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Enabling RF Technologies for Spectrum Sharing

Mark A. Beach, Leo Laughlin, Eyad Arabi, Simon Wilson, Sarmad Ozan, and Chris Gamlath
Department of Electrical and Electronic Engineering
University of Bristol, Bristol, BS8 1UB.
Email: leo.laughlin@bristol.ac.uk

***Abstract*—Spectrum sharing has the potential to significantly increase spectrum utilization in underused spectrum by facilitating shared access between primary/incumbent users and new commercial and private wireless services and applications. The citizen broadband radio service in the United States implements a basic form of dynamic spectrum access and is an example of spectrum sharing becoming a reality. Numerous and various regulatory changes in other countries are soon to follow.**

To make the most efficient use of spectrum in dynamic spectrum access regimes requires transceivers with excellent frequency agility, linearity, and selectivity, in order to opportunistically exploit available spectrum, whilst reducing interference and its impact. This article provides a brief overview of recently introduced spectrum sharing regulations, and discusses hardware requirements for current and future dynamic spectrum access. Recent advances in relevant RF technology enablers are presented, covering transmitter power amplifiers, multiband receivers, self-interference cancellation, and reconfigurable antennas.

I. INTRODUCTION

The unprecedented growth in demand for wireless communications services, and the scarcity of the electromagnetic spectrum in which wireless communication systems operate, has made increased spectral efficiency a key goal for wireless networks. Despite huge technological advances in recent decades producing substantial increases in spectral efficiency, to meet demand, large scale network densification has also been necessary, increasing the cost of deploying and maintaining wireless networks. Communication at millimeter wave frequencies [1], where much greater bandwidths are available, may alleviate some of the demand placed on low and mid range frequency bands (e.g. 600 MHz - 6 GHz), and millimeter wave frequency bands have now been included in the fifth generation of cellular standards (5G). However, the propagation characteristics at millimeter wave frequencies limit the range, and result in poor penetration of objects, making these frequencies ill-suited to providing wide area coverage and outdoor-to-indoor coverage. The limited utility of millimeter wave in these respects means that the low-to-mid frequency range will remain vital to providing reliable services with ubiquitous coverage [2].

Despite the importance of the sub-6 GHz frequency range, this spectrum is in fact underused, offering the potential for substantial gains in capacity through increasing spectrum utilization. Traditionally, spectrum authorization has been either licensed or unlicensed. Under the spectrum licensing model, a system operator is granted exclusive use of a frequency band, and this can result in poor spectrum utilization if the licensee does not make full use of their spectrum allocation. In the unlicensed model, anyone can use an unlicensed band, however the lack of co-ordination between users results in poor spectral efficiency if the spectrum becomes crowded. Spectrum sharing authorization models aim to bridge the gap between licensed and unlicensed models, mixing elements of both, with the goal of achieving reliable services where required, whilst improving spectral efficiency and utilization by providing co-ordinated but widely available access for large numbers of system operators [3].

This article provides an overview of recent regulatory changes, current and future RF hardware requirements for spectrum sharing and dynamic spectrum access, and the corresponding RF technology enablers. Section II gives an overview of recent developments in spectrum regulation, namely the citizen band radio service, and discusses RF system characteristics which will enable more efficient and dynamic spectrum access in future systems. Section III discusses challenges in designing transmitter power amplifiers for dynamic spectrum access systems, and presents recent measurement results for a multiband PA. Section IV gives an overview of self-interference cancellation and its potential use in dynamic spectrum access, and Section V covers multiband receiver technologies. Section VI discusses reconfigurable antenna technologies as relevant to dynamic spectrum access, and Section VII concludes this paper.

II. SPECTRUM SHARING AND DYNAMIC SPECTRUM ACCESS

Spectrum sharing is now becoming a reality in the 3.5 GHz band in the USA, known as the Citizen Broadband Radio Service (CBRS). The CBRS band covers 3550 MHz to 3700 MHz, and users must operate according to a set of spectrum sharing rules established by he US Federal Communications Commission (FCC). This frequency band is to be shared between incumbent users and new users deploying commercial and private wireless networks using a range of different air interface technologies across a wide variety of applications.

