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The Feasibility of Coexistence Between 5G and Existing Services in the IMT-2020 Candidate Bands in Malaysia

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ABSTRACT In 2015, the international telecommunication union (ITU) proposed 11 candidate millimeter-wave bands between 24 and 86 GHz for the deployment of future fifth mobile generation (5G) broadband systems. Furthermore, the ITU called for spectrum-sharing studies in these bands. Since 5G specifications are not yet defined, the utilization of radio spectrum by 5G mobile systems will assist in identifying these specifications. This paper introduces Malaysia as a case study for the deployment of 5G systems. This includes a discussion of the current status of the Malaysian telecommunication market. Then, we investigate the current services that are already deployed in the proposed bands. Our investigation shows that the fixed (F) service is the most deployed as a primary service in the candidate bands. For this reason, a preliminary spectrum-sharing study is conducted on the basis of a modified 5G spectrum-sharing model to evaluate the feasibility of coexistence between 5G and F services in the 28-GHz band. Our modified methodology can be used for spectrum-sharing studies between 5G and any other services for an initial spectrum-sharing investigation. The results show that the F service will be severely affected by the 5G system transition in the 28-GHz band, especially in the base station (BS)-to-BS sharing scenario. The best band from the perspective of current spectrum allocation for 5G systems is the 45-GHz (i.e., 45.5–47 GHz) band, since it is already reserved for mobile service for primary allocation and not utilized. This paper is carried out concurrently with current worldwide efforts investigating spectrum sharing, as requested by the ITU in agenda item 1.13 for the next world radio conference 2019.

INDEX TERMS Cellular phones, fifth mobile generation (5G), IMT-2020, interference, millimeter wave communication, mobile communication, radio spectrum management, spectrum sharing.

I. INTRODUCTION

The increase in data-rate demands for wireless communication systems and networks has led to the evolution of the fifth mobile generation (5G) [1]. This evolution can be approached by allocating more frequency bands for mobile systems and wireless networks. The International Telecommunication Union (ITU) has stated that the data traffic currently generated by mobile and other wireless communication systems is more than expected [1]. It is expected that 5G systems will have peak data rates between 10 and 50 Gbit/s and a latency of 1 ms [2]. In addition, more bandwidth means new RF allocation in the crowded radio spectrum. To achieve these demands, new and more frequency blocks need to be allocated to new mobile systems in the congested UHF and super high frequency (SHF) bands. Since it is very difficult to remove systems in bands at frequencies below 6 GHz, the millimeter wave (mmW) bands are potential candidates for the International Mobile Telecommunication-2020 (IMT-2020) system [2], [3].

A. IMT-2020 CANDIDATE BANDS

At the World Radio Conference 2015 (WRC-15), the ITU proposed 11 new candidate bands, which are listed in Table 1, for IMT-2020 mobile systems on a primary basis [4]. These bands indicate that a total of 36.25 GHz of spectrum is

TABLE 1. IMT-2020 candidate bands [4], [5].

	mWCBs (GHz)	Available Bandwidth	General Remarks	Malaysian Remarks [6]
1.	24.25–27.5	3.25	Resolution 238 [4] sets these bands to the mobile service on a primary basis	This band is allocated for the fixed service for region 1 and the radiolocation system in Regions 2 and 3
2.	37–40.5	3.5		The bands are harmonized in all ITU regions
3.	42.5–43.5	1		
4.	45.5–47	1.5		
5.	47.2–50.2	3		
6.	50.4–52.6	2.2		
7.	66–76	10		
8.	81–86	7		
9.	31.8–33.4	1.6	Resolution 238 [4] considers these bands to require additional allocation to the mobile service on a primary basis [4] (i.e., nonglobal mobile allocation)	
10.	40.5–42.5	2		
11.	47–47.2	0.2		
12.	27.5 –28.5	1	The UJK bands; not suggested by the ITU but by the FCC [5]	
		Total of 36.25 GHz proposed allocation for 5G		

proposed to be available for 5G systems. Not all of the 36.25 GHz is allocated to 5G; it is possible one band or several bands will be chosen at the World Radio Conference 2019 (WRC-19) on the basis of the contributions of studies conducted by ITU members and researchers. These bands need to be investigated for future IMT-2020 systems. Studies on sharing between 5G and other systems have also been requested by the ITU resolution as an input to agenda item 1.13 of the WRC-19 [4].

Table 1 includes another 27.5–28.5 GHz band known as 28 GHz, which is proposed and adopted by the USA, Korea, and Japan [5]. This band is not included in the band proposed the ITU. From Table 1, the widest bandwidth of 10 GHz is available in the 66–76 GHz band; in contrast, the 47–47.2 GHz band provides the narrowest bandwidth of 200 MHz compared to the other mmWave candidate bands (mWCBs). Since the total spectrum allocated by the IMT for all current and legacy mobile systems is not more than 780 MHz [7], this allocation can accommodate about 3,869 million mobile devices in 2016 [8]. This means that the selection of any of the proposed bands (except the 47 GHz band) can accommodate a larger number of devices with the existing IMT bands. The two main reasons for using these higher frequency bands, as stated in resolution 238 of the WRC-15, are as follows. First, there are no bands available below 10 GHz and for new IMT systems. Second, the higher contiguous spectrum blocks can support the IMT's vision of providing very-high-bit-rate applications for the new IMT system and accommodating ultralow latency communications [4]. In addition, these bands have a shorter wavelength, which can permit advanced antenna technology such as beamforming techniques and multiple-input–multiple-output (MIMO) technology. These technologies will eventually increase the spectral efficiency in an optimum way [4]. The resolution also stated that additional regulatory action may be required for the allocation of the new IMT frequency bands, and the current sharing status is expected to change for systems in these bands. The sharing studies that will be conducted must take into account the protection of existing services on primary bases and the services in the adjacent bands [4].

It is expected that the selection of an IMT-2020 band depends on main four criteria. First, it depends on how vital the existing service is and whether it can be turned off, cleared, or shifted to another frequency band or can handle interference from and to the IMT-2020 system (i.e., share spectrum with 5G systems) [4], [9]. Second, it depends on the adjacent service if it can tolerate interference. Third, it also depends on the results of spectrum-sharing studies. Fourth, it depends on international harmonization and the consensus among worldwide country regulators.

5G channel modeling, current 5G system prototypes, and other technological studies regarding the mmWave bands led by the USA, Korea, and Japan are pushing toward the unproposed 28 GHz band. This can be clearly seen in channel modeling studies [10], [11], prototypes [12], and even the announcement of a trial 5G system in worldwide public sporting events such as the Olympic games [13]. They are evidence for the selection of the 28 GHz band for the next mobile service. If the current push remains without the provision of alternative studies and experiments, the 28 GHz band is expected to be the potential band for 5G systems. For this reason, we adopt the 28 GHz band for the spectrum-sharing studies in our study. The last European Communication Commission (CEPT) workshop in November 2016 was conducted with regards to the 5G bands. The CEPT clearly stated that it will not conduct sharing studies in the 28 GHz band for 5G deployment owing to the high usage of the fixed (F) service and fixed satellite service (FSS), but it supports sharing studies in the 26 GHz band, which is titled a pioneer band [14]. It also supports global harmonization by providing a harmonized tuning range that can overcome the differences between regions. For instance, the tuning range of the 30 GHz band can include the 26 and 28 GHz bands. It is also stated that there is a lake of interest in bands above 66 GHz among CEPT members [14].

B. CURRENT STATUS OF THE 5G CANDIDATE BANDS

Officially, there two recommendations published by the ITU for the feasibility of IMT systems operating above the 6 GHz [1], [15]. The vision, objectives, timeline, and framework of the IMT-2020 system are described in detail in [15]. In [1], the technical aspects of the IMT-2020 system operating above 6 GHz are addressed. The recommendation investigates technology enablers such as antenna technologies and the development of passive and active components. In addition, radio propagation models above 6 GHz are investigated, providing information about the path loss, atmospheric loss, and other types of losses.

The current worldwide status of the 5G candidate bands can be found in [16], [17] and [14], where the authors state that spectrum-sharing will play a major role in the deployment of 5G. In [16], the current states of the major regulatory bodies, industry, and academia are addressed. This study shows that 5G spectrum sharing will be more challenging than the previous IMT spectrum sharing. This is due to the differences in spectrum-sharing techniques from country to country and band to band. This study concludes that dedicated licensed spectrum access is more likely in order to achieve a certain reliability for mobile broadband. The sharing scenario would be case-by-case because different bands mean different services would share the spectrum. The study presented in [17] recommends that controlled spectrum sharing is the optimum solution for spectrum reuse in order to complement the existing services operating in these bands. As mentioned in Section I.A, the CEPT had conducted the latest 5G workshop and presented a 5G progress update. In the workshop, it stated that new radio access is expected to be completed in June 2017, and the first 5G official parameters and specifications will be available in 3rd Generation Partnership Project (3GPP) release 15 in September 2018 [14]. In addition, the workshop showed that ITU-R working party 5D will provide sharing parameters in March 2017 [14].

On the basis of the above discussion, our study investigates the feasibility of coexistence between 5G systems and existing primary services, especially F services. In addition, our study provides a general spectrum-sharing model for future studies between IMT-2020 and other services. Fig. 1 depicts our research investigation visually. The figure is based on the Malaysian spectrum chart [18] and shows two of the IMT-2020 candidate bands, i.e., the 24 and 38 GHz bands, which are indicated by the pink-colored background. The additional 28 GHz unproposed band in the purple-colored background is also shown in Fig. 1. It can be seen that many services are being deployed and operating within the bands, especially the F service (in yellow), which is allocated in the proposed and adjacent bands. This shows the importance of conducting spectrum-sharing studies to shape the figure of the 5G system by selecting its appropriate band and reducing its effect on existing services.

As in legacy mobile systems such as the IMT-2000 and IMT-Advanced systems, no parameters were available at the time of their first announcement, and each of these legacy systems needed spectrum-sharing studies before their existence. The unavailability of parameters made it difficult to conduct accurate spectrum-sharing studies at the time of their introduction. This challenge exists with the introduction of the 5G system. Channel modeling of the 5G system is one of the main challenges for spectrum-sharing studies. In addition to the unavailability of parameters or standards for 5G, the IMT system will be deployed in higher bands, where neither a standard path loss for mobile systems is available, nor a spectrum emission mask or blocking response are currently available for the IMT-2020 system. All of these parameters will be available when the ITU sets standards for the 5G system. On the basis of previous preliminary spectrum-sharing studies between the new coming mobile systems and existing services [19]–[22], initial results can be achieved. This study tackles these challenges and investigates the spectrum-sharing studies between the upcoming 5G system and the existing system based on the Malaysian spectrum plan and Malaysian specifications for systems in the mmW bands and addresses the above spectrum-sharing concerns. First, we investigate the services that already operate in the IMT-2020 candidate bands. This is the first step in spectrum-sharing studies between the 5G and primary services. This is followed by investigating the services that will be adjacent to every IMT-2020 candidate band to know the services that most operate in the adjacent bands as a primary service. The systems that are deployed in the mWCBs are defined by the Malaysian specifications published by the Malaysian Communication and Multimedia Commission (MCMC) and ITU recommendations. Then, an investigation of current sharing studies between the current systems in the mWCBs and the legacy mobile systems and 5G services is also presented. Our investigation provides evidence of how the F services will be impacted when 5G is assumed to be deployed in the mWCBs. For this reason, a modified spectrum-sharing model for 5G is designed for a general system compatibility study between the 5G and F services in the most recently investigated 28 GHz band. The model can also be used for other systems for spectrum sharing with 5G services. A coexistence study between the 5G and F services is conducted taking into account new parameters and aspects of new mobile systems such as the new path loss, beamforming, and small cell radius. On the basis of our investigations, we also recommend a certain band for the 5G system. These aspects are considered the main contributions of our study. The study aims to be a

