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Flexible Frequency Discrimination Subsystems for Reconfigurable Radio Front Ends

Bruce E. Carey-Smith
Centre for Communications Research, University of Bristol, Bristol BS8 1UB, UK
Email: b.carey-smith@bristol.ac.uk

Paul A. Warr
Centre for Communications Research, University of Bristol, Bristol BS8 1UB, UK
Email: paul.a.warr@bristol.ac.uk

Phill R. Rogers
Centre for Communications Research, University of Bristol, Bristol BS8 1UB, UK
Email: phill.rogers@bristol.ac.uk

Mark A. Beach
Centre for Communications Research, University of Bristol, Bristol BS8 1UB, UK
Email: m.a.beach@bristol.ac.uk

Geoffrey S. Hilton
Centre for Communications Research, University of Bristol, Bristol BS8 1UB, UK
Email: geoff.hilton@bristol.ac.uk

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The required flexibility of the software-defined radio front end may currently be met with better overall performance by employing tunable narrowband circuits rather than pursuing a truly wideband approach. A key component of narrowband transceivers is appropriate filtering to reduce spurious spectral content in the transmitter and limit out-of-band interference in the receiver. In this paper, recent advances in flexible, frequency-selective, circuit components applicable to reconfigurable SDR front ends are reviewed. The paper contains discussion regarding the filtering requirements in the SDR context and the use of intelligent, adaptive control to provide environment-aware frequency discrimination. Wide tuning-range frequency-selective circuit elements are surveyed including bandpass and bandstop filters and narrowband tunable antennas. The suitability of these elements to the mobile wireless SDR environment is discussed.

Keywords and phrases: software-defined radio, tunable antenna, reconfigurable front end, MEMS, tunable bandpass filter, tunable bandstop filter.

1. INTRODUCTION

The intention of software-defined radio (SDR) is to provide a flexible radio platform capable of operating over a continuously evolving set of communications standards and modes. In contrast to the majority of currently available mobile telephones, which are predefined to operate on a fixed number of standards, SDR must be capable of adapting to both current and future mobile telecommunications standards [1]. The SDR concept imposes demanding requirements on the transceiver front end.[1] Current spectrum allocations and recent regulatory reforms (e.g., [2]) suggest

[1]The front end is that part of the radio which performs channelisation and up- and down-conversion. These functions may be performed in either the analogue or digital domain.

that transceiver operation from 600 MHz to 6 GHz will be required to cover existing and emerging telecommunication services.[2] The front end must not only be capable of operating across this entire band but must do so whilst attaining performance comparable with fixed frequency solutions. In order to achieve the wide frequency coverage required from the SDR front end, two approaches are possible: wideband operation,[3] with all filtering being carried out in the digital domain; or flexible narrowband operation, using tunable narrowband analogue circuits. In this paper, it is argued that, when compared to wideband solutions, flexible narrowband operation holds significant advantages, and with current technology would offer improved overall performance in the SDR transceiver. A key component of narrowband transceivers is appropriate filtering to reduce spurious spectral content in the transmitter and limit out-of-band interference in the receiver. The main focus of this paper is to review techniques for providing tunable frequency discrimination in the analogue front end of a narrowband reconfigurable SDR receiver.

1.1. Practical SDR front ends

Practical implementations of the SDR front end must currently include analogue circuitry to perform frequency up- and down-conversion, amplification, and filtering. In the ideal implementation of SDR, maximum front-end flexibility is achieved by the conversion of the analogue signals to and from the digital domain as close to the antenna as possible [1] employing direct-digital conversion. However, performing direct-digital conversion at RF and microwave frequencies places currently unachievable demands on the conversion hardware and digital processing circuitry. Commercially available analogue-to-digital converters (ADCs) can achieve analogue bandwidths in the order of 70 MHz with greater than 90 dB spurious-free dynamic range (SFDR)[4] but at the present rate of advance it will be some time before direct-digital conversion is possible for the wireless communications environment [3]. The alternative to directly sampling the RF signal is to retain the analogue-digital divide at an intermediate frequency, away from the antenna, and to realise the necessary front-end functionality using analogue circuitry. Wideband analogue transceiver front ends are being explored at both the component and system level [4, 5].

1.2. Limitations of wideband front ends

Although having attractive features, a wideband front end may not necessarily be the optimum solution for SDR. The major advantage of the wideband approach is the wide bandwidth at the analogue-to-digital converter interface, allowing concurrent operation at multiple frequencies. Both the receiver and transmitter are thus able to operate on multiple standards simultaneously. However, design for wideband operation leads to compromise in the transceiver performance, caused by limitations in the front-end components. The nonlinearity of the active analogue front-end components limits the distortion-free dynamic range of both the transmitter and receiver. Wideband linearisation techniques for amplifiers and mixers have demonstrated some linearity improvement [6, 7] and are necessary to limit in-band intermodulation distortion. However, linearity improvements come at a significant cost to overall radio efficiency. Alternatively, by band-limiting the signal of interest, unwanted spectral products can be suppressed, leading to a significant reduction in the overall linearity requirements of the transceiver front end [8].

