INVITED PAPER *Special Section on Dynamic Spectrum Sharing for Future Wireless Systems*

Research & Development of the Advanced Dynamic Spectrum Sharing System between Different Radio Services

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SUMMARY To achieve highly efficient spectrum usage, dynamic sharing of scarce spectrum resources has recently become the subject of intense discussion. The technologies of dynamic spectrum sharing (DSS) have already been adopted or are scheduled to be adopted in a number of countries, and Japan is no exception. The authors and organizations collaborating in the research and development project being undertaken in Japan have studied a novel DSS system positioned between the fifth-generation mobile communication system (5G system) and different incumbent radio systems. Our DSS system has three characteristics. (1) It detects dynamically unused sharable spectrums (USSs) of incumbent radio systems for the space axis by using novel propagation models and estimation of the transmitting location with radio sensor information. (2) It manages USSs for the time axis by interference calculation with propagation parameters, fair assignment and future usage of USSs. (3) It utilizes USSs for the spectrum axis by using methods that decrease interference for lower separation distances. In this paper, we present an overview and the technologies of our DSS system and its applications in Japan.

key words: *dynamic spectrum sharing, spectrum sharing management system, spectrum sharing technology, radio propagation, 5G system*

1. Introduction

The characteristics of the 5th generation mobile communication system (5G system) were defined as "enhanced mobile broadband, massive machine type communications, or ultrareliable and low latency communications" in IMT-2020 [1]. The volume of mobile communication traffic will further increase in the future. To undertake mobile communication with the 5G system, more frequency bands are required. One way to obtain new frequency bands is utilization of high frequencies such as millimeter or terahertz waves. For example, the 5G system has been assigned 17.25 GHz bandwidth in the millimeter wave bands in WRC-19 of ITU-R. The other way is to utilize current frequencies in the time and space domain using spectrum sharing. Frequency bands under 6 GHz have good propagation characteristics for a mobile communication system, but they have already been assigned to many radio systems. Some mobile communication operators have started 5G service in 28 GHz in the millimeter wave band. Reference [2] states that a 26 GHz band is also required for 5G service, but it is used for fixed wireless access in Japan. If dynamic spectrum sharing (DSS) between the 5G system and the other radio systems is realized, it not only will obtain new frequency bands for the 5G system, but also improve spectrum efficiency.

The authors and collaborating organizations have undertaken a research and development (R&D) project on a system for DSS that will operate between different radio systems in Japan. The purpose of our R&D project is the realization of technologies for the advancement of DSS. The objective of these advances is to create more opportunities for spectrum sharing for 5G systems. We will consider the following three points to implement the advanced DSS system shown in Fig. 1.

- (1) Detecting unused sharable spectrum for the space axis
  Current spectrum sharing is based on a fixed separation distance between radio systems. Since it does not consider site-specific radio propagation between them, incumbent radio systems (IRSs) have unused spaces which can be used for spectrum sharing with a 5G system. We refer to the unused spaces of IRSs as "*unused shareable spectrum (USS)*". To assign USSs dynamically to 5G systems by a DSS management system (DSS-MS) requires detection of USS locations in more detail. The main technologies for USS detection comprise a novel site-specific radio propagation model suitable for a DSS system, and a method to estimate the transmitting location of an IRS.
- (2) Manage USSs for the time axis
  If the DSS is widely used, many types of interference occur between IRSs and the 5G system. For example, if the transmission point of an IRS moves or is used temporarily, the interference between them is changed in the time axis. A novel technology for in-

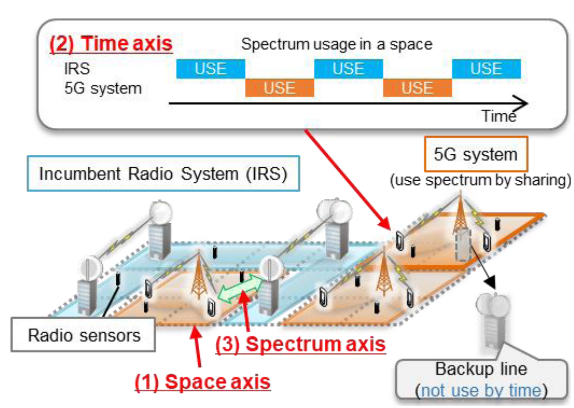

Fig. 1 Points requiring consideration in DSS R&D.

