

Monitoring, Surveillance, and Management of the Electromagnetic Spectrum: Current Issues in Electromagnetic Spectrum Monitoring

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ABSTRACT

This paper discusses the current aspects of the surveillance and management of the electromagnetic spectrum under various topics that are vital to wireless communications. On the basis of the recent technological advancements in conjunction with the discussions on the global approaches toward electromagnetic spectrum monitoring, the paper addresses short-, medium-, and long-term strategies in wireless communications for monitoring, governing, and managing the electromagnetic spectrum of leading countries and multinational organizations. Furthermore, it proposes a novel spectrum monitoring strategy for next-generation wireless systems and outlines the implications of the proposed strategy.

Keywords: Flexible licensing, spectrum monitoring, spectrum refarming, wireless communications

Introduction

Wireless communication has become a necessity in modern life. Ubiquitous connectivity and mobility support without the need for a physical connection are the main features of contemporary wireless communication technologies. Such features attract ever-increasing number of users to utilize a wide variety of wireless services and applications. It is predicted that by the year 2020, seven billion people will be served by seven trillion wireless devices [1].

Aforementioned increase is not only limited to the number of users but also includes the volume of data carried by wireless communication systems. The increase in data volume is not surprising given the availability of vastly diverse and high quality services carried over wireless technologies. Today, any smartphone that has an Internet connection could provide many services beside the traditional voice communications such as file transfer, multi-media sharing, video chat, and online gaming. The predictions indicate that next stage of the evolution of wireless communications will expand into cyber-physical systems such as Internet of Everything (IoE) which is believed to cover virtual and augmented reality; high-definition and interactive television broadcast; a vast variety of sensor applications; smart homes, cities, and infrastructures [2].

The most important step towards the predictions that indicate IoE is the successful realizations and deployment of large scale wireless communication networks and systems. Coexistence of many large-scale networks along with the emergence of recent technologies requires a more comprehensive terminology than large-scale wireless networks. In this regard, next generation wireless networks (NGWNs) are considered to be a generic umbrella term for wireless communication systems which are designed to carry high-volume data and provide a very wide range of services with mobility support to a large number of users with the motivation of "being online anywhere, anytime" via several both inter- and intra-networking strategies.

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NGWNs are based on different forms of connection types; macro cellular and small coverage cellular base stations; and WiFi access points and vehicle-to-everything (V2X) communication platforms. Such diversity leads to heterogeneous structures. It is clear that the true realization of IoE mandates several criteria to be met simultaneously. The prominent criteria are providing high-quality performance under every circumstance for vast variety of services; accommodating increasing number of users seamlessly; achieving low latencies with high-order diversity and so on. Obviously, in order for NGWNs to satisfy those needs, all available resources should be exploited in an optimum way. Electromagnetic spectrum (EMS) is regarded the most important resource among all for wireless communications. In conjunction with the previous discussions, ever-increasing number of users for wireless communications introduces the "spectral crowd and scarcity problem." On the other hand, measurement reports bring out the fact that EMS is underutilized rather than being scarce.

Many of the natural resources are finite and subjected to be exhausted when overused. However, unlike other resources, EMS is theoretically an unlimited and infinite one. But due to wireless propagation characteristics and sizes of the portable devices, only a part of the EMS can be used effectively for NGWNs. From this standpoint, EMS could be considered to be a limited resource in practice. Therefore, NGWNs should utilize the EMS to the greatest extent given the ever-increasing demand observed for wireless communications within the last three decades.

The transmission power is also a very important and a limited resource such as EMS. Battery life of mobile devices manifests one of the aspects of this limitation. The other aspect reveals itself when EMS is accessed by multiple nodes within the same local geographical area, which is known as multi-user interference (MUI). MUI affects negatively all of the elements of wireless systems in various ways. It reduces the performance of receivers, causes the overall capacity of the system to drop, leads to disruptions to the communication link, and so on. One should keep in mind that dominating the communication channel by increasing transmit power seems to be a solution at first glance. However, such a strategy leads to a more severe interference scenario along with a shorter battery life and with a dramatic drop in the overall system capacity. Therefore, when interference is unavoidable, transmit power as a resource should be handled more delicately.

