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FDR Adjustment for Achieving Desired Minimum Distance of Marine ESIM from the Shore

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Abstract—**Determining and observing the minimum allowable distance of the marine earth station in motion (M-ESIM) from the shore prevents its destructive interference on the co-frequency shore fixed station. ESIMs are providing broadband Fixed Satellite Services (FSS). This paper studies the parameters involved in determining the minimum allowable distance of the ship from the shore by the interference simulation. The results show that with decreasing the carrier frequency, decreasing latitude or increasing the number of annual passing vessels, this minimum distance increases. In this paper a methodology is presented and simulated to keep constant the minimum allowed distance by adjusting the values of the frequency dependent rejection (FDR). FDR is caused by shifting the M-ESIM frequency band. The minimum distance of 100, 105 and 110Km is evaluated in this paper. In this way, the M-ESIM can be close to the shore as near as the desired distance using the FDR adjustment.**

Keywords: Marine ESIM; broadband Fixed Satellite Service; Frequency Interference; FDR.

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I. Introduction

One of the important and growing technologies in the satellite communications is providing broadband Fixed Satellite Services to the Earth Station in Motion (ESIM) such as ships, aircrafts and trains. These types of moving stations are Maritime-ESIM (M-ESIM), Aeronautical-ESIM (A-ESIM) and Land-ESIM (L-ESIM) [1]. The increasing demand for these services has led to the issue being discussed at ITU international meetings in 2015, 2019 and its continuation in 2023. Analyzing the frequency interference of these new services and extracting and announcing the

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requirements to prevent their destructive interference on the previous services have been important approvals of ITU meetings. This paper concentrate on M-ESIM.

M-ESIMs provide various services to end users and passengers, such as follows [2]:

- Commercial shipping: Today, most large companies have been able to make large profits from the entire maritime market by investing in this field. The factors of this growth are the provision of passenger welfare, remote IT services, weather information and etc.
- Fishing: This type of market is also a large business in this area. Fishing boats try to stay under satellite coverage at all the times. In addition, connecting a fishing boat to a satellite can provide online sales, auctions and ship monitoring or telemedicine.
- Pleasure and private boats: Cruise ships connect to the broadband satellite to achieve higher data rate according to the increasing demand of end user. Following this sudden influx of traffic and increasing the number of equipment per passenger on board, the using of the satellite ground station networks to provide faster internet, wireless services, entertainment, video and more has been forced.

In order to provide broadband services for earth station in motion, the communications regulatory authority dedicated frequency band 17.7 to 20.2 GHz for down link and frequency band 27.5 to 30 GHz for uplink communications at the World Radiocommunication Conference 2015 (WRC-2015) and WRC-2019 [3-4]. Parts of these recommended frequency bands of the ESIM are allocated for GSO and Non-GSO fixed-satellite service, broadcasting-satellite service feeder links, Non-GSO feeder links of the mobile satellite service, earth exploration-satellite service and meteorological-satellite service, too [3-4]. In general, ESIMs have certain technical and functional specifications that fixed stations do not require them, such as the small size of antennas for cars, trains, planes and ships and a suitable tracking system in order to accurately target the satellite. In addition, providing methods and requirements to manage frequency interference with other fixed or mobile stations will be necessary and unavoidable. The national and international institutions should provide various methods to reduce or eliminate potential interference due to the presence of mobile and fixed stations in the overlapping frequency bands. In this regard, guidelines to manage interference in WRC-2019 have been presented [4].

The predicted frequency bands for the provision of fifth generation (5G) communication network services can be one of the candidates for the possibility of interference with ESIM [5]. For example, the IMT-2020 international project in South Korea, as well as some leading countries, examines the effects of coexistence and the sharing of 5G frequency bands with ESIM. The results of this project show that the frequency coexistence of the fifth generation communication network services and ESIM is guaranteed [6-8]. In [9], the frequency dependent rejection (FDR) parameter was used to interference management in the 5G communication network. In [1], the dynamic power control method is used to prevent the interference of the M-ESIM. In this method, the changes in the transmitted power of the M-ESIM depend on the amount of the off-axis angle as well as the distance of the M-ESIM from the shore. In order to manage interference, methods such as minimum coupling loss (MCL) [10] are used, in which the interference management criterion is determined based on the minimization of distance between the fixed and moving equipment. In addition, in [10] the statistical Monte-Carlo (MC) method is used to manage interference in the two overlapping frequency channels at a central frequency of 28 GHz.

