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Antenna Switch Linearity Requirements for GSM/WCDMA Mobile Phone Front-Ends

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Abstract — The design of the RF front-end part in modern cellular phones is becoming increasingly complex and demanding due to increasing number of frequency bands and modes that the phone needs to operate in. One of the main components of the RF Front-End is the antenna switch that selects which TX/RX path is connected to the antenna. This paper considers the linearity requirements for antenna switches used to switch full-duplex WCDMA signals. The most demanding linearity requirement for WCDMA is shown to be the RX out-of-band blocking performance. The out-of-band blocking problem is shown to be caused by the three dominating intermodulation distortion (IMD) mechanisms of the switch. The switch IMD performance is also shown to depend on the relative phase shift between switch and duplexer. Two measurement setups are shown with measured results.

I. INTRODUCTION

Traditionally the front-end for dual mode mobile phone with several GSM bands but only one WCDMA band has been implemented as an evolution of the GSM-only architecture. A standard GSM antenna switch is used to route the GSM band to the GSM antenna, while the WCDMA duplexer is directly connected to a separate dedicated WCDMA antenna. This approach has mainly been chosen to avoid having to use an antenna switch for the WCDMA path. However, if only one antenna feedpoint or more than one WCDMA band are required this approach is no longer feasible. As the current trend is towards for example 4xGSM (850, 900, 1800, 1900) and 3xWCDMA (850, 1900, 2100) front-ends, it becomes necessary to route some or all WCDMA bands through a specially designed multi-mode antenna switch. An example of the traditional and switched RF front-ends for quad-band GSM and a single WCDMA band is shown in Fig. 1.

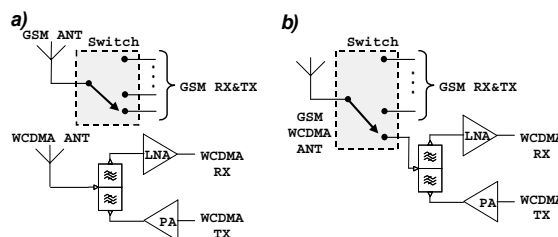


Fig. 1. Example of traditional (a) and switched WCDMA (b) multi-mode multi-band mobile phone RF front-end.

II. SWITCH LINEARITY FOR WCDMA

The simulated input and output spectrums for a nonlinear switch processing a WCDMA (3.84 Mcps QPSK) modulated +20 dBm/3.84 MHz TX signal and a -15 dBm CW signal are shown in Fig. 2, assuming $G = 0$ dB and $IIP_3 = +55$ dBm. Only the 3rd order distortion products in the vicinity of the fundamentals are considered. Third order nonlinearity characterized by the IIP_3 causes spectral regrowth of the modulated signals to approximately three times the original bandwidth [1]. The spectral regrowth due to the switch (-87 dBc/3.84 MHz) is not a problem, as the spectral regrowth caused by the PA is much more significant (typ. -40 dBc/3.84 MHz). Two intermodulation products adjacent to the fundamentals are formed, with one having the same bandwidth as the modulated signal and the other twice the bandwidth. The crossmodulation product is formed around the CW signal due to the transfer of the amplitude modulation of the WCDMA signal onto the CW signal [2], with approximately the same level and bandwidth as the intermodulation product on the opposite side of the modulated signal.

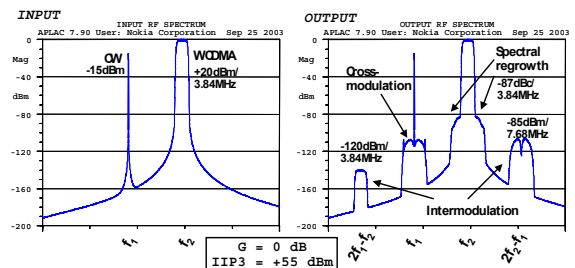


Fig. 2. Simulated input and output spectrums of a nonlinear switch simultaneously processing CW and WCDMA signals.

In addition to having low insertion loss and high isolation, the antenna switch also needs to have very high linearity for full-duplex WCDMA signals. The WCDMA system specification [3] has many linearity related specifications, such as in-band and narrow-band blocking, TX intermodulation, TX spurious emissions and TX ACLR.

