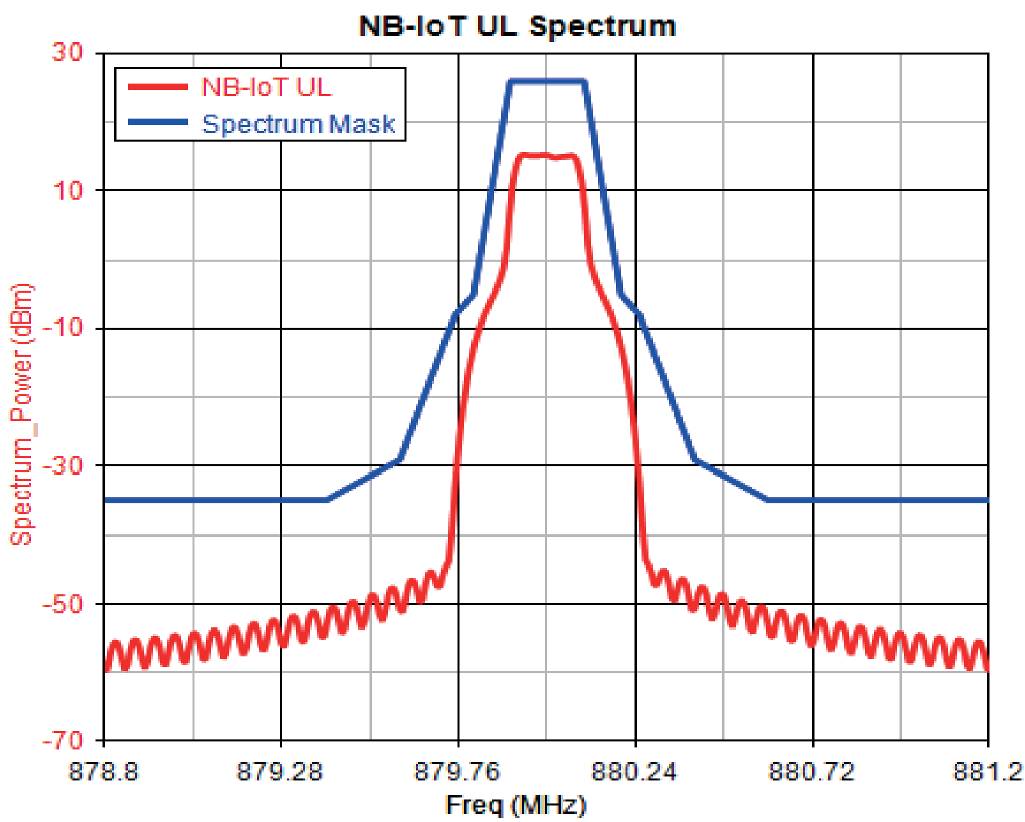

Figure 1. Example of a NB-IoT UL transmitting signal with 15 kHz subcarrier spacing, NPUSCH format; 1,12 subcarriers and a spectrum mask (blue).

The narrowband downlink physical resource block has 12 subcarriers with 15 kHz spacing, offering a 180 kHz transmission bandwidth. It only supports a QPSK modulation scheme. To facilitate low-complexity decoding for downlink transmission in devices, the use of turbo codes was abandoned in favor of a tail biting convolutional coding scheme.

Radio transmission and reception

In order to efficiently employ the spectrum resource, NB-IoT was designed with three different operation modes: stand-alone, in-band and guard-band. Stand-alone aims to replace GSM carriers with the NB-IoT carriers, while In-band operation utilizes resource blocks within a normal LTE carrier. Guard-band operation uses the LTE carrier's guard-band.

For an LTE service provider, the in-band option provides the most efficient NB-IoT deployment. For example, if there is no IoT traffic, a Physical Resource Block(PRB), available for an NB-IoT carrier, may be used instead for other purposes; as the NB-IoT is fully integrated within the existing LTE infrastructure. This allows the base station scheduler to multiplex LTE and NB-IoT traffic in the same spectrum.