In [11], the frequency interference between L-ESIM and co-frequency equipment associated with the 5G access network is investigated. Moreover, the MCL method is used to investigate the interference in the frequency range of 27.5 to 29.5 GHz. Finally, the minimum required distance between 5G equipment and L-ESIM is determined according to existing standards and the minimum interference threshold. In [12], the numerical mask required to manage interference and determine the minimum frequency distance between two adjacent channels of maritime ESIM and the 5G mobile service of the communication network is presented.

In [13] by combining the two methods of MCL and MC, the interference of two adjacent channels of M-ESIM and the 5G mobile service network has been specified. Then, the minimum separation distance required to prevent unwanted interference is determined.

In [14], a method is presented to evaluate the interference from M-ESIM on the fixed receiver at an operating frequency of 28 GHz. In this method, it is assumed that the antenna tracking system of M-ESIM has errors to communicate with the space station.

In this paper, a methodology is presented and simulated to obtain FDR versus the three variables of latitude, carrier frequency and the number of passing ships, separately, so that the minimum allowed distance of the ship from the shore remains desired constant value. FDR is caused by shifting the M-ESIM frequency band [8]. The frequency shift determination is not investigated in this paper. Section II studies and analyzes the interference of an M-ESIM on a shore fixed station and its important parameters that are involved in the minimum allowed distance of M-ESIM from the shore. In section III, the effects of latitude, carrier frequency and the number of ships passing along the shore on the minimum allowable distance of the M-ESIM from the shore are extracted via simulations. Then, it is investigated the achieving desired minimum allowed distance from the shore by adjusting the suitable FDR versus the various latitude, carrier frequency and ship numbers passing along the shore. Finally, the paper is concluded in section IV.

II. Frequency Interference Scenario and Its Main Involved Parameters

The positions of the M-ESIM and the shore fixed station are shown in Fig.1. In this figure, φ is the angle between the main beam of the M-ESIM and the shore fixed station. θ_{FSR} is the -10dB beam of the shore fixed station [15]. d_{ESV} is the length of the path that the M-ESIM travels on this beam. V_{ESV} is the speed of the ship, and d_{xxx} is the distance between fixed station and the ship. FSR and ESV indices denote the abbreviations of the fixed satellite receiver and earth station on the vessel, respectively. The presence duration of the M-ESIM in the -10 dB beam of the fixed station should be lower than its maximum limit. This time depends on the distance between the two stations as well as the speed of the passing ESV. The annual time percentage that the interference on the fixed station can exceed from its maximum allowable limit (p_s) and the minimum allowable distance of M-ESIM from the fixed station are in the interaction with each other. By simulating the block diagram of Fig. 2 [15] as well as the relations of [17], the minimum allowable distance of the ESV from the shore is obtained. In Fig.2, P_{ESV} is the time percentage that the M-ESIM is present in the -10 dB beam of the fixed station. p is the annual time percentage by considering the P_{ESV}. f_{ESV} is the number of annual ships passing and δ is the convergence threshold to stop the minimum distance algorithm, which is equal to 3 km[15].

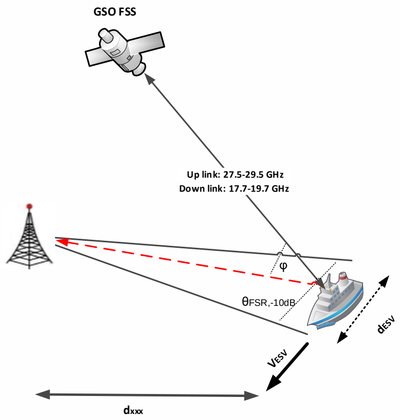


Figure 1. Positions of the M-ESIM and the shore fixed station relative to each other