Under this system, spectrum access will be managed in three tiers: incumbent users, priority users, and general access users. Incumbents operators in the 3.5 GHz band have the highest priority and comprise both Federal users (primarily US Navy radar) and incumbent commercial operators (mainly fixed satellite links that were previously granted licensed access). Incumbent operators are afforded geographical protection zones to prevent interference from newly deployed CBRS systems. In the tier below, “priority access licenses” may be purchased, granting priority use of spectrum by establishing protection zones for the licensee‘s CBRS deployments in their license area. Licenses are available in 10 MHz channel blocks, which can be aggregated up to 40 MHz. The frequency range allocated for a particular license is not fixed and may change dynamically. Furthermore, priority user are not guaranteed access to the spectrum at any given time, and will be instructed to cease operation as, where, and when the spectrum is required by incumbent users. In the lowest priority tier, "general authorised access" may be granted on an unlicensed basis, allowing access when and where the spectrum is not being used by priority or incumbent users.

Spectrum access is actively managed by an automated database driven "spectrum access system" (SAS). Priority and general users must request a channel in a particular area, which may or may not then be granted. Dedicated sensing receivers are also utilised by the SAS, however the sole function of these is to detect signals from federal users - when a federal user is detected, all CBRS users in the federal user's protection zone will be deactivated. Aside from this simple mechanism, no form of sensing capability is used for interference management. The dynamic interference management performed by the SAS is based on estimating approximate geographical protection zones for incumbent and CBRS users using only the locations of these systems, simple propagation assumptions and transmit powers, along with the antenna gain, beamwidth and height. Interference is managed in this way for infrastructure only; individual users are not explicitly managed by the system, although their ability to function is ensured, and their impact on other systems managed, through appropriate estimates of the corresponding infrastructure protection zones.

Spectrum sharing is not unique to CBRS, and whilst the spectrum sharing regulations enacted in the USA are currently the most comprehensive, regulatory changes are in progress in many other countries. In Europe, spectrum sharing is being actively pursued by national regulators and through the European Conference of Postal and Telecommunications Administrations (CEPT). Licensed shared access (LSA) is a notable example, setting guidelines for national regulators of CEPT member states for implementing spectrum sharing in the 2300-2400 MHz band [4]. Technology trials and further national regulation implemented under this framework are now underway in various European countries. The UK regulator, Ofcom, is also implementing licensing based shared access schemes in the 1800 MHz band and at 3800-4200 GHz [5].

A. Implications for RF Hardware

CBRS is a basic example of dynamic spectrum access, and is a long way from the world of *cognitive radio* that has been envisaged for some time now [6]. However, it represents a significant step in this direction. A key point to note is that CBRS mandates no special RF hardware capabilities for either the infrastructure or user equipment. Moreover, CBRS has been developed in such a way as to ensure existing systems, such as LTE, can be deployed without requiring any changes to the specification or hardware. However, it is clear from the existing body of research on dynamic spectrum access and cognitive radio [7] that additional capabilities in the radio hardware, combined with additional features in the spectrum access management, could yield even greater gains in spectrum utilisation and spectral efficiency, compared to the basic spectrum sharing techniques embodied in CBRS.

1) Frequency agility: Dynamic spectrum access across multiple fragmented frequency ranges will require devices and infrastructure that can operate across a broad range of different frequencies, with potentially large separations between frequency bands. Wideband and/or tunable transceiver technologies are therefore a key enabler, requiring agility in all transceiver sub-systems, with particular challenges remaining in the transmitter power amplifiers (PAs), receiver low noise amplifiers (LNAs), and antennas.

2) Transmitter linearity: PA non-linearity results in out-of-band Tx emissions leaking into adjacent channels, impacting on other users (including incumbent users) at nearby frequencies. Improvements in linearity will allow devices to operate at closer distances and frequency separations, increasing spectrum utilization and spectral efficiency.

