Design and Performance Trade-offs in Parallelized RF SDR Architecture

Sami Kiminki, Ville Saari
Vesa Hirvisalo, Jussi Ryynänen
Aalto University

Aarno Pärssinen, Antti Immonen,
Tommi Zetterman
Nokia Research Center

Abstract—**Multi-radio platforms are an interesting design concept. Executing multiple radios on a shared platform presents opportunities not only for component re-use but also for better data throughputs, as non-active radios may dynamically yield resources for active ones. This enhances the conventional SDR approach in the RF domain and provides means to optimize resources in platform level when taking the link and network traffic issues into account. Such flexibility can provide opportunities for future cognitive radios when operating in heterogeneous networks. The downside is increased RF interference, and thus, receiver desensitization. We review the design and performance trade-offs of multi-radio platforms focusing on LTE and WLAN and present motivation for simple co-operation mechanisms to their future revisions.**

I. INTRODUCTION

The multi-standard and multi-service requirements of novel radio communication systems create challenges for the RF designs due to concurrent operation. This increases the need for interference mitigation and/or real-time scheduling [1]. These challenges are amplified by the numerous issues of backward compatibility requirements. The related standards are not featureless. They target specific and distinct applications designed for specific ranges, while having also other design properties. This results in numerous conflicts in design decisions.

Software-defined radio systems (SDR) base their designs on using dedicated hardware (HW) components for digital and RF signal processing. The operation is controlled by software. General-purpose digital processing technology cannot be used yet due to the related power consumption and especially tunability requirements. Considering the RF part, the SDR-approach calls for reconfigurable designs where the practical physical limitations are taken into account.

Our research addresses the problem how the required reconfigurability should be organized. We have studied an approach that utilizes several parallel RF components that can be reconfigured to support the RF requirements of a number of different radio standards. That is feasible using current ASIC technologies [2] but has severe constrains related to RF filtering. The conventional RF SDR approach can be enhanced to coarse-grain reconfigurable radio architecture [3]. In this paper, we present a case study to show that by using such an approach we have the potential to run several radios concurrently with limited RF resources. In our experiment, we ran two radios (LTE and WLAN) on shared radio resources and compared that against a non-shared approach. According to our experiment, shared approach yields competitive data throughputs with significantly improved HW resource utilization.

The presented scenario in this paper reflects shorter term opportunity when data offloading between cellular and WLAN networks is becoming attractive to optimize radio resource use between wide and local area networks. However, the same principles can be applied to more sophisticated, heterogeneous future networks in which different variants of cognitive radios are sharing resources and preferably co-operating [4].

II. CONCURRENCY IN RF HARDWARE PLATFORMS

Concurrent operation means that at least two radio signals (either received or transmitted in one device) are active simultaneously. This can happen in one radio that utilizes frequency domain duplexing (FDD) or in a multi-radio that runs multiple protocols. Concurrent operation of multiple protocols in a multi-radio is reasonable only if they do not interfere each other too much. Each system has its own RF specifications. Current RF platforms are designed to meet those specifications with some margin.

Concurrent operation causes interference between systems. The effect of interference must be mitigated in order to prevent RF performance degradation. There are different techniques to facilitate concurrency. In general, RF platform must contain multiple parallel RX and TX chains to support full parallelism in the time domain. In the simplest form, this means dedicated signal paths for all continuous transmissions and overlapping radio packages (including possible multiplication due to MIMO schemes) with some margin for transitions in activity. In the frequency domain, improved filtering compared to stand-alone system requirements is needed to minimize mutual coupling. In the time domain, scheduling of protocol operations, such that transmission and reception do not happen simultaneously with another radio transmission or reception, eliminates inter-system interference. However, scheduling is not always possible, and thus, both frequency and time domain schemes should be exploited.