Band limiting within the SDR environment must be flexible since both the signals of interest and the unwanted distortion products and interference will vary as a function of the user's environment and choice of standard. In this paper, techniques of introducing flexible frequency discrimination into the transceiver front end are considered. Section 2 examines the different requirements for filtering within the SDR transmitter and receiver. Tunable bandpass and bandstop filters are discussed in Sections 3.1 and 3.2, respectively. Bandpass filters offer general frequency discrimination to reduce the wideband interference level while bandstop filters are particularly suited to removing high-level interferers and providing selective isolation between the transmit and receive bands. Tunable, narrowband antennas are not normally associated with frequency discrimination; however, they are tuned transducers between guided and unguided electromagnetic waves and exhibit filtering behaviour. Narrowband tunable antennas offer significant advantages over wideband antennas, one of which is the additional frequency discrimination which they offer. These advantages are discussed in Section 3.3.

2. FRONT-END REQUIREMENTS OF SDR

The design of the air interface of narrowband transceivers concentrates on achieving compliance with a particular standard's receiver blocking mask and transmitter emission mask. The latter must be met in order to comply with the requirements of the current operating standard while the former provides a guide as to the maximum signal levels that will be encountered by the receiver. In conventional (fixed standard) radio, fixed filters provide the necessary frequency discrimination. An example of a typical transceiver is shown in Figure 1. Some compromise in the performance of individual filtering elements must be made to introduce the flexibility required for SDR. It may be possible, however, to recover some of this through combining their capabilities in an intelligent way. This idea is explored in Section 2.2.

[2]A more conservative goal, encompassing the majority of current standards, still requires a two-octave frequency coverage from GSM at 800 MHz to the lower ISM band at 2.4 GHz.

[3]For the purposes of this paper, the term wideband is used to describe components whose operational bandwidth (frequency range over which they are impedance matched) covers all the communication standards of interest; multioctave for SDR.

[4]For example, analog devices, AD6645.

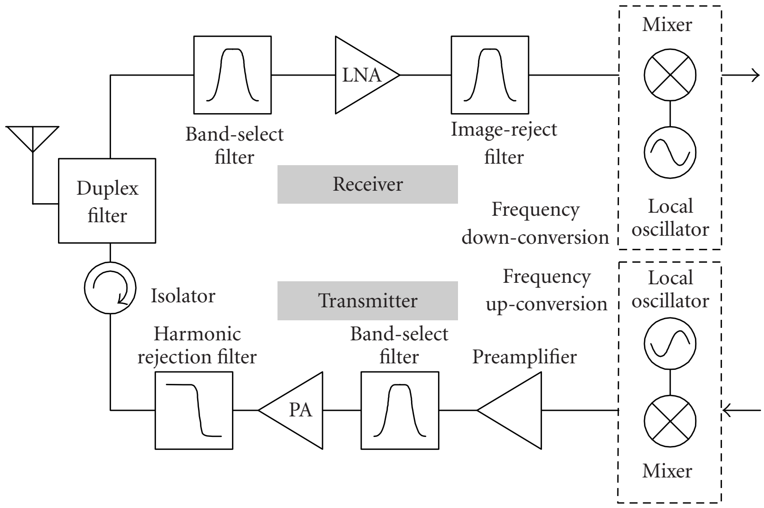


Figure 1: Typical transceiver front end.

2.1. *Frequency discrimination requirements in the transmitter and receiver*

The high power amplification of transmitted signals leads to harmonic (HD) and intermodulation distortion (IMD) products which contaminate the spectrum of the emitted signal [9]. Some IMD products appear in-band and cannot be filtered out, placing fundamental linearity requirements on the power amplifier (PA). Unnecessary IMD can be avoided by harmonic filtering before the PA. This prevents harmonic energy generated in the up-conversion and preamplification stages from producing additional IMD in the PA. It also reduces the wideband noise requirements of these stages. Harmonic filtering after the PA is usually mandatory in order to meet the emission mask for any given standard. Being well removed in frequency from the wanted signal, harmonic attenuation is usually straightforward using a lowpass or bandpass filter. However, the multioctave air interface of SDR demands that this filtering be tunable. The greatest challenge for tunable filters in the transmitter, particularly post-PA, is in tolerating high power levels. There are two factors to consider: the linearity of the tuning elements and their absolute power handling capability. Both of these factors must be considered when selecting the tuning mechanism for transmit filters.

In the receiver, the requirement for filtering is usually more stringent. Signals in adjacent channels are controlled by the current standard and can therefore be tolerated, assuming a degree of linearity in the active front-end components. However, out-of-band signals are not controlled; the only guarantee is that they will fall below some specified maximum level, defined by the blocking mask. The required rejection is usually achieved using a bandpass filter.

