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Impact of non-optimal grounding of the CC2420 RFIC on a 802.15.4 Tyndall sensor wireless mote

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Abstract: *The performance of an RF output matching network is dependent on integrity of the ground connection. If this connection is compromised in anyway, additional parasitic elements may occur that can degrade performance and yield unreliable results. Traditionally, designers measure Constant Wave (CW) power to determine that the RF chain is performing optimally, the device is properly matched and by implication grounded. It is shown that there are situations where modulation quality can be compromised due to poor grounding that is not apparent using CW power measurements alone. The consequence of this is reduced throughput, range and reliability. Measurements are presented on a Tyndall Mote using a CC2420 RFIC to demonstrate how poor solder contact between the ground contacts and the ground layer of the PCB can lead to the degradation of modulated performance. Detailed evaluation that required the development of a new measurement definition for 802.15.4 and analysis is presented to show how waveform quality is affected while the modulated output power remains within acceptable limits.*

Keywords: CC2420, Wireless Sensors, Grounding, 802.15.4, Error Vector Magnitude (EVM),

1. INTRODUCTION

Range, throughput and power consumption are important issues in 802.15.4 [1] Wireless Sensor Networks. While the focus is often on increased power output (at the expense of dc power) and sensitivity to address these issues, little attention is given to waveform quality. Poor waveform quality often measured in terms of EVM can lead to increased packet errors, transmission retries and therefore reduced range and throughput leading to increased power consumption. One important factor in relation to this is proper grounding of the RF devices. This paper describes an investigation into these effects that was triggered when poor throughput was reported from the system integrators.

2. MEASUREMENT TECHNIQUE

As the modulated signal passes through a non-linear function it becomes distorted. This distortion leads to a degradation in the signal quality and ultimately affects the throughput of the system due to an increase in Bit Error Rate (BER) leads to re-transmissions. The relationship between linearity, Adjacent Channel Power Ratio (ACPR) and EVM is well established [2, 3]. Of particular interest in this study was the effect of non-optimal grounding of the radio transceiver on output spectrum and EVM. Test methods were devised to measure these parameters based on the existing 802.15.4 standard.

2.1. Adjacent Channel Power Ratio

The incumbent radio standard defines some parameters for signal quality and ACPR. These are defined to ensure that the wireless system will

perform to specification taking into account regulatory as well as inter and intra system issues. For ACPR it was found that the definition in 802.15.4 was not sensitive enough for this investigation. Therefore, a new measurement was defined to enable the analysis of more detailed linearity effects.

A typical 802.15.4 spectra such as in Figure 1, exhibits well defined troughs that are defined by the channel filter characteristic. From experimentation, it was shown that the spectral degradation of these troughs is very sensitive to non-linearity as shown in Figure 2. Two ACPR points at the first and second trough were established leading to the settings summarised in Table 1 below.

Description	Parameter
Tx Channel Integration Bandwidth	2 MHz
ACPR 1 Integration Bandwidth Spacing	100kHz 1.5MHz
ACPR 2 Integration Bandwidth Spacing	100kHz 2.5MHz
Resolution Bandwidth	30kHz
Video Bandwidth	300kHz

Tab. 1. ACPR spectrum analyser settings.

Figures 1 and 2 below, show examples of good and bad 802.15.4 spectra that were measured on a spectrum analyser. Figure 1 shows an 802.15.4 signal with good linearity typified by the well defined troughs in the spectral shape..
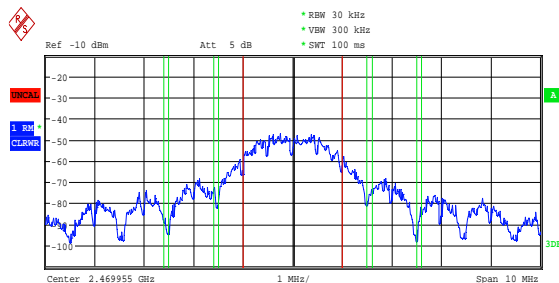

Fig. 1. Typical 802.15.4 spectrum

Figure 2 shows a plot of an 802.15.4 signal that has been subjected to non-linear distortion. It is clear that the spectrum has spread out and the troughs have been filled due to spectral re-growth. Measuring the spectrum in these troughs yields a highly sensitive measurement with respect to linearity.

Fig. 2. Typical 802.15.4 distorted spectrum

2.2. Error Vector Magnitude Measurement

The EVM measurement was conducted as defined in the 802.15.4 standard using a half sine measurement filter. EVM can be used as a measure of SNR, BER and packet loss as it is a measurement of the deviation of the baseband vector from the ideal constellation location. The instantaneous error vector is a function of all noise sources (deterministic and random) and if averaged over time, the noise power and thus SNR can be calculated therefore establishing a correlation with EVM. By applying some analysis, it is also possible to distinguish between random and deterministic noise sources [6]. National Instruments published a graph which is reproduced in Figure 3 below for 802.15.4 and demonstrates the effect of EVM on BER. [3].
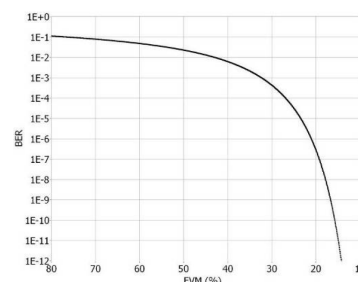

Fig. 3. EVM verse's BER for 802.15.4

EVM is a function of a number of noise sources, both random and deterministic. Assuming that the radio design has taken these into account, at high output powers non-linear distortion can dominate. Even though 802.15.4 selected a modulation and pulse shaping filter to yield a constant envelope, poor

waveform quality and ACP degradation can be seen if the transfer function through the transmitter is non-linear.