In this work, RF performance of the radio HW is measured in terms of a signal-to-noise-ratio (SNR) and/or signal-to-noise-and-distortion-ratio (SNDR). The emphasis is on the receiver as a victim. Noise figure (NF) is the practical measure for sensitivity degradation in RF receivers. In addition to the

NF that describes the performance of the receiver within the desired RX channel, the receiver has to be capable of suppressing interfering out-of-channel signals to avoid violating the current bit error rate (BER) requirement. Considering the concurrent operation of the WLAN and LTE systems, the main two mechanisms that cause performance degradation are broadband TX noise that may mask receive channels and additive internal noise in the receiver as a result of blocking [5]. In Sec. IV-B we consider the requirements to the RF filtering to reduce the effect of these mechanisms.

In a single-chip multi-radio platform, one of the key technology limitations is related to the RF filters. Current technology does not enable implementation of tunable RF filters with adequate performance. Especially, when the number of systems and frequency bands is increasing, this poses a major obstacle. An introduction to the development of electronically tunable microwave filters is given, for example, in [6]. Although switching between certain cellular FDD bands requires only less than 10% of tuning range, competitive or even sufficient performance, compared to conventional highly selective RF filters, cannot easily be achieved. Hence, in most cases, we need to assume full parallelism in RF filters. In short range and TDD based radio systems, the requirements are significantly relaxed. Moreover, tunable antennas [7] and improved RF ASIC linearity performance [8] may provide some relaxation to RF filter requirements in the future.

III. SCHEDULING RF

When protocols require less than full-time access to the RF hardware, a shared platform presents opportunities for executing multiple protocols. By hardware resource scheduling, a non-active protocol can borrow its resources to other protocols to boost their performance. The extra resources could be used to temporarily provide additional RF pipes for spatial diversity or multi-band aggregation.

In LTE FDD networks, user equipment (UE) normally receives every subframe and decodes the physical downlink control channel (PDCCH) to find out its resource allocations and grants. When continuous allocation is not needed, eNodeB can take discontinuous reception (DRX) in use, which allows the UE to power off parts of its circuitry to save energy. Also, it allows the RF platform of the UE to allocate receiver hardware to other radios while the LTE radio is not receiving.

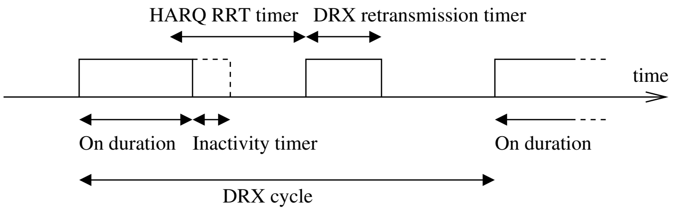

Fig. 1. LTE DRX parameters

The DRX mechanism and the most important DRX parameters are illustrated in Fig. 1. (A more extensive description can be found in, *e.g.*, [9].) The *DRX cycle* specifies the repetition period of *on duration* followed by a possible inactivity period. The *inactivity timer* specifies the number of consecutive subframes the UE has to receive after the reception of PDCCH indicating an initial UL or DL data transmission. The *HARQ RRT timer* specifies the minimum amount of subframes before DL hybrid automatic repeat request (HARQ) transmission, and the *DRX retransmission timer* sets the maximum number of consecutive subframes the UE receives for retransmission. The last two parameters enable the UE to sleep during the idle subframes while there are HARQ processes ongoing during the idle period. In LTE networks the DRX mode is initiated and the parameter values are defined by eNodeB.

In WLAN, the mobile stations initiate all data transfers when associated to an access point in power save mode [10], and thus, a mobile station is able to shape both incoming and outgoing data transfers. This capability can be used to accommodate to given RF resources, provided that some minimum level of resource access is guaranteed to maintain the association.

The DRX mechanism of LTE and the flexibility of radio scheduling in WLAN enable balancing the performance in the time domain. Further, rank indicator (RI) in LTE and modulation and coding scheme (MCS) feedback in WLAN can be used to dynamically switch between SISO and MIMO modes, enabling spatial dimension for further resource balancing. RI and MCS feedbacks also provide means to fallback to dedicated resources mode (by forcing SISO for both radios) when the performance balancing enablers are unavailable. Therefore, even if the current cellular and WLAN protocols are not designed to run on shared hardware with varying resource availability, there is radio scheduling flexibility for protocol co-existence.

