4

Dynamic Spectrum Management and mm-WAVES

Radio spectrum is a prime factor in driving the growth of mobile services. The success of 5G network is based on the unconstrained availability of spectrum. About 1200 MHz of spectrum in the frequency bands below 5 GHz has been identified for IMT services during World Administrative Radio Conference (WARC)-92, World Radio communication Conference (WRC)-2000 and WRC-2007. These frequency bands are 450–470 MHz, 698–960 MHz, 1710–2025 MHz, 2110–2200 MHz, 2300–2400 MHz, 2500–2690 MHz, and 3400–3600 MHz. The identified spectrum is non-contiguous and scattered in different frequency bands from 450 MHz to 3.4 GHz. However, the actual allocation is ranging between the frequency band 700 MHz and 2.6 GHz. The irony is that these identified frequency bands have already been allocated to legacy services long back. Therefore, no vacant spectrum is available especially below 6 GHz at present for mobile communications. The options available to enhance the spectrum availability for 5G communications are spectrum re-farming, spectrum sharing and use of cognitive radio technology. Moreover, this identified 1200 MHz non-contiguous spectrum could not hold the pressure of high mobile data growth, demand for convergence of different varieties of services and speed as envisaged in 5G network. Assigning a new radio spectrum is crucial to meet the expected demands for future 5G networks. This is possible by exploiting higher microwave frequencies, referred as millimeter (mm-wave) bands. Therefore, mm-frequency band is the obvious and the most preferred band for 5G network.

The 5G network envisages as a combination of several micro, pico and femto cells embedded within a macro cell. According to physical law, coverage decreases with increasing frequency. The mm-waves can be divided into different categories, the first one ranging between 20 and 40 GHz frequency bands for micro sites and the other one is around 60 GHz frequency band for pico and femto cell sites.

With the increase in the number of wireless devices, the number of wireless connections and high data rate networks rises. This leads to the two important factors spectrum demand and spectrum congestion, turning out to be the two critical challenges for the forthcoming wireless communication world. Simultaneously the user's requirements such as high multimedia data rate transmission based on the bandwidth demanding applications will make the future wireless networks to suffer from the spectrum scarcity.

4.1 Command and Control Method

The conventional method for allocating spectrum is known as "Command and Control Method" shown in the Figure 4.1. There are some countries following this technique of spectrum allocation. In this method radio spectrum is divided into different spectrum bands that are allowed to specific radio communication services such as satellite services, mobile, broadcast on an exclusive basis.

This method guarantees that the radio frequency spectrum will be exclusively licensed to an authorized user and can use spectrum without any interference [1].

This method of spectrum allocation is not efficient because [1]:

- Spectrum assigned to a particular radio communication service cannot be replaced by other services even though it is witnessed that spectrum is underutilized.
- There is no possibility of questioning the user once the spectrum is allocated to him (during the licensing period) as per the norms, provided he fulfills the terms and conditions.

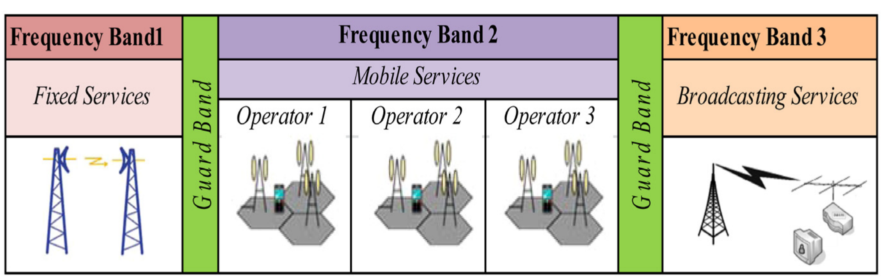

Figure 4.1 Command and Control Method [1].

- This method does not make spectrum to be utilized efficiently in rural areas as the spectrum utilization is heavy in the urban regions and underutilized in the rural areas.

It is sad to see the spectrum underutilized and not accessible to all. It is difficult for some nations to provide 4G services itself. There is a need for taking serious steps in handling spectrum issues by implementing sophisticated technologies for the development of nation. In these cases the techniques like spectrum trading would be a successful solution. This will only lead to the development of 5G communications in these types of countries.

4.2 Spectrum Sharing

The demand for multimedia content and information processing, services such as e-education and e-health, mobile broadcasting, enormous increase in the electronic gadgets necessitate efficient use of all available and usable frequency spectrum. The new generation of mobile broadband networks will require supporting higher data throughput rates.