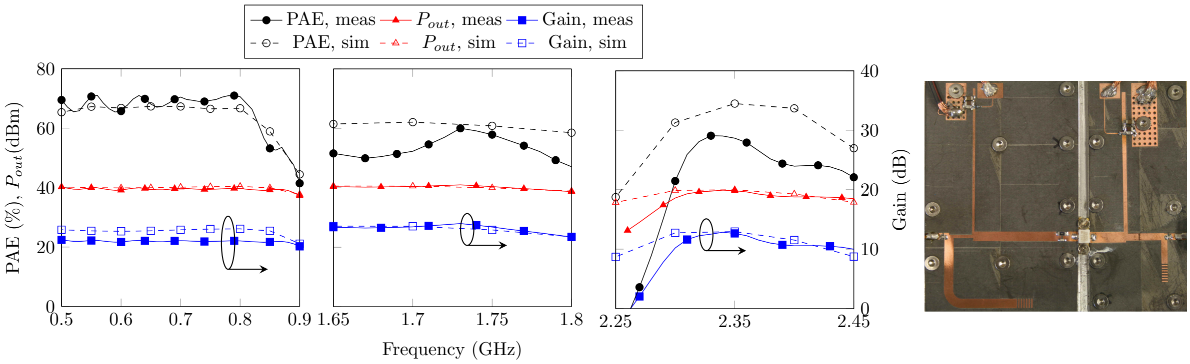
3) Receiver selectivity and Dynamic Range: Increased receiver selectivity and dynamic range improve blocker tolerance, allowing devices to maintain receiver operation in the presence of higher powered out-of-band interferers. Again, this allows devices to operate in closer proximity and at closer frequency separations, making more efficient use of the spectrum. Whilst this is a requirement for today's wireless devices, it is particularly relevant to spectrum sharing and dynamic spectrum access. Spectrum may be shared between a variety of users and applications in close proximity, with substantial differences in transmit powers; compared to today's systems, higher powered interference must be tolerated.

4) Spectrum sensing capabilities: In addition to the aforementioned transceiver characteristics, dynamic spectrum access introduces new requirements for spectrum sensing, which can allow devices to collect information about instantaneous and typical spectrum use in their vicinity. This can facilitate opportunistic exploitation of unused spectrum, and improve spectral efficiency through intelligent dynamic spectrum management. Spectrum sensing introduces additional receiver functionality requirements for wide bandwidths, and fast and efficient signal processing algorithms for spectral analysis.

III. POWER AMPLIFIERS

In this section, the challenges of designing tunable/multiband power amplifiers (PAs) for spectrum sharing are introduced. PAs are designed for high efficiencies, maximum output powers, linearity and wideband operation. For optimal spectrum utilization/sharing, PAs are required to cover all possible operating bands, which can be ideally achieved through a wideband design. However, if the overall bandwidth of the combined bands is wider than one octave, the design of wideband PAs becomes challenging because the second harmonic can no longer be terminated properly. In this case, the other two options are tunable and multi-band designs. Event though MEMS varactors are promising due to their superior linearity as compared to GaAs's, they are still not commonly used in high-power PAs due to their limited power handling capabilities. The other option for spectrum sharing is multiband PAs.

The major challenge in designing a multiband PA is the output matching network (OMN). Multiple matching networks (MNs) connected with switches [8], tunable capacitors [9] or frequency-selective resonators [10] can be used. Such circuits, however, suffer from large sizes and losses. A single MN can be used to reduce the size and complexity as illustrated in our previous work [11], where we have demonstrated a



(a) (b)

Fig. 1: (a) Simulated and measured PAE, power gain, and output power across the three frequency bands for constant input power of 27 dBm. (b) Photograph of the fabricated power amplifier.

methodology to design multi-band PAs using the continuous modes together with mathematical optimization. The method is independent on the topology of the MN and is completely theoretical; therefore, does not rely on costly and time-consuming load pull simulations or measurements. As a proof of concept a triple-band PA operating at 0.8 GHz, 1.8 GHz, and 2.4 GHz has been designed and tested.

A. *Simulated and Measured Results*

A photograph of the fabricated prototype is shown in Fig. 1(b), where a 10 W GaN HEMT device from Cree (CGH40010) has been used. The measured and simulated Gain, power added efficiency (PAE) as well as output power are illustrated for all bands in Fig. 1(a). In this case a single tone continuous wave has been used to excite the PA and the compression level was kept below 2 dB. A good agreement between the simulation and measurement can be observed. Maximum PAEs of 70 %, 60%, and 58% have been measured for the three frequency bands, respectively. A reasonably constant output power of 40 to 41 dBm has been measured with a flat gain between 11 and 12 dB.

This design utilizes a simple MN and is based on a scalable design methodology, which makes it ideal for frequency sharing and frequency agile transmitters. The benefit of this design can also be extended if the intermodulation products are considered.

IV. SELF-INTERFERENCE CANCELING DUPLEXERS

Over the last decade, *self-interference cancellation* (SIC) based duplexers have received substantial interest [12]–[14]. Self-interference cancellation entails processing a copy of the transmitted signal to obtain a replica of the self-interference, and subtracting this at the receiver. Numerous analog, mixed signal, and digital methods have been proposed [13]. If the self-interference can be suppressed to the Rx noise floor, then devices can operate in so-called in-band full-duplex (IBFD) mode, using the same frequency for simultaneous transmission and reception. This paradigm shift in wireless system design has a range of benefits: increasing link capacity, reducing latency, and improving flexibility and spectrum utilization by eliminating the medium access restrictions imposed by time-division duplexing and frequency-division duplexing.