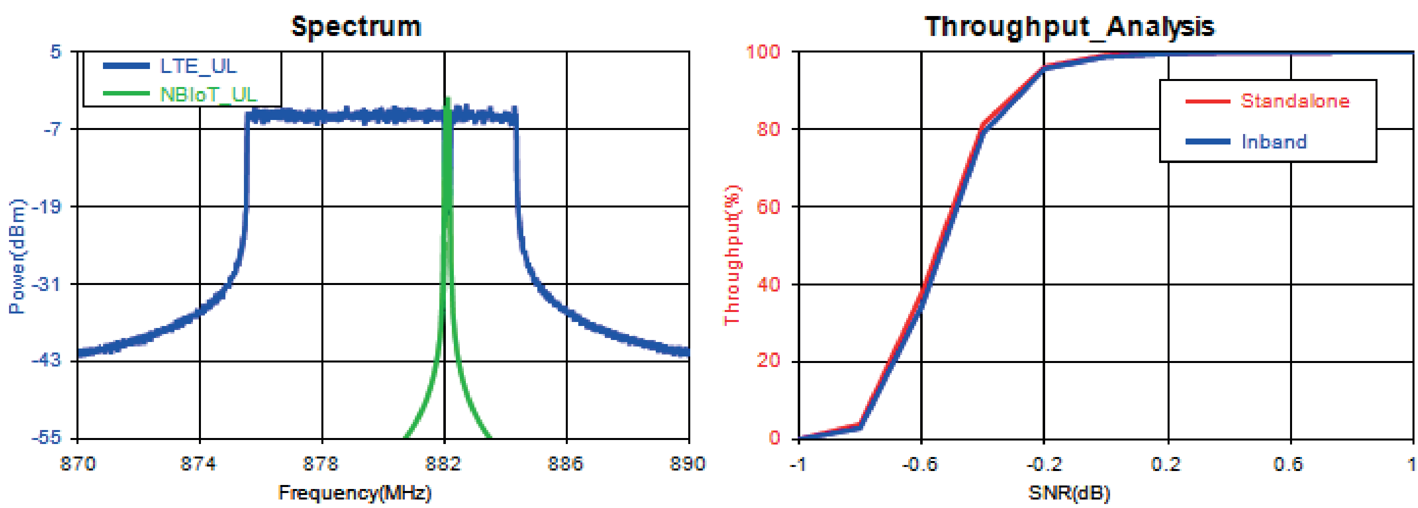

Figure 2. An **in-band operation** uplink coexistence analysis with a victim LTE (10MHz) and an aggressor NB-IoT device. Two spectrum traces (left) intentionally separated and overlapped in the same plot. Total 1000 LTE sub frames transmitted to throughput analysis.