In frequency division duplex (FDD) systems, the transmitter can interfere detrimentally with the receiver since both operate simultaneously. This can occur in two ways. Firstly, the transmitter noise floor is generally much higher than the sensitivity of the receiver and, given inadequate isolation, the receiver will be desensitised. Secondly, leakage of the high power transmit signal into the receiver can cause receiver overload. In both cases, the SDR front end must provide some form of flexible frequency discrimination in the transmit and receive paths. The use of separate, independently tuned, transmit and receive narrowband antennas will lead to some improvement in the isolation. Tunable notch filters could be used to provide additional suppression.

2.2. *Environment-aware frequency discrimination*

For any given operating standard, the SDR transceiver must select an appropriate filtering profile. These profiles could be predefined for different standards, however, flexibility in the front-end circuitry raises the possibility of intelligent, real-time adaptation of the transceiver's frequency discrimination profile to the current operating environment. By constantly assessing the user's signal environment, the transceiver can respond with the appropriate level of suppression on a frequency-by-frequency basis. The potential advantage of this scheme is that the necessary filtering can be provided using lower specification circuit blocks. Through the intelligent and flexible combination of lower performance elements, filtering can be supplied where it is needed rather than by unnecessary blanket coverage.

This concept has greater applicability to the receiver, where the nature of the unwanted signals is changing in an unpredictable way. The customary means of dealing with this unpredictability is to provide a maximum amount of filtering to match the blocking mask for a particular standard. The blocking mask, however, assumes the worst case, where all out-of-band signals are at the maximum interference level (usually 0 dBm). In reality, troublesome interference will be limited to specific frequency bands which will change as a function of the environment. Wideband spectrum measurements at a variety of high-communication traffic locations in a typical European city indicate that seldom do multiple signals approach the typical wideband blocking specification

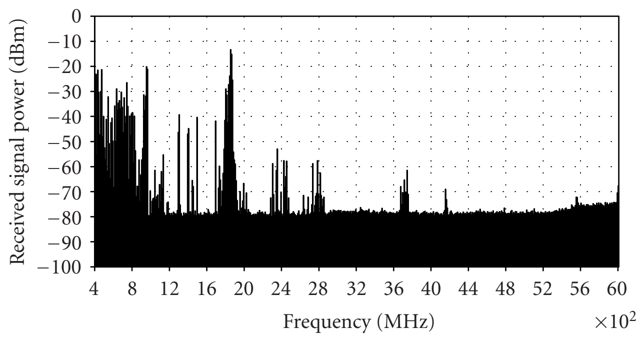


Figure 2: Worst-case power profile.

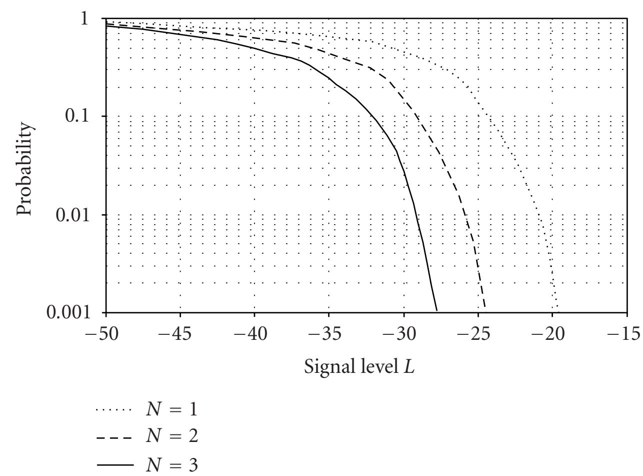


Figure 3: Results of spectrum measurements taken in a typical European city. The graph shows the probability that there will be more than N signals whose power is greater than the signal level L.

simultaneously [10]. The worst-case power profile, combined from measurements taken in 44 different locations, is shown in Figure 2 where a zero dB gain, omnidirectional antenna is assumed in order to calculate the absolute power levels. Few signals exceed −20 dBm at the input to the receiver and the majority of the spectrum is below −40 dBm.

Furthermore, at any given location the probability of receiving a number of high-level interfering signals reduces quickly with their average signal strengths (Figure 3). For example, the probability of receiving more than two interfering signals above −25 dBm is less than 0.4%. The data used in this analysis is the long-term cumulative maximum, so even lower instantaneous probabilities can be expected. These results indicate that, by providing a high level of narrowband suppression at a small number of frequencies, the wideband interference level can be reduced significantly from the typical receiver blocking specification. This, in turn, eases the general filtering requirements, reducing the absolute stopband attenuation required of a front-end bandpass filter. This may enable the use of a lower order filter or a more compact implementation. The remaining sections of this paper look at the performance of various narrowband tunable front-end components, able to provide flexible frequency discrimination.