Many sophisticated technologies have been implemented for making the efficient use of available spectrum. For example, line-of-sight (LOS) systems are usable up to 100 GHz now. Running down the size of electronic components and systems introduces the multiple frequency bands in single equipment leading to the efficient use of available spectrum by the enhanced dynamic sharing of frequency bands.

Spectrum management should be in such a way that there should be always optimum spectral sharing. Greater sharing of frequencies and bands allows more data to be sent by different users in the same amount of available spectrum.

Spectrum sharing has basically three dimensions: frequency, time and location. The Collective Use of Spectrum (CUS) allows spectrum to be used by more than one user simultaneously without requiring a license. Some of the examples that come under spectrum sharing are frequency reuse concept in the existing telecom networks, FDMA, TDMA. Another important challenge is the sharing of spectrum among the heterogeneous networks. While it is easier to achieve efficient and successful spectrum sharing among the homogeneous or similar networks or applications, there arises complexity in heterogeneous networks [2].

The spectrum sharing methods are classified into three categories based on based on the priority level of accessing the radio spectrum as follows [2]:

a. Horizontal spectrum sharing: all the devices have equal rights to access the spectrum.
b. Vertical spectrum handover only: the primary users are allotted priorities to access the spectrum.
c. Hierarchical spectrum sharing: it is an enhanced variant of the vertical spectrum sharing.

4.2.1 Spectrum Using SDR and Cognitive Radio – Dynamic Sharing

Evolution of software defined radio (SDR) and cognitive radio (CR) are the two major milestones in the mobile communications. Dynamic sharing of spectrum improves the spectrum efficiency and the above mentioned technologies play a vital role in this aspect.

Conventionally, transmitters were tuned to specific frequencies, and facilities for multiple frequencies would cost high. But after the development of these technologies, tuning the transmitters to the multiple frequencies has become easier, i.e., switching to the different frequencies in a dynamic way would be possible at a reasonable cost.

Cognitive radio first detects the occupation of the channel, and if it is occupied, it helps the users to switch to the other vacant channels. Also the carrier signals are sensed regularly for usage in other. There is always a need of large amount of spectrum in case of emergency or public safety conditions compared to that of normal conditions. In these emergency cases, dynamic sharing of spectrum would be a promising solution. In some countries spectrum regulators are used for the encouraging dynamic sharing spectrum with public safety requirements. It is to be noted that CR is a combination of administrative (regulatory), technical, and market based techniques to enhance the efficiency of spectrum utilization [2].

Another area of utility for dynamic sharing is White Spaces (TV Band). Normally, the TV broadcasters repeat the same channel/carrier at relatively longer distances, to avoid any interference especially at the border/edger of the coverage areas that are on the border of two adjacent broadcast transmissions on same channel. However, there are very few receivers in this area, and the spectrum utility is not effective and could be utilized for other purposes.

The broadcasters are generally quite protective for their signal transmissions, even in areas beyond the theoretical coverage areas. Hence, only low power systems that cause minimal interference can be considered for shared usage with the TV spectrum. However, gradually with time building collective confidence amongst the users that includes the broadcasters, higher power based systems could be considered [2].

4.3 Spectrum Trading

Spectrum trading is a case of spectrum sharing with the involvement of commercial activities. Spectrum trading is found to be a more economical way of efficient use of spectrum. It is an option through which flexibility can be increased and spectrum assigned to a particular service, and can be easily transferred for other usage. To explain it in brief, spectrum trading is a market based mechanism where buyers and the sellers determine the assignments of spectrum and its uses in which seller transfers the right of spectrum usage, in full or part, to buyer while retaining the ownership. In many countries spectrum trading is already running and the trading procedure is confined to specific bands, which are in demand for commercial use with specified conditions. Spectrum trading improves the efficiency and facilitates new services to enter in the market by making slight modification in the regulatory provisions [2].

The difference between spectrum sharing and spectrum trading can be explained as follows:

In spectrum trading the usage rights are transferred completely from the seller for a specified period. However, in spectrum sharing buyer gets a temporary right of spectrum usage with the exclusive rights resting with the seller. Trading becomes effective only when it is clubbed with liberalization. Spectrum trading can be implemented if there is solid base in understanding advanced technologies and operating systems as the spectrum flexibility demands new approaches and practical methods for monitoring compliance, enforcement and conflict resolution [2].