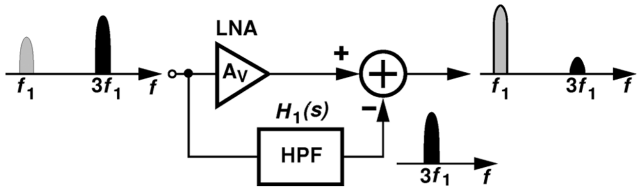
In addition to spectral efficiency gains, In-band full-duplex can allow simultaneous transmission and spectrum sensing, which increasing the availability of information for dynamic spectrum access algorithms. However, IBFD requires $>$100 dB of Tx-Rx isolation, which is typically achieved by combining multiple stages of cancellation, entailing substantial complexity in the cancellation systems [13]. This technology has already been successfully demonstrated in relay and point-to-point microwave systems [15], however further work is required to determine the feasibility for deployment in low-cost low-power applications such as mobile devices.

V. MULTIBAND RECEIVERS

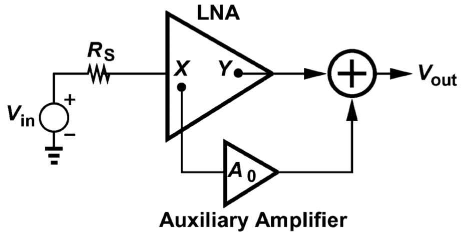
This section reviews the hardware design of receivers, and the challenges involved in the design with possible solutions. The LNA is the heart of receivers as its linearity dictates the linearity of the whole system. Receivers' linearity is an important factor for agility, but it is very challenging to have fully linear devices over multiple bands due to different factors including the nonlinear components used in the RF design. With strong adjacent interferers, any non-linearities can result in leakage of the interfering signals into the desired signal band, reducing the signal to noise ratio (SNR). Commercial designs are also heavily constrained in terms of size, cost, and power consumption. The continued evolution of cellular has brought further challenges, such as carrier aggregation (CA), where multiple carriers, potentially in different bands must be combined. Current solutions typically use multiple LNAs working on different frequency bands to receive the desired signals, with this additional hardware increasing the cost, size, and power consumption.

A. *Wideband LNAs*

The use of a wideband LNA is one solution to cover all the desired frequency bands. This solution requires high linearity and low noise at every frequency in the band, which leads to larger transistors thus higher power consumption. There are different trade-offs in the LNA design, e.g. increased linearity



Low-pass filtering by feedforward.



Principle of noise cancellation.

Fig. 2: Overview of Feedforward and Noise Cancelling Techniques.

at the expense of noise figure (NF), decreasing linearity to decrease power consumption; ultimately, any design is a trade-off between linearity, NF, power consumption and bandwidth [16]. A fundamentally different technique where noise performance is improved through simultaneous source impedance matching is shown in [17]. The method, known as noise canceling, also improves the wideband non-linearity performance through inherent distortion cancellation due to the feed-forward path.

Gallium Nitride (GaN) wideband LNAs typically achieve improved linearity comapred to other implementation technologies, especially CMOS (see Table I for a comparison of the performance of different technologies). GaN transistors are attractive in infrastructure applications due to their high voltage handling capabilities. However, these devices are not well suited to low power operation, and are difficult to integrate, making them unsuitable for hand-held and mobile devices. Hence, CMOS remains the technology of choice in RF receivers, despite the difficulties in circuit design, with linearity being particularly challenging. Feedback and feedforward techniques are potential solutions here. Using such methods, [18] reports IIP3s of around +7dBm with less than 3mW power consumption which is a significant result. A good summary of commonly used circuit techniques used for LNA design in CMOS can be found in [16], [19]. Two of these are shown in Fig.2.

B. Tunable LNAs

The lack of wideband LNAs architectures with low power consumption has led to the research into tuneable architectures. The LNA is optimised for narrowband operation (i.e. the channel bandwidth), but with a tuneable centre frequency allowing operation over a wide range of frequencies. This method requires less power consumption and gives improved linearity (IIP3 ≈ +14dBm) [20], however the tuning and control circuitry increases complexity.