The most demanding antenna switch linearity requirement for the WCDMA system is the out-of-band blocking test case, assuming that the switch power handling capability is sufficiently high for WCDMA use.

The blocking characteristic is a measure of the mobile phone receiver's ability to receive a wanted signal in the presence of an unwanted interferer without causing a degradation of the performance of the receiver. The nonlinearity of the antenna switch that is simultaneously processing the TX, RX and interferer signals may cause distortion products on the RX channel that may significantly increase the RX noise level. Based on 3GPP TS 25.101 (V6.4.0) specification, a blocking signal is injected to the antenna port of the mobile phone. If the antenna switch linearity is not high enough, the intermodulation distortion products of the blocker signal (-15 dBm) and the own TX (+20 dBm) signal may fall on the own RX band. For WCDMA system these mixing products appear as additional noise components on the RX signal and thus degrade the sensitivity of the receiver. An example (assuming switch $IIP_3 = +55$ dBm) of the out-of-band blocking case for 3rd order intermodulation is shown in Fig. 3.

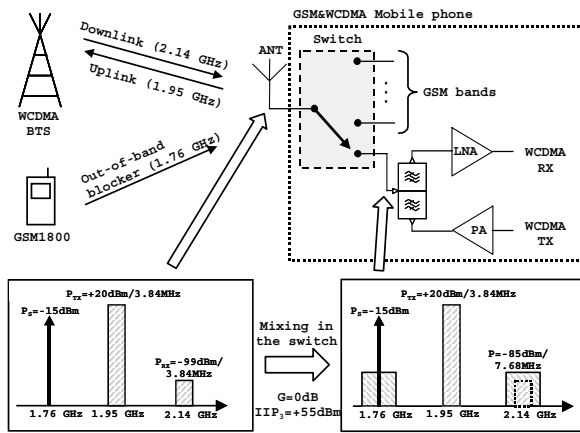


Fig. 3. Example of the out-of-band blocking problem for WCDMA 2100 due to the 3rd order non-linearity of the antenna switch.

The maximum level of intermodulation distortion on the RX band depends on the WCDMA receiver noise properties and generally needs to be below the noise floor of the system. In the specification the blocking characteristics are measured 3 dB above the reference sensitivity level. As the sum of two equal level uncorrelated noise sources is 3dB above the levels of individual sources, the maximum allowable level of the noise due to the blocker may be the same as the receiver noise floor. The sensitivity of typical WCDMA2100 mobile phone RX is often quoted as -99 dBm/3.84MHz. With 6 dB margin, the maximum IMD on the RX band for WCDMA would be -105 dBm when measured with +20 dBm TX and -15 dBm blocker signals.

Based on these signal levels the theoretical switch linearity requirements in 50Ω environment may be derived as shown in Equations (1) and (2).

$$IIP_3 = \frac{P_S + 2P_{TX} - P_{IMD}}{2} = \frac{-15 + 2 \cdot 20 - (-105)}{2} = +65 \text{ dBm} \quad (1)$$

$$IIP_2 = P_S + P_{TX} - P_{IMD} = -15 + 20 - (-105) = +110 \text{ dBm} \quad (2)$$

Antenna switches exhibit three dominating out-of-band blocking mechanisms due to 2nd and 3rd order intermodulation distortion (IMD). These mechanisms are $f_{TX} + f_S = f_{RX}$ (IMD₂ low), $2f_{TX} - f_S = f_{RX}$ (IMD₃) and $f_S - f_{TX} = f_{RX}$ (IMD₂ high), where f_{TX} is the TX frequency, f_{RX} the RX frequency and f_S the blocker frequency. The mechanisms and center frequencies for different bands are summarized in Fig 4. It should be noted that many blocker frequencies overlap with current mobile phone systems, for example Blocker 2 for WCDMA2100 is on the TX band of the GSM1800 system. Thus it is possible that a mobile phone transmitting at GSM1800 may cause a dropped call on a nearby WCDMA2100 phone if the antenna switch linearity is not high enough.

Band	TX f_{TX}	RX f_{RX}	IMD2 low $f_{TX} + f_S = f_{RX}$	IMD3 $2f_{TX} - f_S = f_{RX}$	IMD2 high $f_S - f_{TX} = f_{RX}$
			Blocker 1	Blocker 2	Blocker 3
850	836.5	881.5	45	791.5	1718
1900	1880	1960	80	1800	3840
2100	1950	2140	190	1760	4090

Fig. 4. Dominating out-of-band blocking mechanisms and center frequencies for the 850, 1900 and 2100 WCDMA bands.

