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Kayange, Daniel

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Daniel Sinkonde Kayange[1], Elisha Oketch Ochola[2], Anael Sam[1], Ramadhani Sinde[1]

School of Computational and Communications Science and Engineering[1], Nelson Mandela-African Institute of Science and Technology (NM-AIST)[1], Arusha[1], Tanzania[1]; School of Computing[2], University of South Africa[2], Pretoria[2], South Africa[2].

kayanged@nm-aist.ac.tz[1]; ocholeo@unisa.ac.za[2]; anael.sam@nm-aist.ac.tz[1]; ramadhani.sinde@nm-aist.ac.tz[1]

ABSTRACT

This paper describes the survey approach to building a high-quality of dynamic Spectrum access (DSA) and management in vehicular environment networks in Tanzania as one of the ways of mitigating the shortage of access. Frequency spectrum is a limited resource for wireless communications and may become congested owing to a need to accommodate the diverse types of air interface used in wireless networks. The objective of this paper is to meet these growing demands by provide a brief overview of the cognitive radio technology. The paper explains the existing work and challenges in spectrum sensing. It describes the next network functionalities: spectrum management, spectrum mobility and spectrum sharing and further explains how next network functions can be implemented.

KEYWORDS: ***COGNITIVE RADIO; FREQUENCY SELECTION; DYNAMIC SPECTRUM; ACCESS NETWORKS; TANZANIA.***

CONCLUSION

This paper provides an overview of the most important ongoing research and emerging applications in the DSA-area. It provides general awareness on developments in the telecommunication sector and its potential contribution to national development. It provides education about developments in the telecommunications sector, particularly on Dynamic Spectrum Access (DSA) and Management in Vehicular Environment. Some recommendations that will help the wider spread use of DSA systems include: (i) High-level political and managerial decision (including Government and private sector), commitment and leadership for the immediate promotion and application of DSA operations. (ii) Clarification of the legal, policy-making activities and ethics in the DSA-area.

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I. Introduction

The increasing demand for high-end multimedia services especially in the vehicular environment, driven by the car traffic density and the increasing amount of time spent within the vehicles, the cellular penetration and the growing adaptation to new technologies and data services, represent challenging issues for mobile communication. In fact, cognitive radio based on dynamic spectrum access has emerged as a new design pattern for next generation wireless networks. Cognitive radio aims at maximizing the utilization of the limited radio bandwidth while accommodating the increasing number of services and applications in wireless networks. The driving force behind this cognitive radio technology is the new spectrum licensing pattern initiated by the FCC, which will be more flexible to allow unlicensed (or secondary) users to access the spectrum as long as the licensed (or primary) users are not interfered with. This new spectrum licensing pattern will improve the utilization of the frequency spectrum and enhance the performance of wireless systems. Dynamic spectrum access (DSA) or opportunistic spectrum access (OSA) is the key approach in a cognitive radio network which is adopted by a cognitive radio user to access the radio spectrum opportunistically. Development of dynamic spectrum access-based cognitive radio technology has to deal with technical and practical considerations as well as regulatory requirements. Therefore, there is increasing interest in this technology from researchers in both academia and industry, and engineers in the wireless industry, as well as from spectrum policy makers.

Today's wireless networks are regulated by a fixed spectrum assignment policy, i.e. the spectrum is regulated by governmental agencies (Tanzania Communication Regulatory Authority) and is assigned to license holders or services on a long term basis for large geographical regions.

II. Cognitive Radio

Cognitive radio technology is the key emerging technology that enables the wireless communication and networking, to use spectrum in a dynamic manner. The term, cognitive radio, can formally be defined as follows (1):

A ''Cognitive Radio'' is a radio that can change its transmitter parameters based on interaction with the environment in which it operates.

From this definition, two main characteristics of the cognitive radio can be defined (2, 3):

- ***Cognitive capability***: Cognitive capability refers to the ability of the radio technology to capture or sense the information from its radio environment. This capability cannot simply be realized by monitoring the power in some frequency band of interest but more sophisticated techniques are required in order to capture the temporal and spatial variations in the radio environment and avoid interference to other users. Through this capability, the portions of the spectrum that are unused at a specific time or location can be identified. Consequently, the best spectrum and appropriate operating parameters can be selected.
- ***Reconfigurability:*** The cognitive capability provides spectrum awareness whereas reconfigurability enables the radio to be dynamically programmed according to the radio environment. More specifically, the cognitive radio can be programmed to transmit and receive on a variety of frequencies and to use different transmission access technologies supported by its hardware design (4) before. Since most of the spectrum is already assigned, the most important challenge is to share the licensed spectrum without interfering with the transmission of other licensed users as illustrated in Fig. 1. The cognitive radio enables the usage of temporally unused spectrum, which is referred to as spectrum hole or white space (2). If this band is further used by a licensed user, the cognitive radio moves to another spectrum hole or stays in the same band, altering its transmission power level or modulation scheme to avoid interference.

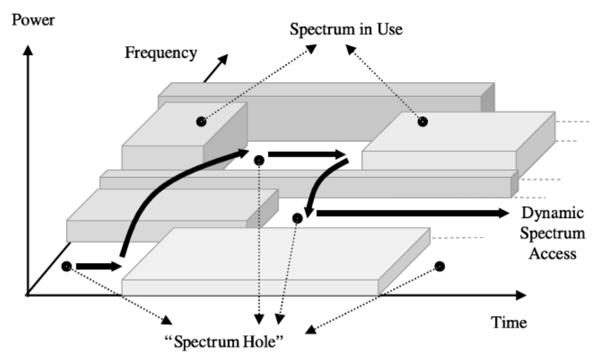

Fig. 1. Spectrum hole concept.

A. Physical Architecture of the Cognitive Radio

A generic architecture of a cognitive radio transceiver is shown in Fig. 2 (5). The main components of a cognitive radio transceiver are the radio front-end and the baseband processing unit. Each component can be reconfigured via a control bus to adapt to the time-varying RF environment. In the RF front-end, the received signal is amplified, mixed and A/D converted. In the baseband processing unit, the signal is modulated/demodulated and encoded/decoded. The baseband processing unit of a cognitive radio is essentially similar to existing transceivers. However, the novelty of the cognitive radio is the RF front-end. Hence, the next focus is on the RF front-end of the cognitive radios.

The novel characteristic of cognitive radio transceiver is a wideband sensing capability of the RF front-end. This function is mainly related to RF hardware technologies such as wideband antenna, power amplifier, and adaptive filter. RF hardware for the cognitive radio should be capable of turning to any part of a large range of frequency spectrum. Similarly, such spectrum sensing enables real-time measurements of spectrum information from radio environment. Generally, a wideband front-end architecture for the cognitive radio has the following structure as shown in Fig. 3 (6).

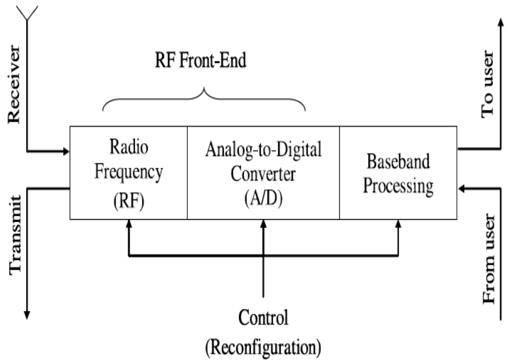

Fig. 2. Physical architecture of the cognitive radio (6, 7): Cognitive radio transceiver

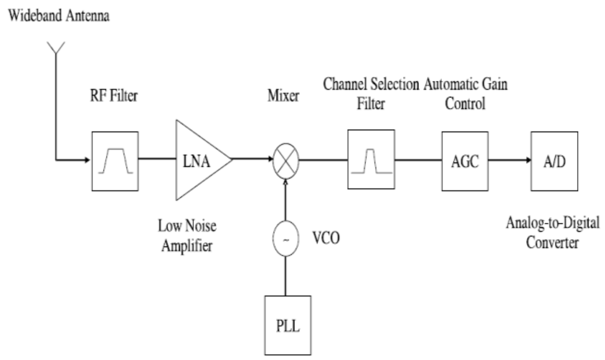

Fig. 3. Physical architecture of the cognitive radio (6, 7): wideband RF/analog front-end architecture.