In principle, with truly shared resources, it is possible to support more concurrently active protocols than there are available RF pipes, conceptually similar to CPU resource sharing by active tasks in computers. However, this is difficult to achieve in practice with current protocols in every situation because of inflexible timing requirements of many RX/TX operations.

IV. CASE STUDY: LTE VS. WLAN

In this section, we study the execution of LTE and WLAN 802.11n on a shared mobile platform with two or three RX and two TX general purpose SDR pipes. First, we study the opportunities gained from running the protocols on a shared resources by performance estimation simulation (Sec. IV-A). We then briefly analyze the bottlenecks in RF design, namely the desensitization as a result of TX-to-RX crosstalk, and its implications for the RF filtering requirements (Sec. IV-B).

A. Multi-radio Performance Opportunity

We study LTE and WLAN on the following platform variants:

1) two transmitter chains and two receiver chains
2) two transmitter chains and three receiver chains

The platform design is illustrated in Fig. 2.

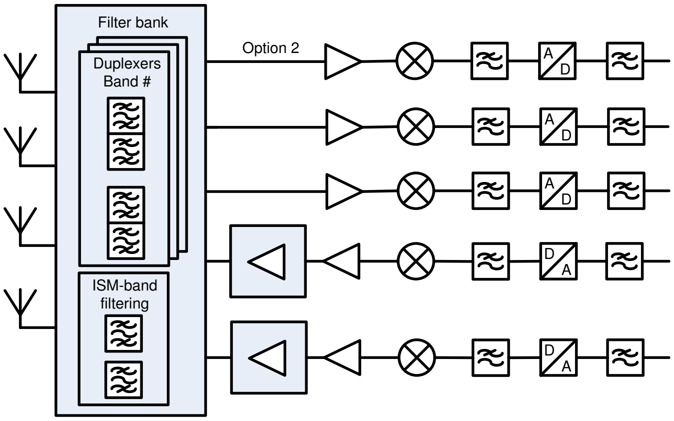

Fig. 2. Receiver architecture used in the case study. The RX and TX pipes are shared between LTE and WLAN.

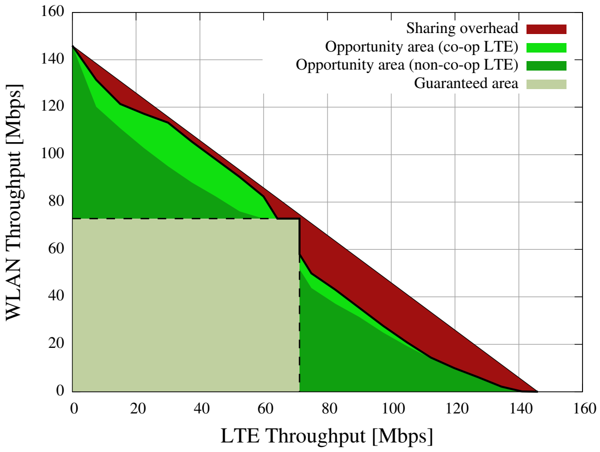

Fig. 3. Link-speed performance estimation for running LTE category 3 terminal and WLAN 802.11n with 20 MHz band on a shared platform with 2xRX + 2xTX RF pipes. The guaranteed area represents dedicated design performance and the opportunity area the extended performance opportunity by shared design.