3. DEVICE CHARACTERISATION

To investigate the reported throughput issues a representative sample of Tyndall Motes [5] were tested. Figures 4 and 5 below, summarises a subsection of these results at 2.44GHz and 2.47GHz respectively.

3.1. EVM

Six out of ten devices measured an EVM of greater than 20%. Simple link budget tests on these motes confirmed that for a given RSSI value the number of received good packet interrupts at the CC2420 was considerably less for the high EVM motes compared to the low EVM motes. It was also observed that the difference in performance between the high and low EVM motes was considerably less at 2.47GHz compared to 2.44GHz. This is in agreement with the EVM measured values in the figures below.
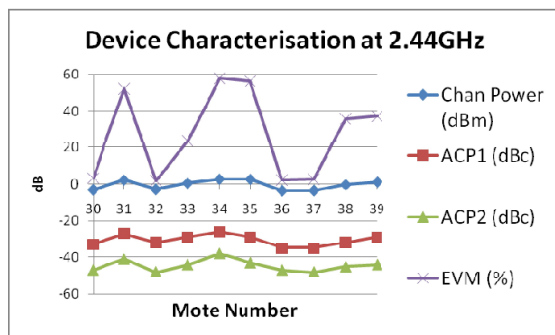

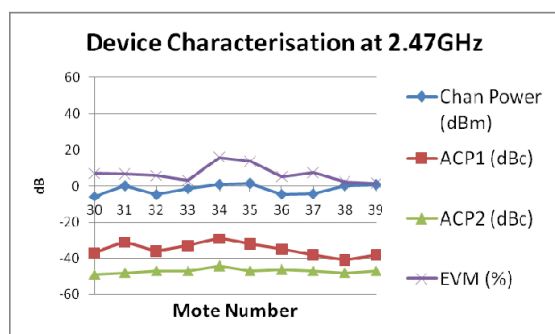**Fig. 4**. Device characterization at 2.44GHz

Fig. 5. Device characterization at 2.47GHz

Closer inspection of the measurements above shows that there is a correlation between EVM, output power and ACPR. As the ACPR is degrading with EVM, this is an indication that the degradation in EVM was due to a linearity issue rather than a random noise source. Further experiments were conducted to test this theory. Figure 6 below plots the output power back off against EVM. One can see that the EVM improves considerably once the power is backed off relative to the maximum output power. This was presented as further indication that the root cause of the problem was linearity rather than noise. If the ACP was dominated by noise (e.g thermal or phase) there would not be such an improvement at back off.
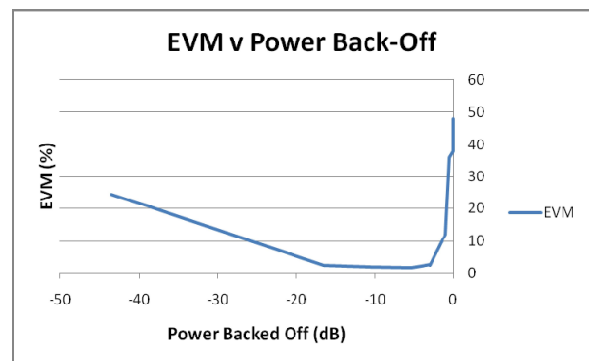

Fig. 6. EVM v Power Back-Off

Note that at the lowest power levels, below approximately-20dBm, the EVM gracefully degrades. This is due to the noise floor of the device beginning to dominate the EVM.

Having established a correlation with linearity, the next step was to establish the source. There are a number of possibilities that all tend to be associated with the output matching and balun circuitry. The investigation focused on the output matching and balun as this is the only part of the design external to the RFIC that could influence the linearity.

3.2. S11 (Output Return Loss)

To determine whether the device is seeing the correct load impedances, a simple S11 measurement was taken using a vector network analyser and a 1 port calibration. Figure 7 below shows a typical plot of a high EVM mote (Mote 35) against a low EVM mote (Mote 30). To simplify the measurement, the RFIC is switched to receive mode. As the matching

circuit and balun is common to both modes, it was concluded that this would give an indication of a correlation of matching impedance between the two types of motes. It is observed that the return loss is lower for the high EVM mote and that the return loss is better at higher frequencies due to the tuning being centered high in frequency. From these results it was ascertained that all the high EVM motes were tuned to a higher frequency compared with low EVM Motes.