The components of a cognitive radio RF front-end are as follows:

- ***RF filter***: The RF filter selects the desired band by band pass filtering the received RF signal.
- ***Low noise amplifier (LNA):*** The LNA amplifies the desired signal while simultaneously minimizing noise component.
- ***Mixer:*** In the mixer, the received signal is mixed with locally generated RF frequency and converted to the baseband or the intermediate frequency (IF).
- ***Voltage-controlled oscillator (VCO):*** The VCO generates a signal at a specific frequency for a given voltage to mix with the incoming signal. This procedure converts the incoming signal to baseband or an intermediate frequency.
- ***Phase locked loop (PLL):*** The PLL ensures that a signal is locked on a specific frequency and can also be used to generate precise frequencies with fine resolution.
- ***Channel selection filter:*** The channel selection filter is used to select the desired channel and to reject the adjacent channels. There are two types of channel selection filters (8); the direct conversion receiver uses a low-pass filter for the channel selection, while on the other hand, the super heterodyne receiver adopts a band pass filter.
- ***Automatic gain control (AGC):*** The AGC maintains the gain or output power level of an amplifier constant over a wide range of input signal levels.

In this architecture, a wideband signal is received through the RF front-end, sampled by the high speed analog-to-digital (A/D) converter, and measurements are performed for the detection of the licensed user signal. However, there exist some limitations on developing the cognitive radio front-end.

The wideband RF antenna receives signals from various transmitters operating at different power levels, bandwidths, and locations. As a result, the RF front-end should have the capability to detect a weak signal in a large dynamic range. However, this capability requires a multi-GHz speed A/D converter with high resolution, which might be infeasible (6, 9).

The requirement of a multi-GHz speed A/D converter necessitates the dynamic range of the signal to be reduced before A/D conversion. This reduction can be achieved by filtering strong signals. Since strong signals can be located anywhere in the wide spectrum range, tunable notch filters are required for the reduction (6). Another approach is to use multiple antennas such that signal filtering is performed in the spatial domain rather than in the frequency domain. Multiple antennas can receive signals selectively using beam forming techniques (9). As explained previously, the key challenge of the physical architecture of the cognitive radio is an accurate detection of weak signals of licensed users over a wide spectrum range. Hence, the implementations of RF wideband front-end and A/D converter are critical issues in next networks.

B. Cognitive Capability

The cognitive capability of a cognitive radio enables real time interaction with its environment to determine appropriate communication parameters and adapt to the dynamic radio environment. The tasks required for adaptive operation in open spectrum are shown in Fig. 4 (2, 10, 11), which is referred to as the cognitive cycle. In this section, we provide an overview of the three main steps of the cognitive cycle: spectrum sensing, spectrum analysis, and spectrum decision.

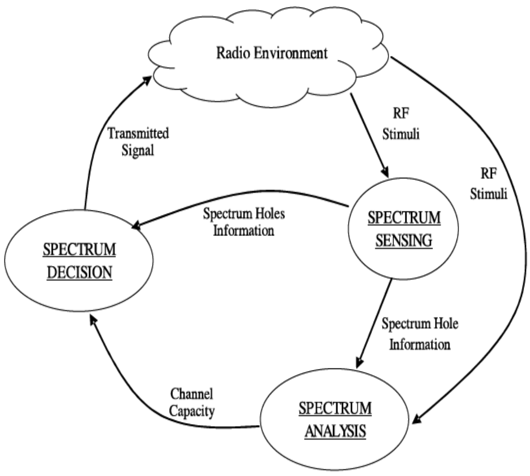

Fig. 4. Cognitive cycle.

The steps of the cognitive cycle as shown in Fig. 4 are as follows:

- ***Spectrum sensing:*** A cognitive radio monitors the available spectrum bands, captures their information, and then detects the spectrum holes.
- ***Spectrum analysis:*** The characteristics of the spectrum holes that are detected through spectrum sensing are estimated.
- ***Spectrum decision:*** A cognitive radio determines the data rate, the transmission mode, and the bandwidth of the transmission. Then, the appropriate spectrum band is chosen according to the spectrum characteristics and user requirements.

Once the operating spectrum band is determined, the communication can be performed over this spectrum band. However, since the radio environment changes over time and space, the cognitive radio should keep track of the changes of the radio environment. If the current spectrum band in use becomes unavailable, the spectrum mobility function that will be explained in Section 4, is performed to provide a seamless transmission. Any environmental change during the transmission such as primary user appearance, user movement, or traffic variation can trigger this adjustment.

C. Reconfigurability

Reconfigurability is the capability of adjusting operating parameters for the transmission on the fly without any modifications on the hardware components.

This capability enables the cognitive radio to adapt easily to the dynamic radio environment. There are several reconfigurable parameters that can be incorporated into the cognitive radio (12) as explained below:

- ***Operating frequency:*** A cognitive radio is capable of changing the operating frequency. Based on the information about the radio environment, the most suitable operating frequency can be determined and the communication can be dynamically performed on this appropriate operating frequency.
- ***Modulation:*** A cognitive radio should reconfigure the modulation scheme adaptive to the user requirements and channel conditions. For example, in the case of delay sensitive applications, the data rate is more important than the error rate. Thus, the modulation scheme that enables the higher spectral efficiency should be selected. Conversely, the loss-sensitive applications focus on the error rate, which necessitate modulation schemes with low bit error rate.
- ***Transmission power:*** Transmission power can be reconfigured within the power constraints. Power control enables dynamic transmission power configuration within the permissible power limit. If higher power operation is not necessary, the cognitive radio reduces the transmitter power to a lower level to allow more users to share the spectrum and to decrease the interference.
- ***Communication technology:*** A cognitive radio can also be used to provide interoperability among different communication systems.

The transmission parameters of a cognitive radio can be reconfigured not only at the beginning of a transmission but also during the transmission. According to the spectrum characteristics, these parameters can be reconfigured such that the cognitive radio is switched to a different spectrum band, the transmitter and receiver parameters are reconfigured and the appropriate communication protocol parameters and modulation schemes are used.

III. Spectrum Management

The regulatory framework for management of the radio spectrum resource can in many ways be seen as a historical description of the development of radio. The international regulations as found in the ITU (International Telecommunication Union) Radio Regulations have traces from the earliest days of radio. Over time, the national and international frameworks have been amended to enable new use of the radio spectrum. As a result of history and the technical evolution, the national and international frameworks are an organized patchwork of different generations of regulation and solutions. One of the prevailing thoughts is that allocations on international level are made for infinity or at least for a very long time. This makes it more and more difficult for new generations of radio technologies to enter the stage.

In some instances the “refarming” tool has been used to free up underused or unused spectrum for new applications. The situation has over history been fairly successful since radio applications have been designed for a specific frequency band, often in close relation between national regulators, international organisations, equipment manufacturers and the monopolistic operators in each national market.