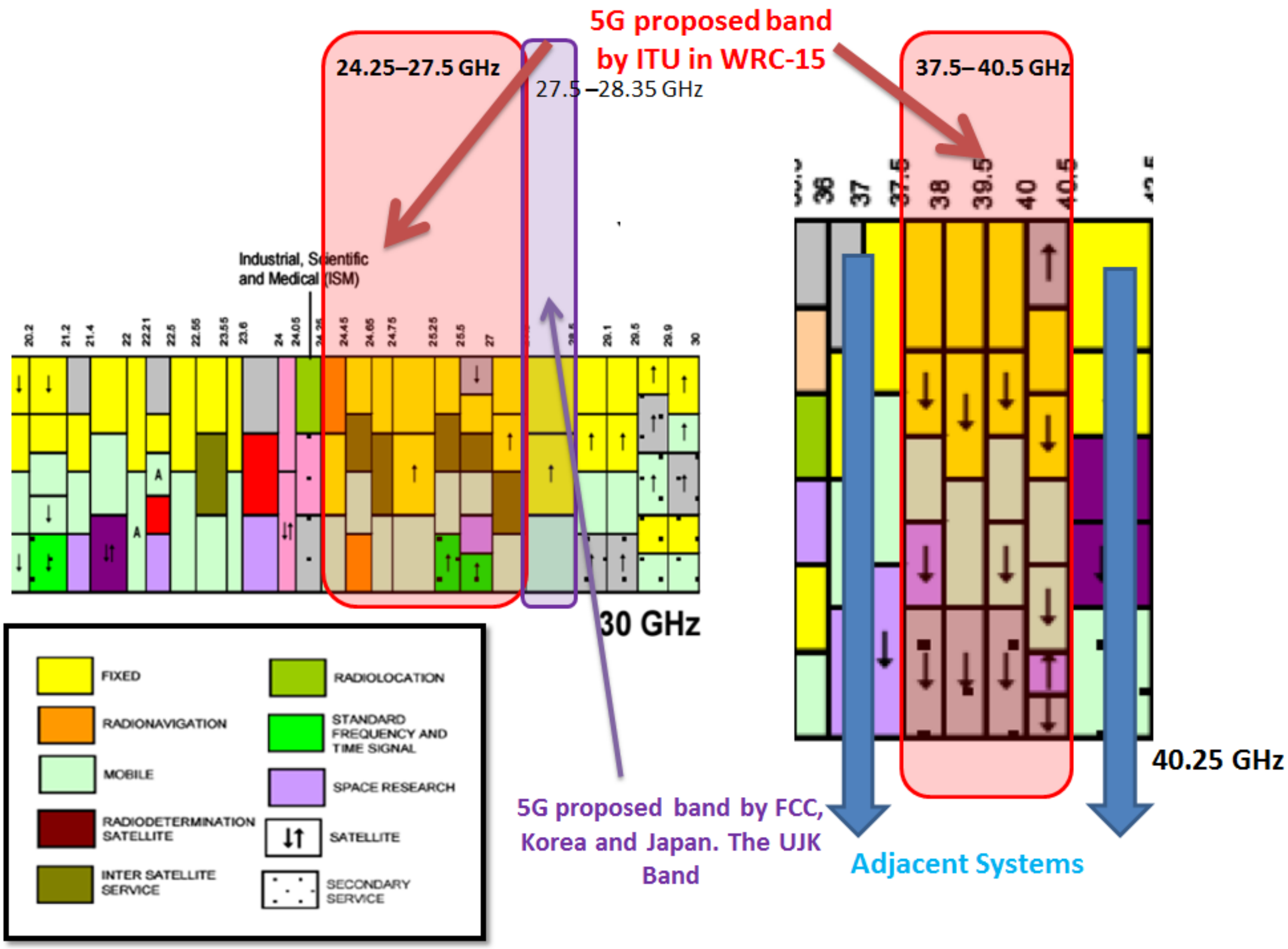


FIGURE 1. Expected Malaysian 5G spectrum-sharing scenario.

guide and reference to researchers, industry, and frequency spectrum regulators for future spectrum-sharing studies.

This paper is organized as follows. In Section II, the current status of the Malaysian telecommunications market and the current services in the mmW bands are reviewed. Moreover, the mWCBs for IMT-2020 mobile systems are discussed along with the current status of the systems and services in these bands. This section also presents the related spectrum-sharing studies of existing services with mobile systems and the Malaysian activities for promoting 5G. The methodology used to investigate the feasibility of coexistence between 5G and other services is given in Section III. Section IV presents the spectrum-sharing scenarios that are adopted in this study, and Section V presents the results. Finally, the main conclusions of the study are summarized in Section VI.

II. 5G PROSPECTS IN MALAYSIA

The Malaysian demand for cellular service is high. In the following, we briefly describe the Malaysian telecommunication market to convey the importance of 5G in Malaysia. The Malaysian population in 2015 was around 30.5 million [23] with 7.435 million households [23]. The cellular penetration in Malaysia is 145% [23], and the broadband penetration among the population is 92% [23]. Table 2 summarizes the current usage of spectrum by telecommunication companies. It can be seen that there are eight telecommunication companies in Malaysia that provide mobile and internet communication services. Table 2 also presents the spectrum usage of each company.

The current second (2G), third (3G), and fourth (4G) mobile generation service coverages in Malaysia are shown in Fig. 2 for Maxis networks [23]. The 4G network population coverage is 83% for all Malaysian state capitals and 80% nationwide [23]. This reflects the high demand in Malaysia for new mobile service.

Owing to the high usage of mobile services and to set fair competition between service providers, the MCMC announced the reframing of 2G spectra (i.e., 900 and 1800 MHz) at the beginning of 2016 for the next 15 years [25]; this an initial step from the Malaysian regulator

TABLE 2. Spectrum allocation of mobile operators in Malaysia [24].

Telecom Company	Operating Frequency (MHz) and Allocated Bandwidth				
	900	1800	2100	2300	2600
Maxis	32	50	30	-	20
CelCom	34	50	30	-	20
DiGi	4	50	30	-	20
UMobile	-	-	30	-	20
P1	-	-	-	30	20
YTL	-	-	-	30	20
RedTone	-	-	-	25	20
Puncak Semagat	-	-	-	-	40

that gives more spectrum to the new mobile system. In the following, the Malaysian services in the mmW bands are investigated by reviewing the current services in the mWCBs and the primary services adjacent to them.

A. MALAYSIAN SERVICES IN THE mWCB BANDS

On the basis of the Malaysian spectrum plan [6], there are 33 subbands in the mWCBs for 5G deployment [6].

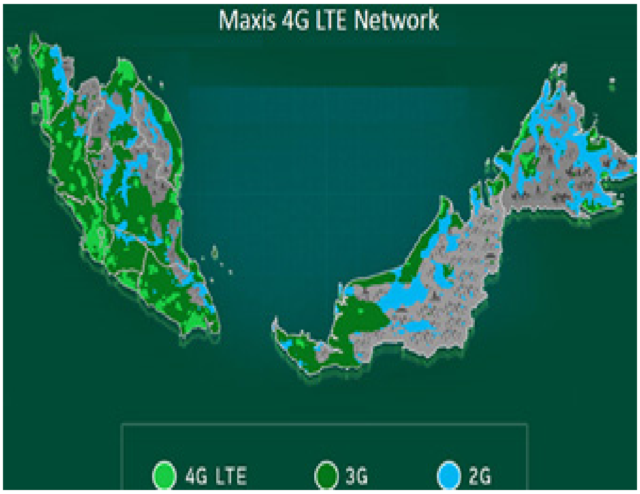


FIGURE 2. The current 2G, 3G, and 4G coverage based on the Maxis mobile network coverage [23].

Each subband contains a number of services ranging from primary to secondary services. Table 3 summarizes the services operating in the mmW bands based on the Malaysian spectrum chart [6] and the number of services available in each subband. For instance, of all primary services, F services

TABLE 3. Services operating in the millimeter-wave candidate bands.

	Candidate Band (GHz)	Malaysian Allocation [26]	Current Usage in Malaysia [26]
1.	24.25–27.5	24.25–24.45	R, F, M
		24.45–24.65	F, IS, M, R
		24.65–24.75	F, IS, M
		24.75–25.25	F, FSS
		25.25–25.5	F, FSS
		25.5–27	EESS, F, IS, M, SR
		27–27.5	F, FSS, IS
2.	27.5–28.35	27.5–28.5	F, FSS
3.	31.8–33.4	31.8–32	F, RN, SR
		32–32.3	F, RN, SR
		32.3–33	F, IS, R
		33–33.4	F, R
4.	37–40.5	37–37.5	F, M, SR
		37.5–38	F, FSS, M, SR, EESS
		38–39.5	F, FSS, M, SR, EESS
		39.5–40	F, FSS, M, MS, EESS
		40–40.5	EESS, F, FSS, M, MS, SR, EESS
5.	40.5–42.5	40.5–42.5	F, FSS, B, BS, M
6.	42.5–43.5	42.5–43.5	F, FSS
7.	45.5–47	43.5–47	M, MS, R, RNS
8.	47–47.2	47–47.2	A, AS
9.	47.2–50.2	47.2–50.2	F, FS, M
10.	50.4–52.6	50.4–51.4	F. FSS, M, MS
		51.4–52.6	F, M
11.	66–76	66–71	IS, M, MS, R, RNS
		71–74	F, FSS, M, MS
		74–76	F, FSS, M, B, BS, SR
12.	81–86	81–84	F, FSS, M, MS, RA, SR
		84–86	F, FSS, M, RA

are the most predominant compared to other services. There are 14 types of systems and services that operate in these bands; in addition to the F services, there are the radiolocation (RL) service, mobile (M) service, intersatellite (IS) service, FSS, earth exploration satellite service (EESS), space research (SR) service, mobile satellite (MS) service, amateur radio (A) service, amateur radio satellite (AS) service, radiolocation satellite (RNS) service, radio astronomy (RA) service, broadcasting (B) service, and broadcasting satellite (BS) service.

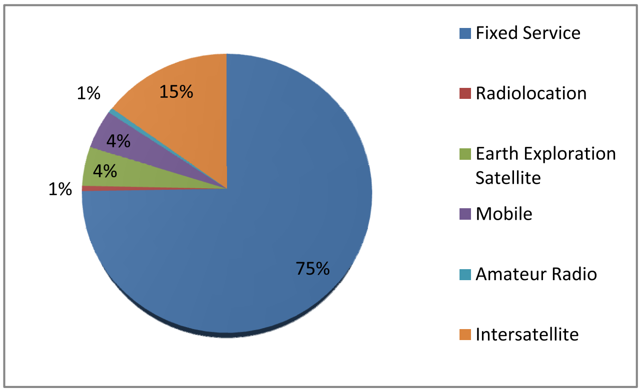


FIGURE 3. Primary services in the mWCBs.

It can be seen from the above table that some services occupy primary allocations more than other services. This is depicted in Fig. 3, which shows the primary services that already occupy the mWCBs in Malaysia by percentage. The F service is the main service that will be affected by the 5G system. From the total of 36.25 GHz of the IMT-2020 candidate band, the F service occupies 24.85 GHz in primary allocation (i.e., 75% of the total mWCBs). Moreover, the A system in the 47 GHz band occupies 1% of the total mWCB allocation, which is considered the system with the lowest amount of spectrum allocation operating as a primary service in the mWCBs.