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terference calculation between an IRS and 5G system is required to address this situation because it is important to avoid interference in DSS. The technology will need to consider propagation parameters such as antenna pattern, and the movement of IRS transmission locations. A fair assignment method for allocating spectrum between 5G systems is also required when many users use a USS. In addition, a way of estimating future USS usage is required to plan for the utilization of USS by 5G operators.

- (3) USS utilization for the spectrum axis
  To increase the possibility of utilizing USSs, methods are required to decrease interference between an IRS and 5G system with a smaller separation distance. If a smaller separation distance can be realized, sharable spectrums can be used more efficiently because many opportunities can be obtained to use 5G systems without interference. Such methods will have to include a method to decrease interference on the 5G system side only, and a method to control transmission parameters (e.g. power) through collaboration between an IRS and a 5G system. The other is restriction on radio wave transmission on an assigned USS in a limited area to avoid interference over the area.

The rest of this paper is organized as follows; in Sect. 2, we present related work and how our R&D project differs from other studies. Section 3 describes our R&D project in detail. Section 4 presents the applications of the methods we developed in the project, and our conclusions are presented in Sect. 5.

2. Related Work and Differences

In Europe and the United States, mechanisms for DSS allocation have been studied. They are referred to Licensed Shared Access (LSA) in Europe [3], and the Citizens Broad Radio Service/Spectrum Access System (CBRS/SAS) in the United States [4]. The "*protection area*" is defined as the area which is used by an IRS. The USS area refers to the area outside the protection area. It is important to determine the protection area to avoid interference between an IRS and 5G system. The protection area is determined based on spectrum databases and sensors. The mechanisms allow the flexible assignment of and operation with hierarchical licensing through a DSS-MS. The DSS-MS of LSA determines the protection area from the elements and usage information of an IRS in advance, and it permits sharing outside the protection area. The DSS-MS of CBRS/SAS senses the usage status of IRSs, and it orders transmission to a mobile communication system to stop or begin based on the usage status.

The current DSS system (including LSA and CBRS/SAS) uses a general radio propagation model and determines a safe protection area with a large and conservative separation distance to avoid interference. If a 5G system would like to obtain more opportunities to use a USS, the separation distance will be decreased. For this, a novel radio propagation model needs to be consistent with both the safety protection of an IRS and a minimum separation distance. In addition, the exact transmission location in an IRS is required to determine the protection area with more precision. To apply DSS to more IRS frequency bands, a method is needed for estimating the exact transmission location without transmission elements such as transmission location, power and antenna pattern. The reason is that some IRSs cannot provide the elements required by IRS operators.

An interference calculation is executed daily to determine the protection area in the current DSS system. This means that no consideration is given to IRS mobility, but some IRSs such as field pick-up units (FPUs) [5] for a broadcasting system move and use their spectrum for a limited time at a location. To realize DSS in the time axis, it requires a high-speed method of calculating interference while taking radio propagation parameters such as the antenna pattern into consideration. In addition, when many users utilize USSs through a DSS system, it requires fair assignment. To create more opportunities to use USS, the operator of a 5G system would like to know if a USS can be used in the future. A method for estimating future USS status from IRS spectrum usage is also required.

A DSS system will expand the opportunities for spectrum sharing with a 5G system, and USSs will be utilized to obtain more spectrum efficiency. For this, to decrease the distance between an IRS and 5G system even more, it requires methods that can reduce interference and automatically adjust the transmission parameters between the two systems. In addition, when a USS is used within a limited area, e.g. a local 5G system [6], a method to restrict the transmission of radio waves within the limited area is required.

3. Overview and Technologies in R&D Project

3.1 Overview of R&D Project

Figure 2 shows an overview of the R&D project, the objective of which is to realize an advanced DSS system. After this, for example, "(F2-1a)" refers to (1a) in Fig. 2 and in the same manner for "(F2-2b)" etc.