When discussing the regulatory framework for radio spectrum it is important to describe the difference between two main processes in spectrum management, namely allocation and assignment. Allocation is the process of allocating a piece of spectrum to a specific use or service, assignment is the process of assigning licenses to use the spectrum to a specific user. The allocation of spectrum is mainly done in the international arena, whilst the assignment of licenses is mainly a national concern.

The regulations of the radio spectrum can be seen as a three layered pyramid, where the three layers are global, regional and national. At the global level, the framework is governed by the Radio Regulations (RR) which is under the control of the International Telecommunications Union's Radio communications Sector (ITU-R). The Radio Regulations provide an overall global framework for the use of spectrum. In the RR, the radio spectrum is allocated to certain use or services, examples are fixed, mobile, broadcasting or Radio navigation. The RR has status of international treaty, thus the national administrations are required to comply with the terms. The main application of the RR is in national border areas to ensure that the use of radio spectrum in one country does not cause interference to users in another country. Given this, there is an element of flexibility in the use of radio spectrum as long as interference is not caused in another country.

At the regional level, there are in Europe, two main paths for spectrum management, The European Union (EU) and the European Conference of Postal and Telecommunications Administrations (CEPT). On the EU-level, initiatives are taken under the Spectrum Decision (13) and other directives under the EU Framework for Electronic Communications1. In some cases, specific harmonization measures may constrain national authorities in how spectrum is used through harmonisation of frequencies. The Electronic Communications framework has been, or is being integrated into national legislation in all EU member states. Directives and decisions from the EU based on the directives are mandatory for member states.

The CEPT is an organization of 45 member states. The CEPT has set up the Electronic Communications Committee (ECC). The ECC brings together the radio and telecommunications regulatory authorities of the CEPT member states. The ECC makes decisions and develops recommendations on the use of radio spectrum in the member states. The national adoption and implementation of decisions and recommendations is optional.

Nationally, there are a number of national rules, laws and regulations regarding the use of spectrum that govern the national allocation and assignment of licenses.

Apart from the regulatory framework for the allocation and assignment of spectrum, there is also regulation on different levels when it comes to the placing on the market and the use of equipment using the spectrum.

A. Existing Trends in Spectrum Management

Over the last decade the markets for electronic communication have been opened up to competition and the relation between regulators, operators and developers of the equipment is no longer as close as it has been. The technical development is generally heading in the direction of smarter and more adaptable systems and solutions. One of the main drivers behind this development is the perceived scarcity of spectrum for new technology.

In a recent report (14)the European commission concluded the following regarding spectrum management:

"All radio-based devices use the radio spectrum to transmit or receive information. The use and therefore the value of the radio spectrum has dramatically increased in recent years, as wireless applications have been very successful in addressing many of society's changing needs, such as for mobility and for data transmission. But spectrum availability is also critical for many other applications, e.g. for accurate weather forecasting, radio astronomy, air and maritime safety, broadcasting and for devices simplifying everyday life such as remote controls and hearing aids.

Because of possible interference between different radio services operating in the same or adjacent frequencies, access to the radio spectrum has historically been closely regulated. Spectrum management has long been seen as a "technical" domain dealing with the avoidance of harmful interference and the technical optimization of spectrum use. More recently, it has been identified as a means of generating public revenues in proportion to a perceived "spectrum scarcity" value. However, a long-term, policy-based approach to the management of this resource aiming at fostering innovation and the introduction of increasingly added-value applications could capture much greater overall benefits for society."

The general development in the spectrum management world is towards increased flexibility and a more liberalized approach to the assignment and management of spectrum. This said, the processes are slow and the hurdles are high.

Some of the hot topics in spectrum management at the moment are:

- ***Flexibility*** – how can licenses be made more flexible. There are two different flavors of flexibility currently on the agenda, namely the market oriented approach and the technical liberalization. The two flavors can be seen as two sides of the same coin, and in many cases the one requires the other.
- ***Market oriented approach*** – in the market oriented approach to flexibility lays the aim to make licenses and the values of licenses visible, and to create a market for

the natural resource spectrum. One potential goal of a market oriented approach is the property rights model, whereby a license holder actually owns the spectrum. The license is indefinite in tenure and the spectrum can, under a limited interference and power level rulebook, be used for whatever purpose the license holder wants.

- ***Technical liberalization*** - the technical aspect of flexibility includes the removal of unnecessary restrictions on licenses to enable a wider use. Such restrictions can include non-radio related obligations, references to services, standards and systems etc. The topic of flexibility includes a number of different dimensions.
- ***Secondary trading*** – the possibilities to sell, buys, rent or lease a license. Secondary trading can be introduced under an ex ante (beforehand) approval regime or under an ex post (after the fact) regime. The ex-post regime would in most cases be equal or similar to general competition law.
- ***Reconfiguration*** – the possibility to reconfigure a license in time, geography and frequency. With reconfiguration a licensee can for example sell unused spectrum in a region or buy additional spectrum for popular services.
- ***Change of use*** – the possibility to change the use of a license outside the limitations given in the license. This could include the changing from fixed services to mobile services, from broadcasting to mobile use etc.
- ***Digitalization*** – more and more services are being digitalized. To name a few, mobile services have gone from 1G analogue system to 2G digital system; Digital television is being introduced, etc. Digitalization is interesting since many old legacy systems are being replaced by standardized systems with known interfaces. One interesting example of the results of digitalization is the potential to free up spectrum for new areas of use. This is a major discussion in the digitalization of broadcasting. As a result of the potential to free up spectrum through the digitalization of broadcasting, the so called digital dividend has been identified. The planning of digital broadcasting will to some extent be made technology neutral and thus enable the use of non-broadcasting solutions in broadcasting bands.
- ***Technology neutrality*** – in recent year's technology neutrality has become an important aspect of assigning licenses. Under previous regimes, spectrum for new services has very often been pinpointed to a system, a technology, a standard etc. Rather than allocating a piece of spectrum internationally for e.g. GSM which was made through an EU-directive, spectrum is allocated to enable different types of services.
- ***License exemption*** – in recent years, the proliferation of services using license exempt frequencies is apparent. The success of license except spectrum is one of the major trends in spectrum management.
- ***Harmonized flexibility*** – the notion of harmonized flexibility is to some extent driving the international discussions on increased liberalization. The boundaries of harmonization are being explored and harmonization will in the future become more open and technology neutral. In order to maintain some level of harmonization, to achieve economies of scale and to avoid complete fragmentation the methods and framework for flexibility will have to be harmonized in some way.

B. Current Initiatives and Trends in Spectrum Management

The traditional model for spectrum management and the assignment of licenses is often referred to as the "command and control" model, whereby the SMA (Spectrum Management Authority) awards licenses to specific applications and to a specific license holder under a non-interference regime, the licenses are assigned exclusively and for a limited time. The restrictions on the license are based on internationally developed standards and interference calculations.

Over the last decade, new models for spectrum management have emerged internationally, namely the commons model and the market model. Furthermore, relaxations have in many instances been made in the command and control model.

The regulatory challenges ahead are generally in the direction of increased flexibility. This transition is towards leaving more of the decision making to the users of spectrum rather than predefining the use and the framework based on rigid technical limitations in old "dumb" radio systems. The main problem is however not going in that general direction, the main challenge is that many of the different flavors of flexibility cannot be combined at the same time. A commons model cannot be combined with any level of exclusivity with regards to interference, thus these different models (commons and command & control) are in direct conflict. Furthermore, frequencies that have been assigned to license exempt use are very difficult, if not impossible to remodel to host other types of systems that require some level of non-interference.