The bands below 60 GHz, such as the 24 and 37 GHz bands, have the largest bandwidths with 10% of the total allocated bandwidth, which makes them more preferable since these bands have a lower path loss compared to bands above 60 GHz. Table 3 and Fig. 3 show that the proposed spectrum allocated for 5G fulfills the high spectrum demand for wireless communication by providing a very large spectrum to 5G systems if any of them are chosen. However, these allocations need to be investigated by every administration for sharing with existing services. It also can be seen that the F service needs to have priority in spectrum-sharing studies due its high deployment in the mWCBs. For this reason, we adopt the F service for the investigation of the coexistence between the 5G and F services.

B. MALAYSIAN SERVICES IN THE BANDS ADJACENT TO THE IMT-2020 CANDIDATE BANDS

In this section, we investigate the primary services expected to be adjacent to the 5G system. We consider the primary services only in the adjacent channel because these services have the right to be protected from adjacent and secondary services. According to the Malaysian spectrum chart, there are six types of primary services: RL, F, EESS, A, M, and RA. Table 3 lists the services that are expected to be adjacent to each mWCB. These services and their frequency allocation are tabulated in Table 4, which lists the upper and lower services that are operating between each mWCB.

On the basis of Table 3, the F service is dominant even in the adjacent bands. This is also shown in Fig. 4, which presents the primary services that will be adjacent to the mWCBs by percentage. From Fig. 4, the F services will be the main services that will be adjacent to the IMT-2020 bands, with a percentage of 39% (i.e., seven F services will be adjacent to the IMT-2020 bands from the overall adjacent primary services). The EESS is also expected to suffer from 5G deployment, as it occupies 33% of the adjacent bands (i.e., six allocations from the overall adjacent primary services).

C. CURRENT STATUS AND RELATED SHARING STUDIES OF SERVICES OPERATING IN THE mWCBs

In the following sections, each system is discussed along with their current status in Malaysia and specifications.

TABLE 4. Primary services located in the bands adjacent to mWCBs.

	Candidate Band (GHz)	Service Below the mWCBs		Service Above the mWCBs	
		Malaysian Allocation (GHz)	Primary Services	Malaysian Allocation (GHz)	Primary Services
1.	24.25–27.5	24.05–24.25	RL	27.5–28.5	F
2.	27.5–28.35	27–27.5	F	28.5–29.1	F
3.	31.8–33.4	31.5–31.8	EESS	33.4–34.2	RL
4.	37–40.5	36–37	EESS	40.5–41	F
5.	40.5–42.5	40–40.5	EESS	42.5–43.5	F
6.	42.5–43.5	41–42.5	F	43.5–47	M
7.	45.5–47	43.5–47	M	47–47.2	A
8.	47–47.2	43.5–47	M	47.2–47.5	F
9.	47.2–50.2	47–47.2	A	50.2–50.4	EESS
10	50.4–52.6	50.2–50.4	EESS	52.6–54.25	EESS
11	66–76	65–66	EESS	76–77.5	RA
12	81–86	79–81	RA	86–92	EESS

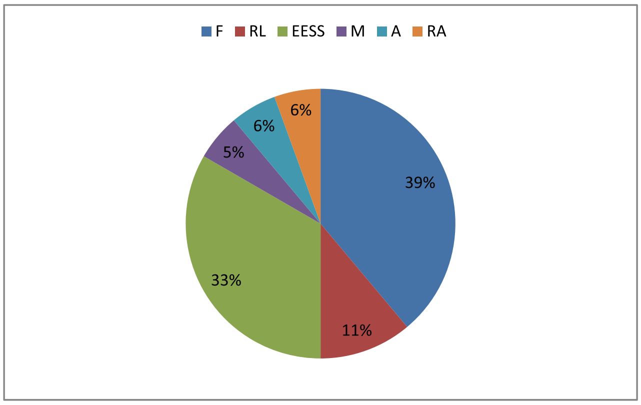


FIGURE 4. **Primary services expected to be adjacent to the mWCBs.**

In addition, the current studies on spectrum sharing with mobile systems or 5G are presented.

1) RADIOLOCATION

The RL system is a type of radio determination system [27]. The system uses a radio wave to find the location of an object [28]. Radiolocation is a primary service in the 24.05–24.25 and 33.4–34.2 GHz bands [6]. The technology in these bands is ultrawide band (UWB) technology [29], in which UWB devices are designed for short-range communication. A very low power is used by these technologies, which allows them to operate over a wide range of frequencies, resulting in overlap with other services allocated in other bands [30]. The application in the 24 GHz band is UWB automotive radar devices (UWB-ARDs). These radar devices are placed on vehicles to alert drivers of the nearby movements of people or objects [29], [30]. On the basis of the Malaysian specifications in [31], a UWB-ARD operates in the frequency bands of 21.65–29.5 and/or 77–81 GHz. The details about UWB-ARDs operating in Malaysia are provided in [30, 32] and are known as the Standard Radio System Plan (SRSP). The SRSP provides details about the minimum requirements in the Malaysian spectrum plan. In addition, the SRSP details the equipment standards [30]. International and Malaysian reports regarding UWB-ARDs indicate that these devices should not cause any interference to primary radiocommunication systems in their allocated bands [29], [30]. That is, their operations are based on a noninterference policy and do not claim protection [29], [30].

As presented in Fig. 3 and Fig. 4 , the RL system occupies 1% (i.e., one allocation) of the primary services in the mWCBs and 11% (i.e., two allocations) of the total number of primary services adjacent to the mWCBs. These allocations should be investigated for coexistence with 5G systems. A study has been conducted by the ITU for sharing between the RL system and the IMT-Advanced system in the 3400 MHz band [33]. This study showed results for the required separation distance and the guard band between the two systems. No studies have been conducted for the mWCBs with mobile systems since there are no mobile systems in these bands [34], [35]. Since UWB technology should not claim any protection [29], [30], the necessary compatibility study is only in one direction (i.e., from the RL system to 5G). The parameters related to the receiver and transmitter for the RL system can be found in [29]–[31], and [36].

2) FIXED SERVICES

The F services are a point-to-point system [37], meaning that communication should be line-of-sight (LOS). The F service in Malaysia operates in the 26 and 28 GHz bands [38], [39]. The application of the F service in Malaysia is the Local Multipoint Communication Services (LMCSs), also known as Local Multipoint Distribution Systems (LMDSs) [38]. The LMCSs are also point-to-point systems and point-to-multipoint systems. The LMCSs consist of local multipoint distribution central stations connected to multipoint terminal stations [38]. In [38], information is provided for the deployment requirements of F services in the 24.25–27.00, 27.00–29.50, and 31.00–31.30 GHz bands in Malaysia. As shown in Figs. 3 and 4, the F services occupy the highest percentage of allocation with 75% of the total primary services in the mWCBs and 39% in the bands adjacent to the mWCBs. This is confirmed by [40], which shows that Malaysian telecommunication networks are dominated by mobile and fixed networks. Table 5 summarizes the subbands that are expected to be adjacent to the IMT-2020 bands. Since the F services in Malaysia are allocated in bands lower than 30 GHz, Malaysia does not have any specifications for F services higher than 30 GHz [6], [39]. Therefore, the international specifications for F services should be considered for the coexistence between F services and 5G in Malaysia for higher bands. These specifications can be found in [41]–[43].

Spectrum-sharing and compatibility studies below 6 GHz are found in the ITU-R F.2326 [44], ITU-R F.2327 [45], ITU-R F.2328 [46], ITU-R F.2331 [47], and ITU-R F.2333 [48] reports. However, there are no spectrum-sharing studies

TABLE 5. **Current Malaysian reports for F services and related studies on sharing with mobile services.**

Frequency band (GHz)	27–27.5	27.5–28.5	28.5–29.1	40.5–41	41–42.5	42.5–43.5	47.2–47.5
Malaysian Application	LMCS [6, 38, 39]			N/A	N/A	N/A	N/A

conducted by the ITU between the F service and mobile systems in the mWCBs since there are no F services in these bands. A recent study [49] assessed the interference between the fixed links and the expected 5G systems. This interference assessment was conducted from both sides (i.e., to and from the fixed link). The results showed that the interference from the 5G system is higher and cannot be tolerated by the fixed links in the co-channel case. The study recommends that a low amount of 5G traffic and beamforming can reduce the probability of interference to 30%. Furthermore, interference can be reduced to 6% when increasing the fixed-link antenna directivity. In addition, the preliminary results for the coexistence between the two services are provided. However, the mWCBs was not considered in the study and the general case in which the frequency band of 15 GHz is used is considered. In addition, the parameters are defined for general mobile services and not for future mobile systems (i.e., IMT-Advanced). Furthermore, the channel bandwidth is 112 MHz in Malaysia [38], whereas the F service bandwidth is 40 MHz in [49]. In addition, neither the spectrum emission mask (SEM) nor the receiver blocking parameters are used in the interference assessment. Many studies such as [21], and [22] have shown the importance of the use of the SEM and blocking when assessing the interference between future IMT systems and other wireless systems. These studies concluded that the SEM and blocking of the receiver provide more reliable results when not many details about the new system are available. However, since the IMT-2020 SEM and blocking are not defined, such studies are accepted as preliminary results for the deployment of the 5G system.

3) EARTH EXPLORATION SATELLITE SERVICE

The EESS is a telecommunication service designed for monitoring the atmosphere and Earth through its receivers [50]. A wide range of frequencies are used by the EESS for such purposes [51]. The EESS uses passive and active sensing tools and exchanges information between satellites and earth stations. Since this service is used internationally, there are no special Malaysian requirements for the EESS [6], [52].

Several studies on sharing between mobile services and the EESS have been conducted, but only two studies considered the mWCBs. The study in [53] investigated the sharing of the 31.5–31.8 GHz band by the F and M services and the EESS (passive). The purpose of this EESS is to sense the ice morphology by allocating a 500 MHz band segment [53]. This study indicated that the upper 300 MHz is not currently utilized and can be shared with other active services. The lower 200 MHz is heavily used by a remote sensing system (passive). The results showed that the compatibility between the EESS and the terrestrial systems depends on the power level of the terrestrial system. Furthermore, the study in [54] summarizes the results of studies on sharing the 36–37 GHz band by the F and M services and the EESS (passive).

4) AMATEUR RADIO

Amateur radio is a method of wireless communication by using the RF spectrum for noncommercial activities to mainly provide communication and technical training [55]. Amateur radio is currently facing a challenge, where the very high frequency (VHF) and UHF bands from other services use it for bands such as those of the mobile systems [55]. In the IMT-2020 candidate bands, the A service is primarily in the 47–47.2 GHz band and a secondary service in the 76–77.5 and 79–81 GHz bands. An ITU report [56] provides the general operational and technical characteristics of radiocommunication systems for A services in the frequency range of 135.7 kHz to 81.5 GHz. The general technical specifications of A radio for all bands are also presented in [56]. The Malaysian specifications and guidelines are provided in [37]. No studies on the sharing between mobile services and the A service in the 47–47.2 GHz band have been conducted by the ITU [34], [35].

5) MOBILE

The M service is allocated as a primary service in the 43.5–47 GHz frequency band. On the basis of ITU recommendations, reports, European Communication Commission (ECC) reports, CEPT reports, and Malaysian reports, there are no specifications for the M service. The only note is that the stations for the land M service can operate in the 43.5–47 GHz band, and they should not cause interference to space services that are allocated in these bands [6].

6) RADIO ASTRONOMY

The RA system is a primary system in the 76–77.5 and 79–81 GHz bands. Since the RA system is passive, the IMT-2020 system should not cause interference with the RA system [57]–[59]. The only sharing study [60] on the compatibility between the RA system and IMT systems was for frequencies below 6 GHz. This study showed that the RA system is very sensitive to interference from the unwanted emission from active services [60]. This indicates that when the initial IMT-2020 specifications are available, protection of RA service will need to be incorporated. Further, in-band spectrum sharing between M and RA systems is impossible in practice. Moreover, a very large separation distance is required in the adjacent bands (i.e., 500 to 1000 km between the RA system and the mobile macro rural base station) [61].