In light of the discussions above, one could conclude that both EMS and the transmission power are fundamental and crucial design concepts for all sorts of wireless communication systems. Therefore, they need to be steadily observed and strictly controlled under certain rules, guidelines, regulations, and standards. It is worth mentioning that EMS should always be considered as the first in comparison with the transmission power at design stages. This stems from the fact that propagation characteristics of electromagnetic waves are dramatically

different from each other at different portions of EMS. Hence, in practice, transmission frequencies and their relevant propagation characteristics are taken into account before considering the transmission power requirements of the system to be designed.

Although EMS is a national resource, propagation behavior and standards render EMS as an international resource. This implies that the observation and control tasks are carried out both at national and international level. The rules, guidelines, and standards used in the supervision of EMS are determined by the United States and European countries for historical reasons. The Federal Communications Commission (FCC) in the United States and the International Telecommunication Union (ITU) at the international level stand out in this regard.

Monitoring and Governance of Electromagnetic Spectrum

As a natural but practically limited resource, the most important characteristic of EMS is that it is not used up in contrast to other natural resources such as oil, natural gas, and its derivatives. Because EMS is not only an inexhaustible but also a limited resource in practice, its utilization is crucial. First step of utilization is to manage EMS and the most important component of EMS management is the spectrum monitoring. Spectrum monitoring involves the recording, processing, and evaluation of collected spectrum data. It is important to bear in mind that spectrum data are obtained in traditional domains such as time, frequency, and space as well as in other artificial domains such as code domain driving the code division multiple access technology (CDMA).

In order to better understand why spectrum monitoring is the most important component in the management of the EMS, it is sufficient to check how the EMS is generally classified. Furthermore, scenarios based on this classification provide an extra insight into the importance of spectrum monitoring. The EMS is generally overviewed in three classes: the exclusive, licensed, and unlicensed spectrum. Exclusive bands are specifically allocated to specific purposes, institutions and/or organizations. Examples include bands that are reserved for space and astrophysics research. Licensed bands are those which require special permissions and regulations to carry out transmission. Mobile phone operators provide their services through the use of licensed bands. Unlicensed bands are the bands that everyone can use provided that they abide by various rules and regulations. Industrial, scientific, and medical (ISM) purposes bands fall into the unlicensed bands category. Therefore, the following scenarios are relevant for all spectrum classes.

Scenario I. Identification and supervision of authorized broadcasts of any spectrum class

Scenario II. Identification and supervision of unauthorized broadcasts of any spectrum class

Scenario I involves the collection of usage statistics for the spectrum band of interest; identification of broadcast; evaluation of whether these broadcasts are authorized, license types are appropriate and their validity is approved, depending on whether the band is licensed or unlicensed. The supervision process covers evaluating the competence of the broadcasts with the local, national and/or international regulations and the compliance with the regulations of the band concerned. Scenario II includes the cases where unauthorized broadcasts are of interest.

As can be understood from Scenario I and Scenario II, the efficient use of a highly valuable natural source such as the EMS depends on a very detailed observation of the EMS in temporal, frequency, and spatial domains (and all possible natural and artificial domains such as code) steadily. Spectrum monitoring, therefore:

- Should be the first step to identify, quantify, track, and control the wireless interference present in all domains at local, national, and international scale.
- Provides ways of identifying whether devices used and techniques/algorithms that they employed comply with protocols, rules, regulations, and standards defined by both national and international institutions and organizations
- Helps identify the infrastructural requirements of local and national governments by obtaining coverage data. Combined with wireless interference map, coverage information paves the way for environmentally-friendly communication technologies by preventing further power consumption and not wasting of national wealth via optimizing installation locations and settings of base stations.
- Ensures that local and/or national television/radio broadcasts can be received by everyone seamlessly, without any problems. It reduces the time and increases the effectiveness in resolving emerging problems.
- Guarantees that broadcasts on the licensed bands, in particular, meet local, national and/or internationally applicable standards (spectrum masks, transmission power, etc.) in high resolution.