One of the main tasks for spectrum managers in the future is to balance the demand for spectrum under the three different models:

- There will be for an unforeseen period of time, a need for certain radio based applications to be under a strict command and control regime, examples are aviation and certain satellite applications.
- The demand for more spectrums for the commons model will be on the increase for quite some time to come.

- The demand for liberalization of the use of spectrum is relatively high in many bands and for a number of applications.

C. Current Trends in Spectrum Management in Tanzania

Tanzania has a fully competitive telecommunications sector. There are two fixed-line operators and seven operational mobile networks, with four additional players licensed. The national fixed telephone operators are the TTCL and Zantel. They also offer national and international mobile telephone services. The TTCL fixed-line network has been digital since 2004. However, teledensity for fixed-line has remained extremely low, with only around 300,000 lines installed and many out of service. The TTCL offers Integrated Services Digital Network (ISDN) with Basic Rate Interface, Primary Rate Interface as well as ADSL broadband services.

TABLE I. TELECOM COMPANIES IN TANZANIA

Network Operator	Fixed line/Cable service	Technology Deployed	Company strategies
TTCL	Yes - copper Cables; leased lines; basic POTS; ADSL; SDSL.	Mobile & Fixed Wireless: CDMA (3G) Coverage area: At first major cities, later to cover the whole country	Major strategy: voice access and backbone provision. National and international calling; Internet access, International gateway license; video on demand in the future
Airtel Tanzania	No	GSM 900/1800/400; GPRS, EDGE, 3G	Mainly voice; carrier of carriers
TiGo (MIC Tanzania Limited)	No	GSM 900/1800, plans for 3G	Voice services; data transfer
Vodacom Tanzania	No	GSM 900/1800, plans for 3G roll out by 2007 (frequency allocated)	Yes – spectrum guaranteed by regulator for 3.5 GHz. Targeting data transfer for corporate sector - major cites
ZanTel Tz	Yes	GSM 900/1800 – planning for 3G CDMA – Dar Es Salaam, Zanzibar, Pemba National roaming agreement with Vodacom on the mainland	Yes

D. Mobile Coverage in Spectrum Management

Mobile telephone service has been liberalized since its introduction in Tanzania. There are seven active operators: TTCL, Zantel, Vodacom, Zain, Tigo, BoL and Sasatel, and two new applicants. The arrival of the Seacom submarine cable in Dar Es Salaam has stimulated new interest and mobile operators are ready to invest in infrastructure to facilitate speedy exploitation of the availed broadband. It is evident that Tanzania had not made adequate plans and preparation for the rollout of the marine cable to the rest of the country. Zain, for example, was ready to invest in laying down the national backbone or lease it from the government to speed up the process. It is now clear that the government is laying down the national backbone in collaboration with telephone operators.

Several mobile company operators, employing the CDMA technology licensed under CLF since 2007, are now becoming operational after setting up requisite infrastructure, administrative and other supportive requirements.

IV. SPECTRUM MOBILITY

Spectrum mobility is the Process by which a cognitive-radio user changes its frequency of operation. Cognitive-radio networks aim to use the spectrum in a dynamic manner by allowing radio terminals to operate in the best available frequency band, maintaining seamless communication requirements during transitions to better spectrum

In cognitive wireless network, spectrum mobility occurs when the current channel performance deteriorates or licensed user appears. Cognitive users communicate on temporal “spectrum holes”. The appearance and departure of licensed users and channel quality deterioration are both random, which lead to random appearance and departure of spectrum holes. That is to say, as time passes by, the available spectrum may be constantly shifting. Cognitive users must make spectrum handoff to maintain its communication (15).

A. Control Channels

Common channels can be accessed both by idle mode and dedicated mode mobiles. The common channels are used by idle mode mobiles to exchange the signaling information required to change to dedicated mode. Mobiles already in dedicated mode monitor the surrounding base stations for handover and other information. The common channels are defined within a 51-frame multiframe, so that dedicated mobiles using the 26-frame multiframe TCH structure can still monitor control channels. The common channels include: Broadcast Control Channel (BCCH): Continually broadcasts, on the downlink, information including base station identity, frequency allocations, and frequency-hopping sequences.

Frequency Correction Channel (FCCH) and Synchronization Channel (SCH): Used to synchronize the mobile to the time slot structure of a cell by defining the boundaries of burst periods, and the time slot numbering. Every cell in a GSM network broadcasts exactly one FCCH and one SCH, which are by definition on time slot number 0 (within a TDMA frame). Random Access Channel (RACH): Slotted Aloha channel used by the mobile to request access to the network. Paging Channel (PCH): Used to alert the mobile station of an incoming call. Access Grant Channel (AGCH): Used to allocate an SDCCH to a mobile for signaling (in order to obtain a dedicated channel), following a request on the RACH.

B. GSM Frame and Bust Structure

Each of the eight users for a full-rate channel utilizes one of the 200-kHz channels and occupies a unique time slot per frame. Each time slot consists of 156.25 bits, out of which 8.25 bits are used for guard time and 6 are the start and stop bits that are used to prevent overlap with adjacent time slots. Each time slot is 0.57692ms. Figure 10 shows normal bust (time slot). Only 148 bits are transmitted at a rate of 270.833 kbps. A single full-rate GSM frame contains 8 time slots with time duration of 4.615 ms and 1250 bits. The frame rate is 216.667 frames/s. The 13^{th} and 25^{th} frames are not used for traffic, but for control purposes.

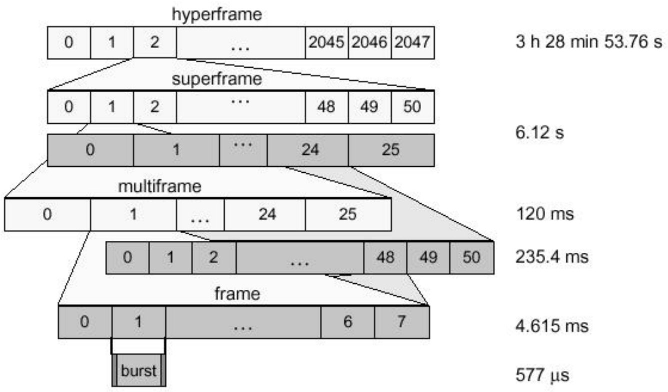

Fig. 10. GSM Frame Hierarchy.

GSM uses five different types of the bursts: normal burst, synchronization burst, frequency correction burst, access burst, and dummy burst. The normal burst is used to carry data and most signaling. It has a total length of 156.25 bits, made up of two 57 bit information bits, a 26 bit training sequence used for equalization, 1 stealing bit for each information block (used for FACCH), 3 tail bits at each end, and an 8.25 bit guard sequence, as shown in Fig. 10. The 156.25 bits are transmitted in 0.577 ms, giving a gross bit rate of 270.833 kbps.

C. GSM Frequency Channel Allocation

A variety of channel assignment strategies have been developed to achieve the objectives of increasing capacity and minimizing interference. Main channel assignment strategies are fixed, dynamic and hybrid.

- **Fixed Channel Allocation (FCA)**

In the FCA strategy a set of nominal channels is permanently allocated to each cell for its exclusive use. Here a definite relationship is assumed between each channel and each cell, in accordance to co-channel reuse constraints.

- **Dynamic Channel Allocation (DCA)**

In DCA all channels are kept in a central pool and are assigned dynamically to radio cells as new calls arrive in the system. After a call is completed, its channel is returned to the central pool. In DCA, a channel is eligible for use in any cell provided that signal interference constraints are satisfied. The main idea of all DCA schemes is to evaluate the cost of using each candidate channel, and select the one with the minimum cost provided that certain interference constraints are satisfied, because, in general, more than one channel might be available in the central pool to be assigned to a cell that requires a channel.