Even though this is a measure of Rx S11, this may indicate the path to ground is different between each mote type and that the impedance difference must be somewhere common to both Tx and Rx possibly the connection from the transceiver ground puck to the PCB.
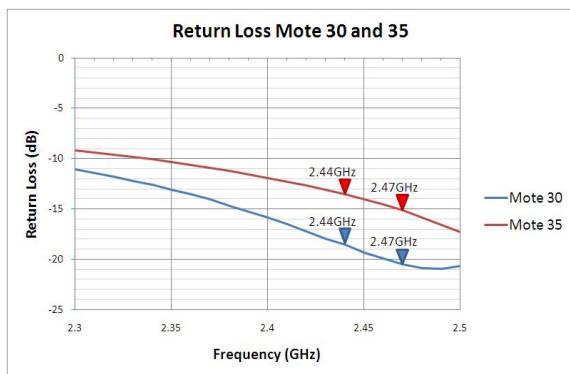

Fig. 7. S11 for motes 30 and 35

3.3. Measurement Summary

Table 2 below summarises the correlation between the measurements at 2.44GHz. The values presented are the average of the 6 Low throughput motes and the average of the 4 expected throughput motes. Note how the output power alone does not reveal the throughput issue.

Description	Good Mote	Poor Mote
Throughput	Expected	Low
EVM	3%	43%
ACP1	-33dBc	-28dBc
ACP2	-48dBc	-43dBc
Tuning Centre	2.54 GHz	2.58 GHz
Output Power	0dBm ± 3dB	0dBm ± 3dB

Tab. 2. Measurement overview.

The test results show correlation between EVM, ACP, high tuning centering and power back off with poor throughput. This combination seems to indicate a linearity, that, given the constant envelope nature of the waveform was rather surprising.

The CC2420 [7] is highly integrated and the only external components that affect the RF are the matching and balun circuit. After confirming that the matching and balun circuit was identical between the high and low throughput motes it was concluded that the only other possible variable was the grounding of the RFIC to the PCB ground.

5. GROUNDING

A number of high and low EVM parts were removed from the PCB and an example of each type is shown in figures 8 and 9 below.
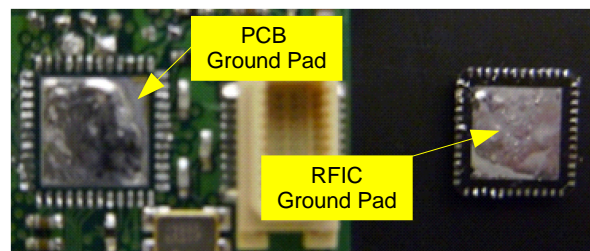

Fig. 8. Low EVM PCB and RFIC

From Figure 8 above although the solder connection is not perfect it has good solder wetting over 70% of its surface area. Also noteworthy was that it took over 5 minutes to remove the part from the board, using a fine nozzle heat gun.
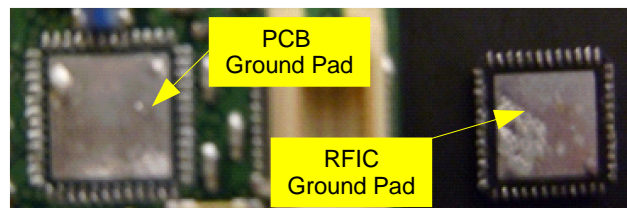

Fig. 9. High EVM PCB and RFIC

This part in Figure 9 above clearly had a very poor ground connection. It also only took a few seconds to remove from the PCB. Neither the ground puck on the IC or the ground plane on the PCB exhibited a shiny solder finish normally associated with a good joint. In this case the joint was obviously dry with ~5%

exhibiting a good contact to ground. This would mean that the device connection to ground would differ significantly from its model used in design. Thus we see a shift in frequency of the S11 response from optimum and poor linearity.

6. CONCLUSION

It has been demonstrated that measurement of output power alone may not be enough to determine whether the RF design is performing to specification. It is possible to get both expected output power and degraded performance at the same time.

It was found that the ACPR measurement technique was not sensitive enough to detect changes in linearity. So a new ACPR measurement was defined that was more sensitive to linearity degradation.

It is proposed that the quality of the grounding of the CC2420 to the ground pad on the PCB has significant impact on the performance. Although the data seems to indicate that this relates to linearity there are two parameters that contradict this view.

i. 802.15.4 uses a constant envelope modulation scheme that is designed to be very robust to non-linear transfer functions.

ii. There is a clear correlation between the tuning centering and a high and low throughput mote, EVM and ACP. It should be noted that the return loss is measured in receive mode and so is only indicative of an impedance shift in Tx mode. Currently it is only assumed that in Tx mode the change in impedance is large enough to cause such a degradation.

It is also shown that monitoring of output power alone may not reveal grounding issues with the RFIC and that the EVM can be as poor 50% in these circumstance thus degrading BER and throughput. Evaluation of the linearity and waveform quality parameters should be undertaken to ensure the integrity of the build. Further analysis and measurements are required to confirm the hypothesis presented in this paper.

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