7) INTERSATELLITE

The IS services are a communication system between satellites [62]. It is expected that no interference potential will be encountered. There are no spectrum-sharing studies in the ITU recommendations and reports between IS systems and legacy IMT systems. The only spectrum-sharing study published involves the coexistence with the FSS service [34], [35] system, which the IS system is allocated as a secondary allocation in the FSS frequency bands [6], [30], [32].

D. MALAYSIAN RESEARCH ACTIVITIES FOR 5G

On September 3, 2014, the Wireless Communication Center (WCC) at the University of Technology Malaysia (UTM) initiated the first meeting with academics in the area of telecommunication to discuss the 5G initiative in Malaysia. In that meeting, the Malaysian 5G committee was established [63]. The 5G committee consists of members from universities, research institutions, industry, and the Malaysian Technical Standards Forum Bhd (MTSFB). The MTSFB is a company that was designated and registered by the MCMC as the technical standards forum. The MCMC is the spectrum regulator in Malaysia [52]. The objectives of the 5G committee [63] are as follows: first, to foster collaboration and partnership between academia and industry in 5G research and development activities in Malaysia; second, to contribute to the standardization of IMT-2020 systems; and third, to be the evaluation group for IMT-2020 standardization. Fig. 5 shows the current organization of the Malaysia 5G committee and the current 5G research trends.

From Fig. 5, there are six subcommittees for 5G research, which are networking, RF microwave, multiple access and modulation coding, antenna, big data, and societal impact. The antenna group also consists of subcommittees, which are propagation, interference and coexistence, antenna design, spectrum management, signal processing, and security. Our research falls within the interference and coexistence category.

Following the establishment of the 5G committee in November 2014, the WCC achieved another milestone with the prestigious status of the Higher Institutional Centre of Excellence (HICoE) of the Ministry of Education Malaysia. Under the HICoE, the WCC focuses its resources on 5G wireless communication—in particular, on the research and development of 5G antennas and propagation. The WCC has secured about 5 million Malaysian Ringgit (around 1.250 million USD) in HICoE funding for 5G research. The MCMC, through its technical standards team in the MTSFB, had the IMT-5G working group collaborate with the Japan 5GMF group. One of these collaborations was implemented in a 5G workshop between Malaysia and Japan [64]. Lately, in December 2016, a Memorandum of Understanding was singed between the UTM and Ericsson for collaboration and development for 5G research. One of these developments was implemented to establish a 5G research lab [65]. Up to this moment, no official announcements have been provided from the MCMC regarding the mWCBs [52].

While writing this article, research in Malaysia is ongoing for the promotion of 5G systems. Some studies on 5G research have been published. In the following, we summarize the research that has been carried out at our centers, which falls under the propagation and antenna design categories in Fig. 5. A review of time division duplex (TDD) and frequency division duplex (FDD) schemes in massive MIMO was presented in [66]. In addition, a detailed survey of pilot contamination and its effects on the performance of massive MIMO was performed. The study also presented different mitigation techniques for pilot contamination and concluded that the majority of published works found that channel reciprocity is the source of pilot contamination. In contrast, in a practical system, hardware impairments and nonreciprocal transceivers are additional sources of pilot contamination. In [67], the time dispersion parameters in the 28 GHz mmW band were presented. A wideband channel was characterized on the basis of the root mean square (RMS) delay spread and mean excess delay, which are the main time dispersion parameters. The results showed that the RMS delay spread varies between 129 ns and 247 ns for the LOS scenario. The results also showed that the correlation between the RMS delay spread and the transmitter–receiver (TX-RX) separation distance is low. The maximum mean excess delay is 454.8 ns. The COST 2100 model was used to extract the parameters of the wideband channel. A new path loss called frequency attenuation was proposed in [68] for 5G system communication. The model is based on an outdoor LOS ultrawideband measurement in the time domain at mmW-band frequencies between 10 GHz and 40 GHz. In [69],

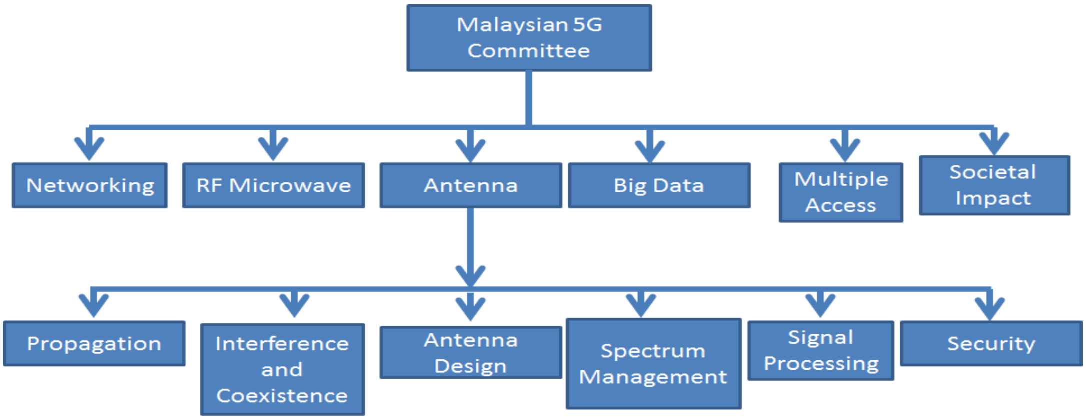


FIGURE 5. Malaysian 5G organization chart [63] and research trends.

a two-dimensional beam-steering array antenna was proposed for 5G communication at mmW frequencies on the basis of modeling and simulation using CST 2015 Microwave Studio. The operating frequency range is 24.4–32 GHz. The beamformer is designed on the basis of a cascaded 2 × 2 Butler matrix. In addition, a single layer was chosen in the design for ease of fabrication and a lower cost. The four ports of the antenna had the ability to produce four orthogonal beam patterns from −18° to 23° in the x–y plane and from −20° to 22° in the y–z plane. The achieved gain was 15.1 dBi for the first port, which is considered the maximum gain. The efficiencies of the radiation from the four ports were 92.6%, 92.1%, 91.4%, and 87.8%. Another advantage of the designed antenna is the null free elevation. The design of a microstrip array antenna in the 28 GHz band fed by multiple ports with a uniform excitation coefficient was addressed in [70]. The reduction in the sidelobes of an unequally spaced array was discussed. On the basis of High Frequency Structure Simulator (HFSS) version 16.0, the sidelobe of an unequally spaced array can be reduced instead of changing the spacing between elements. The results showed that the sidelobe in the broadside direction decreased from −11.77 dB to −14.74 dB (for four elements) and from −12.77 dB to −15.98 dB (for eight elements).

III. SPECTRUM-SHARING METHODOLOGY

In the previous section, we showed that the F service is the most deployed system in the mWCDBs as a primary service and also in the services that are adjacent to mWCBs. In this section, we introduce our modified spectrum-sharing model that is used to evaluate the expected interference between the F service and 5G for exploring the feasibility of coexistence between these systems. In addition, the propagation model, antenna pattern, and system parameters are also discussed to find one of the initial preliminary spectrum-sharing results between the 5G system and the F service.

A. IMT-2020 SPECTRUM-SHARING METHODOLOGY

Currently, the ITU working party is working on a spectrum-sharing model for the IMT network [71]. This model had been adopted from a previous IMT recommendation [72] and 3GPP technical reports [73], [74] and implemented in some spectrum-sharing software such as Spectrum Engineering Advanced Monte Carlo Analysis Tool (SEAMCAT) [75]. The methodology is based on the statistical Monte Carlo (MC) method, which can be found in detail in [71], [73], [76]. Section III.A.1 begins by introducing the current spectrum-sharing model followed by our modifications for adapting it to IMT-2020 network requirements.

1) CURRENT METHODOLOGY

The current methodology is divided into two parts depending the mobile communication direction, which is either the downlink (DL) or uplink (UL). For each communication direction, the IMT-2020 system is considered to be either the interferer or victim. In the following sections, the steps of each communication direction are presented.

In the case where the IMT-2020 system is the DL, the required steps are as follows. First, deploy a BS network grid; then,

i. For the first iteration that starts from $i = 1$ to #, where # is the number of iterations, perform the following:
   1. Randomly distribute user equipments (UEs) throughout the system area.
   2. Calculate the path coupling loss (PCL). The PCL in decibels can be evaluated as follows:

$$PCL = \max\left(\left\{PL + F + G_t + G_r\right\}, MCL\right), \tag{1}$$

   3. where PL is the path loss in decibels, F is the fading in decibels, and G_t and G_r are the gains of the transmitter and receiver antennas, respectively in decibels-isotropic. MCL is the minimum coupling loss in decibels between the UE and the BS.
   4. Link each UE to the BS that had the minimum PCL with it, plus the handover margin (HOM).
   5. Select K UEs from all of the UEs that are connected to the BS; these UEs are considered the active UEs and are considered to be scheduled during the current iteration.
   6. All available resource blocks (RBs) are allocated to the K UEs. Each UE is scheduled with n RBs.
   7. For each BS that is transmitting, the power transmitted to the UE can be calculated as follows:

$$P_{BS}^{UE} = P_{BS}^{Max}\frac{n}{M}, \tag{2}$$

   where P_{BS}^{UE} is the power transmitted from the BS to the active UE, and P_{BS}^{Max} is the maximum power transmitted by the BS. n is the number of RBs per UE, and M is the number of available RBs for each BS, which is equal to $M = n \times K$
   8. Go to Step (ii) if the IMT-2020 DL is an interfering system (i.e., the BS acts as an interfering system) or go to Step (iii) if the IMT DL is a victim (i.e., the UE is the victim system).

ii. Choose the IMT BS to be the interferer.
   1. Depending on the system load, select X% of BSs that are performing transmission in this iteration. In addition, select the interference condition that can be either a close interferer or an aggregate interferer. The value of X depends on the system load.
   2. Loop over all BSs in the network starting from $j = 1$.
   3. Calculate the external interference level in decibels from the j-th BS, BS$_j$, that is serving the active k-th UE, UE$_k$, in the victim system receiver by applying the following equation in the case of adjacent channel interference:

$$I_{IMT_{BS}} = P_{BS_j}^{UE_k} + CL_{IMT-Victim} - ACIR, \tag{3}$$

where $P^{UE_k}_{BS_j}$ is the IMT-2020 DL transmitted power from the BS$_j$ toward UE$_k$ in decibels, $CL_{IMT-Victim}$ is the coupling loss in decibels between BS_j that is connected to the selected user. *ACIR* is the adjacent channel interference ratio in decibels.

The total aggregate interference in decibels at the victim receiver is calculated as

$$I_{External} = 10\log_{10}\left(\sum_{j}\sum_{k} I_{IMT_{BS}}\right), \tag{4}$$

where j is looped for all BSs in the selected area, and k is looped for all active UEs from $k = 1$ to $k = K$ for the selected BS from the X% value.

4. Go to Step vii.

iii. Choose the IMT-2020 UE as a victim receiver.

1. On the basis of the system load, select X% of the BS that are performing communication in this iteration
2. Calculate the interference at the victim receiver on the basis of the carrier-to-interference ratio (C/I). Find the (C/I) in decibels for all UEs in the network.
3. Select k active users in the network.
4. Loop over all BSs in the network starting from $j = 1$.
5. Calculate the C/I for each active k-th UE in the j-th cell as follows:

   $$C/I = C(j,k) - I(j,k), \tag{5}$$

   where $C(j,k)$ is the power received by the active k-th UE at the j-th BS, which can be calculated as

   $$C(j,k) = P^{UE_k}_{BS_j} + PCL(UE_{j,k}, BS_j); \tag{6}$$

   and PCL is the path coupling loss between the k-th UE and the j-th BS.