- **Hybrid Channel Allocation**

Hybrid channel assignment schemes are a mixture of the FCA and DCA techniques. In HCA, the total number of channels available for service is divided into fixed and dynamic sets. The fixed set contains a number of nominal channels that are assigned to cells as in the FCA schemes and, in all cases, are to be preferred for use in their respective cells. The second set of channels is shared by all users in the system to increase flexibility. When a call requires service from a cell and all of its nominal channels are busy, a channel from the dynamic set is assigned to the call. The channel assignment procedure from the dynamic set follows any of the DCA strategies. Variations of the main HCA schemes include

D. Dynamic Frequency Selection

Standards that incorporate DFS define various requirements for the detection of radars using the following terms.

- ***Channel Availability Check Time***: The time a system shall monitor a channel for presence of radar prior to initiating a communications link on that channel. This is also referred to by the acronym CAC.
- ***Interference Detection Threshold***: The minimum signal level, assuming a 0 dBi antenna that can be detected by the system to trigger the move to another channel.
- ***Channel Move Time:*** The time for the system to clear the channel, and is measured from the end of the radar burst to the end of the final transmission on the channel.
- ***Channel Closing Transmission Time:*** The total, or aggregate, transmission time from the system during the channel move time.
- ***Non-Occupancy Time:*** A period of time after radar is detected on a channel that the channel may not be used.
- ***Master Device:*** Device that has radar detection capabilities and can control other devices in the network

(e.g. an Access Point would be considered a master device)

- ***Client Device:*** Device that does not initiate communications on a channel without authorization from a master device (e.g. a laptop Wi-Fi card – note that a Wi-Fi card that supports ad-hoc mode would be considered a master device)
- ***Radio Local Area Network (RLAN) or Wireless Local Area Network (WLAN):*** Generic terms for wireless systems such as 802.11a and 802.11n that operate in the 5GHz unlicensed bands.
- ***Uniform Loading or Uniform Spreading:*** A requirement in many DFS standards to achieve a uniform loading across the available spectrum over a number of devices. It can be achieved by random channel selection in a single device (such as an access point used in a home) or planned selection by a management tool over a large number of devices (such as a coordinated series of networks in a campus).

The operation of a system with Dynamic Frequency Selection capability takes the sequence in Fig. 11.

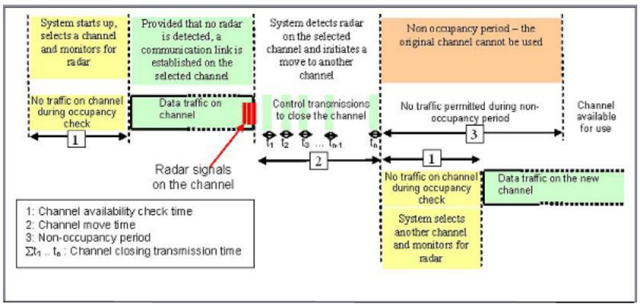

Fig. 11. Dynamic Frequency Selection.

The master device selects a channel and monitors that channel for potential radar interference for a minimum listening time (channel availability check time). No transmissions can occur during this period. If interference is detected then the system has to go and select another channel and repeat the channel availability check on the new channel (the original channel is added to a list of channels with radar).

Once a channel has been selected and passes the channel availability check interference, the network starts to use that channel. While using the channel, the network's master device continuously monitors for potential interference from a radar source (this is referred to as in-service monitoring). If interference is detected then the network master device issues commands to all other in-network devices to cease transmissions. The channel is added to the list of channels with radar and the master device then selects a new channel (one that is not on the list). The sequence starts again with a channel availability check.

While master devices are required to employ interference detection capabilities, client device generally only need to be capable of responding to the master device's instructions to clear the channel. This means that client devices cannot employ active scanning techniques to find a network but must rely on passive scanning (listen-only) to find a network to join.

Point-to-point communication links operating in the DFS bands need to consider the implications of the radar interference potential at one end of the link, which will be very different from the interference potential at the other end of the link. For this reason it is expected that both ends of the link should be performing radar detection functions. The ETSI technical report TR 102 651 V1.1.1 (21) provides additional guidance in implementing a DFS strategy for various wireless network configurations.

To evaluate the DFS functions of a system the regulatory standards describe waveforms to be used when evaluating DFS. These waveforms are defined in terms of the number of pulses, the pulse width and the pulse repetition frequency (or period) for the radar signal. The pulses may be modulated with an FM chirp, and may contain pulses of different widths and different periods. Manufacturers should always bear in mind that their radar detection algorithms should be designed to detect all radar systems.

V. SPECTRUM SHARING TECHNIQUES

A. What is Spectrum Sharing?

Spectrum sharing is not a universal trend for all regulators nor are the approaches taken similar for all regulators. Spectrum-sharing models are fairly diverse worldwide. In its simplest form, it involves leasing of a given quantum of airwaves within a licensed service area for a mutually agreed period. The quantum of airwaves taken on lease is available to other licensee for the period of lease and can be most optimally used for network design and affordable services.

Spectrum sharing encompasses several techniques – some administrative, technical and market-based. Sharing can be accomplished through licensing and/or commercial arrangements involving spectrum leases and spectrum trading. Spectrum can also be shared in several dimensions; time, space and geography. Limiting transmit power is also a factor which can be utilized to permit sharing. Low power devices in the spectrum commons operate on the basis of that principal characteristic: signal propagation which takes advantage of power and interference reduction techniques. Spectrum sharing can be achieved through technical means using evolving advanced technologies such as cognitive radio.

A common issue for both innovative technologies and market-based methods is arriving at the right balance. Resolving interference issues inherent in methods based on the principle of technological neutrality is an issue of great importance. Interference cannot be eliminated and so identifying interference management models which support spectrum sharing under either administrative, market-based or spectrum commons, remain as an ongoing requirement and challenge for spectrum managers.

The spectrum sharing in networks can be mainly classified in three aspects: architecture assumption, spectrum allocation behavior, and spectrum access technique as shown in Fig. 12.

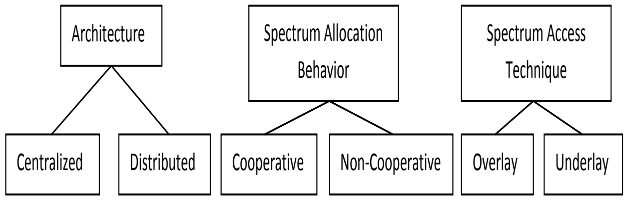

Fig. 12. Classification of spectrum sharing.

In this section, we describe these three classifications and present the fundamental results that analyze these classifications. The analysis of the network spectrum sharing techniques has been investigated through two major theoretical approaches. While some work uses optimization techniques to find the optimal strategies for spectrum sharing, game theoretical analysis has also been used in this area.

The first classification for spectrum sharing techniques in next networks is based on the architecture, which can be described as follows:

- ***Centralized spectrum sharing:*** In these solutions, a centralized entity controls the spectrum allocation and access procedures (22). With aid to these procedures, generally, a distributed sensing procedure is proposed such that each entity in the next network forwards their measurements about the spectrum allocation to the central entity and this entity constructs a spectrum allocation map.
- ***Distributed spectrum sharing***: Distributed solutions are mainly proposed for cases where the construction of an infrastructure is not preferable (23-25) accordingly, each node is responsible for the spectrum allocation and access is based on local (or possibly global) policies.