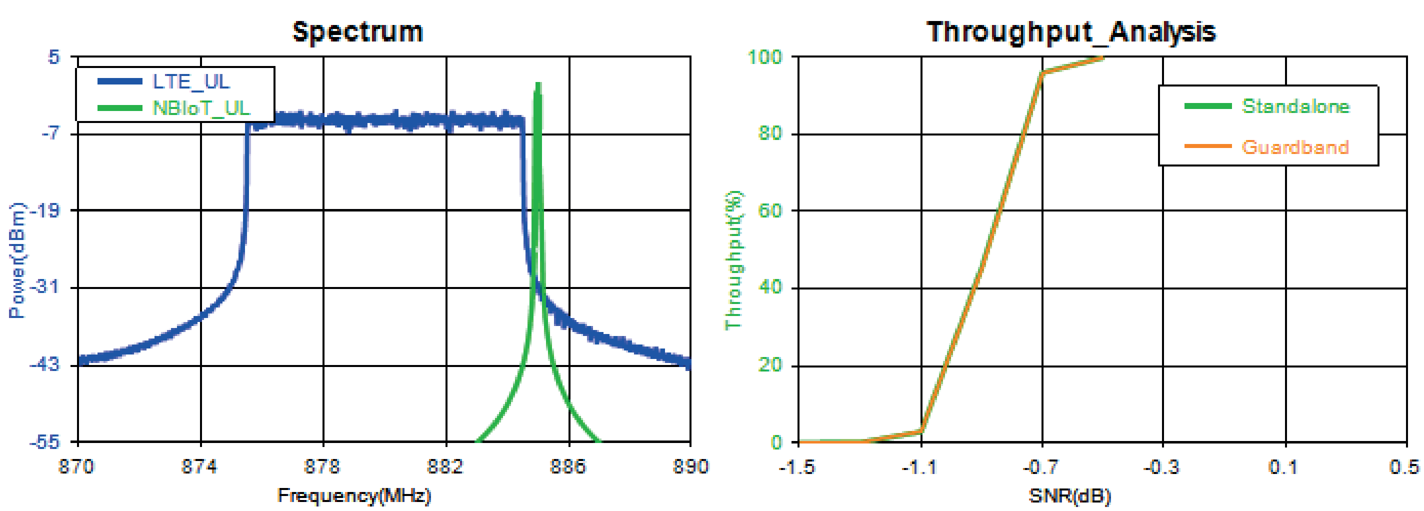

Figure 3. A **guard-band operation** uplink coexistence analysis with a victim LTE (10MHz) and an aggressor NB-IoT device. Two spectrum traces (left) intentionally separated and overlapped in the same plot. A throughput analysis (right) of a total of 1000 LTE transmitted subframes.

The simulation of NB-IoT and LTE coexistence in different operating scenarios is a popular for companies deeply engaged in 3GPP standardization. The examples shown in Figure 2 and 3 are the result of the in-band and guard-band operation modes in a scenario where the LTE system is a victim and the NB-IoT is an aggressor. Considering that the downlink subcarrier of NB-IoT is orthogonal with LTE PRB, and both are transmitting from the same base station, their coexistence was evaluated only for the uplink case. The simulation environments were established using Keysight's SystemVue communication physical layer simulation software and its LTE-A reference library.

Simulation results across companies may differ due to variations in their modeling approaches. Differences may be caused by occurences such as power leaks, modulation, and filtering. However, the basic conclusion of the 3GPP TR 36.802 V13.0.0 simulation example shown above is that the NB-IoT can coexist with LTE. The following points were observed:

- Throughput degradation is less than 5%.
- NB-IoT creates some interference on the first adjacent LTE PRB, while the interference on the other PRBs is insignificant or acceptable.
- Coexistence in the guard band performs slightly better compared to in-band operation.

Hardware Considerations

Design aspects

The NB-IoT specifications include a number of design targets: a greater coverage area, longer device battery life, and lower device cost resulting from the small, sporadic data transmissions. The reduced peak data rate requirements make it possible to employ a simple radio and baseband process in the receiver chain. With half duplex operation of the NB-IoT, the duplex filter in a common LTE type device can be replaced by a simple switch, plus a reduced number of oscillators for frequency generation. By using simplified downlink convolutional channel coding instead of Turbo code, one may facilitate a low complex baseband decoding process.

Rigorous efforts have been invested in the development process to achieve the desired low cost and low power consumption design target. The main architecture contenders so far are the zero-IF and low-IF receivers, which combine analog front-ends and digital base-band signal processing on a single chip. However, each of these architectures has some structural issues that must be resolved. For the zero-IF receiver, the desired signal is degraded by time variant DC offsets caused by LO leakage and self-mixing. For the low-IF receiver, non-ideal hardware results in amplitude and phase mismatches between the I and Q signal paths. This degrades the desired signal with leakage from the interference signal. To better understand their shortcomings, let’s review an architecture with a system model using our simulation software.

