COGNITIVE RADIO AND AFRICA

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The focus of this chapter is on cognitive radio and Africa. There are many questions abut the long term viability and commercial success of cognitive radio. These questions are amplified when set in the context of Africa and other more resource constrained environments. This chapter looks at the general motivations for cognitive radio and questions whether these hold in the African context before going on to suggest a range of key areas in which cognitive radio could play a role on the African continent. This chapter seeks to look beyond the focus on TV white spaces and speculate about the longer-term future of for cognitive radio.

10.1 INTRODUCTION

The purpose of this chapter is to look at the potential for cognitive radio in Africa. The chapter begins with a brief reminder of the varied definitions that are in use for cognitive radio as well as looking at the traditional factors driving cognitive radio. The chapter then goes on to pose the question whether these drivers are valid in the African context. Following this the outlook for cognitive radio in Africa is explored and the issue of cost is discussed.

10.2 THE MEANING OF COGNITIVE RADIO

As cognitive radio is over a decade old, it might seem unnecessary to provide a definition. However, given the wealth of the meaning that is encompassed in the term cognitive radio, it is worth repeating a few definitions as the purpose of this chapter is to focus on the future of this technology in Africa, and hence the definition in use matters. The term

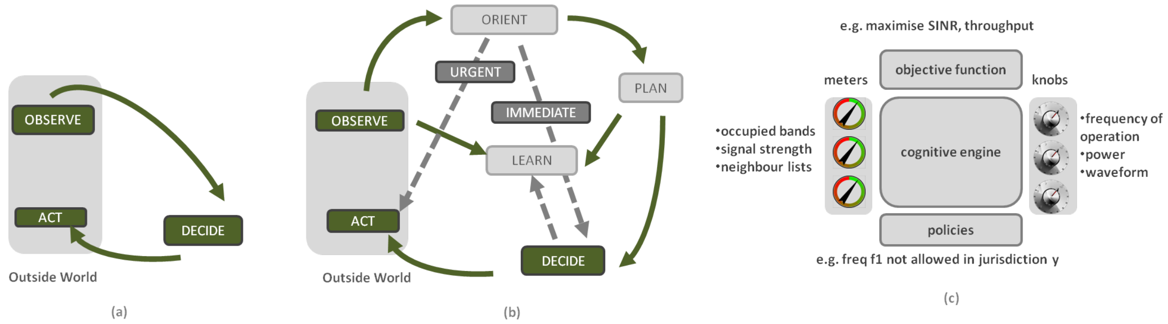

Figure 10.1: Many Ways to View a Cognitive Radio

cognitive radio was coined by Mitola in an article he wrote with Maguire in 1999 [1]. In that article, Mitola and Maguire describe a cognitive radio as a radio that understands the context in which it finds itself and as a result can tailor the communication process in line with that understanding. Over the years the cognitive cycle has been used to define cognitive radio functionality. Using the cycle, a cognitive radio is a radio that can make observations about its environment, take decisions about how to respond to the environment and act by configuring itself appropriately as in Figure 10.1 (a). The type of cognitive radio associated with the use of the TV bands is one that follows this cycle. It makes observations about spectrum availability through reading from a database, decides which frequency to use and acts by configuring the frequency and power of operation of the white space device. However, much more advanced definitions of cognitive radio have also been conceived [2]. For example, some definitions focus on learning and a cognitive radio is often defined as a radio that has the ability to learn from its actions and from this learning to feed into any future actions it may take. In line with this, more complex versions of the cognitive cycle have been used to include this level of functionality as depicted in Figure 10.1 (b). A body of research does exist in which learning algorithms are explored in the context of cognitive radio [3] [4] [5] though it is probably fair to say that no compelling applications yet exist that undisputedly require learning.

The decision-making part of the radio is often referred to as a cognitive engine and some definitions of cognitive radio focus more on this engine. Figure 10.1 (c), for example, places it at the centre of a system and views a cognitive radio as a device that has a set of 'meters' which feed into a cognitive engine that outputs the settings for the 'knobs' on the radio. The meters are the various different sensing and observation mechanisms, the knobs correspond to the parameters of the radio system that can be configured. The engine strives to achieve an objective or set of objectives given the state of the environment and the options for configuration (i.e., range of settings of the knobs). As can be seen in Figure 10.1 (c) there is also a possibility for policy-level input, i.e., for policies to drive the output of the system. Cognitive radios can also,

[1] J. Mitola and G. Maguire, Cognitive radio: Making software radios more personal, IEEE Personal Communications, 37:10 (1999), 1318.

