Antenna Challenges in Cognitive Radio

University of Birmingham, UK.

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Abstract
The cognitive radio concept throws up significant challenges for antenna design. Whilst there are many possible ways in which such systems could be configured, the range of possible antenna requirements is discussed, and some design approaches are outlined. Some demonstrator antennas are described. Results for three antennas, suitable for small terminals, are given, in which integration into a single antenna of wideband and narrowband functionality, necessary for search and operation respectively, is achieved. The performance of these is finally compared to an array with band switching, which may be useful in systems that require both spatial and spectral discrimination.

1 Introduction

A Cognitive radio is a wireless transponder that can sense the environment in which it wishes to operate and can adapt itself to optimise its operation. Sensing the environment may involve the measurement of the communications traffic and interference across a large part of the electromagnetic spectrum. The radio will also have knowledge of the intentions of its user, to enable it to match its searches to the needs of the user. Cognitive radio is also seen as an approach to ease the problem of the very crowded electromagnetic spectrum. For most users access to this spectrum is limited by international regulation. In this sense it is an approach which is linked to the so-called open or deregulated spectrum concept in which users have free access to any part of the spectrum, which will enable them to do what they want.

There are severe difficulties in implementing this concept, both from a system or network point of view and in the technology required to operate it. There will, of course, be a slow evolution towards it, and this means that initial systems will have to operate in an environment populated by two groups of systems; those that are regulated, and those that are allowed to operate as cognitive radios. In this case there are then serious interference problems that have to be controlled, between so-called primary users, such as TV transmitters, and the secondary users, namely the cognitive radios searching for useable, or white, spectrum. Of course, there is in reality no such thing as white (or empty) spectrum, and it is the job of the cognitive radio to have a search facility that measures either the energy, or some feature, of the existing transmissions. Decisions are then taken about the operation of the radio, or more specifically about how much power can be transmitted without interfering with the primary user. In principle then, the cognitive radio needs a search engine and an operating transponder. The search receiver will be designed to cover a very wide bandwidth, whilst the operating transponder could be narrow or wide band depending on the standard used.

From a hardware point of view, cognitive radio can be seen as an extension of the software radio paradigm. Software radio is a concept that has developed due to the enormous possibilities offered by modern signal processing. Wideband antennas could in principle be connected directly to analogue to digital converters and the digitised radio signal is processed. The processor could contain all of the processing previously done using analogue RF and baseband circuits. The key advantage is that the processor can be reconfigured to change the standard that the radio is using, amongst the many that are now in use [1], and those predicted to emerge, such as the use of millimetric bands, [2]. Such flexibility is seen to be necessary to handle the increasing levels of wireless traffic, particularly that produced by multimedia services. Software defined radio (SDR) is a subset of this, in which mixed chip architectures allow practical realisation but somewhat compromised performance. Reconfiguration is determined mainly by the network and spectrum allocation. Cognitive radio, [3-5], then takes the concept further by using model based reasoning in the handset to give local control, with the advantage of ‘spectrum pooling’ giving greatly increased capacity. It has been suggested that a cognitive radio could access bands in the range of 30 MHz to 5.9 GHz, although a more realistic range is for example, 0.4 to 2.5 GHz, which would give an available spectrum of greater than 1.46 GHz, [3]. The advent of the UWB spectrum, from 3 to 10 GHz, places both narrow and wide bands within the remit of cognitive radio and increases the challenge. This means that antenna bandwidths of the order of a decade are needed. We use the term wideband when referring to octave to decade bandwidths. In addition if a software radio is to be used for narrowband channels such as GSM then some additional front end RF analogue components will be needed, such as filters and amplifiers.
2 Cognitive Radio Architectures

In this section, we review some published cognitive radio architecture concepts and consider in particular the implications of these on the antenna requirements.

Cognitive radio networks can be categorised as those in which the decision making about spectrum allocation is made locally by individual terminals or a group of terminals sharing data, and those in which spectrum allocation is performed at a central base station. These systems can then be further divided into:

A. Those which continuously monitor the spectrum usage in a process which runs in parallel with the communication link, as shown in Fig 1, and

B. Those which use a single channel for both spectrum sensing and communication, as shown in Fig 2.

In category A, systems have been proposed that use two antennas [6]. One antenna is wideband and omni-directional, feeding a receiver capable of both coarse and fine spectrum sensing over a broad bandwidth. The second antenna is directional and feeds a frequency agile front end that can be tuned to the selected band. Category A also includes single antenna systems [7], where a single wideband antenna feeds both the spectrum sensing modules and the frequency agile front end.