III. CW IMD MEASUREMENT SETUP

Intermodulation distortion measurements at very low signal levels are challenging, as the resulting distortion products are very close to or even below the noise floor of the measurement system. The TX signal may be WCDMA modulated or a CW signal. The use of correct modulation would give the most correct results, but a wide bandwidth (15 MHz) is required on the spectrum analyzer to monitor the distortion products on the RX band, bringing the noise-like distortion products too close to the spectrum analyzer noise floor, which negatively impacts the reliability and repeatability of the measurements. The TX and blocker power levels could be scaled up to elevate the level of the distortion product well above the noise floor, but this should be avoided as the switch may be near compression at high TX power levels. On the other hand, the use of CW signals for both blocker and TX signal will make it possible to use a very narrow (30 kHz) bandwidth on the spectrum analyzer, in which case the noise floor of the analyzer is no longer a problem.

The IMD measurement setup utilizing CW signals and resembling the mobile phone environment for WCDMA2100 is shown in Fig. 5. The TX signal is fed through a duplexer to the switch. The adjustable phase shifter simulates the unknown phase relationship between the duplexer and switch. Most of the TX power is absorbed in the attenuator connected to the ANT port of the switch. The blocker signal is fed through the attenuator to the switch. When measuring the IMD₂ products the isolator should be replaced with either a low-pass or high-pass filter, to prevent TX signal leakage to the blocker signal generator. The resulting mixing product due to switch nonlinearity is observed on the spectrum analyzer connected to the RX port of the duplexer. The measurement duplexer should preferably be either a ceramic or a cavity filter because e.g. FBAR duplexers exhibit also non-linear behavior, which can mask the effect of switch distortion.

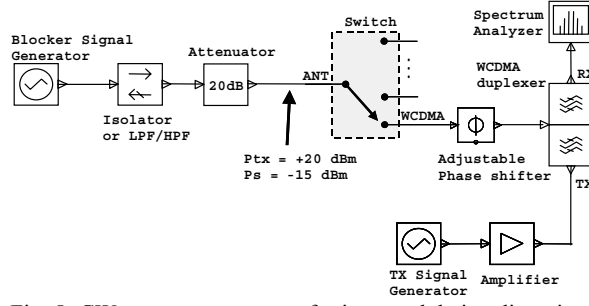


Fig. 5. CW measurement setup for intermodulation distortion for WCDMA antenna switches.

The relative phase angle between the duplexer and the switch has a great impact on the measured IM distortion level as shown in Fig. 6 for IMD_3 for three switch samples. The difference between minimum and maximum IMD may be as high as 20 dB. The duplexer antenna port appears ideally matched (50Ω) on the duplexer passbands (RX & TX), but highly reflective (input impedance on the edges of the Smith chart) on the stopbands. The IMD blocker frequencies are on the stopband of the duplexer and consequently see a highly reflective load, while the TX signal sees a matched load. Thus it is important to sweep the relative phase between the duplexer and switch to find the worst case IMD.

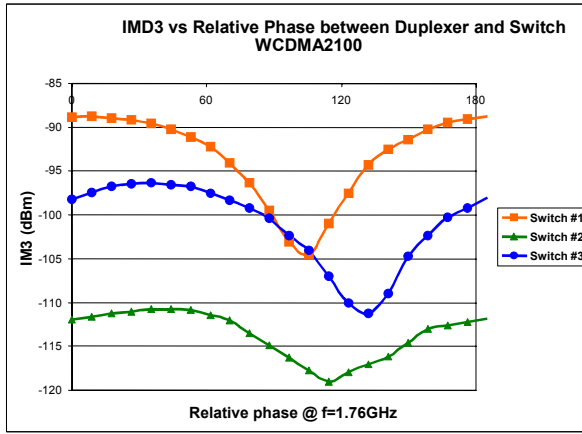


Fig. 6. Measured switch IMD_3 versus relative phase shift between switch and duplexer for WCDMA2100.