- (1) USS detection
  A spectrum database (S-DB) is constructed based on the reported spectrum information from radio sensors etc. A reliable and rapid method is required to collect information from many sensors (F2-1a). Various IRS parameters, such as transmitting power, antenna pattern and geological information, are stored in an environmental database (E-DB). The DSS-MS estimates the spectrum usage status of each meshed location by using an advanced propagation model (F2-1b) based on the S-DB and E-DB, and detects USS. If the IRS location is unknown, the DSS-MS estimates it (F2-1c) from information contained in the S-DB and E-DB.

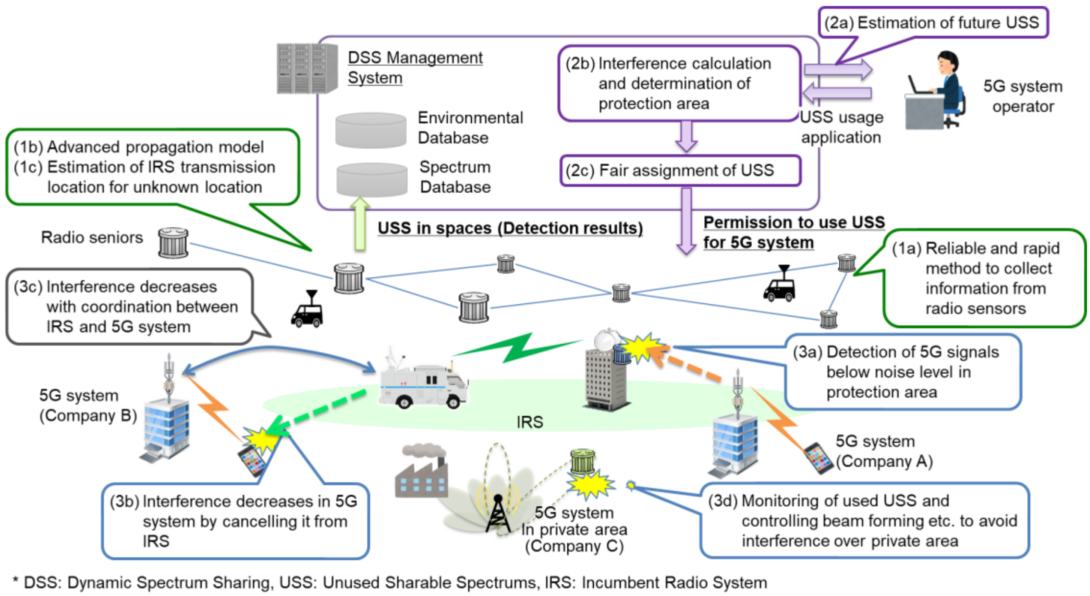

Fig. 2 Overview of R&D project.

- (2) USS management
  When the operator of a 5G system wishes to use frequency bands which are enabled for spectrum sharing, the operator will submit a usage application, which includes the number of radio stations, their location etc., to the DSS-MS. To make the application, the operator needs to know the future usage of the frequency bands (F2-2a). Then, an advanced method (F2-2b) in the DSS-MS calculates the interference between IRSs and 5G systems and determines the protection area of the IRS while taking the information from the E-DB and the application into consideration. Finally, in the case where applications are requested for the same location and USS, the DSS-MS assigns USS in a fair manner using an advanced algorithm (F2-2c).
- (3) USS utilization
  To utilize the assigned USS, the DSS system requires three points to be addressed. The first point is detection of 5G signals below the noise level in a protection area (F2-3a). The second point is decreasing the distance between an IRS and a 5G system. This requires the interference between an IRS and a 5G system to be decreased. One method involves decreasing interference from an IRS in a 5G system by cancelling the interference from the IRS (F2-3b), and the other method involves reducing interference by coordinating the two systems (F2-3c). A third method is to avoid interference from radio wave transmissions in the assigned USS area. It assumes an application for a local 5G, and a management system in the area will monitor the used spectrum in the area and control beam forming (F2-3d).