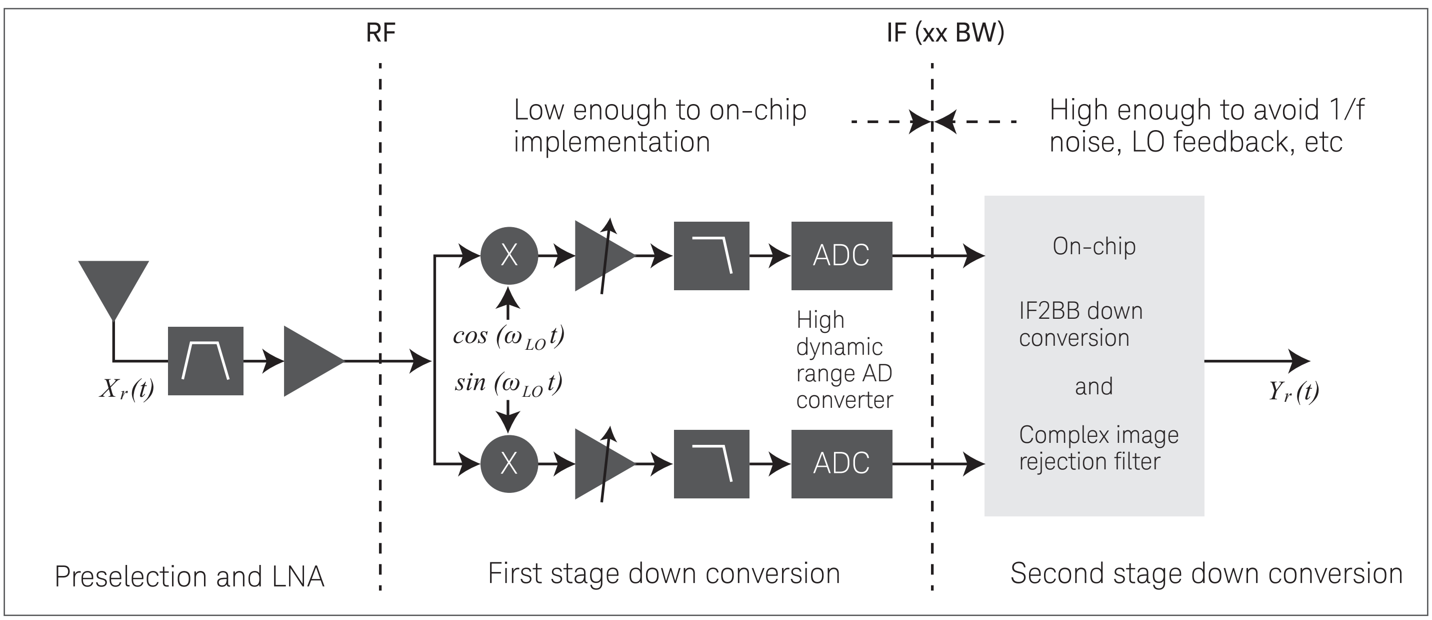

Figure 4. Low-IF receiver architecture.

In the generic Low-IF receiver architecture shown in Figure 4, the incoming radio frequency signal in the antenna is filtered by the band selection filter and amplified by a low noise amplifier. The quadrature demodulator downconverts the RF signal to the complex low-IF signal, which is represented by in-phase and quadrature signals. The intermediary frequency signals pass through low-pass filters (LPFs) and then sampled by the ADCs. After the ADC sampling and conversion, the digitized IF signal is down converted into the base band, yielding digital complex signals.

Using a moderately low intermediate frequency, this architecture can avoid DC offset and 1/f noise problems that frequently arise from zero-IF receivers. However, it also re-introduces image issues. Image cancellation can be achieved after the LNA (Figure 4), but requires narrow band filtering, thus significantly increasing the complexity and cost of the device. This image issue can be handled by using complex mixing and subsequently, the filtering technique in the low-IF receiver.

Figure 5 depicts a good example for modeling the low-IF architecture, including various effects of non-ideal hardware. Both desired and interference signals are generated and combined in a complex envelope data format, as shown on the left side of the schematic. In the middle, there is a quadrature demodulator block modeling I/Q mismatch behavior. The demodulated signal is separated into upper and lower paths, with the low pass filtered and converted to digital domain signals. On the right, the digital domain signal is processed for I/Q imbalance compensation and the error vector magnitude (EVM) is calculated and compared before and after compensation.