[2] Doyle, L.E., The Essentials of Cognitive Radio, Cambridge University Press, The Cambridge Wireless Essentials Series, April 2009, pp240.

[3] Clancy, C.; Hecker, J.; Stuntebeck, E.; O'Shea, T., "Applications of Machine Learning to Cognitive Radio Networks," Wireless Communications, IEEE , vol.14, no.4, pp.47,52, August 2007

[4] I. Macaluso, D. Finn, B. Ozgul, and L. A. DaSilva, Complexity of Spectrum Activity and Benefits of Learning for Dynamic Channel Selection, IEEE Journal on Selected Areas in Communications (JSAC), Cognitive Radio Series, 2013 (to appear).

[5] Gavrilovska, L.; Atanasovski, V.; Macaluso, I.; DaSilva, L., "Learning and Reasoning in Cognitive Radio Networks," Communications Surveys & Tutorials, IEEE , vol.PP, no.99, pp.1,17

therefore, be associated with the ability to process policies [6]. The coining of the phrase cognitive radio is generally considered both a help and hindrance. It has unlocked ideas around the notion of a radio with a brain and led to an embracing of multi-disciplinary investigations in the field [7]. On the other hand it has conjured up notions of radios with emergent properties that will, if left untamed, wreak havoc on incumbent systems. It is against the multiple definitions of cognitive radio and with an acknowledgement that cognitive radio is still an emerging technology that the role of cognitive radio in Africa is now explored.

10.3 DRIVERS OF COGNITIVE RADIO

To determine whether there is a role for cognitive radio, the drivers of the technology need to be identified. Cognitive radio can generally be seen as:

1. a means of enabling new modes of spectrum access
2. a technology for supporting autonomous/self-configuring/self-planning networks.

Broadly speaking, whether considering commercial, military or public safety applications, cognitive radio will play a part if spectrum needs to be accessed in some form of dynamic or shared manner, or if there are requirements for complex autonomous decisions to be made.

10.3.1 Cognitive radio as a Means of Enabling New Modes of Spectrum Access

Traditionally, access to spectrum has been managed in a limited number of ways. Most spectrum has been organised on the basis of some form of exclusive access. Typically, licenses are granted to licensees by a variety of mechanisms (beauty contents, auction, administrative incentive pricing schemes, etc.) and only the licensee can use the specific spectrum. In contrast to this approach, a commons-like approach in which access to the spectrum is open to all (on the proviso that certain rules are followed) has also been in operation. The best known example of this is the ISM band. In the ISM band all devices wishing to transmit can do so provided a certain power level is not exceeded. Cognitive radio has long been seen as an enabler of many more varied and nuanced forms of spectrum access. More specifically, it has been seen as a key technology in the drive towards dynamic forms of spectrum access and spectrum sharing. The term dynamic spectrum access (DSA) can be used to encompass all kinds of spectrum access regimes that do not involve static assignments of access rights but call for the identification of opportunities for using spectrum either that others (i.e.,primary users) are not occupying or through some sort of regime that allows spectrum

[6] Wilkins,D.; Denker,G.; Stehr,M.O.; Elenius,D.; Senanayake,R.; Talcott,C., "Policy Based Cognitive Radios,"WirelessCommunications, IEEE , vol.14, no.4, pp.41,46, August 2007

[7] S. Haykin, Cognitive Radio: Brain-empowered wireless communications, IEEE Journal on Selected Areas in Communications, Special Issue on Cognitive Networks, vol. 23, pp. 201-220, February 2007

to be assigned when needed and subsequently relinquished.[8] The use of the TV white spaces can be seen as a very slow form of dynamic spectrum access. The TVWS device ascertains what spectrum is available in a given area and uses that spectrum - i.e., the TVWS devices do not have static assignments of spectrum. Additionally the TVWS device shares with all other TVWS devices that choose to use the same spectrum. Hence, it is a non-exclusive shared flavour of dynamic spectrum access.[9] In this case the primary user/incumbent is afforded a specific level of protection.