   The interference $I(j,k)$ is the intrasystem interference power level (i.e., the interference from the same system caused by other BSs in the network) plus the thermal noise level N_t, which can be calculated as

   $$I(j,k) = I_{intra}(j,k) + N_t. \tag{7}$$

6. The external interference I_{ext} with a power level of $P_{ext,y}$ can be calculated as

   $$I_{ext} = \sum_{y} P_{ext,y} + PCL(Z_y, UE_{j,k}) - ACIR, \tag{8}$$

   where $PCL(Z_y, UE_{j,k})$ is the path loss between the y-th Z external interferer and the active k-th UE at the j-th BS.

7. Find C/I_{total} for the victim active UE after adding the external power level as follows:

   $$C/I_{total} = C(j,k) - I_{total}(j,k), \tag{9}$$

   where I_{total} is the total interference at the victim receiver, which consists of the intrasystem interference plus the external interference and can be found as follows:

   $$I_{total}(j,k) = I_{intra}(j,k) + I_{ext}(j,k). \tag{10}$$

8. For the case in which the UE is a victim, the performance degradation is calculated on the basis of the throughput loss computed from link-to-system level mapping that is provided in [73]. The throughput is calculated with and without the external interference for the victim UE.
9. Go to Step vii.

In the case where the IMT-2020 system is the UL, deploy a BS network grid; then,

iv. For the first iteration that starts from $i = 1$ to # and for each iteration, perform the following:

1. Repeat Steps i-1 to i-4.
2. The power transmitted by the UE is based on power control.
3. In the UL link case, a fully loaded BS is assumed, meaning that all available RBs are allocated to the k-th active UE. Each UE has the same n and is scheduled in the current iteration.
4. Apply power control for the active users (in decibels):

   $$P_t = 10\log_{10}\left\{P_{\max} \times \min \times \left\{1, \max\left[R_{\min}, \left(\frac{CL}{CL_{x-ile}}\right)^{\gamma}\right]\right\}\right\}, \tag{11}$$

   where P_t is the UE transmission power in decibels, $P_{\max}$ is the maximum transmitted power in decibels, $R_{\min}$ is the power reduction ratio for avoiding good communication channels to transmit at very low power and calculated as

   $$R\min = \left(\frac{P\min}{P\max}\right),$$

   $P_{\min}$ is the minimum transmitted power in decibels, CL is the effective path loss including shadowing in decibels, CL_{x-ile} is the x-percentile path loss, and γ is the balancing factor between UEs with good and bad channels.

5. Go to Step v if the IMT UL is an interfering system (i.e., the UE acts as an interferer system) or go to Step vi if the IMT UL is victim (i.e., the BS is the victim system).

v. Choose the IMT-2020 UE to be the interferer transmitter.

1. Randomly choose X% of the IMT-2020 BSs.
2. Select the active UEs that are connected to the chosen BSs. These active UEs are considered to be interferers.

3. At the victim receiver, the impact of the interference is calculated as follows:
   a. Loop over all chosen BSs from $j = 1$ to N_{cell}.
   b. Loop over the active UEs that are connected to the chosen BSs from $k = 1$ to $k = \text{K}$.
   c. The external interference from the k-th UE is calculated as follows:

$$I_{External}\left(TX_{UE_k}^{BS}, RX^{victim}\right) = PC_{UE_k}^{BS} + CL_{External}\left(TX_{UE}^{BS}, RX^{victim}\right) - ACIR, \tag{12}$$

   where $PC_{UK_k}^{BS}$ is the k-th UE power control. The total aggregate interference ($I_{\text{Agg-external}}$) from the IMT-2020 UE at the victim receiver is calculated as

$$I_{Agg-External} = 10\log_{10}\left[\sum_j\sum_k I_{External} \times \left(TX_{UK_k}^{BS}, RX^{victim}\right)\right]. \tag{13}$$

   d. Go to Step vii.

vi. Choose the IMT-2020 BS to be the victim receiver.
   1. Choose X% of the BSs on the basis of the system load.
   2. Find C/I for the active UEs in all cells.
   3. Repeat Steps iii-4 to iii-6.
   4. Include the external interference I_{ext} that consists of y interferers, each with a power level of $P_{ext,y}$. The location of the external interferer Z_y can be calculated as

$$I_{ext} = \sum_y P_{ext,y} + PCL(Z_y, UE_{j,k}) - ACIR. \tag{14}$$

   5. Find C/I_{total} for the victim active UE after adding the external power level as follows:

$$C/I_{total} = C(j,k) - I_{total}(j,k), \tag{15}$$

   where I_{total} is the total interference at the victim receiver, which consists of the intrasystem interference plus the external interference and can be calculated as follows:

$$I_{total}(j,k) = I_{intra}(j,k) + I_{ext}(j,k). \tag{16}$$

   6. Repeat Steps iii-8 to iii-9 and consider the BS instead of the UE.
   7. Go to Step vii.

vii. Collect the findings.

2) MODIFICATION OF THE EXISTING METHODOLOGY

The methodology that described in Section III.A.1 is intended for the IMT system, which includes the IMT-2020 system; however, the methodology cannot be used for the IMT-2020 system for the following reasons.

1. When modeling the IMT-2020 BS and UE as victims, the results are based on the E-UTRA throughput loss lookup table and cannot be used for the IMT-2020 system. This can be seen in Step iii-9 when the UE is a victim and Step vi-5 when the BS is a victim. The results are compared to the system-link mapping to find the throughput loss with and without external interference. This mapping is based on a lookup table for the IMT system in the 3GPP technical report 3GPP TR.36.942 [73]. This shows that the interference criteria need to be changed for the preliminary results until the IMT-2020 system is standardized.
2. The current methodology is based on the RB in E-UTRA systems; however, the RBs for the IMT-2020 UE are currently unknown.

The modified methodology is based on the legacy fundamental mobile spectrum-sharing studies in [73], [77] and the current draft methodology in [71] and is updated with new 5G aspects such as a small cell radius, beamforming, and a new path loss. The modifications of the model to be used for the IMT-2020 system are as follows. First, the modifications consider the MCL methodology for the BS-to-BS scenario to find the required protection distance, which had been used in previous IMT sharing studies [44]–[48], [60], [61] to reflect the worst-case scenario. Second, the interference criteria for the IMT-2020 BS and UE when they are considered victims are based on I/N instead of throughput loss. I/N is a general interference criteria for mobile systems that is recommended in [72]. Third, two types of propagation models are utilized in the modified model, 3GPP TR 38.900 for IMT-2020 BS and UE communication and the general interference prediction model ITU-R 452-16 for interference evaluation. Fourth, the BS and UE power levels are not based on the RB.

In the following sections, we present the main equations that are used in the modified model and the steps for achieving the results. Both MCL and MC steps are presented.

a: COEXISTENCE MODEL FOR THE SINGLE (INTERFERER/VICTIM) SCENARIO (MCL)

This method is based on analytical equations and physical laws. The results are considered for the worst-case scenario. Since the results are empirical, this method requires much less time and effort than a simulation program [19], [76]. The MCL method is a simple and basic method that results in the calculation of the minimum requirements for spectrum sharing between different services, such as the distance or isolation, and is used when information about new systems is not completely available.

The coexistence model for a single interferer/victim scenario is useful for finding preliminary results [76]. The model used in this study analyzes the impact of interference on the basis of I/N at the victim receiver as a function of the separation distance between the victim and the interferer.

The interference-to-noise ratio (INR) trial (INR_{trial}) in decibels that satisfies the coexistence requirements at the receiver for a given separation distance and frequency can be found as follows:

$$INR_{trial} \geq INR_{target}, \tag{17}$$

where INR_{target} is the interference criterion for the victim receiver. As mentioned earlier, we consider INR_{target} to be −6 dB for the co-channel and adjacent channel sharing scenarios for the IMT-2020 system [72], [78] and −10 dB for the F service [79]. This implies that the interference level should be 6 dB (for the IMT-2020 case) and 10 dB (for the F service case) lower than the noise level at the victim receiver.

The noise floor N (in decibels relative to one milliwatt) of the victim receiver should be evaluated for the INR level, which can be found as follows:

$$N = -114 + 10log_{10}\left(BW_{victim}\right) + N_f, \tag{18}$$

where N_f (in decibels) is the noise figure of the receiver, and BW_{victim} is the victim channel bandwidth in megahertz.

For each trial, the interference at the victim receiver $I(d, f, \Delta f, env)$ can be calculated for a given separation distance d, operating frequency of the receiver f, specified frequency separation Δf, and deployed environment env as

$$\begin{aligned} I\left(d, f, \Delta f, env\right) = {} & Pti + Gti + Gr + (\Delta f) \\ & - Lp\left(d, f, env\right), \end{aligned} \tag{19}$$

where Pti (in decibels) is the power of the interferer, Gti (in decibels-isotropic) is the gain of the interferer antenna, and Gr (in decibels-isotropic) is the gain of the victim antenna. The path loss (L_p) (in decibels) between the interferer and the victim is a function of the distance d (in kilometers), operating frequency f (in megahertz), and the type of environment env. L_p is based on the victim receiver type.

$INR_{trial}(d, f\ , \Delta f, env)$ is calculated as follows:

$$INR_{trial}\left(d, f, \Delta f, env\right) = I_{trial}\left(d, f, \Delta f, env\right) - N, \tag{20}$$

and Δf in decibels can be calculated as follows:

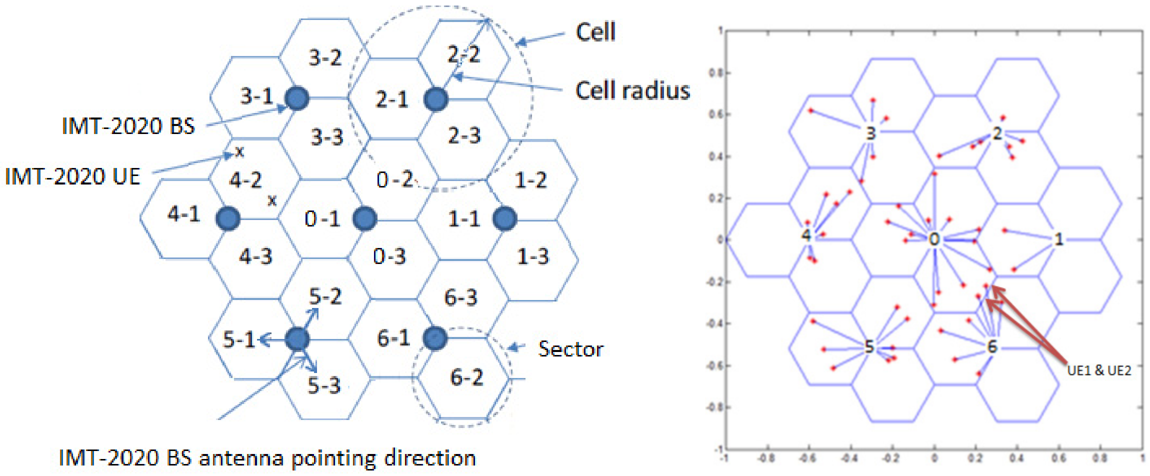
$$\Delta f = \begin{cases} 0 \ in\ case \quad co-channel\ Sharing\ scenario \\ ACIR \quad for\ adjacent\ channel\ sharing\ scneario \end{cases}$$

where $ACIR$ (in decibels) is the adjacent channel interference ratio.

b: COEXISTENCE MODEL FOR THE AGGREGATE (INTERFERER/VICTIM) SCENARIO (MC)

For evaluating multiple interferers with the victim receiver or finding the impact of interference on multiple users, the MC method is needed [76]. In the MC method, each iteration consists of different variables such as the distance and interference level. After certain number of iterations, the average of the results is calculated. This model is needed when dealing with mobile users because of their temporal locations. For this, we designed a 3GPP network with 7 BSs and 21 sectors, as shown in Fig. 6(a), for the random deployment of mobile users to reflect a real mobile network. The network topology is based on the current IMT-2020 model [71] and previous IMT sharing studies [33], [46], [60]. Our designed modified model for the 5G-system user distribution is shown in Fig. 6(b). In this model, we adopt the current model in Section III.A.1 and add our modifications in Section III.A.2 .