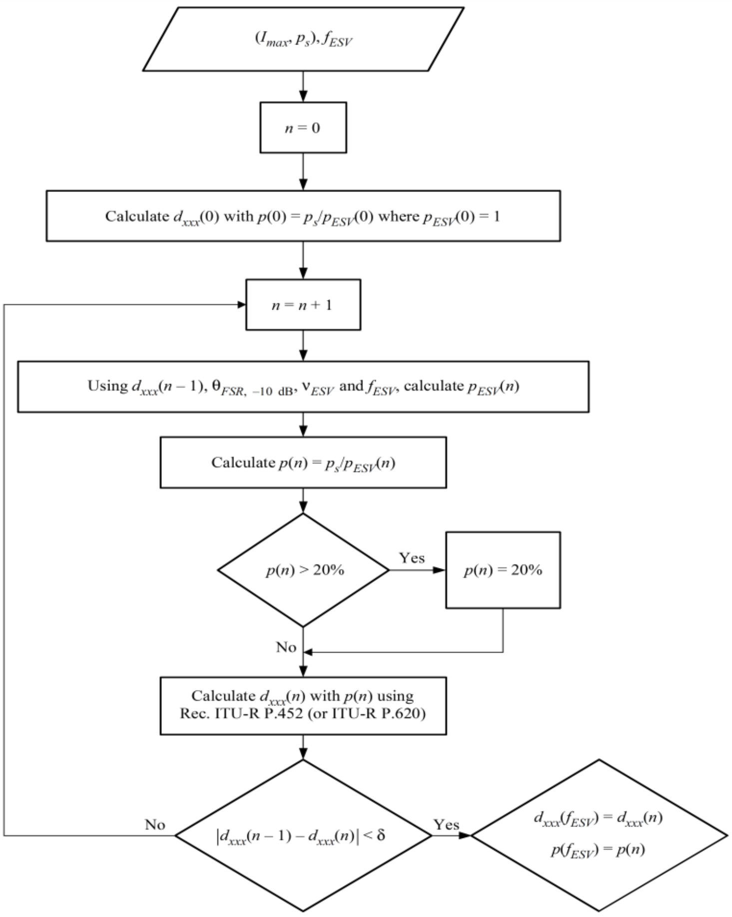


Figure 2. Calculation method of the minimum allowable distance of M-ESIM from the shore in terms of its presence duration percentage in the -10 dB beam [15].

The maximum tolerable frequency interference on the receiver is equal to [15]:

$$I_{max} = (I/N)_{th} + 10\log_{10}(k \times T_{FSR} \times B_{FSR}). \quad (1)$$

where I_{max} is the maximum tolerable interference of the receiver. $(I/N)_{th}$ is the interference to the thermal noise ratio. k is the Boltzmann constant. T_{FSR} and B_{FSR} are the noise temperature and the bandwidth of the fixed receiver, respectively. In order to applicability of the simulation results for a specific area, the parameters of the most sensitive receiver of that area are usually used in the interference analysis and simulation.

The minimum expected loss is expressed as follows [13]:

$$L_{min}(P_s) = P_{t,max} + G_t + G_{r,AVE} - I_{max} - FDR. \quad (2)$$

where $L_{min}(P_s)$ is the minimum expected transmission loss of the signal transmitted by the M-ESIM. It is in the interaction with p_s. $P_{t,max}$ is the maximum transmitter power. G_t is the transmitter antenna gain in the direction of the receiver antenna. $G_{r,AVE}$ is the average receiver antenna gain in the beamwidth of -10dB and FDR denotes the interference decrease in the receiver due to the frequency offset between channels of the interfering transmitter and the receiver [8-9].

ITU relation for the maximum allowable effective isotropic radiated power (e.i.r.p) of the antenna is given in relation (3), which is used to interference calculation, instead of using the actual transmitted power of the M-ESIM [16].

$$\begin{array}{ll} \text{Maximum e.i.r.p. per } 40kHz & \text{Angle off}-\text{axis} \\ (19-25\log\varphi)dB(W/40kHz) & 2^{\circ} \le \varphi \le 7^{\circ} \\ -2dB(W/40kHz) & 7^{\circ} < \varphi \le 9.2^{\circ} \\ (22-25\log\varphi)dB(W/40kHz) & 9.2^{\circ} < \varphi \le 48^{\circ} \\ -10dB(W/40kHz) & 48^{\circ} < \varphi \le 180^{\circ} \end{array} \quad (3)$$

A. *The interference reduction due to the frequency offset between channels of the transmitter and the victim*

The FDR is used to reduce the level of interference in the receiver. It depends on the characteristics of the transmitted signal as well as the receiver filter. FDR is the measure of the transmitter spectrum rejection that produced by the receiver [13]. It is determined by the receiver selectivity curve, and calculated as follows [8] and [18-20]:

$$FDR(\Delta f) = 10\log_{10}\left[\frac{\int_{-\infty}^{+\infty} S(f)df}{\int_{-\infty}^{+\infty} S(f)F(f+\Delta f)df}\right], \quad (4)$$

where $S(f)$ is the power spectral density function of the interfering signal in terms of W/Hz, $F(f)$ is the normalized frequency response of the receiver and Δf is the frequency offset between the victim receiver and the interfering transmitter.