Over the past number of years more nuanced forms of sharing have come to the front. The 2012 PCAST report [10] from the FCC suggests a broad framework for a tiered model of shared-access of Federal spectrum. In this spectrum management model there are three tiers of access; Federal Primary Access, Secondary Access and General Authorised Access (GAA). The Federal Primary Access users register their actual deployments within a database. These Federal Primary Access users enjoy full exclusive use of their assigned spectrum but do not have the right to block others from using it, if they themselves are not using it. Secondary Access (SA) users are issued with short-term access rights and must also register in the database. These rights give them certain guarantees of levels of service and assure them protection from interference from the lowest users in the tiered access model. The final and lowest layer of the hierarchy is the General Authorised Access (GAA) tier. GAA usage is purely opportunistic, and hence this tier of users only gets assigned whatever frequencies are left over at any given time and in any given location. It is clear that there is a role for cognitive radio if any of these ideas were to become reality. Currently, the PCAST report remains a set of aspirations though the FCC has released as "notice for proposed rule making" for the 3.5 GHz bands in the USA which embrace a lot of the PCAST concepts.

In resonance with some of the approaches in the PCAST report, concepts such as Licensed Shared Access (LSA) have also been gaining traction. This approach to sharing spectrum was initially proposed by an industry consortium under the name Authorised Shared Access (ASA) and currently the term ASA tends to be used in the USA and LSA in Europe. The LSA framework sees the initial licensed user or users, i.e., the incumbents, sharing their spectrum with one or more new users who may be offering the same service or a different one, according to conditions imposed on both the incumbent and new user. It can be seen as a type of highly controlled sharing and not hugely different in concept from some of the concepts mentioned in the PCAST report. The EU's approved Radio Spectrum Policy Programme endorsed the LSA concept and CEPT is fleshing out the details of how such a system would work in practice, both within the confines of technology and with the confines of the European Treaties [11].

It can be reasonably argued that the main motivation for dynamic spectrum access and spectrum sharing has always been the so-called *spectrum crunch*. The term spectrum crunch is used to emphasise the scarcity

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8. Note DSA does not necessarily imply unlicensed access.

9. In exclusively shared systems, a network will dynamically get a spectrum assignment for a given period of time for its own exclusive use.

10. President's Council of Advisors on Science and Technology. Realizing the Full Potential of Government-Held Spectrum to Spur Economic Growth. July 2012.

11. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committe of the Regions, Promoting the shared use of radio spectrum resources in the internal market. September, 2012.

of the spectrum resource. There are numerous graphs forecasting the explosive growth of future mobile data [12]. A plethora of measurements exist to highlight the fact that assigned spectrum is not always used efficiently and effectively by the licensee and hence (exclusive or non-exclusive) sharing can alleviate the pressure on the resources. A second and also very powerful motivation for sharing comes from a more political *open spectrum* perspective. Open spectrum advocates promote freer and easier access to spectrum and believe that much like in the ISM band new forms of innovation will follow and most importantly opportunity for new players, including smaller entities, will emerge. In this context, sharing is seen as a means of gaining access to a resource that is central to any wireless communication system and gaining access to a resources that is typically limited to a number of powerful controlling entities. A third motivation is the fact that *sharing is the new clearing*. Clearing refers to the moving of incumbents out of specific bands and in most cases this is done to allow the emptied bands to be auctioned for exclusive usage. Clearing can be a costly and slow process. In some cases incumbents must be paid to move to other bands. And typically nothing happens in a band until all the incumbents have moved. The times involved can vary from years to decades. Sharing can be seen as a dynamic form of clearing. Figure 10.2 explains how. Initially a strong vibrant service is in operation in a band. As the need for this service wanes or because of the existence of large amounts of idle capacity within the band, sharing can be permitted (on a hierarchical basis, for example). Over time it may be the case that the incumbent needs increasingly less spectrum - either as mentioned already because the needs for the service reduces, or as for example in the case of Digital TV, more effective use of the spectrum is made. Roles may then be reversed. Using the terminology of primary and secondary user, the primary incumbent starts as a primary and exclusive user, subsequently permits sharing with a secondary system on some kind of hierarchical basis, over time both become equal sharers of the band and finally the secondary becomes the new primary as its services gain popularity and the old primary assumes secondary status as its popularity decreases until it finally dies out. Taking this approach means that there is a constant recycling of bands.