- Enables to collect and process valuable real-time usage and occupancy statistics. As a result of processing these data:
 - Dynamics of EMS in all domains could be analyzed and understood in a detailed manner via versatile reporting tools.
 - Problems could be identified almost instantaneously via high-resolution statistics. Anomalies which might lead to serious problems in the future could be detected at their early stages.
 - Future plans and predictions could be established accurately by taking into account the evolution of the real-world data. Therefore, waste of such a valuable resource is avoided.

Classification of Monitoring of Electromagnetic Spectrum

Monitoring the EMS has many aspects since the EMS is a multi-dimensional phenomenon as discussed above. Each dimension or domain plays an important role not only in determining both the quality and the quantity of data to be collected but also in estimating the size of the requirements such as equipment, software, and communication infrastructure to be used. However, when importance of the EMS as a national and international resource is considered, it becomes clear that the most general classification will be based on spatial domain, namely the size of the area to be monitored. From this perspective, the classification can be divided into the following subcategories: national; regional; local; outdoors; and in-doors.

Similarly, monitoring in frequency domain can be classified as narrowband; broadband; and wideband. Classification in temporal domain can be categorized as instantaneous; short-term (minute, hour); medium-term (hour, week); and long-term (month, year). In Figure 1, prominent classification classes and their subcategories are presented.

One of the fundamental issues in spectrum monitoring is to store and/or transfer the data collected. Sizes of the data to be collected are generally significant since, as shown in Figure 1, high-resolution spectrum monitoring accommodates multiple domains with high degrees of freedom. In this regard, measurement resolution should also be included into the classifi-

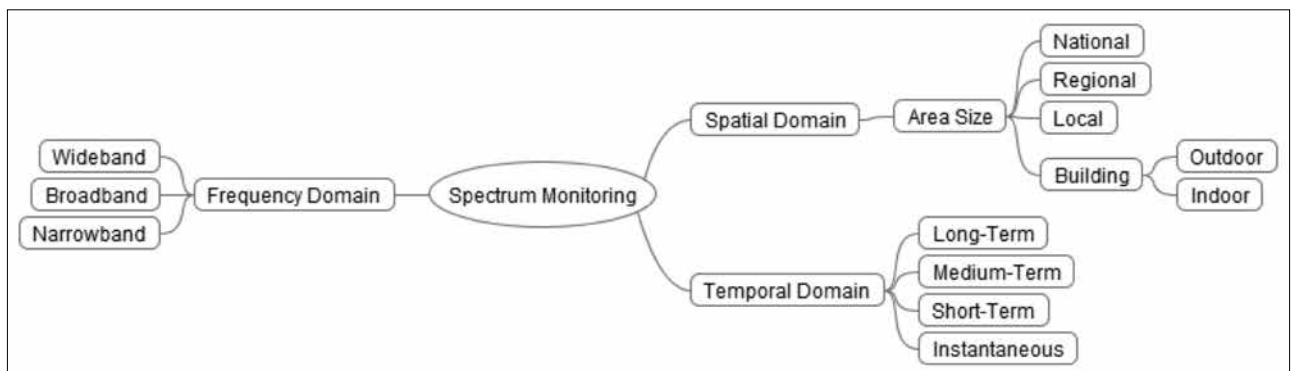


Figure 1. Prominent classification types for spectrum monitoring

cation not maybe as a new domain but as a parameter such that High-resolution sampling (above Nyquist rate); Critical sampling; Low-resolution sampling (below Nyquist rate). There is a direct ratio between the bandwidth used in the frequency domain and the monitoring resolution. Since the number of monitoring data points in the spatial domain will be equal to the number of data sets, the size of the total monitoring data is given as:

$$C \propto N \times B \times T \times S \quad (1)$$

where the total number of monitoring points is equal to , the size of the total monitoring data is given as ; denotes the total bandwidth measured/monitored at one time instant; stands for the monitoring duration, and represents the sampling rate.

Techniques

Detection and locating of unauthorized broadcasts and/or interference sources are at the forefront of main goals of spectrum monitoring. Sophisticated radio wave propagation characteristics, physical and geographical obstacles between the source and measurement location make it difficult to determine the precise location of the interference source solely by using EMS data. For this reason, the first step in determining the location of the source is to find the direction of the emission. It is worth mentioning that beside its direction, the EMS can be monitored to classify and extract a very large set of features, parameters, and/or identifiers, such as the type of modulation used in emission or any signal received.