It can be seen that the model is able to determine the smallest path loss between users and the BS, as stated in the current IMT-2020 model in Steps i-3 and iv-1. This is shown in Fig. 6(b), where UE1 and UE2 are in the cell coverage area of BS0, but the distance from the UEs to the BS6 is shorter than that for BS0; thus, the two users are connected to BS6.



(a) (b)

FIGURE 6. The adopted mobile network: (a) the network structure and (b) the simulation of distributed users in a cell based on the modified method of connecting to the BS with the smallest path loss plus the HOM [46].

B. PROPAGATION MODELS

The propagation model depends on the victim receiver. In our study, the communication of IMT-2020 systems will be based on two propagation models. In the case of communication between the IMT-2020 BS and the UE, the propagation model is based on the 3GPP propagation model in the 3GPP TR 38.900 technical report [80]. In the case where the IMT-2020 system is considered to be a victim or an interferer to other systems, the general interference propagation model is considered as the channel model and is based on the interference prediction model of the terrestrial system in ITU-R 452-16 [81]. The following sections will provide more details about these propagation models.

1) PROPAGATION MODEL FOR IMT-2020 COMMUNICATION

Recently, the 3GPP released its latest report regarding a study of a channel model for systems operating above 6 GHz [82]. Later, a study conducted by several industrial and academic researchers investigated different models for the IMT-2020 system for bands up to 100 GHz [80]. The study presented in [80] is considered as a living document, which means that it is frequently updated on the basis of updated studies. Our study utilized the latest standard model in [80] to represent the path loss for the IMT-2020 system, which is considered applicable to mobile-system-level simulation [80].

This model cannot be used for interference assessment because the results are valid up to a separation distance of 10 km between the transmitter and the receiver in a rural environment and 5 km in an urban environment. This is considered to be a limitation if we need a higher separation distance [80]. In addition, the model is based on a measurement conducted between a BS and a UE. For these reasons, the model is used only in the case of IMT-2020 BS and UE communication. This propagation model is used on the basis of the following conditions:

- The separation distance is up to 10 km for a rural environment and 5 km for an urban environment.
- The environments supported are a rural macrocell (RMa), an urban macrocell (UMa), an urban microcell (UMi), and indoors.
- A bandwidth larger than 2 GHz is not supported.
- LOS and non-LOS (NLOS) are supported.

In our study, we adopt the RMa and UMa categories for the LOS. The path loss $PL_{RMA-LOS}$ (in decibels) is as follows:

$$PL_{RMa-LOS}\begin{cases}PL_{1-1}10m \leq d_{2D} \leq d_{BP}\\ PL_{1-2}d_{BP} \leq d_{2D} \leq 10km,\end{cases} \tag{21}$$

$$\begin{aligned}PL_{1-1} = {} & 20\log_{10}\left(\frac{4\pi d_{3D}f_c}{3}\right) + \min\left(0.03 * h^{1.72}, 10\right)\\ & \times \log_{10}(d_{3D}) - \min\left(0.044h^{1.72}, 14.77\right)\\ & + \left[0.002\log_{10}(h) * d_{3D}\right] + \sigma_{RMa-LOS1},\end{aligned} \tag{22}$$

$$PL_{1-2} = PL(d_{BP}) + 40\log_{10}\left(\frac{d_{3D}}{d_{BP}}\right) + \sigma_{RMa-LOS2}. \tag{23}$$

The path loss $PL_{UMa-LOS}$ is as follows:

$$PL_{UMa-LOS}\begin{cases}PL_{2-1}10m \leq d_{2D} \leq d'_{BP}\\ PL_{2-2}d'_{BP} \leq d_{2D} \leq 10km\end{cases} \tag{24}$$

$$\begin{aligned}PL_{2-1} = {} & 32.4 + 20\log_{10}(d_{3D}) + 20\log_{10}(d_{3D})\\ & + 20\log_{10}(f_c) + \sigma_{UMa-LOS},\end{aligned} \tag{25}$$

$$\begin{aligned}PL_{2-2} = {} & 32.4 + 40\log_{10}(d_{3D}) + 40\log_{10}(d_{3D})\\ & + 20\log_{10}(f_c) - 10\log_{10}[\left(d'_{BP}\right)^2 + (h_{BS} - h_{UE})^2]\\ & + \sigma_{UMa-LOS},\end{aligned} \tag{26}$$

where $d_{BP} = \frac{2\pi h_{BS}h_{UE}f_c}{c}$, $d'_{BP} = \frac{2\pi h'_{BS}h'_{UE}f_c}{c}$, and h'_{BS} and $h'UE$ can be calculated as follows:

$$h'_{BS} = h_{BS} - 1, \quad h'_{UE} = h_{UE} - 1.$$

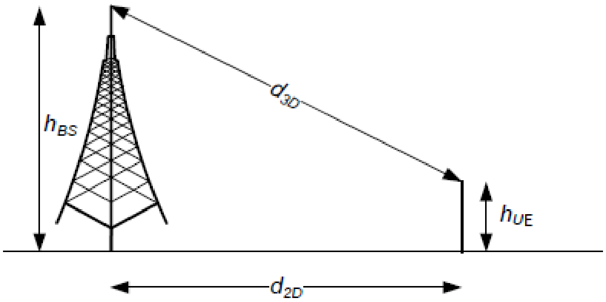


FIGURE 7. Concept of d_{3D} [82].

In the above equations, d_{3D} (in kilometers) is the three-dimensional (3D) distance. This concept is depicted in Fig. 7. d_{3D} is based on the two-dimensional distance d_{2D}. d_{3D} and d_{2D} can be calculated as follows:

$$d_{3D} = \sqrt{(h_{BS} - h_{UE})^2 - d_{2D}},$$

$$d_{2D} = \sqrt{(x_2 - x_1)^2 - (y_2 - y_1)^2}.$$

Table 6 summarizes some of the parameters that are needed in the path loss equations, such as the street width, building height, and channel shadow fading for RMa and UMa networks.

TABLE 6. Path loss parameters [82].

IMT-2020 Parameter	RMa	UMa
Street width (m)	20	50
Building height (m)	5	50
Shadow fading (dB)	4 for 10 m $\leq d_{2D} \leq d_{BP}$ 6 $d_{BP} \leq d_{2D} \leq$ 10 km	4 for 10 m $\leq d_{2D} \leq$ 5 km

2) PROPAGATION MODEL FOR F SERVICE COMMUNICATION

ITU-R P.452-16 is a prediction model for evaluating the interference between two stations on the surface [81].

The model is applicable to assess the interference between stations operating between 0.1 GHz and 50 GHz. The propagation model had been used previously in IMT spectrum-sharing studies with the F service [44]–[48]. In this study, the recommendation is used to represent the clutter loss and gas abortion (GA). The total loss PL_{452-16} (in decibels) can be calculated with [81]

$$PL_{452-16} = 92.5 + 20\log(f) + 20\log(d) + CL + GA, \tag{27}$$

where CL (in decibels) is the clutter loss and can be calculated with [81]

$$CL = 10.25 \times F_c \times e^{-d_k}\left\{1 - tanh\left[6\times\left(\frac{h}{ha} - 0.625\right)\right]\right\} - 0.003, \tag{28}$$

where d_k (in kilometers) is the distance between the nominal clutter point to the received antenna, h (in meters) is the received antenna height above the ground, and h_a (in meters) is the nominal clutter height above the ground.

The nominal factor F_c can be calculated wth [81]

$$F_c = 0.25 + 0.375 \times [1 + \tanh(0.75 \times (F_s - 0.5))], \tag{29}$$

where F_s is the operating frequency in gigahertz. The values of d_k are 0.1 and 0.002 km for rural and urban areas, respectively. h_a (in meters) is the nominal clutter height, varies according the measurement environment, and has values of 4 and 20 m for rural and urban areas, respectively. Fig. 8 shows a schematic illustrating the clutter loss parameters.

The total GA in decibels is based on ITU.R recommendation P.676, which reflects the specified attenuation of the signal due to water vapor and dry air, which can be found from Fig. 9.

Fig. 9 shows the specific frequency gas attenuation in the frequency range of 100–350 GHz. It can be seen that the total gas attenuation (red line) is the sum of the water vapor attenuation and dry air.

C. ANTENNA PATTERN

1) IMT-2020

The study in [82] provides information regarding antenna modeling for the IMT-2020 system. The model is based on an antenna array structure to represent the beamforming for the IMT-2020 system. The IMT-2020 BS is a rectangular panel array composite of M_g (the number of columns with a spacing of $d_{g,H}$) and N_g (the number of rows with a spacing of $d_{g,V}$) plans with spacing. The elements of radiation are placed uniformly along the z axis, as shown in Fig. 10. The figure also shows that the azimuthal angle is between 180° and −180° and that the elevation angle is between 0 and 180°.

In the following, we will present the antenna pattern equations that are used in the study. The 3D beamforming radiation consists of a vertical radiation pattern $A_{E,V}$ at the elevation angle θ and a horizontal radiation pattern $A,_{E,H}$ at the azimuthal angle φ, which are as follows:

$$A_{E,V}(\theta) = -min\left\{12\left(\frac{\theta - 90^\circ}{\theta_{3dB}}\right)^2, SLA_V\right\}, \tag{30}$$

$$A_{E,H}(\varphi) = -min\left\{12\left(\frac{\varphi}{\varphi_{3dB}}\right)^2, A_m\right\}. \tag{31}$$

The combined antenna radiation pattern $A_{Combind}$ (in decibels) is calculated as follows:

$$A_{Combind} = -\min\left\{-\left[A_{E,V}(\theta) + A_{E,H}(\varphi)\right], A_m\right\}. \tag{32}$$

2) FIXED SERVICE

The ITU-R recommendation F.699 [79] presents the radiation pattern for F services at operating frequencies between

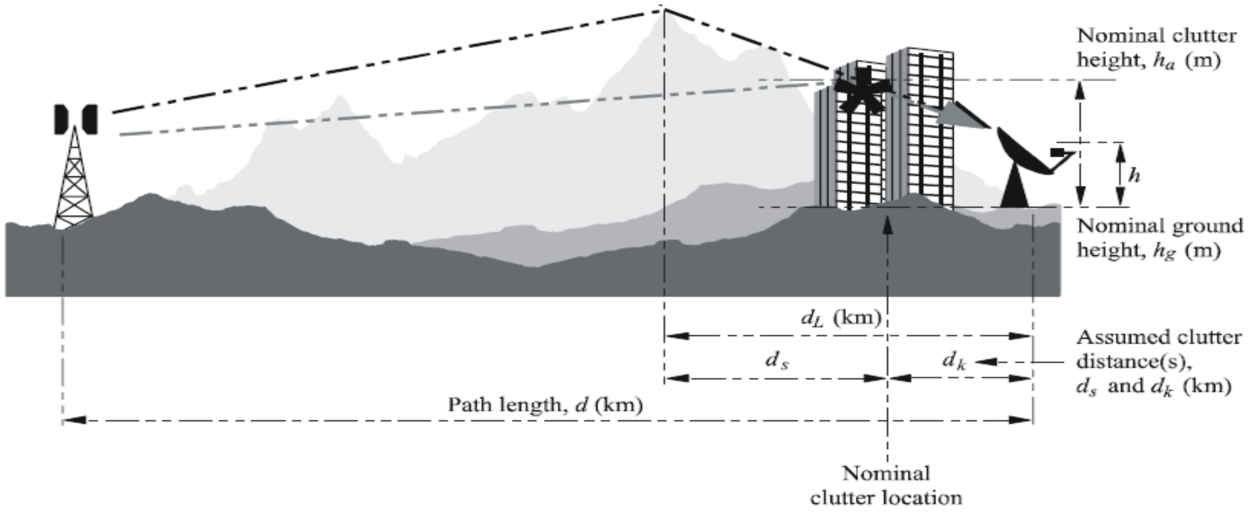


FIGURE 8. The clutter loss parameters [81].