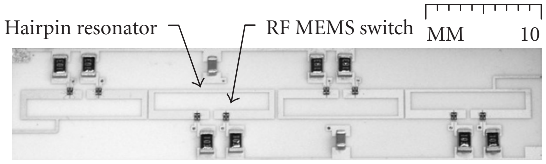
3. FLEXIBLE FREQUENCY FRONT-END SUBSYSTEMS

3.1. *Tunable bandpass filters*

All practical transceivers employ bandpass filtering to provide wideband suppression of unwanted interference and distortion products. In an SDR, this element must be flexible. There are a number of filter tuning technologies applicable for use in mobile telecommunication. Varactor-tuned filters have been widely used due to their fast tuning speeds and octave-frequency tuning range. However, their considerable loss and poor linearity have limited their use to IF sections of the transceiver. The most promising emerging technologies for RF are tunable ferroelectric films and RF microelectromechanical systems (MEMS). Both technologies result in filters which have fast tuning speeds, are small, introduce little distortion, and consume minimal power. Ferroelectric films such as BST consist of a thin film of ferroelectric material placed on a nonferrous substrate, creating a two-layered structure. The dielectric permittivity of the structure can be varied by applied external electric field. Currently these materials exhibit high loss and require large bias voltages, however, greater than 30% tuning range has been documented and resonator Q's greater than 800 can be obtained [11, 12].

The introduction and continuing improvement of microelectromechanical systems (MEMS) has led to the possibility of MEMS-tuned filters for applications where size and tuning speed are critical. Recently, considerable attention has been given to their use at high frequencies. MEMS for RF (RF MEMS) and microwave applications have been fabricated and characterised for frequencies up to 40 GHz [13]. MEMS-tuned microwave filter design, although being a relatively new research area is attracting considerable interest. The majority of lumped-element MEMS-tuned filter designs use fixed air-core inductors and achieve tuning via adjustable MEMS capacitors and are generally limited to frequencies below 3 GHz. A group at Raytheon have developed a number of MEMS-tuned lumped element filters using MEMS digital capacitor arrays to give continuous tuning in frequency bands from 70 MHz to 2.8 GHz [14]. An octave tuning range lumped element MEMS filter with concurrent bandwidth tuning from 7 to 42% is presented in [15]. This is impressive performance although the 4-bit MEMS capacitor arrays lead to uneven coverage across the tuning band.

Numerous planar distributed designs have also been published, for example, [16]. The majority of these designs use some form of tunable capacitive loading to alter the resonant frequency of transmission-line resonators. The tuning ranges tend to be more modest due to the reduction in resonator Q as the capacitance is increased at lower tuning frequencies. An alternative is to directly adjust the length of the resonators. The use of MEMS switches to connect additional lengths of transmission-line to a hairpin-line filter has



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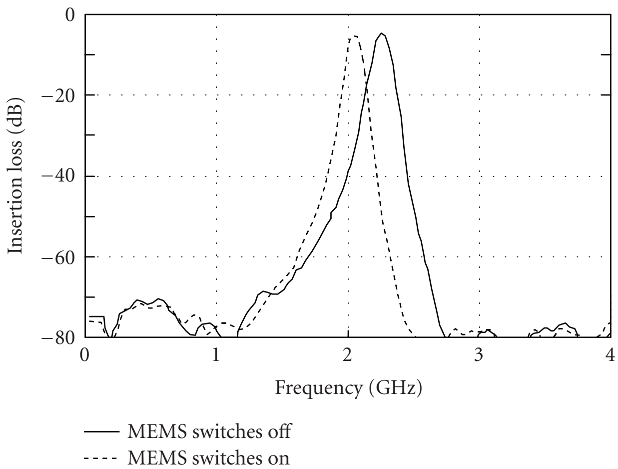

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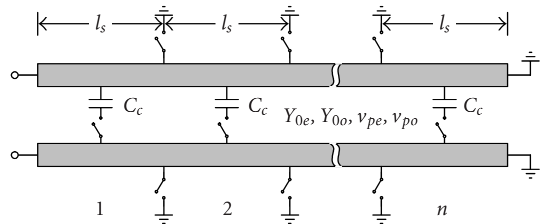
Figure 4: (a) Filter layout and (b) measured performance of a MEMS-tuned coupled hair-pin filter.



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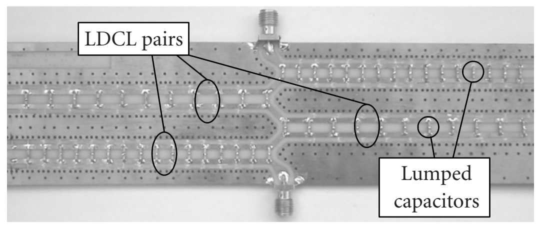

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Figure 5: (a) Schematic of a pair of lumped-distributed coupled lines (LDCLs). (b) Partially cropped image of 3-element filter with four pairs of LDCLs.

been proposed [17]. Measured results show a tuning range from 2.05 GHz to 2.25 GHz with a constant percentage bandwidth of 4.5%. The filter layout and performance are shown in Figure 4.

A limitation of distributed filter designs is that it is difficult to alter the interresonator coupling and, because this coupling dictates the overall filter Q, this leads to difficulty in bandwidth tuning. This limitation is overcome by using capacitively loaded dual-behaviour resonators which allow for independent control of the attenuation poles of the filter [18]. The reported frequency tuning range is somewhat limited however, due to the frequency invariance of the impedance inverters.