4.3.1 Spectrum Trading Merits

The merits of spectrum trading are as follows [2]:

- Improves efficient spectrum usage
- Facilitates the evaluation of spectrum licenses, and gaining knowledge of market value of spectrum

- Quicker process, with better and faster decision-making by those with information
- Removes barriers to entry by allowing small operators and start-ups to acquire spectrum rights of use more readily, thereby facilitating the development of market competition
- There is an opportunity for more rapid redeployment and faster access for spectrum
- Encourages new technologies to gain access to spectrum more quickly
- Existing operators gain an opportunity to sell unused or under-used spectrum and make more flexible use of spectrum
- Reduction in the transactions costs of acquiring rights to use spectrum
- Allows operators increased flexibility to accommodate shifting demand driven by market changes.

4.4 Cognitive Radio

IEEE approved definition of cognitive radio (CR) is a radio in which communication systems are aware of their environment and internal state, and can make decisions about their radio operation based on that information and predefined objectives. The environmental information may not include location information related to communication systems. Cognitive radio is a very good solution for increasing the spectrum utilization.

Cognitive radios should be able to self-organize their communication based on sensing and reconfigurable functions as stated below [3]:

- *Spectrum resource management:* this scheme is necessary to manage and organize efficiently spectrum holes information among cognitive radios.
- *Security management:* cognitive radio networks (CRNs) are heterogeneous networks in essence and this heterogeneous property introduces a lot of security issues. So this scheme helps in providing security functions in dynamic environment.
- *Mobility and connection management:* this scheme can help neighbourhood discovery, detect available Internet access, and support vertical handoffs, which help cognitive radios to select route and networks.

4.4.1 CR Device Concept

This section explains the features of CR whose implementation in a single device offers a very smart and high performance user terminal – CR terminal. The Figure 4.2 shows the CR properties.

A. Spectrum sensing

Spectrum sensing operation can be divided into the three step functions [4]:

- *Signal Detection:* In this step of operation existence of the signal is sensed. There is no need to know the type of signal in this step.
- *Signal Classification:* In this step of operation the type of signal is detected, which is done by extracting the features of the signal.

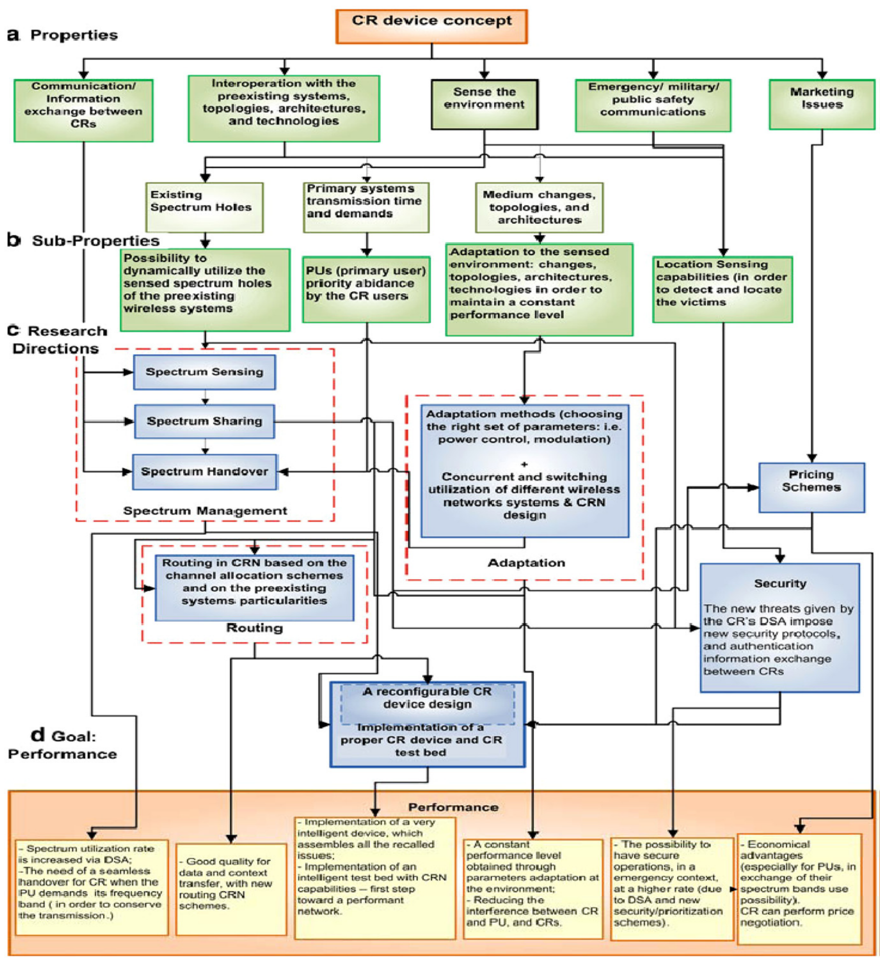

Figure 4.2 Concept of CR Device [4].