10.3.2 *Cognitive Radio as an Enabler of Autonomous System Configuration and Management*

A cognitive radio, or possibly more correctly a network of cognitive radios, can be considered to be a self-organising system. The network can understand the context it finds itself in and can configure itself in response to a given set of requirements, in an autonomous fashion. The configuration need not just focus on frequency issues, such as dynamic spectrum access, and can involve many other features of the network such as power, beam pattern, routing algorithm in use, cod-

[12] http://www.cisco.com/en/US/solutions/collateral/ns341/ns525/ns537/ns705/ns827/whitepaperc11-520862.pdf

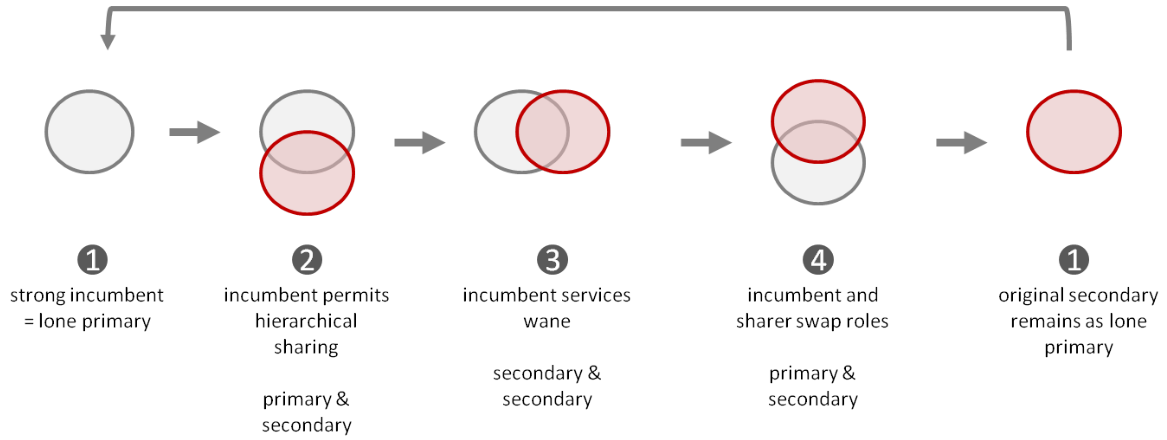

Figure 10.2: Sharing is Clearing

ing techniques, filtering techniques, etc. However, an element of spectrum management is likely to feature in many configuration processes. Looked at from this self-organising point of view, we can say that any communication application that requires a radio or network of radios to self-organise can justifiably make use of a cognitive radio. We can consider the need for autonomous self-configuration within more traditional communication systems. Consider for example an LTE-A system. The reality is that the number of parameters (knobs) which can be set in such a system is vast. Variable parameters include numbers of antennas in use, multiple-input, multiple-output (MIMO) mode, modulation, power, frequency, scheduling options, number of frequency bands that are aggregated, spatial configuration of primary and serving cells associated with the aggregated spectrum among many others. It seems infeasible that the true potential of LTE-A networks can be achieved without some advanced decision-making and optimization based on contextual information. Hence, it is possible to argue that the realization of LTE-A systems, whether explicitly labelled as such or not, will need some elements of cognition to function. Context will have to be determined through observation of the environment (meters) and the many parameters (knobs) configured (with the help of a cognitive engine) to suit the context, as per Figure 10.1 (c). Taken from this perspective cognitive radio is a natural part of the roadmap for future mobile communication systems. The same argument can be made in the context of the self-organisation of large numbers of small cells and other user deployed infrastructure that cannot depend on centrally coordinated human intervention. We can also consider autonomous system configuration in the context of any system using spectrum dynamically. It naturally goes hand-in-hand with the requirement to seek out spectrum opportunities and configure appropriately to exploit those opportunities. In addition, cognitive networks sharing the same spectrum must act like autonomous interference management systems to co-exist with one and another.

10.4 ARE THE DRIVERS OF COGNITIVE RADIO DIFFERENT FOR AFRICA?

We return now to focus on the specifics of Africa. The key question that arises is whether the drivers for cognitive radio remain the same or whether there are others that might be relevant or even if there is an absence of drivers in the African context.