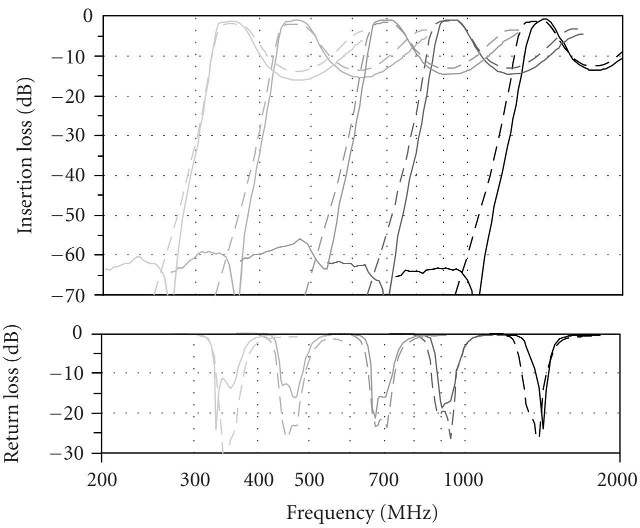
A wide-range, multioctave centre-frequency tunable filter with concurrent bandwidth tuning capability has been reported by the authors [19]. This design, suitable for use with MEMS bistable contact and capacitive switches, utilises switches and switched capacitors distributed at intervals along pairs of coupled transmission lines (Figure 5) to achieve both bandwidth and centre-frequency tuning. Being discrete in nature, there are a finite number of tuning points. However, the distributed topology means that the tuning range and resolution are limited only by the placement density and electrical size of the resonators. Illustrative performance is given in Figure 6.

3.2. Tunable bandstop filters

Bandstop filters have found application in base-station installations where substantial rejection is required over a limited bandwidth to avoid cosite interference. They are preferable to bandpass filters, particularly in the transmitter, due to their low passband insertion loss and high attenuation in the stopband. Bandstop filters may find application in the receiver path where a high level of suppression is needed over a limited bandwidth. Their low passband insertion loss means they can be employed without greatly affecting the receiver sensitivity.

The majority of tunable bandstop filters use some form of variable capacitance to tune the electrical length in a capacitively coupled shunt stub design [20]. With some modification, these designs can yield tuning ranges of almost an octave [21], although the use of lumped capacitive elements produces an asymmetric stopband response and introduces spurious parasitic behaviour at frequencies above the stopband. Discrete tuning of bandstop filters has recently been demonstrated using MEMS switches to alter the resonator properties also reaching almost an octave tuning range [22]. The disadvantage of discrete tuning is that, to affect a high tuning resolution, large numbers of tuning elements are needed.

Wide-range, continuous tuning can be attained by employing a composite tuning mechanism, consisting of varactor-loading and discrete transmission-line length adjustment using PIN diode switches [23] as shown in Figure 7. This composite approach not only extends the relative



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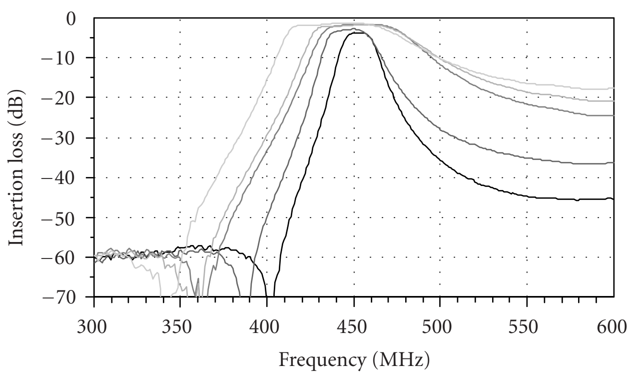


(b)

Figure 6: Measured and modelled performance of LDCL filter at a selection of tuning points. (a) Measured (solid) and modelled (broken line) centre-frequency tuning. (b) Measured bandwidth tuning at a nominal centre frequency of 450 MHz.

centre-frequency tuning range beyond that achievable using solely reactive loading, but also permits the independent tuning of the pass- and stopbands. Independent placement of both the pass- and stopbands is advantageous in that it relaxes the passband constraints by reducing the range of frequencies over which minimum loss must be maintained. The region of minimum loss can be tuned to the required frequency and the loss of the filter at other frequencies becomes less important. Measured results of the filter, showing a two-octave tuning range and variable, relative passband position, are given in Figure 8. The use of active semiconductor components leads to moderate linearity performance. This may be alleviated by employing MEMS counterparts throughout the filter.