- *Channel availability decision:* In this channel availability is detected. Once the free channels are detected, the step next to it is, sharing the spectrum holes which can be achieved by the spectrum allocation scheme.

The CR technology also brings new *security and pricing challenges* which are shown in the Figure 4.2.

- New security threats appear with the dynamic spectrum access concept, as well as the CR's authentication needs.
- The pricing is very much influenced by the used channel allocation scheme. Additionally, CRs must be designed with strong capabilities to negotiate the available channels' price.

B. Spectrum handover

The phenomenon of frequency changing dynamically is said to be spectrum handover. A secondary user changes its frequency on appearance of a primary user or due to transmission degradation. This necessitates designing a handover scheme [4].

C. Environment adaptation

Different changes like topological changes, noise or interference power may occur while sensing the information. In order to adapt to these changes and to maintain the constant performance new adaptation techniques have to be implemented which is an important point of concern [4].

D. CR routing

CR routing is based on the requirement for CR device to interoperate with different systems, and is influenced by the spectrum sharing techniques [4].

CRNs inherit the PSs (Primary Systems) network characteristics: infrastructure - based, mesh, ad-hoc, sensor networks, etc. and these architecture types impose a specific routing algorithm, which must also include the CR devices and the possibility for a CR to be a relay node for another CR.

4.4.2 CR based on 5G

As already stated earlier CR technology would be a major modality to build the integrated 5G network. The various functionalities for 5G that could be met with CR usage are as follows [4]:

- Advanced PHY and MAC technologies.
- Implementation of novel and flexible protocols.

- Capacity to support homogenous and heterogeneous systems.
- Adaptation to different changes like environment changes, dynamic frequency changes, etc.

Correlation between WISDOM and CR in reference to 5G could be given as:

"5G brings the convergence concept through WISDOM and CR represents the technological tool to implement it." The 5G technology eliminates the radio terminals that are specific to particular wireless technologies and proposes a universal terminal which must include all of the predecessor features in a single device. This terminal convergence is supported by the users' needs and demands and is strongly found in CR terminal [4].

There are many issues that still remain to be addressed [4]:

- How to connect the CR terminal to the wired networks?
- How to reach the maximum 5G's 1 Tera bps data rate threshold when using the CR technology at the access level?
- How to implement the good techniques in order to combine the flows coming from multiple access networks?

4.5 Millimetre Waves

Most of the radio communications including TV, satellite communications GPS, Bluetooth are utilizing frequency band ranging from 300 MHz to 3 GHz. But this band is getting crowded and the focus is on releasing and utilizing the additional spectrum. In mm-waves are the promising solution for this problem.

The spectrum bands identified under the IMT umbrella do not have the capacity to carry such enormous data required for 5G services. Therefore, mm-waves could be the candidate bands for 5G mobile communications due to high data carrying capacity. The mm-waves have the following advantages [5, 6]:

(a) Not much operation at mm-waves so more spectrum is available at mm-waves
(b) Very large blocks of contiguous spectrum to support future applications.
(c) Due to high attenuation in free space, frequency reuse is possible at shorter distance
(d) Spatial resolution is better at mm-waves hardware with CMOS technology

(e) Advancement in semiconductor technology allows low cost equipment
(f) Small wavelength makes possible use of large antenna arrays for adaptive beam forming
(g) Small size of antenna at mm-waves facilitates easy integration on chip and installation at suitable locations.

In mm-waves allow larger bandwidth and offer high data transfer and low latency rate that are suitable for high speed reliable Internet services. The small wavelength facilitates small size antenna and other part of radio hardware, which reduces costs and also easy to install. The transmitter's antenna would be like a lamppost, which could be installed on building, street lamppost, etc. [6].

High directionality attained in this band can be used to increase spatial multiplexing. The size of antenna required for a mm-waves radio can be one-tenth or less of an equivalent lower frequency radio which is an advantage to the manufactures to build smaller and lighter systems.