3.2 USS Detection Technologies

USS resources change dynamically by location, radio environment and the usage status of an IRS and a 5G system. Accordingly, technologies to measure these parameters will contribute to the determination of USS. One important method is propagation estimation. If propagation estimation is erroneous, the 5G system will cause interference to an IRS. Since an IRS and a 5G system will be used in various environments such as moving, locations and spaces (including height), the estimation method must be highly precise and site-specific. When interference from a 5G system exceeds the allowable range of an IRS, it is necessary to detect this situation quickly. A difference in the propagation characteristics by frequency band (e.g. under 6 GHz and millimeter wave) also needs to be considered. The other main method is for estimating the IRS transmission location with radio sensors. It is required in the case where there is no IRS element about the transmission point.

1) Propagation estimation and USS detection for under 6 GHz bands (related to (F2-1b))

In the R&D project, two approaches are studied to realize highly precise and site-specific radio propagation estimation. One approach is based on a propagation model. A simple propagation estimation model is based on ITU-R P.2108 [7], and it has been modified to consider a small clutter loss in a propagation path [8]. The simple model can be applied to the current DSS-MS system with a little calculation. To obtain a more precise estimation, a highly precise propagation model for each location is also being studied based on a spectrum map [9]. The other approach is for future implementation, and it uses AI/ML for more precise propagation estimation [10]. In addition, to ascertain the operation status of IRSs and 5G systems at low cost, a method of collecting spectrum usage by sparse radio sensors is being studied.

2) Minimum propagation loss estimation for a millimeter wave band (related to (F2-1b))

A propagation characteristic of the millimeter wave band is straightness due to its short wavelength, and blockage occurs by a building etc. This means that there are many opportunities for spectrum sharing. However, if a 5G system causes interference to an IRS such as a fixed wireless access, the IRS is affected by the 5G system. In the R&D project, a minimum propagation loss model for DSS is being studied [11]. The model can estimate a worst-case value for site-specific interference from a 5G system to an IRS. A detection method for IRS stations by fixed and moving sensing is also being studied. The method is required for a moving IRS, and it can detect a very weak received signal strength indicator (RSSI) such as that lower than the noise level to detect a preamble signal of IRS. In addition, an antenna for sensing is being studied [12]. The antenna can measure very low RSSI with an unknown plane of polarization, and it measures by rotating to detect the IRS's radio wave effectively.

3) Method for collecting data from radio sensors (related to (F2-1a))

To ascertain the operation status of an IRS, it is necessary to collect RSSI information effectively and rapidly from radio sensors in a large field. Many radio sensors in a field measure RSSI from an IRS at the same time. In the R&D project, a protocol is being studied which can quickly collect information from many radio sensors with a narrow frequency bandwidth [13]. The collected information has spatial continuity, and it includes RSSI less than the noise level. An information compression method is also being studied to realize more spectrum efficiency in information collection [14].

4) Estimation of transmission location (related to (F2-1c))

For USS detection and decision-making regarding a protection area, it is necessary to know the exact transmission location of the IRS. However, some IRSs cannot provide the location information required by the IRS operator or the transmission point is moving. To identify the exact transmission location in this situation, a method to estimate it from radio sensor information [15] is being studied in the R&D project. The method adopts an algorithm based on a centroid of transmission power and supports moving of transmission points.

3.3 USS Management Technologies

Figure 3 shows USS management procedures in DSS along the methods that will be presented in this section. When a 5G system uses USSs, its operator will submit a usage application. At this time, the operator will know if a USS can be used in the time axis or not, i.e., it will be predicted with certainty if the USS for operating the 5G system is available or not. To ascertain this, as part of the R&D project, we are studying a method to estimate the spectrum usage status of each location in the future. Then, before permission is given to use the USS, the DSS-MS checks the impact of interference from the 5G system on the IRS, and determines the protection area of the IRS. This is decided based on the information contained in the S-DB and E-DB, the usage application and the propagation models described in Sect. 3.2. To decide a suitable protection area to allow utilization of the USS, many calculations are performed to ascertain interference in the time axis. Many propagation parameters are needed to consider relationships between the 5G system and the IRS which are changed in the time axis. The parameters include the antenna pattern, beam forming pattern, locations of base stations, movement of the transmission point and etc. In the R&D project, a high-speed method of calculating interference and a method of determining the propagation parameters are being studied. Finally, a fair assignment method is under study. When USSs are used by many 5G system operators, the case will arise where several usage applications will be submitted for the same USSs and locations. Since a spectrum is limited and public, it requires an assignment method based on previous usage status such as the number of USSs used and the not used status of the USS assignment.