There are many direction finding techniques and methods in the literature. In case the direction finding is performed on a single channel, three classes are prominent in the literature: amplitude-based, phase-based, or hybrid forms. The same classes could be considered for multi-channel systems except for infrastructure required by multi-channel systems. Hence, it is sufficient to review single-channel methods for direction finding.

The most frequently encountered methods for single-channel applications are:

- Watson-Watt [3]
- Doppler and pseudo-Doppler [4]
- Correlative vector [5]
- High-resolution direction finding [6,7]
- Maximum likelihood model
- Principal component analysis

There are, of course, some other methods present in the literature, which demonstrate a certain degree of high performance. Algorithms that employ subspace separation of the received signal [8] and the use of linear prediction [9] based approaches are two examples that stand out. Phase-locked loop assisted direction finding methods are also present in the literature [10].

The above-mentioned methods could generally be regarded as deterministic methods since they draw conclusions at the result of following a certain statistical construction. Apart from deterministic methods, there are direction finding algorithms relying on heuristic strategies. There are studies in the literature benefiting from both evolutionary methods [11] and heuristic methods supporting subspace-based algorithms [12] as well.

Monitoring Area

Size of the area to be monitored shows considerable variability in scale due to the propagation behavior (reflection, diffraction, scattering, etc.) of the radio waves and the losses to be experienced within the environment. Especially in large cities demographic structure changes rapidly due to the construction of large buildings (skyscrapers, shopping malls, etc.) and/or the demolishing of existing buildings in a very short period of time. Such changes imply that the usage statistics fluctuates dramatically because of the rapid alteration of the demographic structure. Coverage area and all related transmission parameters will be different as well. Hence, handover rates, traffic loads, and resource allocation mechanisms and many other metrics will be affected. Therefore, reliability of the measurements taken especially in densely populated regions, downtowns, and metropolitan areas should be checked and verified very frequently by validating measurement setup, devices, and parameters. Hidden node issues, out-of-coverage measurement problems, and uncalibrated device recordings are some of the prominent topics that need to be contemplated.

Equipment

With the great advances in digital technology, spectrum monitoring equipment has been reduced in size and become cheaper. Putting the antenna dimension issues aside, monitoring devices equipped with computationally powerful and multi-tasking chips have become available on a considerably larger scale [13, 14]. Furthermore, monitoring hardware is generally software reconfigurable; therefore, it can be customized to serve for any desired purpose. With a few simple plug-ins, the monitoring data can be processed directly on-site and only the results can be transferred to desired locations and/or centers.

The aforementioned equipment will also enable authorities and institutions to take advantage of high altitude platforms, unmanned aerial vehicles, and other remotely controllable equipment. Such diversified options will bring extreme agility and flexibility into operational capabilities of institutions and/or organizations performing the spectrum monitoring tasks [15].

Current Issues in Electromagnetic Spectrum Monitoring

Importance of spectrum monitoring for public safety agencies and first responders is slightly different from that for commercial and governmental agencies since radio communications

for public safety agencies and first responders is a life-critical operation. Any problem, disruption or failure in communications might lead to death and/or serious injuries and/or severe damage. From this point of view, (i) spectrum bands dedicated to public safety agencies and/or organizations should always be available. Furthermore, (ii) these bands should not be occupied by any other parties apart from authorized agencies. Considering the ever-increasing demand and services, one should anticipate that some of the dedicated bands could be densely populated whereas some of them are totally vacant. Therefore, (iii) the spectral load should be distributed uniformly and future plans and predictions could be established accordingly. Spectrum monitoring is the only solution for the issues indicated in (i)-(iii).

This chapter will cover a variety of emerging topics in spectrum monitoring around the globe on both national and international scale. Concepts of reallocating and refarming the spectrum proposed by several countries will be discussed as well.