Beam width is the measure of how a transmitted beam spreads out as it gets farther from its point of origin. But due to limited availability of radio frequency (RF) bands the fifth generation wireless communication systems will move to ultra-high capacity mm-wave bands. High frequency makes mm-wave band more attractive for wireless communication system and these frequencies are used in terrestrial and satellite communications. Wireless products that use millimeter waves already exist for fixed, LOS transmissions

But the absorption rate of the mm-wave electromagnetic signal poses great challenges for their utilization in the non-LOS and mobile connections. On the other hand, high directionality achieved in this band can be used to increase spatial multiplexing. Wireless backhaul will be another key enabler of 5G-mm-wave small cells [8].

Within the mm frequencies, the frequency band of 60 GHz has attracted the researchers to work with, as the large amounts of bandwidth are unallocated in this band, bandwidths that are required for communication systems at the intended data rates of 100 Mbps and above. Also, another advantage of 60-GHz band is due to a physical property of the propagation channel at this frequency that provides a natural way for reduction of frequency reuse factor, which tends to compact cell size [8].

It is a general property of the mm-wave propagation that the behaviour of the propagation rays is well characterized by the geometric optics. That is, the waves do not penetrate the walls or other obstacles and wave reflection is the main mechanism leading to a multipath [8]. In mm-waves have the potential to support broad-band service access which is especially relevant because of the advent of Broadband Integrated Service Digital Network (B-ISDN).

With the development of personal wireless communication systems, two things are appearing to be significant:

- Exploiting high frequency bands, such as mm-waves to provide broadband for high rate data transmission.
- To integrate multi-tasks in one system which greatly extend the application of wireless device.

The utility of mm-waves for the micro cells that form the WISDOM based GIMCV are well positioned to be served by these mm-waves. It has been elaborated in these following points:

- It is relatively easy to get licenses for big blocks of mm-wave spectrum, which would allow carriers to deploy large backhaul pipes over 1 Gbps in size. While a single small cell may not need that much capacity, the complexity of heterogeneous networks will require daisy-chaining many small cells together, each cell passing its load down the line.
- Small cell backhaul makes the best use high frequency characteristics of mm-waves. The higher the frequency the shorter distance a wave propagates unless it gets a serious power boost. But the heterogeneous network by definition will be composed of densely packed cells in urban environments, meaning no mm-waves will have to travel far between hops.

The traditional uses of the mm-waves include radio navigation, space research, radio astronomy, earth exploration satellite, radar, military weapons and other applications. The backbone/backhaul networks (point to point network) for existing telecom network to connect base station to main switching centre (MSC), Local Multipoint Distribution System (LMDS), indoor WLAN, high capacity dense networks are also present in the mm-waves. The typical microwave backhaul bands are at 6.0 GHz, 11.0 GHz, 18.0 GHz, 23.0 GHz, and 38.0 GHz frequency bands.

The light use of mm-waves could be attributed to high attenuation and low penetration. At such high frequency, waves are more prone to rain and other atmospheric attenuation. The wavelength is in the order of millimeters, and rain drops are also of the same size. Rains absorb high frequency waves and make it difficult for propagation. However, the experimental results show that in heavy rain condition, attenuation is 1.4 dB and 1.6 dB for 200 meters distance at 28 GHz and 38 GHz, respectively [8]. The rain attenuations at 60 GHz for a rainfall rate of 50 mm/h, is approximately 18 dB/km [11]. A proper link design with slightly high transmit power may take care of rain attenuation.

Slight change in the position would affect the signal strength at the receiving end, due to which mm-waves are deeply affected by scattering, reflection and refraction. The root mean square (RMS) delay spread for mm-waves is of the order of few nano seconds, and it is high for are non-LOS (NLOS) links than (LOS) links [9]. Similarly, path loss exponent for NLOS links is higher than LOS links. Due to higher path loss and RMS delay spread, it is assumed that mm-waves are not suitable for (NLOS) links. However, these difficulties could be managed by using carrier aggregation, high order MIMO, steerable antenna, beam-forming techniques.

Recently, extensive measurements to understand the propagation characteristics for defining the radio channel have been carried out at 28 GHz in the dense urban areas of New York City and at 38 GHz cellular propagations measurements were conducted in Austin, Texas, at the University of Texas main campus. The measurements were conducted to know the details about angle of arrival (AoA), angle of departure (AoD), RMS delay spread, path loss, and building penetration and reflelction characteristics for the design of future mm-wave cellular systems. The propagation feasibility studies at 28 GHz and 38 GHz showed that propagation is feasible up to 200 meters of distance [6,10] in both the conditions, i.e., (LOS) and (NLOS) with transmit power of the order of 40–50 dBm in a difficult urban environment. This is size of micro cell in the urban areas.