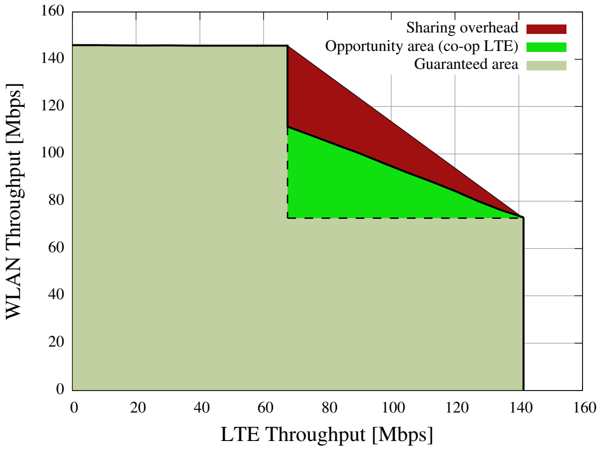

Fig. 4. Link-speed (RX) performance estimation for running LTE category 3 terminal and WLAN 802.11n with 20 MHz band on a shared platform with 3xRX + 2xTX RF pipes. With three RX pipes, one of the radios can always get MIMO mode for receiving data.

Hardware resource scheduling can be exploited in both platform variants. This means that the chains can be dynamically shared between LTE and WLAN. If a conventional platform with dedicated chains were used, the number of required RX chains would have been four.

We analyze the multi-radio performance opportunity by a simulation experiment. The protocols for the experiment are LTE and WLAN 802.11n. For LTE we assume that the communication is predictable to at least 3 ms in advance, *i.e.*, at subframe N, we know whether we need to receive and/or transmit at subframe $N + 3$. The subframe duration is 1 ms in LTE and the 3-subframe advance is motivated by that the data at Nth subframe is acknowledged at subframe $N+4$. We model two LTE variants. In the co-operative variant, all received transmissions are known perfectly beforehand. In the non-co-operative variant, DRX inactivity timer is non-zero causing extra allocation overhead in reception.

The WLAN station is assumed to be associated to an access point in power save mode [10]. In this mode, the station is expected to listen to beacons, and based on traffic indicator in the beacon frames, fetch possibly awaiting buffered incoming data from the access point by sending PS-Poll frames. Outgoing data transmissions are also initiated by the station.

In LTE, the radio scheduling is essentially dictated by the eNodeB, and the mobile equipment is not generally allowed to deviate from the communication schedule. Therefore, in the experiment, we let LTE reserve the hardware resources at a higher priority while WLAN is considered as a background-priority protocol.

The workload for the experiment is configured as follows. For LTE we use a periodic workload model where new data to transmit and receive arrives at 20 ms intervals. The workload data rates are controlled by loading factor L so that the target downlink speed is $L \times (100\text{Mbps})$ and the target uplink speed is $L \times (50\text{Mbps})$. Thus, $L = 0\%$ represents idling and $L = 100\%$ represents maximum throughput for LTE category 3 terminal with 2x2 MIMO on downlink and SISO on uplink using FDD bands [11]. To take into account the effects of HARQ processing, we use 5% packet retransmission rate. The workload corresponds to the following DRX parameter values: DRX cycle = 20 ms, inactivity timer = 0 ms for co-operative LTE and 4 ms for non-co-operative LTE, HARQ RRT timer = 8 ms and DRX retransmission timer = 1 ms.

WLAN in our experiment uses 20 MHz bandwidth. The theoretical maximum link data rate is thus 150 Mbps in 2x2 MIMO mode. WLAN allocates resources in 0.5 ms allocation slots. We assume that the communication transactions can take at most 0.4 ms. We therefore require that the last 0.4 ms of a continuous allocation chunk must be left unused, because the communication transaction may not fit into it. Thus, if 11 ms continuous allocation is obtained, the first 10.6 ms is accounted in throughput estimates. The 0.4 ms tailing overhead in performance estimates is based on the fact that sending 1500-byte IP packet requires approximately 320 µs without contention on 802.11g (interframe spacings + data frame + ack) [10]. The conservative timing overhead assumptions are

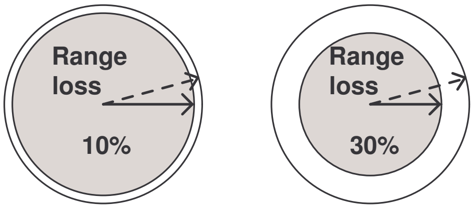

Fig. 5. Operating circles in the case of a 10% and 30% communication range loss corresponding to a 1-dB and 3-dB sensitivity loss, respectively.

used to prevent overly optimistic performance estimates.