1) USS prediction technology (related to (F2-2a))

USSs dynamically change in the time axis because there are changes in usage and movement in an IRS. In DSS, although one principle is protection of the IRS, there are restrictions in time and space on the utilization of spectrum sharing. As part of planning, the operator of a 5G system will know "when and where" a USS can be used. In the R&D project, we are studying this technology to forecast future spectrum usage in each location by adopting machine learning [16]. The forecasting is based on measured data obtained from radio sensors and calculation from the propagation model as described in Sect. 3.2. The target of forecasting is fluctuations of propagation environments originating from moving persons and vehicles, not changes in usage status as a result of operations. One study target is a forecasting algorithm with machine learning for predicting fluctuations of RSSI in the time axis, and the other is to decrease USS false positives, when a forecasted RSSI is lower than the actual RSSI.

2) Method for calculating interference for DSS judgement (related to (F2-2b))

When a USS is used by the 5G system, the 5G system must not cause interference to the IRS. For this, it is important to be able to perform a high-speed interference calculation with high reliability and a small separation distance between the IRS and 5G system. To achieve this, four points need to be studied. The first point is an interference calculation method which corresponds to information on the IRS, such as location granularity and operation elements (e.g. antenna pattern and transmission power). Since some IRSs are

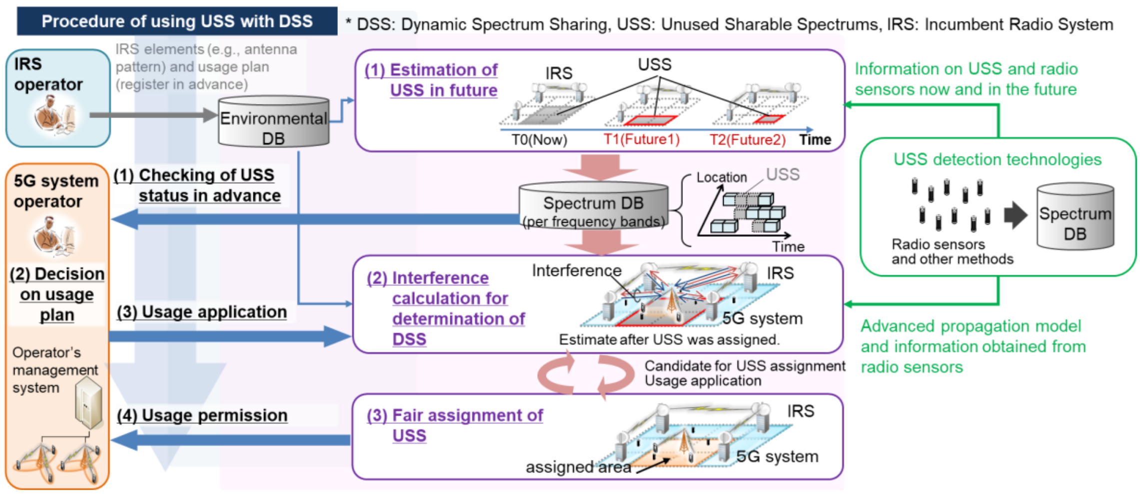

Fig. 3 Procedure of using USS with DSS.

moving and they cannot provide the operation elements, the method needs to be able to calculate the interference levels by predicting the missing IRS information. By means of the prediction, the method can increase the DSS opportunities for the 5G system [17]. The second point relates to uncertain location information for an IRS. Some IRSs cannot provide definite location information, which is required by their operators. An estimation method of IRS location is needed for the interference calculation [18]. The third point is an interference calculation with the abilities of a 5G system such as an antenna and beam forming pattern. The 5G system has a dynamic method for controlling the radio beam, and it causes interference between the 5G system and an IRS [19]. The fourth point is a method for reducing the volume of calculations taking the above points into consideration. To do this, it has to calculate many combinations of parameters, but the time for deciding a USS assignment is not infinite. A method capable of performing calculations in a limited time is needed in order to realize DSS with complex parameters [20].