Refarming the EM Spectrum

Refarming the spectrum is a recent concept which aims to distribute the occupancy statistics of spectrum bands in a uniformly manner. As can be inferred, the driving force behind spectrum refarming is the underutilization of some of the bands. Of course, underutilized spectrum is not the sole motivation. Significant progress has been made in communication and digital signal processing techniques. With the recent advances, many wireless services are provided with less bandwidth but with a higher quality. For example, terrestrial analog television broadcasts have been replaced by digital technology in the United States, and 698-806MHz has been emptied and reopened for further use. Since a similar process will also take place in the rest of the globe soon, new concepts and paradigms such as interference temperature, spectral white holes, spectrum leasing and bidding, and band aggregation will arise. In this regard, legislators and auditors will have to go beyond traditional approaches previously employed in spectrum monitoring for fair usage, security, privacy, and so on. Preparation towards spectrum refarming concept should start with collecting, analyzing, and interpreting space, time, and frequency usage patterns and statistics of EMS. Next, resource planning, licensing, and pricing procedures and processes should be reviewed and revised in the near future especially taking into account the paradigm so-called "flexible licensing" [16].

It is important to emphasize one more time that spectrum refarming aims to ensure that the occupancy in the EMS is homogeneous. This way, white bands could be taken advantage of more efficiently and contribute to wealth and economy. However, maximum utilization comes at the expense of a highly detailed, continuous, and super resolution monitoring, which implies high volume of data storage, process, and transfer infrastructures.

Emerging Technologies and Non-Civilian Usage

Beside the refarming paradigm, emerging technologies, applications, and services which penetrate the market rapidly should be observed as well. One of the prominent examples is the deployment of high-altitude platforms when the coverage area needs to be expanded and/or capacity within certain geographical areas drops below a certain threshold. Similarly, unmanned aerial vehicles and their derivatives with wireless broadcasting capability, both for civil and non-civilian use, are now being used for a variety of purposes [17]. Another instance of recently emerging technologies and mass penetration to market is related to intelligent transport systems (ITS). The European Union has initiated formal studies to ensure that ITS are employed in all European Union countries via embedding appropriate infrastructures into roads and vehicles manufactured after 2018. For instance, 77GHz radars for vehicles already included in ITS for parking and roadblocks.

IoE and many other technologies are among the services and applications that will need to be included into the horizons of spectrum management in the very near future. Spectrum monitoring therefore should be established in such a way that institutions and organizations in charge need to take into account all of the emerging technologies along with their possible extensions.

Disaster Communication

Disasters manifest the importance of spectrum management/monitoring in a very dramatic manner. For instance, when the great Düzce earthquake occurred, cellular base stations in the local region were out and physical infrastructure damaged. There was a long-term communication blackout in the region. This posed several problems. People who were exposed to the disaster were not able to communicate outside the region and vice versa. Furthermore, people who were not in the region attempted to communicate and failed due to the network congestion. Blackout in the region coupled with congestion hampered the coordination, collaboration, and cooperation of public safety agencies and first responders. Unable to react rapidly to the disaster region disrupted the rescue operations and led to loss of many lives.

In order not to experience such tragedies due to communications failures, the spectrum should be continuously monitored in both large and small scale geographical regions. Monitoring data should be examined with the aid of advanced statistical methods such as anomaly detection and machine learning. In case an anomaly or problem is identified, the relevant institutions and/or organizations should be informed instantaneously so that management, command and control can be carried out as efficiently as possible. Monitoring the spectrum on both large and small scale is the key to determining and identifying the physical locations exposed to disasters. Also, spectrum monitoring helps first responders and public safety agencies act in coordination with each other in the most effective way.

Impact on Health

There are scientific studies on the negative effects of electromagnetic radiation on health. Studies report that the operation of cardiac pacemakers is impaired or completely stopped under electromagnetic radiation and serious health problems occurred or triggered [18, 19]. This suggests that monitoring the spectrum is a necessity, especially in the areas where hospitals and healthcare professionals provide healthcare.

Installing base stations within and/or around living spaces in an unauthorized manner can also be examined under this topic. Detection and identification of stations which broadcast with non-standard parameters are also possible with continuous, wide-area, and high-resolution spectrum monitoring activities. This way, the conditions that negatively affect social health could be eliminated.