B. *The influence of latitude on the interference level from M-ESIM to the fixed station*

To include the effects of the weather on the loss calculations, β_p is introduced as the atmospheric radio parameter [17]. It depends on the latitude and is calculated as follows:

$$\beta_p = \begin{cases} 10^{1.67-0.015\zeta_r} & \text{for } \zeta_r \le 70^{\circ} \\ 4.17 & \text{for } \zeta_r > 70^{\circ} \end{cases}$$
$$\zeta_r = \begin{cases} |\zeta| - 1.8 & \text{for } |\zeta| > 1.8^{\circ} \\ 0 & \text{for } |\zeta| \le 1.8^{\circ} \end{cases} \quad (5)$$

where ζ is the latitude of the ground station. In addition, the latitude influences the annual time percentage (p), the path center sea level surface refractivity that is used in the propagation model, distance related losses relations and so on [17].

C. *The influence of carrier frequency on the interference level from M-ESIM to the fixed station*

Another relation to calculate the path losses is [21]:

$$P_L(r) = 92.5 + 20\log(f) + 20\log(r) + A_g,$$
$$A_g \approx 0.107 \times r. \quad (6)$$

where f is the transmitted signal carrier frequency, r is the traveled distance and A_g is the environment gas loss coefficient, which is obtained from the curves in [22]. f also influences the minimum allowable distance, horizontal angle correction factor, shield losses, the specific attenuation due to dry air, frequency-dependent ducting attenuation, tropospheric losses, etc [17].

D. *The influence of passing ships number on the interference level to the fixed station*

As seen in Fig. 2, passing ships number has a direct effect on the time percentage (P_{ESV}) that the M-ESIM is present in the -10 dB beam of the fixed station. The more M-ESIM in the -10dB beam causes the more possibility of interference on the fixed station. So, each of the above parameters influences the amount of interference on the fixed station. In other words, these parameters are effective in determining the minimum allowable distance of the ship from the shore. As seen in relation (2), FDR decreases the interference to the fixed station. Thus, by increase of FDR, the minimum allowable distance decreases. Curves of the minimum allowable distance can be obtained in terms of joint values of FDR and one of the above mentioned parameters, by using the simulation. In this way, for each value of the above parameters, a suitable FDR can be found to achieve the desired minimum allowable distance of M-ESIM from the shore. In other words, if the ship wants to be closer to shore, it should adjust the suitable FDR to this new desired minimum allowable distance.

III. SIMULATION RESULTS

Several parameters influence the minimum allowable distance of M-ESIM from the shore. By attention to the Figs. 1, 2 and the mentioned relations, these parameters and their initial values are presented in TABLE I. All parameters and symbols of the paper are also listed in TABLE II.

TABLE I. INITIAL VALUES OF THE SIMULATION PARAMETERS THAT INFLUENCE THE MINIMUM DISTANCE.

Parameters	Value
θ_{FSR}	1.7 degree
B_{FSR}	100 MHz
f_{ESV}	365 ships per year
V_{ESV}	18 km/h
G_t	45 dBi
G_{rAVE}	42.5 dBi
I_{max}	−118.7 dBW
Fixed station antenna height above mean sea level	80 meters
M_ESIM antenna height above mean sea level	40 meters
Transmitter angle with the horizon in the worst case [12]	10 degree.

TABLE II. LIST OF PARAMETERS AND SYMBOLS

Parameters	Explanations
f	The transmitted signal frequency
G_t	The transmitter antenna gain in the direction of the receiver antenna
$P_{t,max}$	The maximum transmitter power
θ_{FSR}	The -10dB beam of the shore fixed station
V_{ESV}	The speed of the ship
d_{ESV}	The length of the path that the M-ESIM travels in this beam
d_{xxx}	The distance between fixed station and the ship
p_s	The annual time percentage that the interference on the fixed station can exceed from its maximum allowable limit
P_{ESV}	The time percentage that the M-ESIM is present in the -10 dB beam of the fixed station
p	The annual time percentage by considering the P_{ESV}
f_{ESV}	The number of annual ships passing
δ	The convergence threshold to stop the minimum distance algorithm, which is equal to 3 km
I_{max}	The maximum tolerable interference of the receiver
$(I/N)_{th}$	The interference to the thermal noise ratio
k	The Boltzmann constant
T_{FSR}	The noise temperature of the fixed receiver
B_{FSR}	The bandwidth of the fixed receiver
$L_{min}(p_s)$	The minimum expected transmission loss of the signal transmitted by the M-ESIM
$G_{r,AVE}$	The average receiver antenna gain in the beamwidth of -10dB
$S(f)$	The power spectral density function of the interfering signal in terms of W/Hz
$F(f)$	The normalized frequency response of the receiver
Δf	The frequency offset between the victim receiver and the interfering transmitter
βp	The atmospheric radio parameter
ζ	The latitude of the ground station
r	The traveled distance
A_g	The environment gas loss coefficient