10.4.1 Africa and New Modes of Spectrum Access

In terms of an enabler of new modes of access to spectrum the question firstly arises as to whether there is or will be a spectrum crunch in Africa. On the grand scale of things, the simple answer must be no, as a large proportion of the population remains unconnected. There is much to be done in Africa to enable basic connectivity for large percentages of the population. In addition, it could be argued that there are many other techniques that can be exploited before cognitive radio is called on to squeeze more efficiency out of the spectrum. To build a counter argument to this we should focus on the fact that in the developed world spectrum has been managed into scarcity. In other words its scarcity is more due to how it is managed than anything else. The many measurements which show vast tracts of idle spectrum substantiate this point. The highly static nature of the spectrum management regimes and the historical tendency to regulate for 'how technologies work now' rather than 'how technologies could work in the future' are at fault. Rather than wait for a similar situation to eventually build in Africa, it could make sense to proactively regulate for more dynamic forms of spectrum access and sharing for when these approaches are eventually needed. Africa is the most rapidly urbanizing region on the planet. Though the vast bulk of the mobile technology in Africa is based on GSM with movement to 3G continuing, there are LTE deployments planned for 14 countries in Africa.[13] There are around 8 networks in service. While the deployment of LTE is highly limited it does at least flag that there is an increase in pace in the take-up of new technologies. Around 350 000 Huawei IDEOs Android handsets were sold in the first six months in Kenya since its launching in January 2011. While the smart phone is beyond the means of the vast majority of Africans this number is a large number for a country where 40% of the population live on less than $2 a day, and indicates an appetite for data and new services. Reiterating the point about regulating for the future, there is no reason not to plan and regulate for the kinds of dynamic and sharing situations that cognitive radio enables rather than wait to respond when it becomes necessary. In addition, as mentioned in section III-A, the facilitation of sharing ultimately supports clearing. It may of course seem extravagant to be discussing long

[13] These numbers are based on http://ltemaps.org/home/ as of July 2013.

term regulation plans when there are so many pressing challenges in enabling connectivity in Africa. Jensen provides an excellent summary of the many challenges in Chapter 2 of the book Accelerating Development Using the Web: Empowering Poor and Marginalized [14]. The challenges range from regulatory to practical such as the lack of internet interconnection points or to challenges relating to power supply and off-grid issues to the lack of content in specific languages and education. In that chapter Jenson also points out that, '*The decline of the small Internet provider continues, especially in developing countries where mobile providers are taking most of the consumer market share. When combined with the ongoing consolidation of fixed and mobile operators, their massive economies of scale and ownership of the delivery media leaves fewer niches for small providers, who have been largely relegated to countries where local-loop unbundling has taken place.*' He also provides a set of ten points for action that should be taken to address the technical challenges around access. These include (a) increase competition in the market, (b) implement infrastructure sharing for providers and (c) liberate more radio spectrum for broadband. These suggestions resonate strongly with the more open approaches to spectrum sharing (enabled through cognitive radio) which can provide a means of gaining access to, as stated earlier, a resource that is central to any wireless communication system and that is traditionally monopolised by a number of powerful controlling entities. To set the wider context Safari.com has 78% of the mobile market in Kenya and 18% of the country's GDP flows through that company. It is vital that alternative forces can come into play, in Kenya and elsewhere in Africa. The wide deployment of WiFi is largely because of the fact that it uses unlicensed spectrum and its low cost. This has spurred many schemes and innovative approaches in Africa. However, ultimately a mix of frequencies are needed (lower for longer distances) and more generally there is a need for increased access to spectrum. And while Jenson's call to implement infrastructure sharing was meant mainly in the context of cellular networks, cognitive approaches can enable much more advanced forms of sharing, and cognitive networks can lend themselves very well to virtualisation, which can be the basis of extreme forms of sharing.