Environment-friendly Communication

Cellular network service providers have been incorporating more and more base stations in order to meet the requirements of the ever-increasing number of users and maintain the quality of the services provided. The increasing number of base stations naturally implies high volume of energy consumption [20, 21] as well. Surveys reveal that the information and communication technology industry receives 0.5% of total global energy consumption and this share is expected to increase further in the near future. As shown in Figure 2 and Figure 3, communication networks consist not only of base stations but also of users, transmission lines carrying mobile data traffic to the core network, and many other system components operating within the network. It is evident that such a complicated and crowded topologies increase energy consumption and should be taken seriously from green communications perspective.

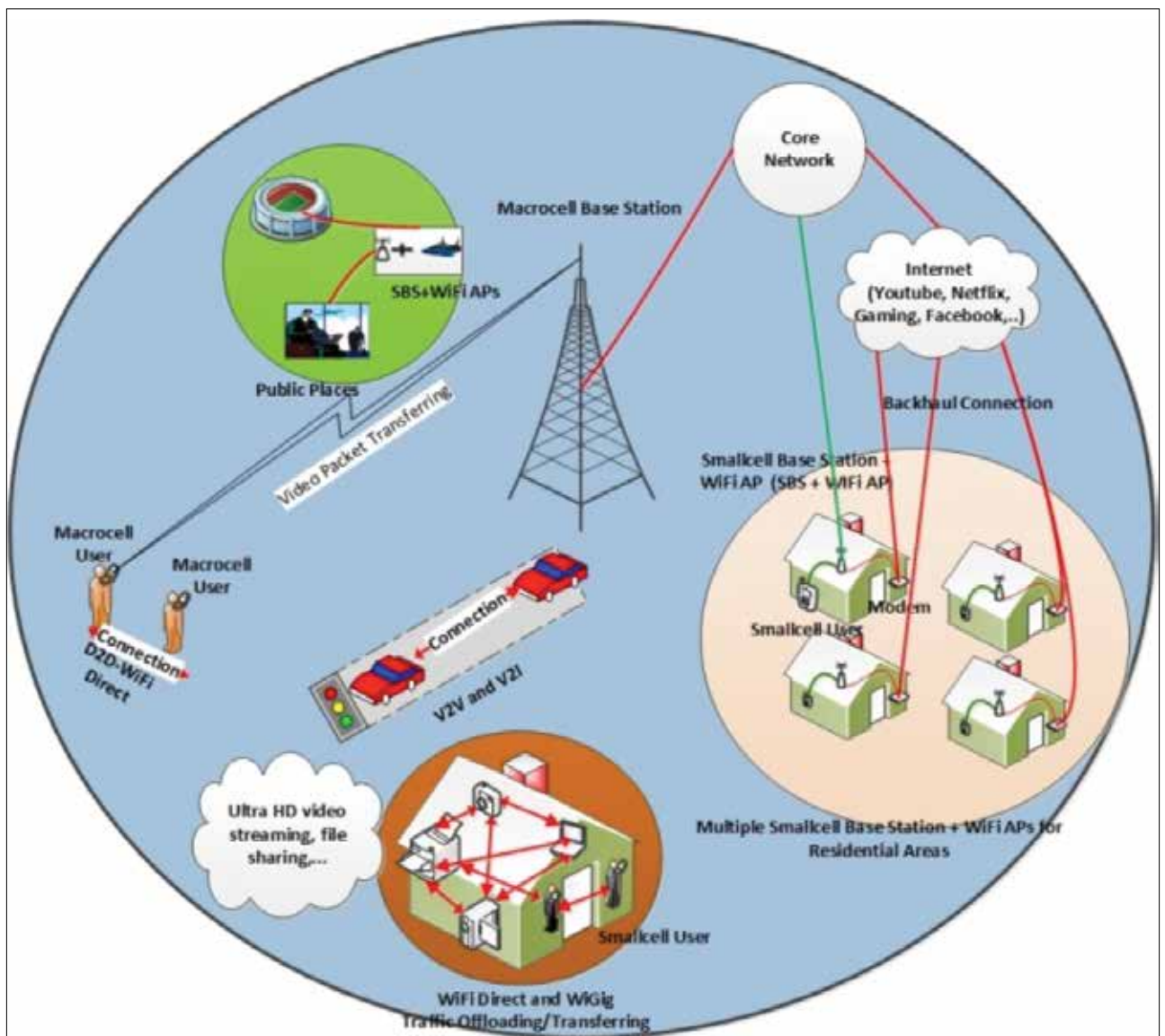


Figure 2. A conceptual framework for heterogeneous next generation wireless networks