3) Fair USS assignment method (related to (F2-2c))

If more efficient spectrum allocation is achieved by DSS in the future, a USS assignment technique is required based on demands on 5G systems. In addition, since high traffic areas in 5G systems are almost the same between their operators, they will try to use a USS at a certain location and at a certain time. This will need a method that allows fair USS assignment while taking the demands on 5G systems into account. One study point is an algorithm that facilitates fair assignment that considers the base stations in a 5G system. The algorithm is based on an "unfairness index" between 5G systems, and it will take control to minimize the fair of the indexes [21]. The algorithm needs to consider each base station to utilize a USS in the space axis. The other point is how to reduce calculation for assignment. The calculation is based on an optimization problem, but it requires an inordinate amount of calculation time. To decrease the time, two approaches are being studied. One approach is for small-scale assignment such as that for less than 100 base stations: the range to calculate the optimization problem is divided into pieces of the time axis, and the last result is applied to the next limitation of the optimization problem [22]. This approach enables to manage the inter-base station interference and improves the spectrum efficiency, but the computational complexity increases exponentially with the number of base stations. The other approach is for large-scale assignment: grouping is applied to the optimization problem based on the assumption that there is no interference between base stations [23]. This approach can reduce the calculation size of decision variables even if the number of base stations becomes large. However, the spectrum efficiency is lower than that of the first approach, because the grouping is unable to manage interference individually between base stations.

3.4 USS Utilization Technologies

To utilize USS in DSS, there are three issues. The first issue is that interference from a fixed IRS is changed dynamically by shadowing and fading which occur as a result of the movement of UEs in a 5G system. If a change in the interference occurs, the efficiency of using USS is decreased because more separation is needed between the IRS and the 5G system. A method is required to decrease the separation distance. The second issue is discrepancy between an estimation and the real level of interference caused by movement of an IRS. This results in serious interference to both the IRS and the 5G system, and DSS cannot work normally. A method is required to prevent serious interference. The third issue is using a USS in a private area such as a factory, a school or a shopping mall because one of applications for DSS is a local 5G system. It is difficult to generalize about the blockage effect inside or outside a private area. However, the efficiency of USS is decreased if the blockage effect is unknown. More separation is required because the blockage

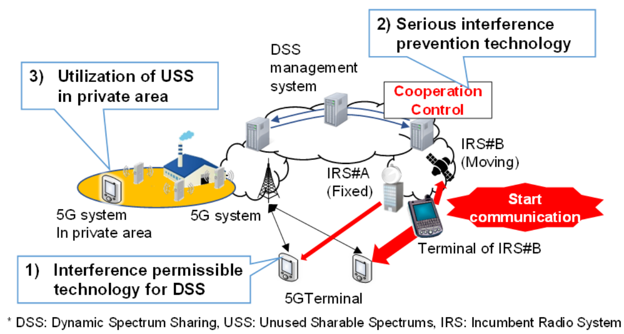

Fig. 4 Overview of USS utilization technologies.

effect cannot be considered when calculating interference. A method is required that allows a shared spectrum to be utilized within the private area.

In the R&D project, the technologies are under study and an overview of the technologies is shown in Fig. 4.

1) Interference permissible method for DSS (related to (F2-3b))

If the separation distance between an IRS and a 5G system becomes small for dense DSS, interference from the IRS by fading and shadowing decrease the performance of the 5G system. However, since IRSs have been deployed as radio systems, it is difficult to modify them to fit this situation. To permit interference from the IRS only in the 5G system, two approaches are being studied. One approach is an IRS interference cancellation method [24]. If elements of IRSs on E-DB such as a standard specification are known, a digital processing method can be applied to remove an IRS radio signal from a received signal of a 5G system by replication of the IRS radio signal. The other approach is a method that changes the radio resource assignment in the 5G system. When the IRS causes interference to the 5G system, some radio resources are affected by the interference, while others are not affected or less affected. The method judges effects caused by interference and assigns the radio resources based on these effects [25]. This approach is useful when elements of IRSs on E-DB are unknown or not known in detail.