10.4.2 *Africa and the need for Autonomous System Configuration and Management*

The second key driver for cognitive radio, as described in section III-B, is based on the fact that cognitive radio facilitates the making of autonomous decisions, of self-configuration etc. This kind of functionality bodes well for scenarios in which operational costs (OPEX) need to be kept to a minimum. In addition, returning to Figure 10.1 (c) for a moment, the objective function of the cognitive system can be one that takes power consumption as well as communication related issues into

[14] Michael Jenson, Chapter 2: Technical Access Issues, in Accelerating Development Using the Web: Empowering Poor and Marginalized, George Sadowsky, ed. Published by the World Web Foundation, May 2012 http://public.webfoundation.org/publications/accelerating-development/

account. Hence cognitive radio can be exploited to make best use of scarce energy as well as spectral resources. Depending of the sophistication of the cognitive system, behavioural patterns can be learned and the network can be adjusted to take these into account. It is already the case that existing systems perform 'semi-cognitive' like functions. For example, there are communication systems such as those from Altobridge, which recognise when traffic is local and do not waste resources by directing the traffic back to the core network only to have to re-emerge it again locally. Using cognitive radio language, these systems can be described as making observations about traffic, making decisions on how to respond and subsequently taking actions regarding the redirection of the traffic. While a simple example, it is illustrative of the trends that are emerging and the opportunities for increasingly cognitive capabilities. Perhaps the most potent area in which the autonomous, self-configuring functionality of a cognitive radio might bear fruit is in the context of backhaul. This links with the previous section, section 10.4.1, on new modes of spectrum access as it is predicated on the notion that access to spectrum becomes easier and more plentiful. In the last decade there has been improved connectivity in terms of fibre connections being brought to Africa. There are huge challenges in connecting users with these fibre backbones. There is still very limited fibre within the continent. There is also the usual problem of urban centres being much better catered for than suburban and rural areas. Wireless backhaul has to be a key enabler of connectivity - i.e., a means of connecting users to the fibre infrastructure. It is more competitive from a price perspective as it does not incur the costs associated with trenching etc. There is no reason why large tracts of spectrum could not be made available to provide wireless backhaul services. Suppose for a moment, as a thought experiment, that all and any spectrum were deemed usable for backhaul (except for argument's sake the spectrum belonging to mobile operators) BUT on a dynamic basis and of course on the premise that no harmful interference is experienced by legacy systems. In other words the balance would be tipped from a world in which the status quo is about exclusive rights to one in which the vast majority of access is non-static or dynamic. It is possible to envisage a series of dynamic links, criss-crossing Africa, that self-configure while managing interference to protects incumbents, making the most of any spectral assets that can be used. There are whole areas in Africa in which there may be no incumbents to avoid in the first place and in the longer term a dynamic system will allow for much flexibility should assigned but unused spectrum made available. In summary, the autonomous self-configuring functionality of a cognitive system could, in theory, be ideally suited to solving key challenges in Africa provided that regulations are put in place to exploit the opportunity.

10.5 THE ISSUES OF COST

It is not possible to tackle the issue of cognitive radio and Africa without addressing the issue of cost. Most people will reasonably argue that cognitive radios are expensive radios. Typically, these radios are frequency agile and hence have more sophisticated RF frontends. In addition, they can have complex processing capabilities, especially if learning is included. Many of the sharing paradigms envisage the requirement for some sort of database, typically an advanced version of what is needed for TV white space databases. In fact, cognitive radio is considered expensive in the developed world even before developing world incomes and other challenges are considered. While progress is being made on the reduction in cost of smart phones, for example, which would bode well for the future of cognitive radio, there are still many challenges. Again, even before considering cognitive radio, LTE is seen as hugely expensive technology whose cost of deployment is not warranted in many places in Africa. Hence it seems reasonable to assume that even if cognitive radio can facilitate spectrum sharing and perhaps reduce barriers to entry for new players or provide the kinds of autonomous behaviour that could be essential in remote areas of Africa, it would remain prohibitively expensive for the long-term future. There are some dissenting voices however, and it is worth airing these to provide a fuller picture. Marhsall has long contended that *cognitive radio can be a cheaper radio*. In [15] and [16] he argues that a new business case is possible. His main argument is built around the notion that linearity and filtering in the RF front ends are the drivers of cost. Typically, linearity is essential for high dynamic range. His work shows that non-cognitive radio systems have significant 3rd Order Intermodulation noise increase, even for high performance filters. Cognitive radios, which use dynamic spectrum access techniques and can therefore have a choice about the spectrum bands they use, can operate in a manner that ensure that intermodulation products do not become an issue. Marshall has shown that cognitive radio can enable a 30 dB reduction in required IIP3 performance, while creating a lower noise floor simultaneously, even for moderate filter selectivity (20%) therefore saving on costs. An unrelated work, but relevant in terms of explaining the concepts that underpin this approach is [17]. In essence Marshall argues to re-think RF design, leveraging the smarts of the radio to make a low cost front end. Fettweis and his team take a somewhat connected approach under the heading *Dirty RF*[18]. They point out that building compact and low-cost but flexible and reconfigurable radios for future wireless systems is generally a challenging task. The trade-offs between using flexible hardware and at the same time trying to keep radios as small and power efficient as possible while at the same time exploiting multiple antenna techniques means that various imperfections and impairments surface in the radio transceivers, especially in the radio frequency (RF) analogue electronics. Examples of the imperfections are, e.g., mirror-frequency interference due to I/Q imbalance,