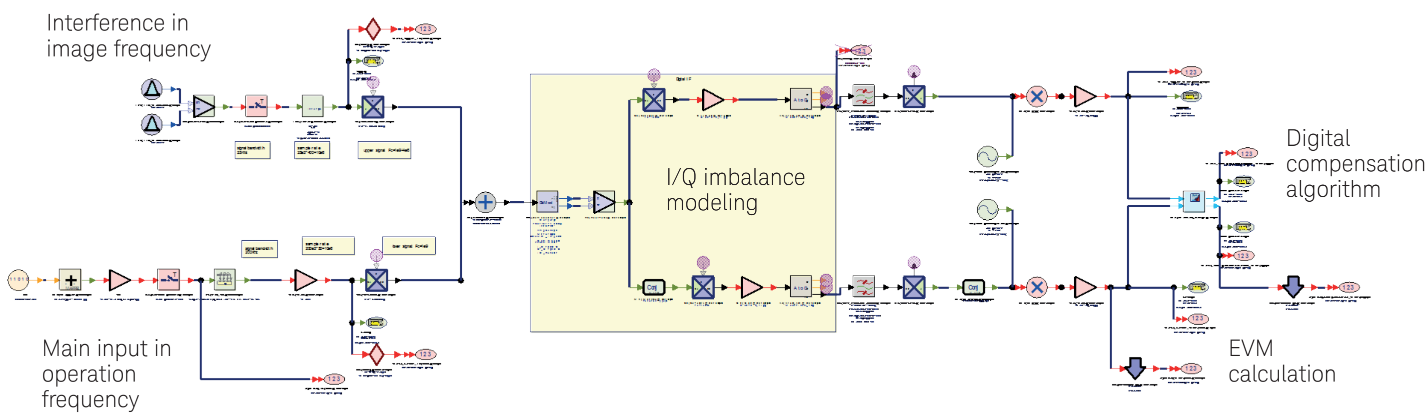

Figure 5. Simulation setup for Low-IF receiver I/Q imbalance compensation.

This type of electronic system level design (ESL) and simulation is essential for the IC designer prior to performing circuit level design for the devices. The simulation environments should support efficient methodologies for:

- Analog and digital signal processing
- The combination of time and frequency domain behavior
- Dynamic simulation with adaptive parameter updates
- Hardware imperfection modeling-such as:
  - Non-linearity (PA)
  - Group delay (filter)
  - Phase noise (oscillator)
  - Frequency offset
  - I/Q mismatch (modulator/demodulator)
  - Jitter
  - And the quantization effects of the active components

In this case study, we used Keysight's SystemVue Communication Physical Layer simulation software.

RF system-on-a-chip approach

In order to meet the challenging budget needs for NB-IoT applications, a low cost single-chip product should be developed for successful deployment of the service. The integration of the power amplifier and antenna switch simplifies routing by reducing the number of RF components in the front end. It also makes for a smaller area requirement for the printed circuit board (PCB). A PA with a low Peak-to-Average Power Ratio (PAPR) is possible with the adoption of the single tone transmission technique. This facilitates the implementation of a system level RF chip that includes a power efficient on-chip PA that may be operated near its saturation region for maximum output power.

While the choice between an integrated on-chip PA versus an external PA has tradeoffs, we will analyze the effect of a nonlinear PA's EVM in a NB-IoT uplink using an RF and baseband cross domain simulation technique. Let's consider the simulation setup shown in Figure 6. The baseband signal is generated using the SystemVue LTE-A library, which supports both single-tone and multi-tone transmission. The baseband signal is filtered by two digital filters and fed into the modulator to generate a spectrum centered at the carrier frequency. The signal is then amplified using an amplifier behavior model. The linearity of the PA can be set via the one dB compression point or P1dB. After the signal is amplified by the PA, it is demodulated by the receiver to determine the EVM. We simulate EVM versus P1dB of the PA to evaluate the nonlinear effects of the PA on the quality of the transmission signal.