Both LTE and WLAN assume no other users on the network. For multiple network users, the peak data rates must be scaled down accordingly.

Based on the assumptions presented, we performed simulations to produce indicative link-level speed estimates. We used a custom simulator which is primarily a reconfiguration scheduling simulator for coarse-grain reconfigurable RF platforms. The simulator contains scheduling algorithms for concurrent resource access and a number of workload models for different protocols.

The simulated results are shown in Fig. 3 and Fig. 4. The guaranteed area represents the case when the HW resources are dedicated for protocols, and there, the protocols may operate independently. The opportunity area represents obtainable link speeds when dynamic resource sharing between the protocols is used. In the figures, sharing overhead is also included representing the gap to ideal co-operation.

The experiment indicates clear advantages for resource sharing, as the idling of one radio system can be transformed into better performance of another, thus, enhancing the combined data rates. Typically, in a mobile device only one radio performs high-speed data transfers at any given time. Consider web browsing as an example. The notable exception, however, is a mobile platform performing gateway function, *e.g.*, by providing LTE-based internet access to another device via WLAN. However, even in that case, the traffic patterns are likely asymmetric for the gateway, as often, there is high-speed data for either incoming or outgoing direction at a time but not both, and sharing would still provide benefits.

B. Bottlenecks in RF Design

In order to evaluate the impact that a multi-radio HW platform has on RF requirements, we need to analyze the effect of the aforementioned TX noise and additive RX noise over a multitude of bands. The number of bands in the current LTE specification is in the order of 40 [12]. Such an evaluation necessitates simple measures that are based on realistic RF parameters so as to be able to determine not only the performance penalty paid within the own desired channel but also the communication range losses inflicted on other radio systems operating concurrently in the same multi-radio terminal. Only after that the feasibility of different tunable RF technologies for a multi-radio HW platform can reasonably be evaluated.

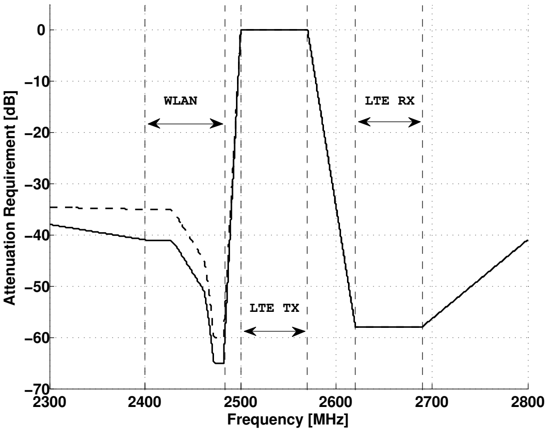

Fig. 6. Analyzed stopband attenuation requirement for the LTE band 7 TX filter in order to achieve a sensitivity loss of 1 dB (solid line) and 3 dB (dashed line) within the 2.4-GHz WLAN band.

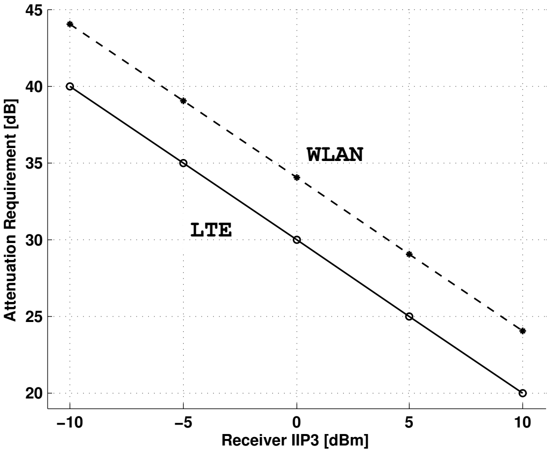

Fig. 7. Analyzed requirements for the LTE and WLAN RX filters to achieve a sensitivity loss of 1 dB.