It is also possible to measure the switch IMD by using a standard IIP setup, where all signals are terminated to 50Ω . If the duplexer reflection coefficient (ρ) on the blocker frequency is known, the IMD as a function of the relative phase angle (ϕ) may be calculated as shown in Equation (3). It is assumed that the IMD behaviour is dominated by voltage dependent nonlinearity, as seems to be the case with most semiconductor switches.

$$IMD_{\phi} = IMD_{50\Omega} + 10\log(1 + \rho^2 - 2\rho\cos(2\phi)) \quad (3)$$

In the worst case the duplexer reflection coefficient has a value of $\rho=1$ and the phase angle is $\phi = \pi/2$, which leads to approximately 6 dB increase in the worst-case IMD versus the IMD measured with the standard 50Ω IIP setup. Thus the IMD specification must be 6 dB tougher when measured with standard IIP setup. As the measurement setup shown in Fig. 5 is a swept phase

setup, it is suited best for R&D purposes, while the faster standard IIP setup may be used in production testing. The IMD measured with swept phase setup and IMD measured with standard IIP setup with calculated phase behaviour based on Equation (3) are shown in Fig 7. The results show good agreement between measured and calculated IMD.

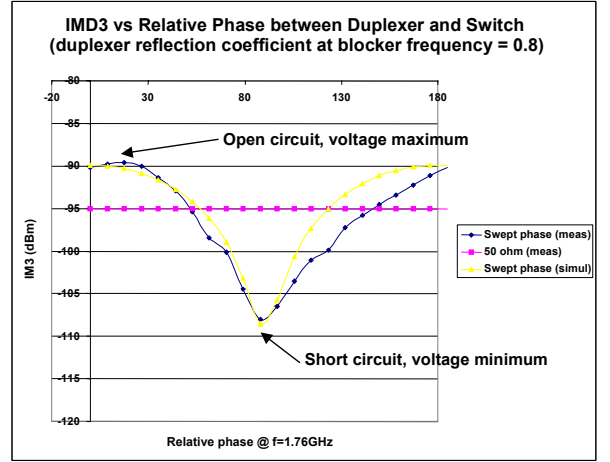


Fig. 7. Measured and simulated IMD vs. relative phase shift between switch and duplexer.

The nonlinearity mechanisms of the switch may be either voltage (e.g. nonlinear shunt capacitance) or current (e.g. nonlinear series resistance) dependent or a combination of the two. In typical semiconductor switches the dominating nonlinearity mechanism is the nonlinear capacitance of the OFF paths. As the phase angle of the mismatch affects the relationship between current and voltage swings, the IMD changes as a function of the phase angle. For voltage dependent nonlinearity it is advantageous to minimize the peak voltage across the nonlinear capacitance. This may be achieved by ensuring that the switch sees a short circuit (minimum voltage, maximum current) on the blocker signal frequencies. Similarly, the distortion products for current dependent nonlinearity may be minimized by adjusting the phase so that the switch sees an open circuit at the blocker frequencies.

IV. PHONE IMD MEASUREMENT SETUP

An alternative way to measure the switch IMD performance is to use a WCDMA test station and a conventional WCDMA mobile phone. In this test an interfering signal is fed from the tester to the phone while the tester is in a phone call with the mobile phone. This setup is shown in Fig. 8 for the WCDMA2100 band.

The out-of-band blocking test case in the spurious search mode may be used to determine the highest level of the interfering (blocking) signal until Bit Error Rate increases past a certain limit due to the desensitization of the own RX. This desensitization is caused by additional wide-band noise on the RX band caused by the mixing of the interferer and the own WCDMA modulated TX signal in the non-linear parts of the switch. In the out-of-band blocking test the TX signal level at the antenna port