TABLE I: Typical LNA performance figures for common technologies.

Technology	Freq	Gain/NF	IIP3	Power
0.13umCMOS	3-10 GHz	15/2.5 dB	-7 dBm	9 mW
0.35umBiCMOS	3-5 GHz	11.8/2.1 dB	-5 dBm	9 mW
0.25umGaN	0.25-3 GHz	20/3 dB	+31 dBm	8000 mW
0.15umGaAs	0.1-20 GHz	29/3 dB	+12 dBm	500 mW

Tuneable wideband LNAs ideally employ a tuneable input impedance/filter with a high quality factor (Q) in order to reject unwanted signals at nearby frequencies, this being especially important in spectrum sharing regimes. One attractive method for obtaining a high Q factor is the use of N-Path filters [21] which gained popularity recently for demonstrating Q factors higher than 50 at GHz frequencies. N-path filters exploit translational circuits to process the signal at low frequencies. They are widely tuneable, this being controlled by the frequency of a clock signal used to upconvert and downconvert the signal, and can be integrated on CMOS which make them applicable for handheld devices. Tuneable LNAs using N-path filtering give a higher linearity than most of wideband CMOS LNAs (IIP3 ≈ +15dBm) [22], and can provide wide tuning ranges in the sub-6GHz band. MEMS resonators are an alternative tuning technology, and have demonstrated promising results with MEMS based tuneable LNAs achieving a Q factor over 100 at high GHz frequencies in [23]. However, the transmission loss, cost and reliability problems have hindered widespread adoption of MEMS in wireless receivers.

VI. RECONFIGURABLE ANTENNAS

In recent years, substantial advancements have been made in the field of tunable and reconfigurable antennas, demonstraitng antenna systems which are able to vary the operating frequency, antenna pattern, and polarization according to a variety of requirements for operation in different standards. Reconfigurable antennas can also achieve smaller sizes, improved out-of-band rejection, reduced RF front-end complexity, and better isolation in multi-antenna systems. Frequency agility is a key requirement for dynamic spectrum access and cognitive radio, and antenna beam/null steering has substantial benefits for interference mitigation.

Wideband and multi-band antennas facilitate operation over wide frequency ranges, however in antenna design there is a fundamental tradeoff between bandwidth, size, and efficiency, and thus wideband antennas cannot also be small and efficient. Antenna tuning is therefore an attractive alternative, and is now common in multiband consumer wireless equipment, e.g. mobile devices, where multi-band support and small form factor are essential. For similar reasons, antenna tuning will likely become a de facto requirement for dynamic spectrum access in fragmented frequency spectrum [24].

Antenna arrays offer high levels of reconfigurability through control of the antenna pattern. This is typically achieved through control of the amplitude and phase of the signals on individual antenna elements, for example using tunable elements, or separate transceivers for each element [25]. However, system complexity increases with the number of antenna elements.

RF switches can also be used for antenna reconfiguration, allowing optional connections between different parts of the radiating element or feeding network to change the radiation pattern, resonant frequency, and/or impedance of the antenna [26]. Switches can be either semiconductor or mechanical, with system requirements dictating the choice between these; switching time and switch linearity are key parameters of interest. In recent years MEMS technologies (both MEMS switches and tunable MEMS capacitors) have become important enablers in reconfigurable antennas [27]. MEMS devices are smaller and less expensive compared to mechanical alternatives, but also provide improved linearity compared to semiconductor switches. MEMS have low insertion loss, low power consumption, and high isolation. However, their drawbacks are the limited power handling and high losses at high GHz frequencies.

VII. CONCLUSION

Spectrum sharing is now becoming a reality, with CBRS in the United States, and various other regulations being introduced in numerous countries. Dynamic spectrum access has the potential to provide substantial improvements in spectrum utilization, however the benefits of such systems are predicated on the ability of the RF hardware to exploit spectrum as and when it becomes available, whilst minimizing the impact of interference. Whilst CBRS allows for the use of widely available infrastructure and user equipment (e.g. LTE equipment), and therefore mandates no changes to RF hardware performance, moving towards more dynamic and intelligent spectrum access will require improvements in frequency agility, linearity, and selectivity. This article has provided an overview of relevant RF enabling technologies, covering PAs, multi-band receivers, self-interference cancellation, and reconfigurable antennas. Improvements in all of these technologies, along with improvements in overall system design, will underpin improved flexibility and performance of future dynamic spectrum access systems.

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