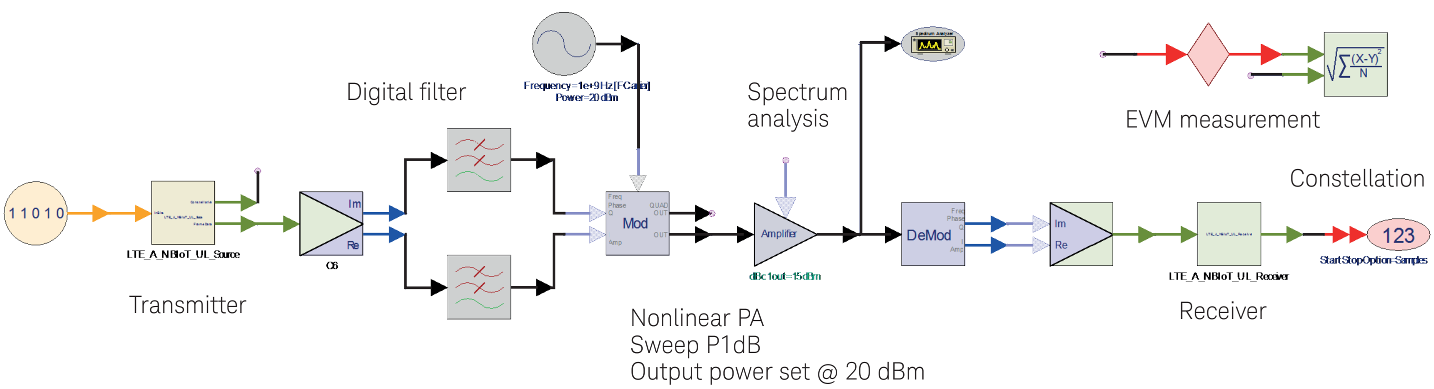

Figure 6. Simulation setup for the NB-IoT Uplink.

For a single-tone transmission, the EVM values are very small(less than 0.08% for a 3.75 kHz sub-carrier spacing case and less than 0.9% for 15 kHz case). Therefore, we can conclude that the nonlinearity of PA has little effect on the EVM for single-tone subcarrier spacing.

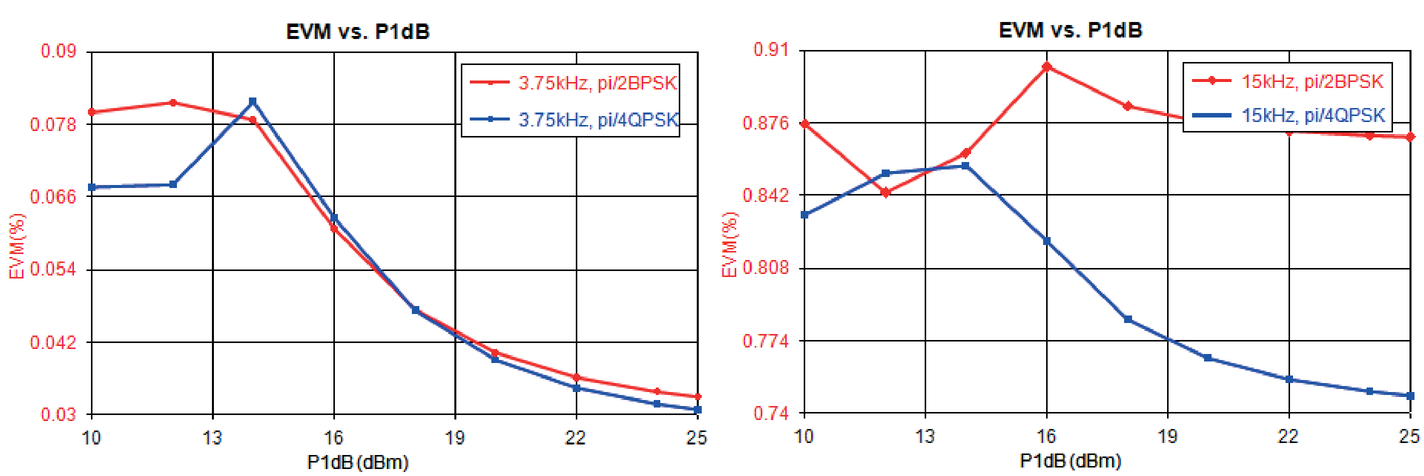

Figure 7. EVM vs. P1dB for a backed off PA with a single tone transmission with 3.75 kHz (left) and 15 kHz (right) subcarriers. We used a 200 kHz bandwidth digital filter. The PA input power was 20 dBm and gain was set to 0 dB intentionally for the simulation.

According to the simulation, PAPR is 4.8 dB, 5.7 dB and 5.6 dB for a signal with tone numbers of 3, 6 and 12, respectively. Figure 8, shows that EVM increases significantly when the P1dB of the PA decreases. Therefore, we can conclude that the nonlinearity of PA has unfavorable effects on EVM for multi-tone transmissions.