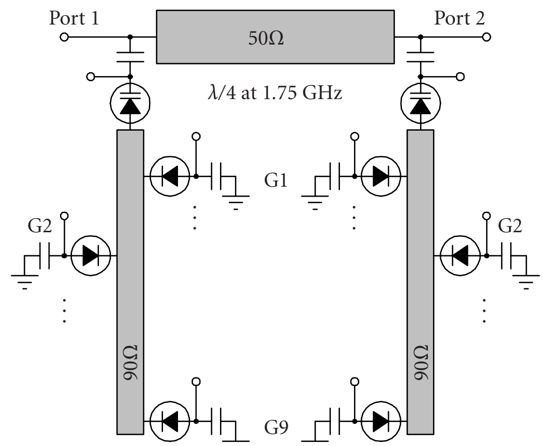


Figure 7: Tunable notch filter schematic.

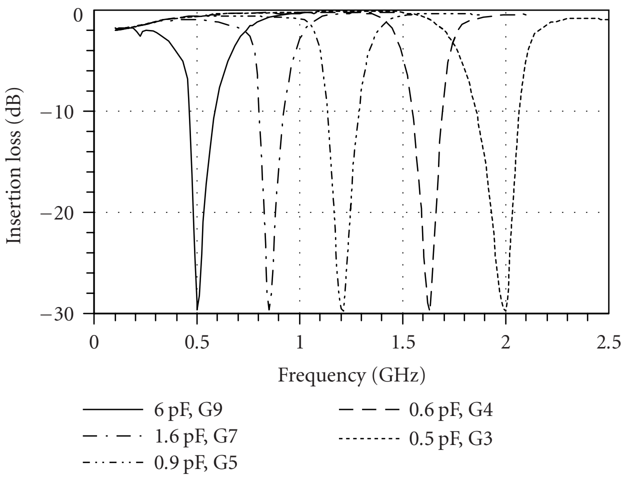
3.3. Narrowband tunable antennas

The performance of an SDR terminal hinges on its interface with the radio channel: the antenna. Acceptable radiation efficiency must be attained across the complete operational frequency range. In addition, current market expectations place constraints on the size of the SDR terminal. These requirements, wide operational bandwidth and small size, are incompatible. Reducing the size of an antenna results in either its efficiency decreasing (which is unacceptable for a terminal antenna) or its bandwidth narrowing, for example, [24]. Conversely, the (instantaneous) operational bandwidth of an antenna may be widened by increasing its size, for example, [25].

The current practice is to design a passive antenna with a wide operational bandwidth, and then conform its shape to fit inside an acceptable volume [5]. Analysis of such elements is normally based upon input response measurements. Whilst this may seem a useful metric, it precludes the most important characteristic of an antenna: its ability to radiate. When radiation patterns are considered, they are usually simple 2D cuts,[5] for example, [26]; though most show the trend of pattern degradation as a function of frequency [27]. Comparison of channel capacity data based on antennas whose only significant difference is polarisation and pattern purity suggests that antennas with high polarisation and pattern purities can yield higher channel capacities relative to those that have poor polarisations and varying patterns [28].

An alternative to a large passive wideband structure is a narrowband tunable antenna. Here the antenna can be made arbitrarily small provided its instantaneous input response (bandwidth) covers at least one channel of the standard. By loading the antenna with a variable reactance, be that capacitive (e.g., using a varactor diode) or inductive, it is possible

[5]Although this may seem a succinct way of characterising an antenna's radiation, it is insufficient as it only accounts for one or two planes about the structure; for an accurate characterisation, full 3D (co- and cross-polar) patterns should be measured.



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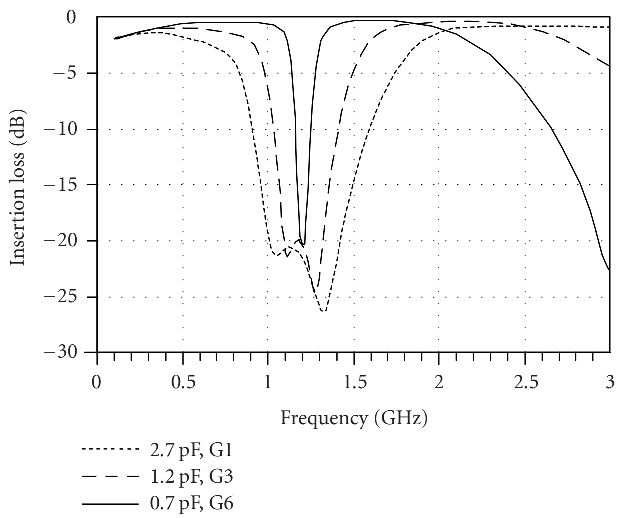

(b)

FIGURE 8: Measured performance of a compositely tuned bandstop filter showing (a) centre-frequency tuning and (b) decrease in filter Q and the associated shift in passband frequency. (Approximate varactor capacitance is measured in pF and G denotes ground position with reference to Figure 7.)