B. Why do we need to Share Spectrum?

The role of wireless communications is becoming increasingly important in providing fixed and mobile broadband coverage and capacity. In the fixed sector, wireless can provide broadband connectivity to premises that are too remote to utilise metal pairs or fibre. In the mobile sector, cell sizes are becoming smaller to cope with increasing capacity. Predictions of growth of data rates and in numbers of connected devices are increasing over time; strong growth in the mobile telecommunication data rates towards the year 2020 was reported by the International Telecommunication Union Radio communication (ITU-R) sector in 2005 in (26), whereas later predictions for the next decade (2012-2022) in (27) show even stronger growth. Wireless needs to cope with this growth and so far has been achieving this through two mechanisms, namely the shrinking of cell sizes and usage of more spectrum. Whereas these two can be traded to an extent, unavoidably the increasing data rate requirements will lead to increasing spectrum demand (28, 29), which will be challenging under the current spectrum regulatory framework. Another estimate from the Wireless World Research Forum (WWRF) is that 7 trillion devices will serve 7 billion people 24 hours 7 days a week until 2017 (30).

Today's spectrum usage is largely licensed access, while only a small part of the spectrum uses licence-exempt equipment. With licensed access, operators can acquire spectrum with sole governance over the bands and deploy communication networks to carry a range of services with predictable quality of service (QoS). The amount of licensed spectrum that could be made available for communications in the future is limited by the unavailability of unallocated spectrum, especially below 2GHz. In the license-exempt bands, such as the 2.4 GHz industrial, scientific and medical (ISM) band, the users need to fulfill a set of criteria to facilitate coexistence of different systems on the same band which in practice means limited transmission power levels and hence reduced coverage. Thus, the ability of license-exempt bands to satisfy the growing data rate demand in the future is limited to short range deployments without predictable QoS due to interference from other uncoordinated users.

In parallel, the spectral efficiency of wireless systems in terms of achievable throughput per system bandwidth in bits/s/Hz has been improved significantly by the development of IMT-Advanced systems (31). In the future, there will be less room for improvement in the spectral efficiency due to the natural limits of wireless communications. Another dimension in the spectrum use is the spectrum occupancy which characterises the utilization rate of a frequency band (32). The spectrum occupancy dimension can offer more room for improvements by facilitating coexistence of different systems on bands where the current spectrum occupancy is low. In fact, several general spectrum occupancy measurement studies covering a wide range of frequency bands have indicated that there are large portions of frequencies with very little usage. Focused spectrum occupancy studies on selected frequency bands have highlighted this in more detail showing that there indeed is room for more efficient sharing.

In order to meet the growing data rate requirements of the mobile telecommunication market towards 2020, future mobile communication systems will need to find new ways to access spectrum in addition to the current licensed and licence-exempt approaches. A promising approach to respond to the growing traffic predictions is to develop efficient spectrum sharing techniques that could allow fixed and mobile systems to operate on new spectrum bands whose current occupancy is low. Indeed, spectrum sharing can be estimated as being equivalent to the acquisition of extra spectrum, the usage of which yields major economic benefits. It is in general believed that spectrum sharing, in particular when considering wireless broadband, could significantly boost the EU economy and bring additional social benefits to Europe's citizens (33).

In line with the Radio Spectrum Policy Programme (RSPP), the European Commission has published a Communication on 'Promoting the shared use of radio spectrum resources in the EU' in September 2012. It highlights the importance of technologies that can share radio frequencies as well as the need to create incentives and legal certainty for innovators in the internal market(34).

The sharing of spectrum can also offer benefits in terms of energy saving. One way this can be achieved is through sharing a lower frequency part of the spectrum than would otherwise be used in a non line-of-sight situation where the penetration loss is less and therefore lower transmit power is required. Another way is if there is a portion of spectrum that is currently not used, that spectrum could be utilized by another existing system to allow for that system to provide greater capacity per deployed base station. This could allow the system in question to reduce its number of active base stations, enabling power saving modes for some of its base stations thereby saving energy (35). Of course, such solutions can be considered in tandem with offloading of users between networks in order to enable power saving modes (36). In the case of licensed spectrum, such possibilities would require an agreement between the licensees of the spectrum bands as well as a reliable mechanism/protocol to be established for the temporary exchange of spectrum access rights. In the case of unlicensed spectrum access, such sharing of course is routine.

Finally, spectrum sharing can also assist realisation of capacity demands. In fact, energy saving potential through spectrum sharing and its potential to increase capacity can be traded-off for one another. Even if similar long-term averages in traffic load persist between networks, statistical fluctuations in the number of users at any one time between networks can be significant. This can allow for spectral reorganisation and sharing of spectrum from the lightly-loaded network to a heavily loaded network, or the offloading of users between the networks. Both have the effect of increasing achievable capacity at given time. This concept can be applied also to the spatial dimension, taking advantage of differences in spatial distributions of traffic. In this sense, it may also be extended to cases such as where some networks or spectrum are newly deployed or recently acquired, and therefore lightly loaded at an initial stage. Much of this spectrum could be shared in order to maximize capacity in collocated networks, or users could be offloaded to these new networks in order to increase capacity. Such ideas concur with the concept of "Authorized Shared Access" (ASA) (37), whereby a spectrum owner may allow opportunistic access to its spectrum that is locally unused, or indeed another form sharing of its unused spectrum, for a fee. This facilitates the spectrum licensee extracting income from the spectrum, even if its network is not yet fully deployed.

Sharing discussed in this paper would apply either to opportunistic secondary spectrum access, or to organized sharing between licensees with an established underlying mechanism and agreement. The use of solutions such as opportunistic secondary spectrum access requires careful guarding against issues such as the potential for mobility and shadowing unpredictability to cause missed detection hence interference to the spectrum licensee.

C. Spectrum Sharing Techniques in Next Network

The second classification for spectrum sharing techniques in next network is based on the access behavior:

- ***Cooperative spectrum sharing:*** Cooperative (or collaborative) solutions consider the effect of the node's communication on other nodes (38-41) In other words, the interference measurements of each node are shared among other nodes. Furthermore, the spectrum allocation algorithms also consider this information. While all the centralized solutions can be regarded as cooperative, there also exist distributed cooperative solutions.
- ***Non-cooperative spectrum sharing:*** Contrary to the cooperative solutions, non-cooperative (or non-collaborative, selfish) solutions consider only the node at hand (24, 25, 42). These solutions are also referred to as selfish. While non-cooperative solutions may result in reduced spectrum utilization, the minimal communication requirements among other nodes introduce a tradeoff for practical solutions.

These two solutions have generally been compared through their spectrum utilization, fairness, and throughput. The utilization and fairness in spectrum access has been investigated in (43), where the spectrum allocation problem is modeled as a graph coloring problem and both centralized and distributed approaches are investigated. Using this model, an optimization framework is developed. In this framework, secondary users allocate channels according to the interference that will be caused by the transmission. Both cooperative and non-cooperative approaches are considered such that cooperative approaches also consider the effect of the channel allocation on the potential neighbors. The simulation results show that cooperative approaches outperform non-cooperative approaches as well as closely approximating the global optimum. Moreover, the comparison of centralized and distributed solutions reveals that distributed solution closely follows the centralized solution. A similar analysis has also been provided in (44), where the effects of collaboration in spectrum access are investigated. An important assumption in these works is that secondary users know the location and transmit power of primary users so that the interference calculations can be performed easily. However, such an assumption may not always be valid in next networks.