The frequency bands around 60 GHz is best suited for pico and femto cell due to high data carrying capacity and small reuse distance due to strong oxygen absorption at the rate of 15 dB/Km. The usage in frequency bands around 60 GHz is highly sparse, which provides freedom to allocate a large bandwidth to every channel. Moreover, equipment can be made very compact due to the very small antenna size.

Much research work has been done for indoor channel characteriszation at 60 GHz band but a very few work has been done for outdoor characteriszation. In reference [12] measurements were carried out for narrowband CW for received power against separation distance in different environments mainly airport field, urban street and city tunnel. A channel sounder based on correlation has been used for the measurement for centre frequency of 59.0 GHz with a bandwidth of 200 MHz. A 90°-horn antenna was used at transmitting end and a biconical horn with an elevation beamwidth of 20°

was used at receiver in all the measurements. The measurement was carried out for path loss exponent and RMS delay spread. The result found that path loss exponent was between 2 and 2.5 for outdoor environment and RMS delay spread was lower than 20 ns. Result also included that multi-path phenomenon was bad at parking garage due to large dimensions and smooth surface as compared to city streets and road tunnel, where multipath phenomenon was not much significant.

In [13] measurements were carried out at 55 GHz in city streets of London (UK) with moderate traffic density using a fixed transmitter and a mobile receiver, with link distances not greater than 400 m. The transmitter installed at 10 m above the ground level and receiver was mobile mounted over the roof of a car. The test signal was narrowband FM signal generated through Gunn oscillator and fed to a 25-dBi horn antenna. The result found that path loss exponent was 3.6 for a T-R separation of 400 m with LOS path and path loss exponent was 10.4 for same Tx-Rx separation in NLOS condition.

In order to understand the radio channel propagation characteristics, extensive propagation measurements in urban environment hasve been carried out long back at the campus of Delft University of Technology, Netherlands [14]. The measurements for frequency fading over 100 MHz bandwidth centered around 59.9 GHz were done almost exclusively in the time-domain by using network analyzsers and channel sounders. The block diagram of the measurement system used in reference [14] for the frequency-domain characteriszation of the radio-channel is shown in Figure 4.3.

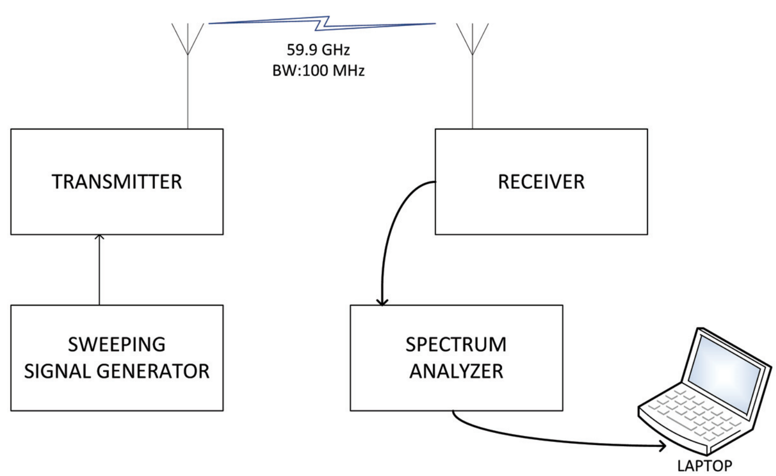

Figure 4.3 Measurement setup.

The two main components are signal generator towards transmitter side and spectrum analyser at receiver side. A flat omnidirectional antenna (2 dBi, 120°) was used at transmitter side and omnidirectional (120°) and patch directional antenna (pencil beam, 19.5 dBi, 15°) were used at receiver side. Measurements with both were done in order to see the difference in performance, because omnidirectional antenna allows for more reflected components to enter the receiver. The measurements were conducted for statistics of the 'k' factor of Rice distribution and the path loss coefficient for the pico cell of the order of 50 m radius at three different locations including outdoor and indoor. The measurements were done in possible locations for the mobile multimedia communication.

The measurements were taken in the corridor area (indoor) of the University for the Rice factor *k* and received power versus distance with T_X–R_X separation of 12–15 m are shown in Figures 4.4 and 4.5 below.