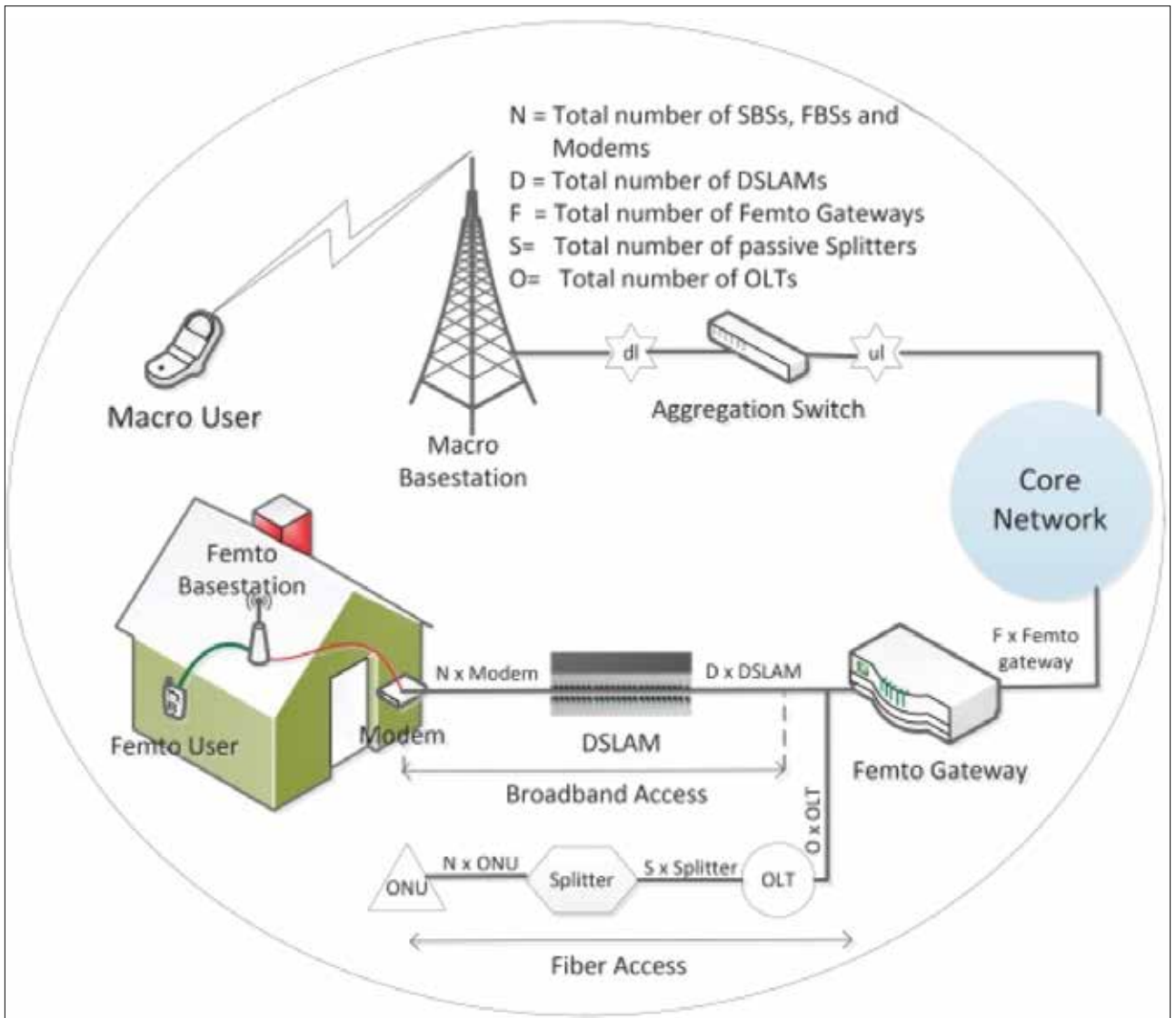


Figure 3. Data transfer and major components in heterogeneous next generation wireless networks