In following case studies, we will concentrate on the stopband attenuation requirements for the TX and RX RF filtering needed to reduce the interference between the 2.4-GHz WLAN and LTE bands 1–4, 7, and 8 [12]. As a measure of RF performance we use sensitivity loss of the link. Sensitivity loss is defined as incremental noise and distortion on top of the intrinsic NF of the receiver within the received channel which is due to multi-radio interference. Sensitivity losses of 1 and 3 dB correspond to reduced communication ranges of 10% and 30%, respectively, as shown in Fig. 5.

In the first two case studies, the requirements for both the WLAN and LTE TX filtering are analyzed when the LTE and WLAN receivers are assumed to be the victims. The following standard and implementation related parameters must be defined to be able to find the theoretical requirement for the minimum stopband attenuation of the WLAN filter. The broadband output noise of the WLAN TX with a 20-dBm output power is modeled to be -110.5 dBm/Hz, which is in accordance with the values given in the publically available data sheets of WLAN chips (*e.g.*, [13]). The NF of the LTE receiver is set to be 8 dB, resulting in a reference noise level of -166 dBm/Hz at the RX antenna connector. Finally, assuming 10-dB isolation between the WLAN and LTE antennas and allowing 1-dB and 3-dB sensitivity losses, the attenuation requirements for the WLAN TX filter are 52 dB and 46 dB, respectively. On the basis of a similar approach with the -122 dBm/Hz noise of a 24-dBm LTE TX, the corresponding requirements for the LTE TX filters, except for the LTE band 7, become 40 dB and 35 dB. The requirement for the LTE TX filter of the band 7 located close to the 2.4-GHz WLAN band becomes more stringent (65 dB in the worst case), as shown in Fig. 6.

As a concrete example, we evaluated four commercial WLAN RF filters and found that the theoretical requirements can be met only on a few LTE receive channels on bands 1–4, 7, and 8. Even with the best filter, less than 1-dB sensitivity loss is achieved only on 15 out of 69 LTE 5-MHz RX channels. Correspondingly, the sensitivity loss is less than 3 dB only on 50 channels.

Next, the requirements for both the WLAN and LTE RX filtering are analyzed when the receiver operates in the presence of the LTE and WLAN TX blockers, respectively.

RX performance requirements to mitigate undesired nonlinearity effects (*i.e.*, degradation of IIP2 and IIP3) are presented in [8]. Instead, additive RX noise that is due to a high TX blocker is of concern here because it is typically the dominant reason for performance degradation. The analysis is based on the NF increment calculated by means of [5]:

$$\Delta NF \approx 20\log_{10}\left[1-\frac{3}{2}\cdot 0.145\cdot\frac{10^{P_2/10}}{10^{(IIP3-10-CF)/10}}\right]^{-1} \quad (1)$$

where P_2 is the power of the TX blocker after the RF filtering, $IIP3$ is the known or expected input-referred third-order intercept point of the receiver, and CF is a correction factor. A correction factor of 5 dB was obtained by comparing the original theoretical NF increment result with the NF data reported as a function of TX blocker power in [14]. In RF receiver implementations, a typical figure for the IIP3 is in the range from -10 to +10 dBm. As a result of the analysis, Fig. 7 shows the LTE and WLAN RX filter requirements as a function of the receiver IIP3 when the sensitivity loss of 1 dB is allowed. Transmitted powers are 22.8 dBm and 18.9 dBm for LTE and WLAN, respectively. Antenna isolation is assumed to be 10 dB and 3 dB implementation margin has been added to the results. The performance of commercial LTE and WLAN RF filters can be evaluated by using these theoretical results as a measure.

The given analysis applies to various multi-band, multi-standard usage scenarios. Such simple and systematic method is needed when a large number of different band and system combinations is implemented in a single multi-standard or cognitive radio platform.