It is also assumed that the fixed station is located right next to the shore. Considering section II part B, the minimum allowable distance of the ship from the shore is simulated versus the latitude for the various gains of the transmitter antenna. As seen in Fig. 3, if the technical and physical characteristics of the fixed stations are constant and the latitude increases, the minimum allowable distance from the shore will decrease.

Based on section II part C, the minimum allowable distance of the ship from the shore is obtained versus the carrier frequency via simulation, for different gains of transmitter antenna (Fig. 4). As a result, at lower frequencies, the minimum allowable distance of the ship from the shore increases.

According to section II part D, the minimum allowable distance of the ship from the shore is obtained in terms of the number of ships passing through the shore annually via simulation, for different gains of the transmitter antenna. As shown in Fig. 5, the minimum allowable distance from the shore increases as the number of ships passing annually along the shore increases.

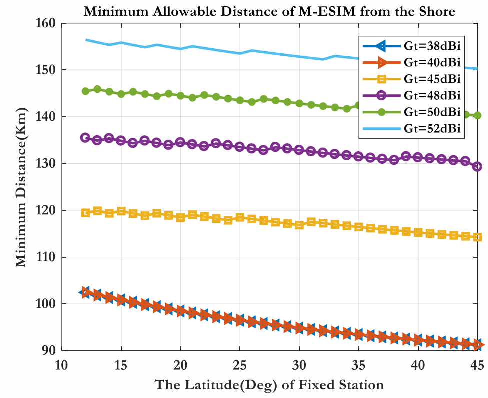


Figure 3. The minimum allowable distance versus latitude for different gain of the transmitter antenna.

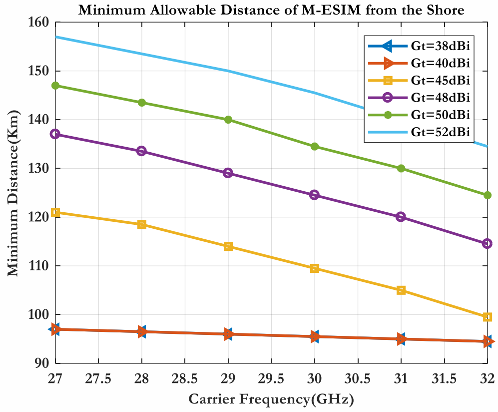


Figure 4. The minimum allowable distance versus the carrier frequency for different gain of the transmitter antenna

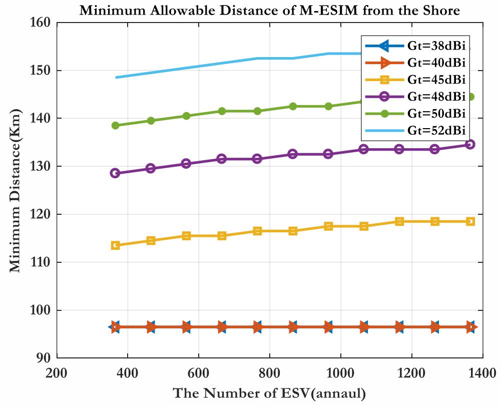


Figure 5. Minimum allowable distance in terms of the annual number of ships passing the shore for different transmitter antenna gain.

As shown in Figures 3 to 5, with the same simulation conditions, for gains equal to or less than 40dB, the minimum allowable distance curves are identical. For instance, the curve for the gain of 38dB coincides with the curve for the gain of 40dB.