[15] Marshall,P.F.,"Dynamic Spectrum Management of Front End Linearity and Dynamic Range, "New Frontiers in Dynamic Spectrum Access Networks", 2008. DySPAN 2008. 3rd IEEE Symposium on , vol., no., pp.1,12, 14-17 Oct. 2008

[16] Marshall, P.F.,Quantitative Analysis of Cognitive Radio and Network Performance (Mobile Communications) (Artech House Mobile Communications), June 2012

[17] Marshall, P.F., Scalability, Density, and Decision Making in Cognitive Wireless Networks, Cambridge University Press, December 2012.

[18] Fettweis, G.; Lohning, M.; Petrovic, D.; Windisch, Marcus; Zillmann, P.; Rave, W., "Dirty RF: a new paradigm," Personal, Indoor and Mobile Radio Communications, 2005. PIMRC 2005. IEEE 16th International Symposium on , vol.4, no., pp.2347,2355 Vol. 4, 11-14 Sept. 2005

non-linear distortion due to mixer and amplifier nonlinearities, timing jitter and non-linearities in sampling and analogue-to- digital (A/D) converter circuits, and oscillator phase noise. Fettweis et al, stress that if these impairments are not properly understood and taken into account, they can easily become a limiting factor to the quality and performance of the radio device and thereon of the whole wireless link. Their approach is to use baseband processing algorithms to compensate for the impairments. They show that by knowing the statistical properties of impairments in the analogue front-end and using powerful digital baseband processing, future wireless communications systems may be able to cope with dirty RF. They extend the transmission rate by joint optimization of RF components and baseband processing - opening the path for high performance devices at reasonable cost. While this work does not explicitly reference cognitive radio it implicitly does - a radio can self-profile, have an in-depth awareness of its own flaws and can correct those flaws through appropriate techniques. Without a doubt the term low-cost and reasonable-cost are relative. However, the work described here does challenge conventional wisdom and at least postulate that there are different ways of doing things. This work shifts the perspective. Rather than build systems that are highly tuned to certain bands, with strict filtering requirements and high-level performance that pushes the cost up, it is possible to use lower cost entities and compensate for their performance in different ways. It is an entirely different mindset but one that could ultimately unlock new possibilities.

10.6 CONCLUSIONS

Cognitive radio is an area in which much academic work has taken place in the past decade. It can be seen as part of the natural progression of radios, i.e., they simply get smarter and therefore a natural part of a future roadmap for LTE-A for example. Seen in this manner cognitive technologies will eventually become part and parcel of many future communications systems and eventually be deployed in Africa as much as anywhere else. However, as a key enabler of dynamic spectrum access and new forms of spectrum sharing, cognitive radio may also have a more powerful role to play in underpinning communication systems that are outside the traditional domain of the large operators and provide opportunities for different players. They also have a role to play in providing the level of robust autonomous behaviour that is needed in remote areas. The cost, as for most technologies, remains a significant factor. However, there is work which can contribute to the creation of lower cost systems. While the challenges of cost matter more in Africa, there is no reason why Africa cannot be a role model or take a leadership position in at least regulating for a dynamic future. Whatever the timescale for deployment of more flexible, cognitive and dynamic systems elsewhere in the world or within Africa, it is worth bearing the longer term in mind when regulating.