The measurements were taken in the parking area (outdoor) of the University for received power versus distance on logarithmic scale with T_X–R_X separation of 12–15 m is shown in Figure 4.6.

The measurement results show that propagation is feasible upto 10–15 m in the indoor and outdoor urban environment, which is normal size of pico cell.

The Radiocommunication Sector of International Telecom Union (ITU) is responsible for management of radio spectrum at international level. As per ITU-R frequency allocation plan [15], the frequency band 10–40 GHz has

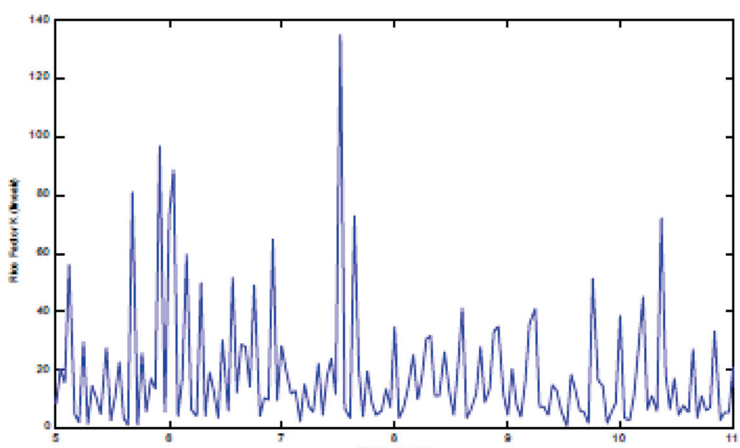

Figure 4.4 Rice factor *k* versus distance in the corridor. Directional receiver antenna used.

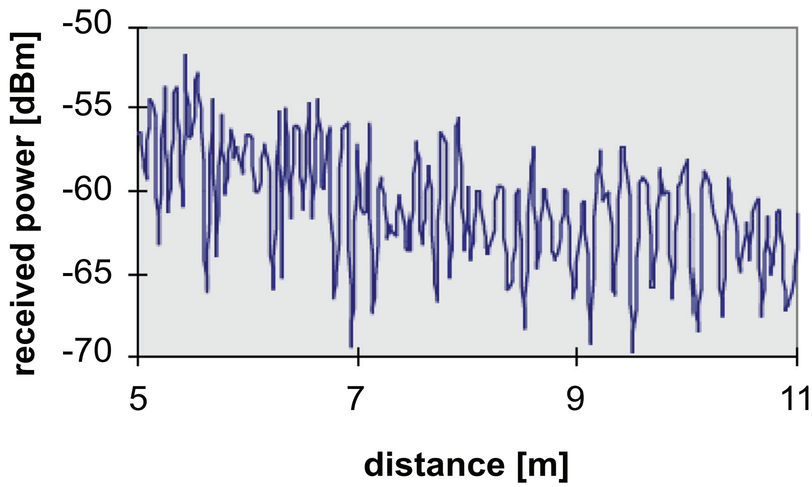

Figure 4.5 Broadband average received power in the corridor with omnidirectional receiver antenna used.

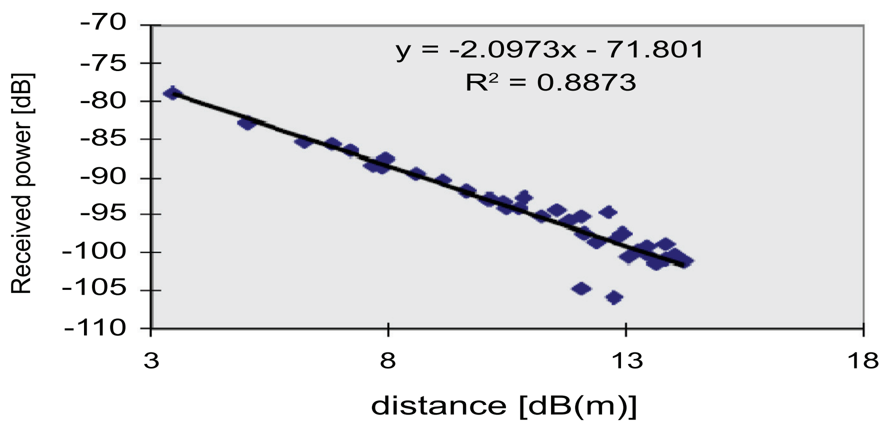

Figure 4.6 A scatter of the plot of the measured power [dB] versus the distance on a log scale for outdoor location (parking) with omnidirectional antenna.

been earmarked for satellite based services in all the three regions along with Fixed and mobile services. Local Multipoint Distribution System (LMDS), WLAN, Satellite services and High capacity dense network etc. are main services present in mm-waves. Several point to point fixed microwaves links are also working in this band. These links are basically for backbone/backhaul network for GSM and other services. A good amount of vacant spectrum is available at mm-waves which could be utiliszed for 5G communications services. 5G services may transmit high power approximately 40–50 dBW. Therefore, coexistence study needs to be carried out with existing LMDS and satellite services, that would be working in neighbouring spectrum bands.