In category B, spectrum sensing and radio reconfiguration are performed when the communication link quality falls below defined thresholds. In [8], two thresholds are used. Link quality falling below the first threshold triggers spectrum sensing, so that a better system configuration can be identified that will meet the link quality requirements. When the quality degrades below a second lower threshold, the system is reconfigured.

An important issue in the front end architecture is to limit the instantaneous dynamic range to avoid non-linear distortion of signals in the wanted channel. Many authors envisage the use of tuneable filters to reduce interference and therefore limit the dynamic range. Interference can also be limited by the use of directional antenna properties. In [9], a simple switched pattern technique was described which could limit interference from primary sources whilst maintaining communications between users in the local network, enhanced by a multi-hop approach. In addition, the use of a switched wide band directional antenna, combining spatial and spectral discrimination may also be useful.

Whether both of these techniques are used will depend on available space. In the case of a base station both spatial and spectral sensing may be used, but in the case of handheld terminals it is likely that only spectral sensing may be possible.

These issues have been further discussed in [10].

There are significant antenna challenges in such systems.

- In general wideband antennas are bigger than narrowband ones, which will be a significant problem for handsets.
- The design of wideband arrays for base stations gives great difficulties in element spacing.
- Narrowband antennas provide a degree of pass band filtering, which, by supplementing the filtering in the RF stages, provides control of the noise level, which is mainly determined by interference.
- The fundamental limits of electrically small antennas, in terms of bounds on Q factor and gain, also limit the instantaneous coverage that can be achieved. Combining these two bounds implies that an antenna with an extremely wide band will be very inefficient, if it is small compared to the wavelength. This will limit the sensitivity for search.

3 Novel Antenna Approaches

From the system considerations discussed above, we have chosen some novel antenna configurations and investigated their feasibility. For small terminal applications we have examined how

- A narrow band and a wideband antenna may be integrated into the same volume, and then demonstrated how external tuning circuits can be
used to tune the narrow band antenna over the wide bandwidth.
- To switch between wideband and narrowband operation

For these examples we have chosen the FCC UWB as our wide band and WLAN/WIMAX as our narrow band for some cases. The solutions shown may also be useful when these two standards are combined into the same unit.

For base station applications, we have shown how a log periodic dipole array can be band switched, to produce an agile wideband directive antenna.

3.1 Integrated wide-narrow band antenna for switched operation

Fig 3 shows a wideband UWB monopole antenna integrated with a microstrip patch antenna designed for operation around 7.6 GHz. The patch is excited by a long microstrip line on the ground plane. The ground plane for the patch itself is a narrower extension of the lower ground, with horizontal slots. The lower slot, between the lower ground plane and the patch ground plane, serves to isolate the patch ground plane, and two switches are located along its length as shown. When these switches are closed the two ground planes are effectively connected, and the combined structures operate as a narrowband patch radiator. When the switches are open then the patch ground plane becomes part of the wideband monopole, formed by the patch conductor. The upper slot in the patch ground plane is necessary to remove a notch in the wideband input return loss characteristic. Due to the introduction of this slot, a third switch is also required. The switch positions affect the performance of the antenna and the positions shown give best results.

Fig 4 shows the measured and simulated return loss in the wideband and narrow band modes. For the purpose of this experiment active switches were simulated using small squares of copper. It can be seen that in the wideband mode a return loss better than -7 dB is obtained from 3.6 to 11 GHz. In the narrowband mode, return loss better than -10 dB is obtained over a 6.8% bandwidth at 7.6 GHz.

In this demonstrator, the patch was designed for 7.6 GHz, to give a physical size that was somewhat smaller than the ground plane, whose dimensions were chosen to meet the UWB requirement. It is envisaged that narrowband operation in the 5 to 6 GHz WLAN range could be obtained by the use of external matching circuits. For a cognitive radio application, tuning right across the UWB band could also be achieved using tuning circuits. Although this has not been demonstrated on this antenna, it has on the antenna in the next section.

3.2 Integrated wide-narrow band antenna for simultaneous operation

The previous section described an antenna that could be switched between wide and narrowband operation. As the cognitive radio architectures are not yet fixed, it is useful to see what can be achieved with regards to the integration of
wide and narrowband elements that can be used simultaneously. Fig 5 shows such an antenna.

The wideband element is an hour glass shaped monopole fed by a coplanar waveguide. On the other side of the substrate a planar inverted F antenna (PIFA), designed for operation at 5.5 GHz, is configured to operate on a ground plane formed by the monopole. The short circuit connection for the PIFA is placed at the opposite end of the patch to the feed, unlike conventional PIFAs, and this was found necessary to get good matching. The feed of the PIFA crosses the gap between the monopole and its ground plane and this possibly creates some reactive loading, which is compensated for through the design of the PIFA.