Game theory has also been exploited for performance evaluation of next spectrum access schemes. Especially, the comparison between cooperative and non-cooperative approaches has been presented in (45) through game theoretical analysis. In (45), game theory is exploited to analyze the behavior of the cognitive radio for distributed adaptive channel allocation. It is assumed that users deploy CDMA and determine the operating channel and the coding rate by keeping transmission power constant. It is shown that the cooperative case can be modeled as an exact potential game, which converges to a pure strategy Nash equilibrium solution. However, this framework has been shown not to be applicable for non-cooperative spectrum sharing and a learning algorithm has been proposed. The evaluations reveal that Nash equilibrium point for cooperative users is reached quickly and results in a certain degree of fairness as well as improved throughput. On the other hand, the learning algorithms for non-cooperative users converge to a mixed strategy allocation. Moreover, the fairness is degraded when non-cooperative approach is used. While this approach results in slightly worse performance, the information exchange required by selfish users is significantly low.

The third classification for spectrum sharing in next networks is based on the access technology as explained below:

- ***Overlay spectrum sharing:*** Overlay spectrum sharing refers to the spectrum access technique used. More specifically, a node accesses the network using a portion of the spectrum that has not been used by licensed users (25, 38, 39, 41, 42). As a result, interference to the primary system is minimized.
- ***Underlay spectrum sharing:*** Underlay spectrum sharing exploits the spread spectrum techniques developed for cellular networks (40). Once a spectrum allocation map has been acquired, an next node begins transmission such that its transmit power at a certain portion of the spectrum is regarded as noise by the licensed users. This technique requires sophisticated spread spectrum techniques and can utilize increased bandwidth compared to overlay techniques.

The effects of underlay and overlay approaches in a cooperative setting are investigated in (46) where non-cooperative users are analyzed using a game theoretical framework. Using this framework, it is shown that frequency division multiplexing is optimal when interference among users is high. As a result, the overlay approach becomes more efficient than underlay when interference among users is high. The lack of cooperation among users, however, necessitates an overlay approach. The comparative evaluations show that the performance loss due to the lack of cooperation is small, and vanishes with increasing SNR. However, in this framework, the cost and inaccuracies of information exchange between users are not considered.

Another comparison of underlay and overlay approaches is provided in (47). The comparison is based on the influence of the secondary system on the primary system in terms of outage probability and three spectrum sharing techniques have been considered. The first technique (spreading based underlay) requires secondary users to spread their transmit power over the full spectrum such as CDMA or Ultra Wide Band (UWB). The second technique (interference avoidance overlay) requires nodes to choose a frequency band to transmit such that the interference at a primary user is minimized. Also, an hybrid technique (spreading based underlay with interference avoidance) is investigated where a node spreads its transmission over the entire spectrum and also null or notch frequencies where a primary user is transmitting. Consequently, first, the interference statistics for each technique are determined for outage probability analysis. Then, the outage probability for each technique is derived assuming no system knowledge, perfect system knowledge, and limited system knowledge. Similar to other existing work, when perfect system knowledge is assumed, the overlay scheme outperforms the underlay scheme in terms of outage probability. However, when interference avoidance is incorporated into spectrum sharing, the underlay scheme with interference avoidance guarantees smaller outage probability than the pure interference avoidance. In a more realistic case, when limited system knowledge is considered, the importance of the hybrid technique is exacerbated. The overlay schemes result in poor performance due to imperfections at spectrum sensing. More specifically, a node can transmit at a channel where a primary user is transmitting. However, when underlay with interference avoidance is used, the interference caused to the primary user is minimized. Another important result is that a higher number of secondary users can be accommodated by the hybrid scheme than the pure interference avoidance scheme.

The theoretical work on spectrum access in next networks reveals important tradeoffs for the design of spectrum access protocols. As expected, it has been shown that cooperative settings result in higher utilization of the spectrum as well as fairness. However, this advantage may not be so high considering the cost of cooperation due to frequent information exchange among users. On the other hand, the spectrum access technique, i.e., whether it is overlay or underlay, affects the performance in each setting. While an overlay technique focuses on the holes in the spectrum, dynamic spreading techniques are required for underlay techniques for interference free operation between primary and secondary systems. Considering the tradeoff between system complexity and performance, hybrid techniques may be considered for the spectrum technique. In the following section, we explain the existing spectrum sharing techniques that are combinations of the three classifications we have discussed in this section.

D. Inter-network Spectrum Sharing

This setting enables multiple systems being deployed in overlapping locations and spectrum as shown in Fig. 13. Hence, spectrum sharing among these systems is an important research topic in next networks. Up to date, inter-network spectrum sharing has been regulated via static frequency assignment among different systems or centralized allocations between different access points of a system in cellular networks. In ad-hoc networks, only the interference issues in the ISM band has been investigated focusing mostly on the coexistence of WLAN and Bluetooth networks. Consequently, intra-network spectrum sharing in next networks poses unique challenges that have not been considered before in wireless communication systems. In this section, the recent work in this research area is overviewed.

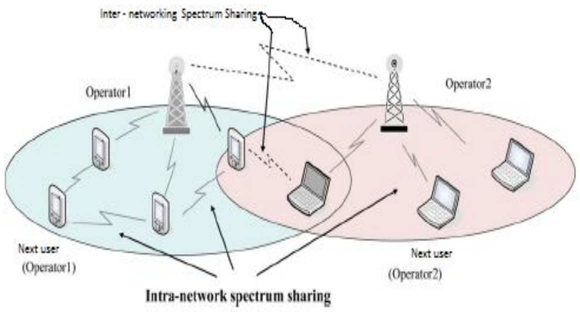

Fig. 13. Inter-networking and intra-network spectrum sharing in network.

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REFERENCES

1. FCC E. Docket No 03-222. Notice of proposed rule making and order, December 2003.
2. Haykin S. Cognitive radio: brain-empowered wireless communications. Selected Areas in Communications, IEEE Journal on. 2005;23(2):201-20.
3. Tang H, editor. Some physical layer issues of wide-band cognitive radio systems. New Frontiers in Dynamic Spectrum Access Networks, 2005 DySPAN 2005 2005 First IEEE International Symposium on; 2005: IEEE.
4. Van der Perre L. Software Defined Radios.
5. Akyildiz IF, Lee W-Y, Vuran MC, Mohanty S. A survey on spectrum management in cognitive radio networks. Communications Magazine, IEEE. 2008;46(4):40-8.
6. Cabric D, Mishra SM, Brodersen RW, editors. Implementation issues in spectrum sensing for cognitive radios. Signals, systems and computers, 2004 Conference record of the thirty-eighth Asilomar conference on; 2004: IEEE.
7. Dubey R, Sharma S, editors. Distributed shared spectrum techniques for cognitive wireless radio networks. Computational Intelligence and Communication Networks (CICN), 2010 International Conference on; 2010: IEEE.
8. Razavi B, Behzad R. RF microelectronics: Prentice Hall New Jersey; 1998.
9. Cabric D, Brodersen RW, editors. Physical layer design issues unique to cognitive radio systems. Personal, Indoor and Mobile Radio Communications, 2005 PIMRC 2005 IEEE 16th International Symposium on; 2005: IEEE.
10. Mitola J. Cognitive radio: An integrated agent architecture for software defined radio. Doctor of Technology, Royal Inst Technol(KTH), Stockholm, Sweden. 2000:271-350.
11. Thomas RW, Friend DH, DaSilva LA, MacKenzie AB. Cognitive networks: Springer; 2007.
12. FCC E. Docket No 03-222 Notice of proposed rule making and order. December; 2003.
13. Commission E. Information Society and Media Directorate-General, Radio Spectrum Committee,"Opinion of the RSC pursuant to Article 4.2 of Radio Spectrum Decision 676/2002/EC", RSCOM08-06final, April 2008.
14. EU DI. ITS 15TH BIENNIAL CONFERENCE.
15. Liu H-j, Wang Z-x, Li S-f, Yi M, editors. Study on the performance of spectrum mobility in cognitive wireless network. Communication Systems, 2008 ICCS 2008 11th IEEE Singapore International Conference on; 2008: IEEE.
16. Goldsmith A. Wireless communications, 2005. Cambridge University Press.
17. Mat DAA, Kho F, Joseph A, Kipli K, Sahrani S, Lias K, et al., editors. Electromagnetic radiation from mobile phone near ear-skull region. Computer and Communication Engineering (ICCCE), 2010 International Conference on; 2010: IEEE.
18. Laiho J, Wacker A, Novosad T. Radio network planning and optimisation for UMTS: Wiley; 2006.
19. Rahnema M. Overview of the GSM system and protocol architecture. Communications Magazine, IEEE. 1993;31(4):92-100.
20. Garg V. Wireless Communications & Networking: Morgan Kaufmann; 2010.
21. Briggs M. Dynamic Frequency Selection (DFS) and the 5GHz Unlicensed Band. 2010.