V. CONCLUSIONS

Multi-standard radio devices need to handle concurrency in RF operations by filtering, scheduling, or just plainly by accepting some performance degradation in the rare worst-case conditions. At the same time, cellular communications are rapidly diverging in multitude of bands due to the lack of available spectrum both locally and globally. Another trend to solve scarce spectrum resources is to offload traffic between local and wide area networks.

Hence, efficient means to handle complex multi-band and multi-standard RF performance scenarios are required. We have shown with practical examples a method to define key bottlenecks and quantify them in the large scale. Significant range loss can be expected over many channels in certain LTE and WLAN band combinations when using currently feasible RF filters and ASICs.

The multi-standard operation provides also opportunities for RF platform implementation. Scheduling is one option to solve interference issues. Advanced internal mechanisms, such as discontinuous transmission modes in cellular, will momentarily free HW resources for use by other protocols. With efficient scheduling, this allows concurrent protocol execution on shared resources. We have shown with simulations the feasibility of parallelized multi-radio RF SDR architecture. According to our analysis, the combined data rate penalty is small highlighting the HW reuse opportunity, excluding the most critical RF filters. On the same principles, HW resource sharing is possible with other existing radios, such as GPS, Bluetooth and DVB, and also with future cognitive radios. The multi-standard requirements can be taken better into account when specifying the behavior of protocols in respect of concurrency and co-existence.

REFERENCES

[1] T. Zetterman, A. Piipponen, K. Raiskila, and S. Slotte, “Multi-radio coexistence and collaboration on an SDR platform,” in *Proc. SDR*, 2010.

[2] V. Giannini *et al.*, “A 2-mm^2 0.1–5 GHz software-defined radio receiver in 45-nm digital CMOS,” *IEEE J. Solid-State Circuits*, vol. 44, no. 12, pp. 3486–3498, Dec. 2009.

[3] A. Immonen *et al.*, “A reconfigurable multi-standard radio platform,” in *1st International Workshop on Energy Efficient and Reconfigurable Transceivers (EERT)*, 2010.

[4] “IEEE 802.19.” [Online]. Available: http://www.ieee802.org/19/

[5] R. Meyer and A. Wong, “Blocking and desensitization in RF amplifiers,” *IEEE J. Solid-State Circuits*, vol. 30, no. 8, pp. 944–946, Aug. 1995.

[6] P. Wong and I. Hunter, “Electronically tunable filters,” *IEEE Microw. Mag.*, vol. 10, no. 6, pp. 46–54, Oct. 2009.

[7] A. Mak, C. Rowell, R. Murch, and C.-L. Mak, “Reconfigurable multi-band antenna designs for wireless communication devices,” *IEEE Trans. Antennas Propag.*, vol. 55, no. 7, pp. 1919–1928, Jul. 2007.

[8] Z. Ru, N. Moseley, E. Klumperink, and B. Nauta, “Digitally enhanced software-defined radio receiver robust to out-of-band interference,” *IEEE J. Solid-State Circuits*, vol. 44, no. 12, pp. 3359–3375, Dec. 2009.

[9] C. Bontu and E. Illidge, “DRX mechanism for power saving in LTE,” *IEEE Commun. Mag.*, vol. 47, no. 6, pp. 48–55, Jun. 2009.

[10] M. S. Gast, *802.11 Wireless Networks The Definitive Guide*, 2nd ed. O’Reilly, 2005.

[11] H. Holma and A. Toskala, Eds., *LTE for UMTS — OFDMA and SC-FDMA Based Radio Access*. John Wiley & Sons, Ltd, 2009.

[12] “3GPP TS 36.101, v9.6.0.” [Online]. Available: http://www.3gpp.org/ftp/Specs/archive/36_series/36.101/

[13] “MAX2831/2832 802.11g RF transceivers with integrated PA.” [Online]. Available: http://www.maxim-ic.com/datasheet/index.mvp/id/5160

[14] B. Tenbroek *et al.*, “Single-chip tri-band WCDMA/HSDPA transceiver without external SAW filters and with integrated TX power control,” in *IEEE Int. Solid-State Circ. Conf.*, Feb. 2008, pp. 202–203.