2) Serious interference avoidance method (related to (F2-3a) and (F2-3c))

In DSS, there are some situations that cause serious interference between an IRS and a 5G system such as movements of an IRS. Serious interference adversely affects DSS. To avoid serious interference through cooperative control of the IRS and the 5G system in the future, three approaches ranked by the degree of cooperation are being studied in the R&D project. The first approach is the use of control signal information of an IRS for the assignment of radio resources in a 5G system. The 5G system senses the control signal of the IRS, and it communicates via channels which are judged to be empty by the control signal. In addition, it studies radio sensor data to detect the noise level such as the permitted interference level for DSS based on this approach. This is useful for protecting the IRS with greater certainty, because an order to stop the 5G system is based on detection by the noise level. The second approach is the use of a common control channel. This method involves the IRS and 5G system checking the same control channel and judging if there are sufficient radio resources for communication. The third approach is mutual transmission control by means of a special communication system. The IRS and 5G system are associated through mutual transmission control to prevent serious interference. Furthermore, the radio resources which are obtained by the above approaches are changed dynamically. To utilize the radio resources, a novel radio communication system is also being studied [26].

3) Utilization of USS in a private area (related to (F2-3d))

It is important that radio waves of a 5G system in an assigned USS band are not transmitted over an assigned area. If the radio waves are transmitted over the area, they will cause interference to an IRS. However, if the transmission power or number of 5G base stations in the area is decreased to avoid causing interference, the USS cannot be utilized. For USS utilization, two matters are being studied in the R&D project. The first is a method of determining radio sensor locations in the private area. To check whether the radio waves of the 5G system is over the area or not, radio sensors are needed, but there is a cost associated with the installation of many radio sensors. To address this matter, the method optimizes locations and number of radio sensors for monitoring interference from base stations in the area based on a propagation simulation. The simulation also estimates interferences by changing usage of the USS in the area. The other matter concerns a method of controlling radio resources in the private area in order to utilize USS in the area [27]. It controls beam forming and the transmission power of the 5G system appropriately based on the interference estimation.

4. Application of DSS among Different Radio Services in Japan

4.1 DSS between FPU and Mobile Communication Systems in 2.3 GHz Band

Ministry of Internal affairs and Communications in Japan has announced in its Action Plan for Spectrum Reallocation in 2020 [28], that DSS should be studied for spectrum sharing between FPUs and mobile communication systems (MCSs) in the 2.3 GHz band from the fiscal year of 2021. In addition, some other bands were specified for study for possible DSS application, which include the 2.6, 26 and 38 GHz bands. We are now working on the application of some technical breakthroughs in our study on DSS methods described in the previous section.

In Fig. 5, an example is presented for the possible application of DSS between FPUs and an MCS in the 2.3 GHz band. In this case, the 2.3 GHz band spectrum is allocated to an FPU as an IRS, while the MCS uses the band as a

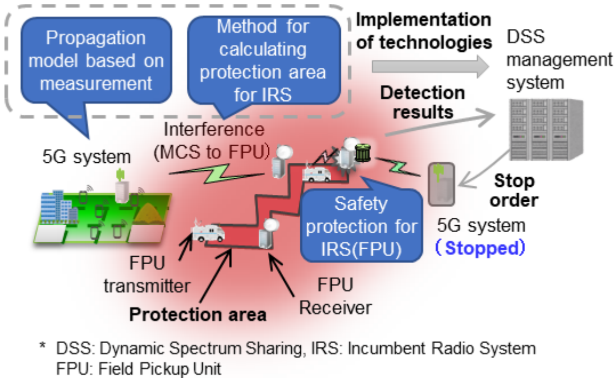

Fig. 5 DSS between a FPU and a MCS in 2.3 GHz band.

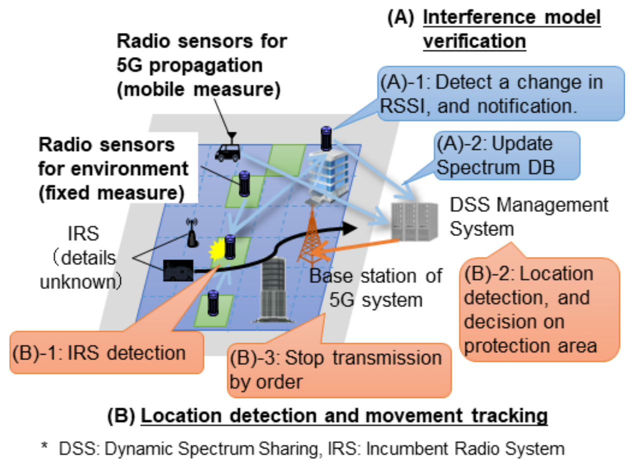

Fig. 6 High precise detection of USS by radio sensors.