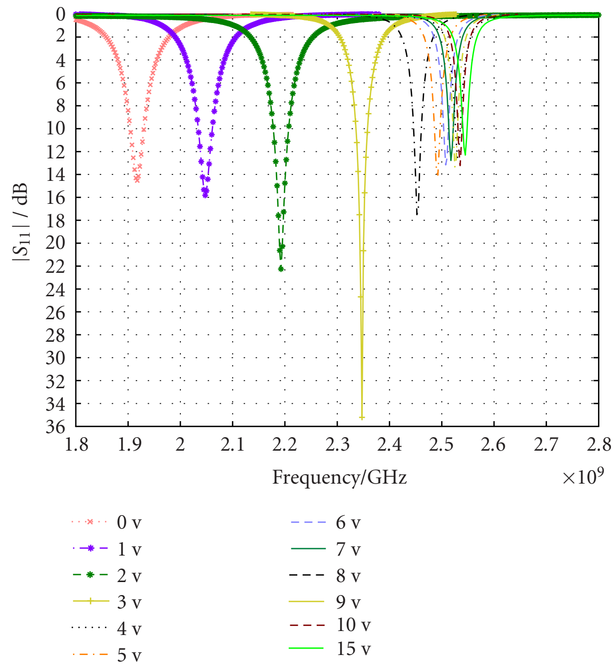

FIGURE 9: Measured S_{11} response of the tunable narrowband antenna with variation of varactor bias voltage.

to vary, in a controlled fashion, the resonant frequency of the antenna. Figure 9 shows the tuning range of an electrically small antenna that is capacitively tuned using a varactor diode. An example of the measured copolarisation pattern for this antenna is shown in Figure 10. Because only the resonant frequency of a single mode is varied, the radiation characteristics remain relatively constant over the tuning range, when compared with those of a passive wideband antenna [29]. However, the use of a reactive element will introduce losses (which are a function of bias voltage) and nonlinearities (due to the semiconductor junction). Prior research has shown the efficiency of a tunable antenna to be comparable to that of a passive wideband conformal antenna [30], and the nonlinearities to be within thresholds of current standards [31]. It is envisaged that with the development of MEMS technologies, tunable devices with lower loss will emerge.

Effectively, a tunable narrowband antenna is little more than a tunable filter. Previous work has shown that the use of such an antenna, whose instantaneous input bandwidth is optimised for operation on a single channel, offers significant interference rejection relative to a passive wideband antenna [32]. Given the congested nature of the spectrum this filtering prior to the RF front-end is highly desirable.

3.4. Discussion

There remain significant challenges in the design and production of flexible components for frequency discrimination in SDR transceivers. New technologies capable of multioctave tuning ranges have been demonstrated and emerging technologies promise lower loss and higher linearity performance. However, for mobile applications, where size is a primary consideration, the fabrication of such devices must be addressed. Suitable filters and antennas must be monolithic in order to simplify production and achieve appropriate footprints while at the same time being environmentally robust. For transmitter applications, power handling capabilities must be addressed. High power RFMEMS-tuned filters capable of 25 W have been investigated at VHF frequencies [33], however, the tuning capabilities of these filters are limited.

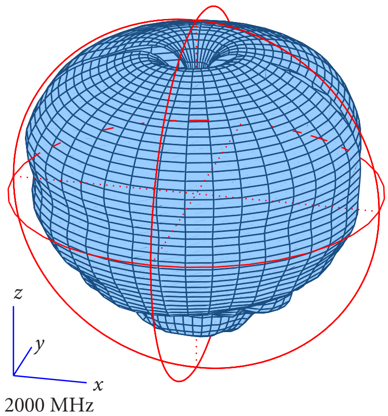

Figure 10: Typical measured copolarisation pattern of the tunable narrowband antenna.

From a system implementation perspective, the SDR air interface requirements will play a key role in determining the optimum combination of flexible filtering subsystems. The majority of the frequency discrimination requirements for the transceiver can be determined from known signal information. For example, the suppression of transmit noise in the receive band can be determined from a knowledge of the transmitter noise profile and the receiver cochannel interference rejection ratio for a given set of up- and downlink channel parameters. For those requirements which deal with signal information that is not known beforehand (i.e., receiver blocking), some relaxation in front-end filtering requirements may be gained by defining them on a statistical basis (i.e., number of simultaneous interferers above a given power level which must be tolerated by the receiver). In this case, the wideband suppression level of the receiver may be able to be reduced by employing notch filters to deal with high-level interferers. Once the complete specifications have been defined, the optimum combination of subsystems can be designed, based on their individual performance.

A method of intelligent control is a critical prerequisite for the use of flexible subsystems in an SDR front end. In all cases, it is necessary to have knowledge of the tuning relationship between the frequency response of the subsystems and the signals used to control them. However, the major difficulty lies in determining the appropriate frequency profile for each subsystem. Within the wanted channel, centre frequency and bandwidth information can be used to tune bandpass filters and antennas for optimum passband loss and radiation efficiency. The appropriate receiver stopband profiles are not known *a priori*, and the most efficient profile will assign bandstop filter suppression at the frequency of the most problematic interference. Two control approaches exist: blind adaptation, where the filters are tuned to minimise broadband detected power; and spectrum monitoring, where a parallel receiver determines the offending signal characteristics. The former suffers from search algorithm latency; complex algorithms are needed due to local minima in the tuning space. The latter introduces the cost and complexity of an additional receiver. The requirements of this receiver are reduced significantly since the only output required of the spectrum monitor is the frequency of the largest signal, with an accuracy relating to the bandwidth of the bandstop filter.