4.6 Summary

Spectrum is a key to mobile wireless communications. The concept of spectrum sharing and spectrum trading are mainly discussed in this chapter. The concept of spectrum trading brings awareness towards its importance as it is not much successful in many countries. Spectrum management is an important challenge for the evolution of 5G communications. Extra high frequency bands have to be explored for the quick data transfers. Working on this, mm-waves have proved successful for the short-range communications. But still further research has to be carried out for the advancements in the existing technologies like cognitive networks, for the efficient use of spectrum.

References

[1] Purnendu. S. M. Tripathi, Ramjee Prasad, "Spectrum Trading in India and 5G", Journal of ICT standardization", Journal of ICT standardization, volume 1, No.2, pp. 159–174, November 2013.

[2] P. K. Garg, T. R. Dua and Ashok Chandra "Spectrum Challenges for Modern Mobile Services", Journal of ICT standardization", volume 1, No. 2, pp. 137–158, November 2013.

[3] Kwang-cheng and Ramjee Prasad, "Cognitive Radio Networks", John Wiley and Sons, Ltd, Publication, 2009.

[4] Cornelia-Ionela, Neeli Prasad, Victor Croitory, Ramjee Prasad, "5G based on Cognitive Radio", Wireless Personal Communications, volume 57, Issue 3, pp. 441–464, April 2011.

[5] Millimeter Waves. [online]. Available: http://www.ieeeghn.org/wiki/index.php/Millimeter_Waves

[6] R. Prasad and L. Vandendorpe, "An overview of millimeter wave indoor wireless communication systems," Universal Personal Communications, 1993. Personal Communications: Gateway to the 21st Century. Conference Record., 2nd International Conference on, vol. 2, no., pp. 885, 889 vol. 2, 12–15 Oct 1993 doi: 10.1109/ICUPC.1993.528506

[7] Rangan, S.; Rappaport, T. S.; Erkip, E., "Millimeter-Wave Cellular Wireless Networks: Potentials and Challenges," Proceedings of the IEEE, vol. 102, no. 3, pp. 366, 385, March 2014 doi: 10.1109/JPROC.2014.2299397

[8] Ramjee Prasad, OFDM for Wireless Communications, Artech House, 2004.

[9] T. S. Rappaport et. al. Millimeter Wave Mobile Communications for 5G Cellular: It will work. Open Access, IEEE. (2013). DOI: 10.1109/ACCESS.2013.2260813

[10] R. H. Ott and M. C. Thompson Jr., "Characteristics of a Radio Link in the 55 to 65 GHz Range", IEEE Transactions on Antennas and Propagation, pp. 873–877, 1976.

[11] S. Geng et al. "Millimeter-Wave Propagation Channel Characterisation for Short-Range Wireless Communication" IEEE Transaction on Vehicular Technology Vol. 58, No.1, January 2009.

[12] P. F. M. Smulders, L. M. Corria, "Characterisation of Propagation in 60 GHz Radio Channels," Electronics & Communication Engineering Journal, Vol. 9, No.2, pp. 73–80, Apr 1997.

[13] H. J. Thomas, R. S. Cole and G. L. Siqueira, "An Experimental Study of the Propagation of 55 GHz Millimeter Wave in an Urban Mobile Radio Environment", IEEE Transactions on Vehicular Technology, pp. 140–146, 1994.

[14] D. M Matic, H. Harada, R. Prasad, "Indoor and outdoor frequency measurements for mm-waves in the range of 60 GHz," Vehicular Technology Conference, 1998. VTC 98. 48th IEEE, vol.1, no., pp. 567, 571 vol.1, 18–21 May 1998. doi: 10.1109/VETEC.1998.686638.

[15] ITU-R Preparatory Studies for WRC-15 [online]. Available:www.itu.int/en/ ITU-R