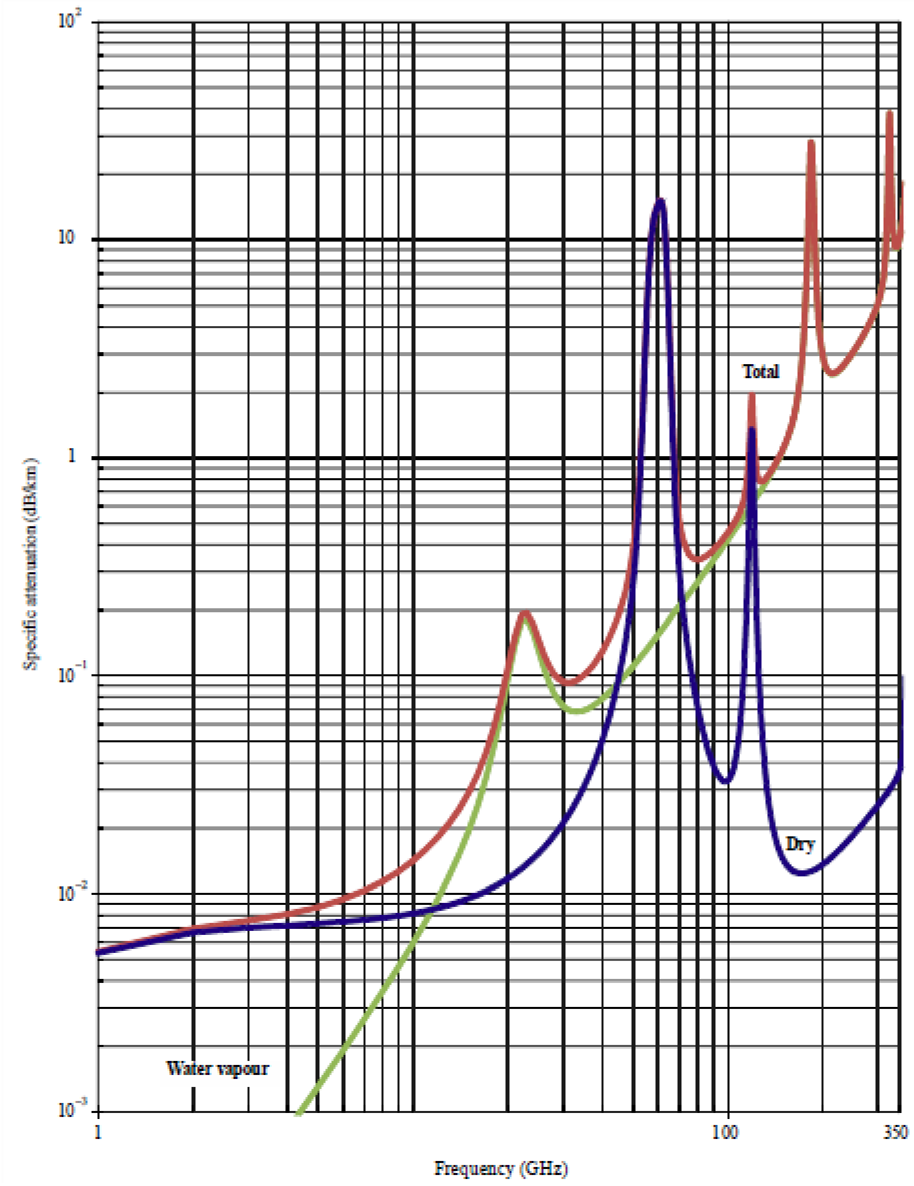


FIGURE 9. Specific gas attenuation between 1 GHz and 350 GHz [83].

100 MHz and 70 GHz. Several sharing studies between the IMT and F services conducted by ITU have adopted this pattern [44]–[48]. For the frequency range between 1 GHz and 70 GHz, the following equations are used:

$$G(\varphi) = \begin{cases} G_{max} - 2.5 \times 10^{-3} \left(\frac{D}{\lambda}\varphi\right)^2 & for\ 0^\circ < \varphi < \varphi_m \\ 2 + 15 \log_1 \frac{D}{\lambda} \quad for\ \varphi_m \le \varphi < 100\frac{D}{\lambda} \\ 52 - 10 \log_{10}\left(\frac{D}{\lambda}\right) - 25 \log_{10}(\varphi) \\ \quad for\ 100\frac{D}{\lambda} \le \varphi < 48^\circ \\ -10 - 10 \log_{10}\left(\frac{D}{\lambda}\right) & for\ 48^\circ \le \varphi < 180^\circ, \end{cases} \tag{33}$$

where G_{max} is the maximum antenna gain in decibels-isotropic, D is the antenna diameter in meters, and φ_m and φ_r (in degrees) are as follows:

$$\varphi_m = \frac{20\lambda}{D}\sqrt{G_{max} - G_1} \text{ and } \varphi_r = 15.85\left(\frac{D}{\lambda}\right)^{-0.6}. \tag{34}$$

D. SIMULATION PARAMETERS

In order to conduct spectrum-sharing studies between two systems, the parameters of both systems are needed. In our study, some of the IMT-2020 characteristics are based on the existing IMT Recommendation M.2292 [72], which is applicable to the IMT-Advanced system. Others parameters that are included in our study, such as the antenna pattern,

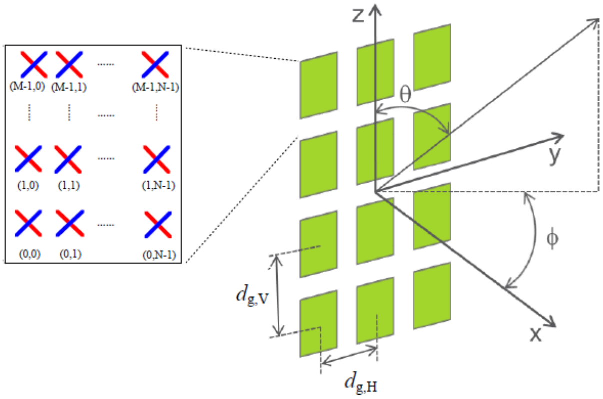


FIGURE 10. **IMT-2020 BS array antenna structure [71], [82].**

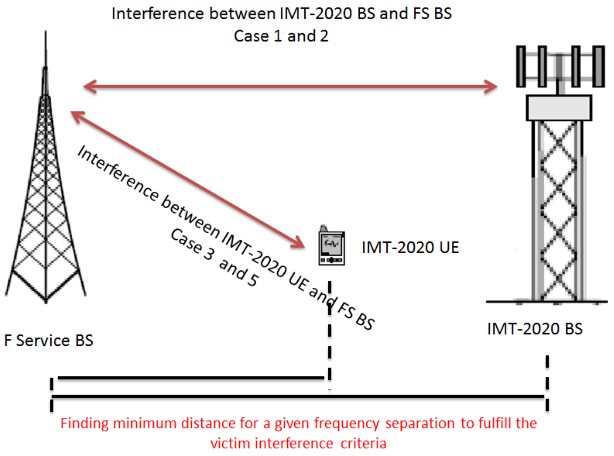


FIGURE 11. **The four CSs used in the spectrum-sharing study by using the MCL method.**

are based on the recent ITU draft for the IMT-2020 system [71], which includes beamforming for the IMT-2020 system. The parameters of the F service are based on the ITU specifications in [79] and the Malaysian recommendation [38]. Table 7 lists the parameters that are used in the simulation study for rural and urban environments for both systems when they are the interferer (It) and victim (Vr).

IV. CASE STUDIES

In this section, we present case studies that are conducted on the basis of sharing scenarios. The sharing scenario in our study is split into two categories, a single interferer or victim based on the MCL method and multiple interferers or victims based on the MC method. The following section will detail the case studies (CSs) that are adopted in our study.

A. SINGLE INTERFERER OR VICTIM SCENARIOS (MCL)

The MCL method is used in this sharing scenario for stations that are stationary. Fig. 11 shows four CSs by using the MCL method. The first two CSs are considered in this sharing scenario: the impact of the IMT-2020 BS on the F service (CS1) and vice-versa (CS2). In the case of spectrum sharing between the F services and a UE, four CSs are considered. The first two are between a single F-service BS and a single UE using the MCL method, the other two are between a single UE and multiple UEs using the MC method, which will be discussed in the following subsection. The interference impact between the F service and a single IMT-2020 UE is represented in CS3. Finally, CS5 is considered for the interference impact between an IMT-2020 UE and the F service.

Our preliminary spectrum-sharing results are based on finding the required protection separation distance for a given frequency separation to satisfy the interference criteria, as shown in Fig. 11. The results are considered for co-channel and adjacent channel sharing scenarios.

B. MULTIPLE INTERFERER OR VICTIM SCENARIOS (MC)

As mentioned earlier, to evaluate the interference between the F service and IMT-2020 UEs, we consider two coexistence

TABLE 7. **System parameters.**

Parameter	IMT-2020		F	
	BS (It and Vr)	UE (It and Vr)	It	Vr
Operating frequency (GHz)	28			
Transmitted power (dBm)	For RM Scenario 43 [72] For UM Scenario 24 [72]	23 [72]	11	X
Modulation	OFDMA		16 QAM	
Bandwidth (MHz)	500		112 [38]	
BS gain (dBi)	For RM Scenario 8[82]	-4 [72]	31.5 [46]	
Noise figure (dB)	For RM Scenario 5 [72] For UM Scenario 10 [72]	9 dB [72]	X	8 [79]
Antenna height(m)	For RM Scenario 35 [82] For UM Scenario 10 [82]	1.5[82]	30[46]	
Protection criteria (dB)	I/N = -6 [72, 78]		X	I/N = -10[79]
Coverage (km)	Cell radius For RM Scenario 1 For UM Scenario 0.2	X	X	

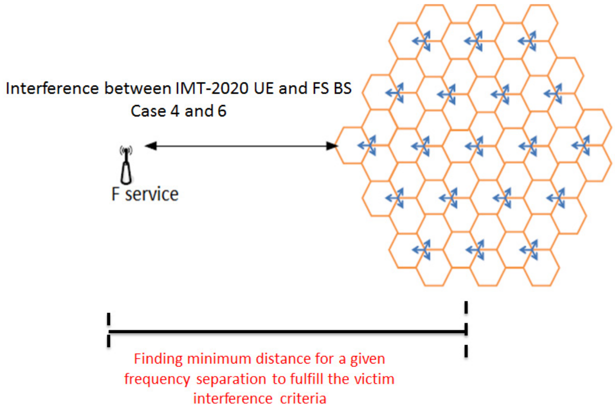


FIGURE 12. The case studies in the MC method for finding the required separation distance between a single F service station and the IMT-2020 network [45].

methods, the MCL and MC. The MCL is used to present the worst-case scenario between a single UE and an F service BS, which are denoted as CS3 and CS5, as discussed in the previous subsection, and the MC model reflects the distribution of multiple IMT-2020 UEs across the network for evaluating the aggregate interference. To find the required separation distance between multiple UEs and the F service, two case studies are considered, CS4 and CS6, which are shown in Fig. 12. CS4 is considered to evaluate the aggregate impact of interference from multiple IMT-2020 UEs on a single F service station and CS6 for the opposite direction. The separation distances for interference protection are the expected results of the MC method, which are shown in Fig. 12.