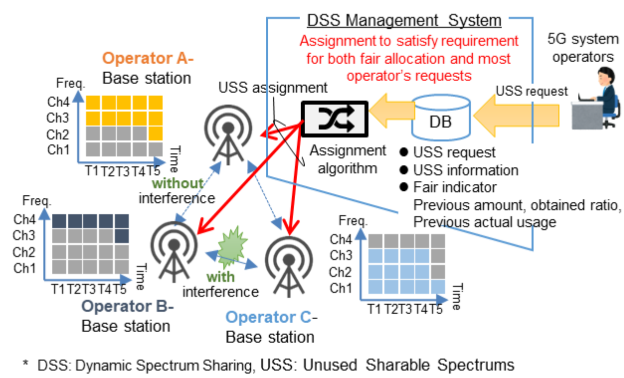

Fig. 7 Increase of spectrum efficiency by fair assignment.

shared frequency. Therefore, the MCS should not cause harmful interference to the receivers in FPU systems. The operation plans of radio stations in FPU are available in advance, therefore, the MCS operators can identify the FPU radio stations to be protected and thus can schedule their radio stations that could potentially cause interference to the FPU receivers without having to monitor FPU system operation by radio sensors. In order to protect the primary FPU systems, the unused shared spectrum detection technology described in Sect. 3.2 could be applied to identify possible interference caused by MCS stations. An appropriate radio propagation model should first be applied to predict the interfering radio signals originating from transmitters in MCS that would affect the receivers in FPU systems. In the R&D project of [8], a site-specific radio propagation prediction model is under development so that the actual interference signal strength does not exceed the predicted level in more than 99% of spatial areas.

Following on from the above, the shared spectrum management technologies discussed in Sect. 3.3 would be used to determine whether the MCS stations cause interference to the receivers in FPU based on the propagation model and sharing criteria. In addition, in order to avoid unpredicted interference from MCS stations to the receivers in the FPUs, radio sensors could be helpful to monitor sudden changes in propagation conditions. Such radio sensors are required to measure weak radio signals, i.e., much lower signal levels than the desired FPU radio signals. For this purpose, interference signal detection algorithms are being developed in conjunction with the interference avoidance method described in Sect. 3.4 [29].

To use these technologies, the DSS-MS is under development [30] together with verification trials being run as field experiments [31] and the development of spectrum sharing rules in the 2.3 GHz bands such as interference criteria, operation workflows and so on [32].

4.2 Further Enhancements of Dynamic Spectrum Sharing Applications

As the demand for additional spectrum is increasing, DSS will become more significant and even essential to ensure the efficient use of limited spectrum resources. To cope with these requirements, the methods for DSS have to be enhanced to deal with advanced spectrum sharing conditions.

Different from the radio stations in the FPU case, the operation plan such as operation time and locations are not available in advance in some radio stations with primary spectrum allocation. In this case, spectrum sensing methods are required to protect unknown radio stations as depicted in Fig. 6. In this example, it is essential to identify the location of radio stations have primary allocation by sensing and monitoring the radio signals from the IRS stations [15]. Furthermore, it is necessary to predict the usage of the spectrum resources by the IRS stations in order to develop the operation schedules of the secondary radio stations.

When the number of secondary radio operators increases, fair spectrum allocation algorithms [21] contribute to enhancing dynamic spectrum usage among the radio operators as shown in Fig. 7.

5. Conclusions

In this paper, we presented R&D project for DSS in Japan. To realize an advanced DSS, many technologies related the detection, management and utilization of USS are being studied. In addition, several applications based on the studied technologies were also described. As stated in Sect. 4.1, DSS in the 2.3 GHz band in conjunction with the technologies described in this paper will start as a social infrastructure system from the fiscal year of 2021. The authors and joint research organizations will endeavor to apply these technologies to other applications of DSS in the coming years.

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