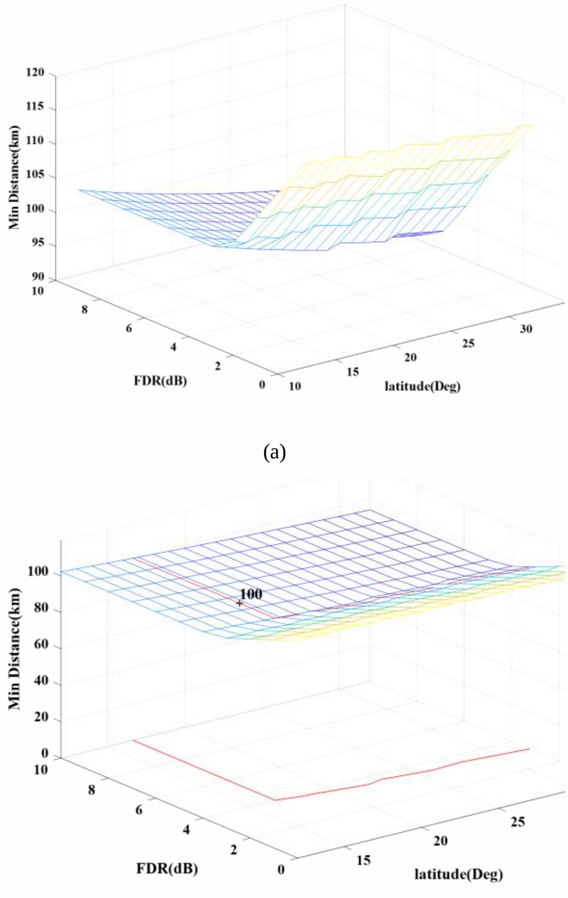
For practical reasons and also to take account of assumptions that have to be made about the radio path, it is necessary to set lower limits to the minimum allowed distance (d_{min}), calculated as follows up to 40GHz [17]:

$$d_{min} = 100 + \frac{\beta_P - f}{2} \qquad (7)$$

Thus d_{min} depends on the carrier frequency (f (GHz)) and the latitude (according to relation (5)) of M-ESIM. d_{min} is used as the lower limit of the minimum distance in the algorithm of [17] to find the minimum allowable distance (Fig. 2).
As shown in Figures 3 to 5, with same simulation conditions, by reduction of the gain, d_{min} is obtained at the gain of 40dB or less. In Fig. 3, the values of d_{min} are shown versus the latitude for a constant frequency of 28GHz. This profile has an exponential behavior that is in accordance with relations (5) and (7). In Fig.4, the values of d_{min} are shown versus the frequency for a constant latitude of 25 degree. This profile has a linear behavior that is in accordance with relation (7). In Fig. 5, the values of d_{min} are shown versus the number of ESV for a constant frequency of 28GHz and a constant latitude of 25 degree. Given that d_{min} depends only on these two parameters, so it is independent of the number of ESV.

According to section II parts A and B and considering relation (2), the joint effect of the latitude and FDR is simulated on the minimum allowable distance from the shore. As seen in Fig. 6(a), with a constant FDR, the allowable distance increases with decreasing latitude. By increasing the FDR, this effect can be compensated and the allowable distance from the shore can be reduced. If we want to keep unchanged the minimum allowable distance by variation of the latitude, we must create an appropriate frequency shift in the M-ESIM transmitter. This frequency shift will cause a suitable FDR that maintains constant the minimum allowable distance, despite the change in latitude. For example, Fig. 6 (b) shows the curve of FDR variation versus latitude that leads to a constant allowable minimum distance of 100 kilometers from the shore. As can be seen, as the latitude decreases, the FDR and the frequency separation must be increased to a certain extent so that the minimum allowable distance from the shore remains constant. However, for latitudes below a certain value (about 16 degree), the minimum allowable distance, regardless of the FDR value, will be greater than 100 kilometers. This means that it cannot achieve 100 kilometers minimum distance for any amount of FDR for these latitudes.

According to section II parts A and C and considering relation (2), the joint effect of carrier frequency and FDR is simulated on the minimum allowable distance from the shore. As shown in Fig. 7 (a), with a constant FDR, the minimum allowable distance increases with decreasing the carrier frequency. By increasing the FDR, this effect can be compensated and the minimum allowable distance from the shore can be reduced. Of course, according to this result, the minimum allowable distance will not fall below a certain value for any carrier frequency and FDR. This value approximates to 100 kilometers, under the simulation assumption. If we want to keep unchanged the minimum allowable distance by varying the carrier frequency, we must create a frequency shift in the M-ESIM transmitter. By adjusting the frequency shift correctly and creating the appropriate FDR, it is possible to maintain the desired constant minimum allowable distance despite varying the carrier frequency. For example, Fig. 7 (b) shows the FDR curve versus the carrier frequency that results in minimum allowable distance from the shore of 110 kilometers.