V. RESULTS

In this section, we present the simulation results for various cases studies of spectrum-sharing studies. The results are divided into two categories, IMT-2020 BS communication and UE communication. Fig. 13 shows an example of results obtained for CS1 (Figs. 13(a)–(b)) for the MCL method and CS4 (Figs. 13(c)–(d)) for the MC method, reflecting rural and urban environments.

In the Fig. 13, the y axis represents the INR in decibels, whereas the x axis represents the separation distance in kilometers between the interferer and the victim. The interference criterion is indicated by the red line, which is -6 dB when the IMT-2020 system is the victim and -10 dB when the F service is the victim. Five curves are plotted in each

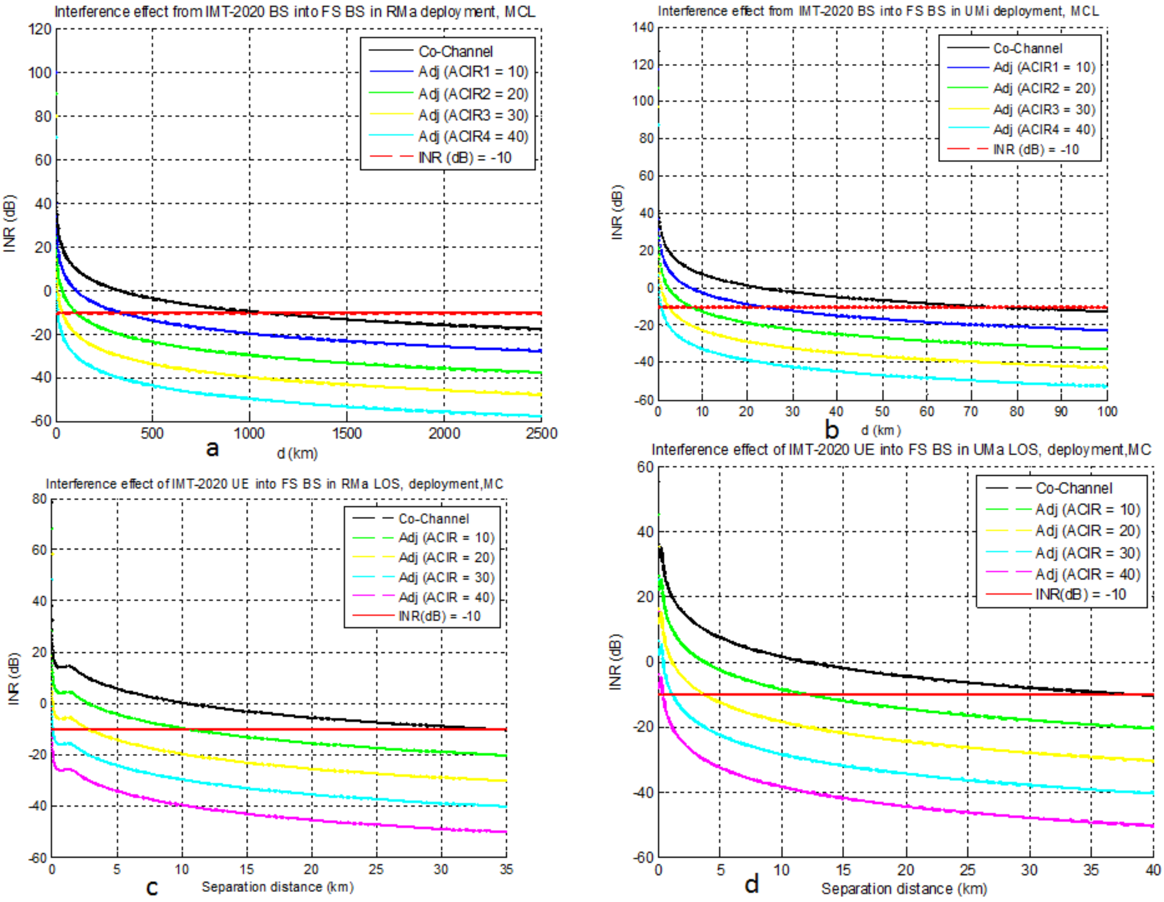


FIGURE 13. Examples of the results obtained for (a)–(b) CS1 (MCL method) (c)–(d) and CS4.

TABLE 8. Summary of the required separation distance for the IMT-2020 system and F service.

Case Study No.	Separation Distance (km)			
	Co-Channel		Adjacent Channel	
	Rural	Urban	Rural	Urban
CS1 IMT-BS → F MCL	1082	76	362@ACIR1 109@ACIR2 37@ACIR3 12@ACIR4	24.6@ACIR1 7.9@ACIR2 2.7@ACIR3 0.8@ACIR4
CS2: F → IMT-BS MCL	7.07	0.624	2.28@ACIR1 0.76@ACIR2 0.23@ACIR3 0.07@ACIR4	0.194@ACIR1 0.06@ACIR2 0.021@ACIR3 0.0069@ACIR4
CS3: IMT-UE → F MCL	26.69	27.16	8.46@ACIR1 2.8@ACIR2 1.1@ACIR3 0.36@ACIR4	8.64@ACIR1 2.83@ACIR2 0.96@ACIR3 0.38@ACIR4
CS4: IMT-UE → F MC	34.3	38.8	10.7@ACIR1 3.3@ACIR2 0.2@ACIR3 0.02@ACIR4	12.3@ACIR1 3.9@ACIR2 1.2@ACIR3 0.4@ACIR4
CS5: F → IMT-UE MCL	0.23	0.18	0.07 @ACIR1 0.027@ACIR2 0.008@ACIR3 0.003 @ACIR4	0.059@ACIR1 0.019@ACIR2 0.006@ACIR3 0.0019@ACIR4
CS6: F → IMT-UE MC	7.01	7.85	1.93@ACIR1 0.23@ACIR2 0.1@ACIR3 0.03@ACIR4	2.53@ACIR1 0.7@ACIR2 0.2@ACIR3 0.02@ACIR4

figure, which represent the calculation of the INR for the co-channel case (black) along with four adjacent channel cases with ACIR values of 10, 20, 30, and 40 dB (the remaining colors). The intersection between the curves and the red line represents the required separation distance.

A summary of the CSs results is tabulated in Table 8 to present the required separation distance for a certain frequency separation in order to fulfill the protection criterion for the victim receiver. Table 8 summarizes the spectrum-sharing studies for the six CSs for rural and urban environments.

As can be observed, the highest separation distances are required for CS1 (i.e., the impact of interference of the IMT-2020 BS on the F service), which are 1082 and 76 km for the rural and urban environments, respectively. This is due to the high power transmitted from the IMT-2020 BS (43 dBm) and the high victim gain of the F service (31.5 dBi). The interference is mitigated to 12 km and 800 m for the rural and urban environments, respectively, in the adjacent channel sharing scenario with $ACIR = 40$ dB. A larger frequency guard band is required for this sharing scenario. This sharing scenario shows that the F service will be highly impacted by the deployment of the 5G service in the 28 GHz band. The F service has less impact on the IMT-2020 BS in CS2; this is because the F service has a lower transmitted power (11 dBm) than that of the IMT-2020 BS. The required separation distance is reduced from 7.07 km (co-channel case) to 70 m (adjacent channel case with $ACIR = 40$ dB) for a rural environment and from 624 m (co-channel case) to 6.9 m (adjacent channel case with $ACIR = 40$ dB) for a urban environment.

For the UE sharing scenario, the impact of its interference on the F service is nearly similar for the rural and urban environments for the MCL (CS3) and MC (CS4) methods. This is due to the fact that the UEs have similar characteristics in both environments, and the UE status depends on the IMT-2020 BS status and the environments. The impact of the IMT-2020 BS on the F service is higher than the impact in the opposite direction. Furthermore, the transmitted power of the UE (which is based on the power control method) is higher than the F service specification in the 28 GHz band. For the MCL method (CS3), separation distances of 26.96 km and 27.16 km for the rural and urban environments, respectively, are needed for the co-channel scenario. The separation distance can be reduced to 360 and 380 m for the rural and urban environments, respectively, for $ACIR = 40$ dB in the adjacent channel sharing scenario between a single UE and a single F service receiver. For the MC method, a higher separation distance than the MCL method for the same CS is required owing to the higher number of UEs. Protection distances of 34.3 and 38.8 km are needed for the co-channel sharing scenario for rural and urban environments, respectively. These distances can be reduced to 20 and 400 m for the adjacent channel sharing scenario with $ACIR = 40$ dB. This also shows that the IMT-2020 UE can impact the performance of the F service.

Finally, a lower separation distance is required to reduce the impact of the F service on the UE, as shown in the results for CS5 and CS6. As mentioned earlier, this is due to the fact that the transmitted power for the F service is lower compared to those for the IMT BS and UE. For a single F service operating in the co-channel scenario, the separation distances are only 230 and 180 m for CS5, whereas they are 240 and 173 m in the MC method for the co-channel case. In both methods, the separation distance can be reduced by up to 1.9 and 3 m for the adjacent channel sharing scenario with $ACIR = 40$ dB in CS6 for rural and urban environments, respectively.

VI. CONCLUSION

5G is the current research target of researchers, telecommunication companies, and spectrum regulators in many countries. This paper contributes to the worldwide effort toward 5G deployment by showing the Malaysian research effort. Our study presents the current Malaysian telecommunication market and the Malaysian research efforts for 5G systems. The study also investigated the services in mWCBs by presenting the current status of the primary services and the services that are operating in the bands adjacent to the 5G system. A modified spectrum-sharing model is presented for 5G systems and was utilized to find preliminary results for the feasibility of coexistence between the 5G and F services in the 28 GHz band. The model can be updated by the time 5G is standardized. On the basis of the spectrum-sharing results, we found that the F services will be the main services that will be affected in the mmW bands owing to 5G deployment. This can be seen clearly in the BS-to-BS spectrum-sharing scenario that required separation distances of 1082 km in a rural environment and 76 km in an urban environment for the co-channel scenario based on the MCL method. Moreover, the impact of the IMT-2020 UE on the F service BS is high, which needs separation distances of 34.4 and 38.8 km in the co-channel sharing scenario based on the MC method. Thus, rigorous studies on sharing between the 5G and F services are needed. It is expected that the 28 GHz band currently has the highest probability of adoption for the 5G system. This is because the 28 GHz band is being pushed to be the candidate band, as evidenced by channel modeling studies of this band and system prototypes provided by several spectrum regulators and academia. Our study also recommends another band for the 5G system, which is the 45.5–47 GHz band from spectrum-sharing and current spectrum allocation perspectives. This band is recommended because it is already allocated for mobile systems, but it is not utilized. Similarly, the 43.5–47 GHz is the best adjacent band for sharing with 5G systems since it is already allocated for mobile systems and not utilized. On the basis of our study, the selection of the best mWCB for 5G is as follows. The selection depends on (1) the service that will be removed, turned off, or shifted from mWCBs to be replaced by 5G; (2) the type of system in the adjacent bands; (3) the spectrum-sharing studies that show the best system for sharing spectrum; and (4) the harmonization between spectrum regulators worldwide. Thus, intensive sharing studies are required worldwide for 5G deployment.

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