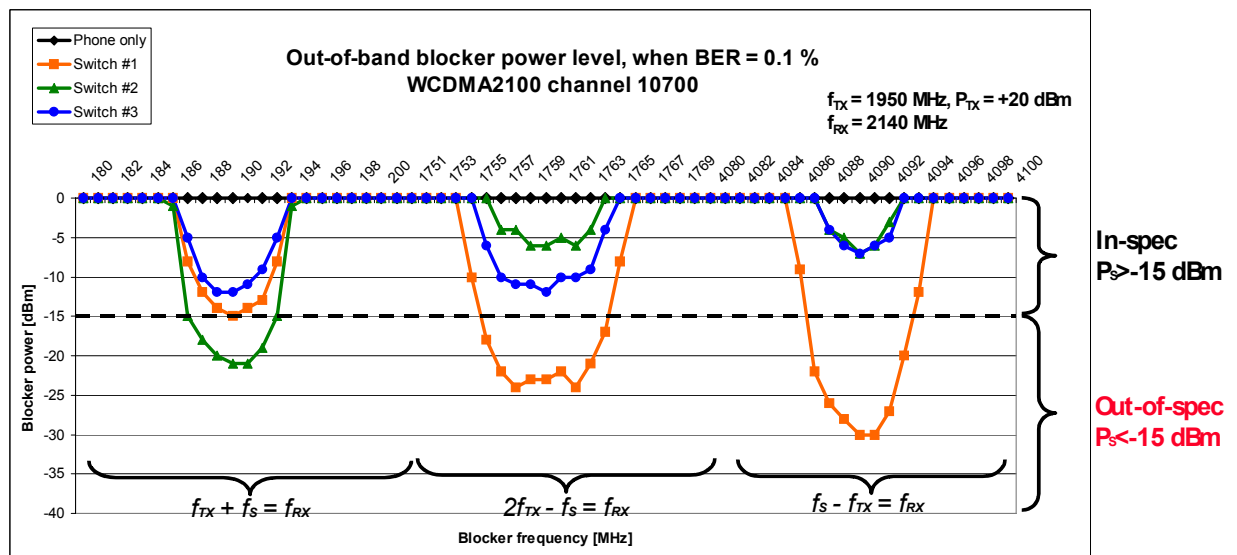


Fig. 9. Measured blocker tolerance as a function of blocker frequency.

is +20 dBm and the blocker level (-44.0 dBm) is swept at 1 MHz stepping (0-2.025, 2.255-12.750 GHz). The blocker level at each frequency point is increased in 1 dB steps until the BER exceeds 0.1%, which is the system standard specification. For all spurious mechanisms the level must be at or above -15 dBm. Also in this case the relative phase shift between the switch and the mobile phone duplexer affects the results.

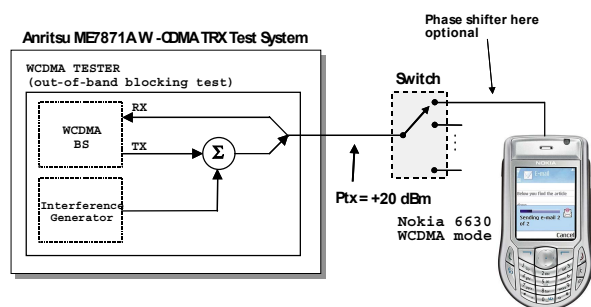


Fig. 8. Switch IMD measurement setup with actual mobile phone for WCDMA2100 band.

Several switch samples were measured with the phone measurement setup. Fig. 9 shows the blocker power level, which causes the BER to exceed 0.1% as a function of the blocker frequency. The mobile phone measured without the switch (phone antenna port connected directly to duplexer) shows constant 0 dBm blocker tolerance, while the addition of the switch degrades the blocker tolerance significantly. Of the 3 measured switch samples only Switch #3 is fully spec compliant regarding all three non-linearity mechanisms, while the two other samples fail in some of the cases.

VI. CONCLUSION

Antenna switching for WCDMA signals will be a crucial part of the future multi-mode multi-band mobile phone RF front-ends. The WCDMA system standard places high linearity requirements for the RF front-end. The antenna switch is especially problematic, as it is

usually connected directly to the antenna port without any filtering. Thus the antenna switch must be linear enough to withstand any outside signals that may be injected to the antenna port without degradation of the mobile phone receiver performance.

We have shown a way to characterize the linearity for antenna switches for WCDMA full-duplex antenna switching. The linearity requirements were derived directly from the system standard specification. Usually only the degradation of TX ACP and harmonics are considered for WCDMA switching, but we have shown that the most demanding linearity requirement is actually the out-of-band blocking specification, which requires extremely low levels of intermodulation distortion. The three dominating IMD mechanisms were shown. Several methods to measure the switch IMD were discussed and measurement results shown. The relative phase shift between the switch and the duplexer on the blocker frequency was shown to have a significant effect on the measured IMD levels.

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