4. SUMMARY

A wideband radio front end is attractive for SDR, however, the resulting compromise in performance suggests that a narrowband tunable approach is worthy of consideration. The essential advantage of narrowband systems is the frequency discrimination they offer, thereby reducing the linearity and dynamic range requirements of the transceiver. This paper has surveyed recent techniques to extend the tuning range and overall flexibility of three key elements of the narrowband radio front end; bandpass and bandstop filters and antennas.

Multioctave centre-frequency tuning ranges have been demonstrated in bandpass and bandstop filters with concurrent bandwidth tuning. However, miniaturisation and integration issues must be addressed to yield solutions suitable for wireless terminals. Tunable narrowband antennas have been shown not only to contribute helpful frequency discrimination but also to display far superior performance for a given size when compared to wide operational bandwidth designs.

With a selection of tunable filtering components in the front end, the potential exists for intelligent real-time adaptive control of the transceivers frequency discrimination profile. Analysis of radio spectrum measurements suggests that, for the receiver, a high-level of discrimination is needed only at a few select frequencies at any given time. An adaptive filtering profile may allow the specifications of the individual filtering components to be relaxed.

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Bruce E. Carey-Smith received a B.E. degree in electrical and electronic engineering from the University of Canterbury, Christchurch, NZ, in 1995, and is currently pursuing postgraduate study at the University of Bristol, Bristol, UK. From 1995 to 2002, he was with Tait Electronics Ltd., Christchurch, NZ, involved in the design of RF circuits and systems for mobile radio applications. Subsequently he joined the University of Bristol, Bristol, UK, as a Research Associate in the Centre for Communications Research where his current research interests are in the areas of tunable microwave circuits and amplifier linearisation for software reconfigurable radio.

Paul A. Warr received his Ph.D. degree in 2001 from the University of Bristol, Bristol, UK, for his work on octave-band linear receiver amplifiers, his M.S. degree in communications systems and signal processing also from Bristol in 1996, and his B.Eng. degree in electronics and communications from the University of Bath, UK, in 1994. He is currently a Lecturer in radio frequency engineering at the University of Bristol where his research covers the front-end aspects of software (reconfigurable) radio and diversity-exploiting communication systems; responsive linear amplifiers; flexible filters; and linear frequency translation. Funding sources for this research have included UK DTI/EPSRC alongside CEC ACTS and IST programmes and industrial collaborators. Dr. Warr is a Member of the Executive Committee of the IEE Professional Network on Communication Networks & Services. Prior appointments have included the Marconi Company where he worked on secure, high-redundancy, cross-platform communications.

Phill R. Rogers obtained the M.Eng. degree (first class) in electrical and electronic engineering from the University of Bristol in 2000. He obtained his Ph.D. degree in 2004 which was titled "An electrically-small tuneable annular slot antenna for future mobile terminals." Since October 2003, he has been employed as a Research Assistant at the University of Bristol in a number of areas including UWB antennas, MIMO antennas and systems, and terminal antennas. He is currently involved in several European projects and has authored and coauthored over twenty publications.

Mark A. Beach received the Ph.D. degree from the University of Bristol, Bristol, UK, in 1989. In 1989, he joined the University of Bristol as a member of academic staff where he currently holds the post of Professor of radio systems engineering. He has made contributions to the European collaborative projects, TSUNAMI, SATURN, ROMANTIK, TRUST, and more recently SCOUT. At present his interests are focused toward multiple-input multiple-output (MIMO) channel characterization and the design and optimization of space-time coded wireless architectures for 3G and 4G wireless networks. His research interests include smart antenna technology for wireless as well as analogue RF circuitry for software definable radio (SDR). Professor Beach is an active Member of the Institution of Electrical Engineers (IEE) Professional Network on Antennas and Propagation as well as an Editor of the IEEE Transactions on Wireless Communications.

Geoffrey S. Hilton received the B.S. degree from the University of Leeds, UK, in 1984, and the Ph.D. degree from the Department of Electrical and Electronic Engineering, the University of Bristol, Bristol, UK, in 1993. From 1984, to 1986, he worked as a design engineer at GEC-Marconi, before commencing research in the area of microwave antennas, first as a postgraduate student and later as a member of research staff at Bristol University. This work included design and analysis of printed antenna elements and arrays, and also involved the development of finite-difference time-domain (FDTD) models for these structures. In 1993, he joined the academic staff at the University and currently holds the post of Senior Lecturer. Current research interests include radiation pattern synthesis; array design and modelling; the design of electrically small antennas, active antennas, and integrated antenna transceivers, primarily for use in small portable terminals as well as wideband applications, such as ground penetrating radar. This has led to publications (on both practical and simulation work) in refereed journal and conference proceedings in Europe, America, and Asia.