Fig 6 shows the input return loss of the antenna, measured with the other port matched. It can be seen that the wideband element has a return loss below -7 dB over the band 3 to 10 GHz. The narrowband port shows a return loss below -10 dB over a 9.9% band at 5.2 GHz.

External matching circuits have been designed to tune the PIFA to three other frequencies in the UWB band, including both the lowest and highest frequencies, thus confirming that such tuning is possible. Details of these circuits and their performance will be given in the presentation.

One of the possibly important factors in the use of this sort of antenna in a cognitive radio is the out of band rejection of the narrowband antenna. This rejection, in conjunction with other parameters such as the rejection of the front end filter, will set the receive sensitivity. If Fig 6 is compared with Fig 4, it is clear that both antennas have a good rejection below their operating band, but above it is less good. Our studies so far indicate that, in both antennas, the coupling of the narrow band element with the wideband element is significant, and is thus an important parameter for further study.

3.3 Switched wide-narrow band antenna using external filter circuits

The two antennas described above were integrated; in that both wide and narrowband elements occupied the same space. However it was also noted that tuning the narrow band element across the wide band would require external matching circuits. It is also interesting to explore whether a switched wide-narrow action can be obtained by external elements using a single wideband radiator. Fig 7 shows such an arrangement.

A disc monopole fed by a microstrip line is used as the wideband element. Two meandered slot resonators, located in the ground plane, are configured to couple strongly with the microstrip feed line (I think??). This arrangement is similar to that of UWB monopole antennas with notches in the WLAN band, [11], but in this case the filters are configured...
to produce a pass band. If switches are placed across the slots under the feed line then the filter action can be switched in or out.

Fig 8 shows the measured and simulated results when the filter is operating and when it is switched out using metallisation across the slots as can be seen in the right hand photograph. With the filter switched out the input return loss is less than -8 dB across the 3 to 10 GHz band. When the filter is not shorted out then the input return loss is about 7 dB across the 5 to 6 GHz band. Current work is aimed at improving this match. However the rejection both above and below this narrow band is much better than in the integrated antennas above.

Fig 7 Switched wide-narrow band antenna using external filter circuits
(left) disc monopole, (right) switched filter circuit in ground plane

Fig 8 Measured and simulated input return loss of switched wide-narrow band antenna using external filter circuits
Upper solid = measured with filter in, dotted = simulated with filter in, lower solid = filter out

3.4 Band switched log periodic array

In systems that require both spatial and spectral discrimination, then wideband directive antennas will be used. One candidate for this is the log periodic dipole array, which could then be configured in a circular array to give all round coverage. If a search receiver, containing a tuneable bandpass filter, is used for each array, it is possible that performance would be enhanced if the antenna was also band tuneable. This has been demonstrated in [12], and the performance is shown again here, for comparison with the small antennas described above.

Fig 9 shows the 8 element dipole array that was fabricated as part of this study. The frequency range is 3 to 1 and in this case the 3 to 10 GHz band was scaled to 1 to 3 GHz to make the construction easier. Switches are simulated with the absence or presence of metallisation. Figs 10 and 11 show the measured input return loss, with two sets of dipole switched in, giving bandpass characteristics. It was found necessary to locate switches on both arms of each dipole and in the feed line. Harmonic traps were also needed in the low frequency dipoles. Fig 10 shows switching for the bottom part of the band. Again rejection below the band is good, but poor above. This is assumed due to the radiative coupling between the low and high frequency dipoles. This problem is also noticed in Fig 11, but is less severe.
Fig 10 Measured input return loss of switched log periodic dipole array with dipoles 5, 6 and 7 switched in

Fig 10 Measured input return loss of switched log periodic dipole array with dipoles 2, 3 and 4 switched in

4 Conclusions

Architectures for cognitive radio have been reviewed and some novel antennas were presented that demonstrate some of the features needed in this requirement. Antennas that integrate a wide and a narrowband element have been shown, that either allow simultaneous action or that are switchable. A concept for a wideband antenna with a switched filter to achieve the same end is also given. In these small antennas for terminal applications interaction between the wide and narrowband elements is a considerable design difficulty and this seems to result in reduced out of band rejection in the narrowband element. This problem is also seen in a log periodic dipole array with bandpass switching. It is, however clear that there are a number of new configurations that offer some possibilities for use in cognitive radios.

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6 References