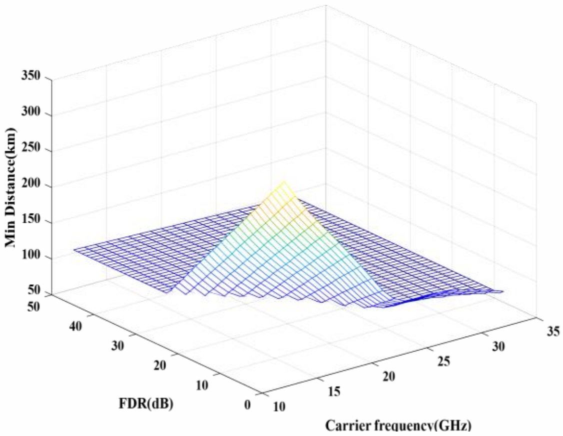


(a)

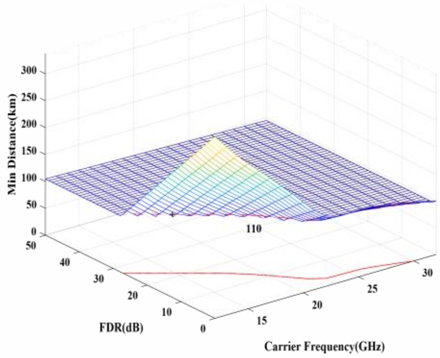
(b)

Figure 6. (a) Joint effect of latitude and FDR on the minimum allowable distance of M-ESIM from the shore. (b) The curve of FDR versus latitude to maintain a minimum allowable distance of 100 kilometers.

Based on section II parts A and D and considering relation (2), the joint effect of the annual number of passing vessels and FDR is obtained on the minimum allowable distance from the shore via simulation. As shown in Fig. 8 (a), by increasing the FDR, the minimum allowable distance from the shore can be reduced. Of course, according to this result, the minimum allowable distance will not fall below a certain value (about 97kilometers) for any number of annual vessels and FDR. If we want to keep unchanged the minimum allowable distance by varying the number of annual vessels, we must create a frequency shift in the M-ESIM transmitter. By adjusting the frequency shift correctly and creating the appropriate FDR, it is possible to maintain constant the desired minimum allowable distance. For example, Fig. 8 (b) shows the FDR curve versus the annual number of vessels that results in the minimum allowable distance from the shore of 105 kilometers. According to relation (2), if G_t decreases, the required FDR to compensate the interference will decrease, and vice versa.



(a)



(b)

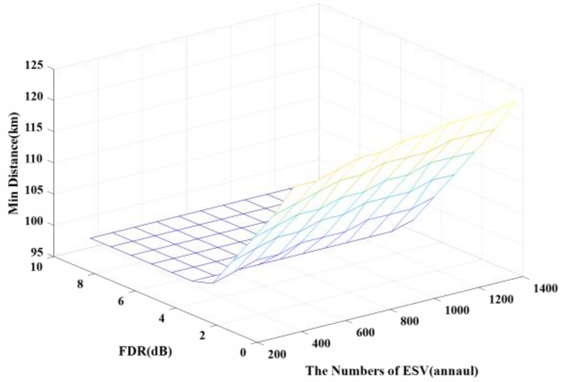
Figure 7. (a) Joint effect of carrier frequency and FDR on the minimum allowable distance of M-ESIM from the shore. b) The curve of FDR versus carrier frequency in order to maintain a minimum allowable distance of 110 kilometers.

The same scenarios in Figs. 6 to 8 are applied for various G_t and the results are shown in Figs. 9 to 11. As a result, for the lower G_t the required FDR values to achieve the same minimum allowable distance, for the same carrier frequency, latitude or the annual number of passing ships are decreased.