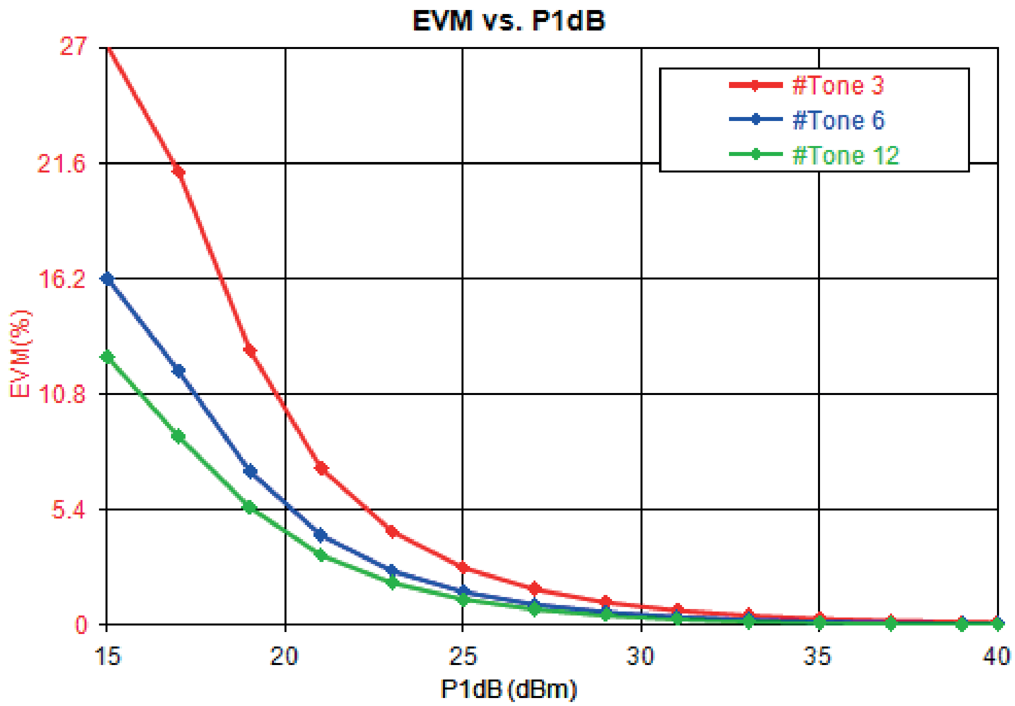

Figure 8. EVM vs. P1dB for a backed off PA with a multi-tone transmission with 15 kHz subcarriers. The digital filter is bypassed. Input power of PA was 20 dBm and gain was set to 0 dB intentionally for the simulation.

From this simulation we learned that, in case of single-tone transmission, some of the PAPR reduction circuit inside the chip can be removed which decreases chip design complexity significantly. Considering the key aspects of NB-IoT applications, devices that only support single-tone transmission combined with an on-chip nonlinear PA are much more advantageous in ultra-low power and low cost applications.

Conclusions

The first specification for NB-IoT was completed in the 3GPP release 13. Its aim was offer a low-cost device, increase the coverage area, and provide longer battery life with sustained reachability. Even though the NB-IoT applications have reduced performance requirements and use the same LTE infrastructure, developing these new products are not an easy task, but need precise design targets.

The development of a low cost device should consider different transceiver topologies, component integration methods and the performance evaluation of selected system specifications. During the pre-silicon process, engineers should test devices in a virtual environment with sophisticated simulation tools, as well as for post-silicon verification. This paper highlighted Keysight's SystemVue for the pre-silicon simulation examples and methodology for NB-IoT.

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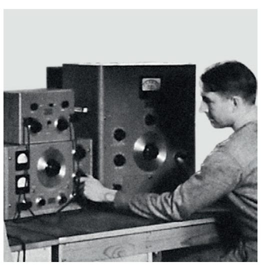

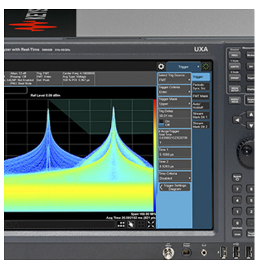

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