22. Zekavat SA, Li X, editors. User-central wireless system: ultimate dynamic channel allocation. New Frontiers in Dynamic Spectrum Access Networks, 2005 DySPAN 2005 2005 First IEEE International Symposium on; 2005: IEEE.
23. Zhao J, Zheng H, Yang G-H, editors. Distributed coordination in dynamic spectrum allocation networks. New Frontiers in Dynamic Spectrum Access Networks, 2005 DySPAN 2005 2005 First IEEE International Symposium on; 2005: IEEE.
24. Zhao Q, Tong L, Swami A, Chen Y. Decentralized cognitive MAC for opportunistic spectrum access in ad hoc networks: A POMDP framework. Selected Areas in Communications, IEEE Journal on. 2007;25(3):589-600.
25. Zheng H, Cao L, editors. Device-centric spectrum management. New Frontiers in Dynamic Spectrum Access Networks, 2005 DySPAN 2005 2005 First IEEE International Symposium on; 2005: IEEE.
26. Ohmori S, Yamao Y, Nakajima N. The future generations of mobile communications based on broadband access technologies. Communications Magazine, IEEE. 2000;38(12):134-42.
27. Dahlman E, Parkvall S, Skold J, Beming P. 3G evolution: HSPA and LTE for mobile broadband: Access Online via Elsevier; 2010.
28. Takagi H, Walke BH. Spectrum requirement planning in wireless communications: Model and methodology for IMT-Advanced: John Wiley & Sons; 2008.
29. Hashimoto A, Yoshino H, Atarashi H. Roadmap of IMT-advanced development. Microwave Magazine, IEEE. 2008;9(4):80-8.
30. Jefferies N, editor. WWRF setting the research agenda for the wireless world. Int Conf On Beyond 3G Mobile Communications; 2008.
31. Yang Y, Hu H, Xu J, Mao G. Relay technologies for WiMAX and LTE-advanced mobile systems. Communications Magazine, IEEE. 2009;47(10):100-5.
32. Spaulding A, Hagn GH. On the definition and estimation of spectrum occupancy. Electromagnetic Compatibility, IEEE Transactions on. 1977(3):269-80.
33. Kai J, Crosland A. Perspectives of people with enduring mental ill health from a community-based qualitative study. The British Journal of General Practice. 2001;51(470):730.
34. Cave M. New spectrum-using technologies and the future of spectrum management: a European policy perspective. artículo en línea] Ofcom[Fecha consulta: 23 de mayo 2010]< http://stakeholders.ofcom.org uk/binaries/research/research-publications/section4.pdf. 2006.
35. Holland O, Friderikos V, Aghvami AH, editors. Green spectrum management for mobile operators. GLOBECOM Workshops (GC Wkshps), 2010 IEEE; 2010: IEEE.
36. Aijaz A, Holland O, Pangalos P, Aghvami H, editors. Energy savings for cellular access network through Wi-Fi offloading. Communications (ICC), 2012 IEEE International Conference on; 2012: IEEE.
37. Nolan K, Doyle L. Applications and Opportunities for Cognitive Radio and Networks. 2012.
38. Brik V, Rozner E, Banerjee S, Bahl P, editors. DSAP: a protocol for coordinated spectrum access. New Frontiers in Dynamic Spectrum Access Networks, 2005 DySPAN 2005 2005 First IEEE International Symposium on; 2005: IEEE.
39. Cao L, Zheng H, editors. Distributed spectrum allocation via local bargaining. Proc IEEE SECON; 2005.
40. Huang J, Berry RA, Honig ML, editors. Spectrum sharing with distributed interference compensation. New Frontiers in Dynamic Spectrum Access Networks, 2005 DySPAN 2005 2005 First IEEE International Symposium on; 2005: IEEE.
41. Ma L, Han X, Shen C-C, editors. Dynamic open spectrum sharing MAC protocol for wireless ad hoc networks. New Frontiers in Dynamic Spectrum Access Networks, 2005 DySPAN 2005 2005 First IEEE International Symposium on; 2005: IEEE.
42. Sankaranarayanan S, Papadimitratos P, Mishra A, Hershey S, editors. A bandwidth sharing approach to improve licensed spectrum utilization. New Frontiers in Dynamic Spectrum Access Networks, 2005 DySPAN 2005 2005 First IEEE International Symposium on; 2005: IEEE.
43. Peng C, Zheng H, Zhao BY. Utilization and fairness in spectrum assignment for opportunistic spectrum access. Mobile Networks and Applications. 2006;11(4):555-76.
44. Zheng H, Peng C, editors. Collaboration and fairness in opportunistic spectrum access. Communications, 2005 ICC 2005 2005 IEEE International Conference on; 2005: IEEE.
45. Nie N, Comaniciu C, editors. Adaptive channel allocation spectrum etiquette for cognitive radio networks. New Frontiers in Dynamic Spectrum Access Networks, 2005 DySPAN 2005 2005 First IEEE International Symposium on; 2005: IEEE.
46. Etkin R, Parekh A, Tse D. Spectrum sharing for unlicensed bands. Selected Areas in Communications, IEEE Journal on. 2007;25(3):517-28.
47. Menon R, Buehrer RM, Reed JH, editors. Outage probability based comparison of underlay and overlay spectrum sharing techniques. New Frontiers in Dynamic Spectrum Access Networks, 2005 DySPAN 2005 2005 First IEEE International Symposium on; 2005: IEEE.

ABOUT THE AUTHORS

Daniel Sinkonde Kayange was born in 1976 Dar es Salaam, Tanzania. He received a B.E. degree in Electronics and Communications Engineering from St. Joseph College of Engineering and Technology - Dar es Salaam, Tanzania in 2008. Currently he is pursuing a Master degree in Information and Communications Science and Engineering at Nelson Mandela-African Institute of Science and Technology, Arusha. His current research interests include available bandwidth estimation techniques for an efficient telemedicine content transport network. He also works as a Tutorial Assistant at Mbeya University of Science and Technology, Tanzania. Mr. Kayange is a registered Engineer in The United Republic of Tanzania.

Elisha Oketch Ochola received his BSc. (Hons.) in Computer Science degree from Egerton University, Kenya, in 2004. He received double masters' degrees in Electronic Engineering (MSc. in Electronic Engineering) and Electrical Engineering (MTech. Telecommunication Technology) from *Ecole Supérieure d'Ingénieurs en Electronique et Electrotechnique (ESIEE),* France, and Tshwane University of Technology (TUT), South Africa, respectively in 2008. He is a senior lecturer and advancing a PhD in Computer Science at University of South Africa (UNISA), South Africa. His research interests include routing protocol development, power consumption management, and security in Mobile Ad-hoc Networks (MANETs).