Importance of green communications stems from the fact that oil-based fuels have been at the forefront of the main energy sources. Therefore, carbon emission rates escalate and become an environmental issue affecting the entire globe. Monitoring the spectrum plays a very important role at this point. Studying the high-resolution data obtained by spectral monitoring enables authorities to detect unnecessary stations operating and to find transmitters that employ higher power levels than necessary. Thus, spectrum monitoring directly protects the national wealth and paves the way of realizing more environment-friendly communication systems.

Proposed Spectrum Sensing Strategies for Next Generation Spectrum Monitoring

As discussed above, next generation spectrum monitoring should be comprehensive in terms of both geographical di-

versity and electromagnetic hyperspace including time, frequency, code, polarization, and so on. This forces one to contemplate a hybrid strategy for future spectrum monitoring infrastructures, services, and applications.

Another important building block for the next generation spectrum monitoring is to deploy a dynamic, adaptive, reconfigurable measurement setup. It is clear that easy-to-deploy campaigns inherently points out mobility. Therefore, it is certain that regulatory bodies should be able to make use of certain technologies such as software-defined radios and/or reconfigurable platforms. Combined with over-the-air update capabilities, such settings could be established once and reused everywhere with their high mobility support. Having said that, one should also consider very cheap, disposable spectrum sensors, which are believed to take their places in the market soon. Note that this idea should be extended in such a

way that all idle, available, no-battery-problem devices could be used to contribute spectrum monitoring efforts as in Search for Extraterrestrial Intelligence (SETI) project.

Such a system should encompass superior modeling, estimating, and predicting capabilities with the historical data at hand along with the contemporary measurements. In conjunction with the adaptation and reconfigurability characteristics, the system needs to take advantage of linear, nonlinear, and heuristic tools depending on the scenario. It is obvious that this enforces the system to have some sort of awareness capability as well, which enables it to choose the appropriate tool.

Decision fusion mechanisms are also integral parts of next generation spectrum monitoring systems. Considering the geographical spread of the possible spectrum sensors, linear, nonlinear, and binary fusion techniques should be employed by such systems too.

Conclusions and Future Directions

The EMS is a never-ending, unlimited, reusable natural resource. Efficient use of the EMS facilitates countries to benefit both economically and technically (non-civilian usage, security intelligence, communication, remote sensing, meteorological observation, etc.) from this source through its commercialization. Countries should monitor, control, and manage the EMS in light of the state-of-the-art techniques, concepts, and paradigms.

The EMS should be monitored in a highly detailed, on a very large-scale, and with high-resolution on each and every possible domain such as space, time, frequency, and code. The monitoring data should be analyzed statistically in such a way that both concurrent and the past observations are exploited to develop accurate planning and smart allocation strategies. Otherwise, the EMS will not be utilized and will become unmanageable rapidly as new technological developments emerge and penetrate the wireless communications ecosystem. Leading countries and multinational organizations in the field of wireless communications technologies have already started experiencing the aforementioned problems. Hence, new concepts and paradigms such as spectrum refarming and flexible licensing are proposed. This implies that countries that follow the leading countries will have a similar roadmap and face almost the same set of issues and problems in the near future.

It should be mentioned that EMS is important from various other perspectives apart from technological and economic aspects. Disaster communications, health, and environment-friendly communications are the most prominent ones. It should be noted that all of the aforementioned topics place serious responsibilities and agendas on the institutions and/or organizations that have the authority to monitor the spectrum.

Finally, one could foresee that next generation spectrum monitoring strategies imply, by definition, massive information flow

in various formats and in both structured and unstructured way. Big data and relevant issues inherently take their places. Infrastructure, data processing algorithms and techniques, and effective storage and database designs are important aspects from these perspectives.

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