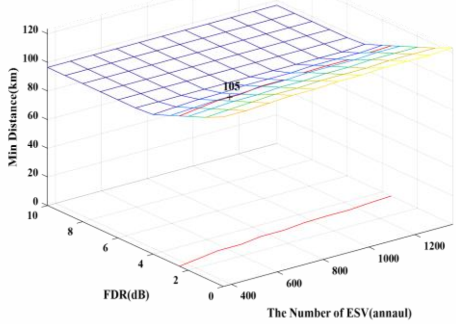
The minimum allowable distance and *p* extraction algorithm in carrier frequency of 28GHz has been simulated in [23] using the recommendation ITU-R SF.1650 [15]. Therefore, in order to validate the simulations performed in this paper, the minimum allowable distance extraction algorithm is simulated with the conditions mentioned in [23] for both 3 and 6 passing ships, daily. The simulation results and the results of [23] are shown in TABLE III. The contents of this table show that the algorithm simulation for determining the minimum allowable distance in this paper is consistent with the simulation performed in [23] for this purpose.

TABLE III. MINIMUM ALLOWABLE DISTANCE AND *P*(%) FOR THE SIMULATION CONDITIONS OF [23]

		Simulation results	**Results of [23]**
3 vessel every day	***p* (%)**	0.0381	0.0392
	Distance	126.6	126 km
6 vessel every day	***p* (%)**	0.0187	0.0193
	Distance	128.5	128 km



(a)



(b)

Figure 8. (a) Joint effect of the annual number of vessels and FDR on the minimum distance of M-ESIM from the shore. (b) The curve of FDR versus the annual number of vessels in order to maintain the minimum allowable distance of 105 kilometers.

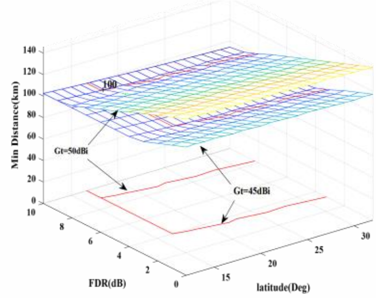


Figure 9. The curve of FDR versus latitude in order to maintain a minimum allowable distance of 100 kilometers for Gt=45dBi and Gt=50dBi.

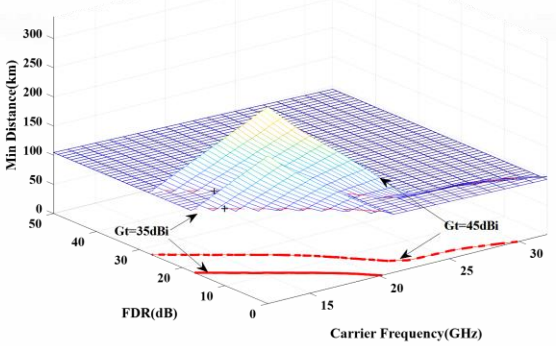


Figure 10. The curve of FDR versus carrier frequency in order to maintain a minimum allowable distance of 110 kilometers for Gt=45dBi and Gt=35dBi.

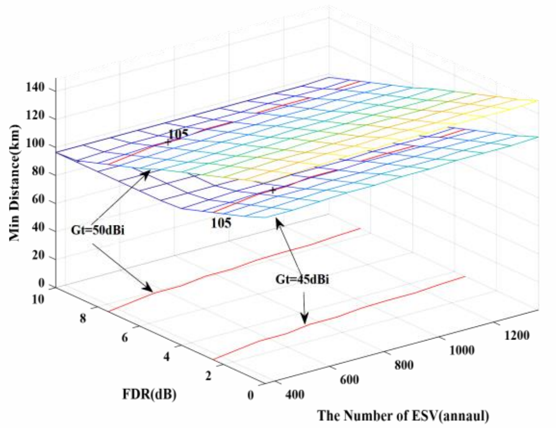


Figure 11. The curve of FDR versus the annual number of vessels in order to maintain a minimum allowable distance of 105 kilometers for Gt=45dBi and Gt=50dBi.

IV. CONCLUSION

To reduce or remove the damaging frequency interference of M-ESIM on the fixed shore station, it should not be closer to the shore than the minimum allowed distance. The important parameters of the minimum allowable distance of the ship from the shore investigated in this paper. The minimum protection distances are determined versus the latitude, carrier frequency and annual number of crossing ships along the shore, separately. The simulation results show that decreasing the carrier frequency and latitude or increasing the number of annual passing vessels increases the minimum allowable distance of the ship from the shore. One way to keep constant the minimum allowable distance from the shore is FDR increase by the frequency shift of the M-ESIM. As a result, FDR values are obtained versus the three variables of latitude, carrier frequency, and the annual number of passing ships, separately so that the minimum allowable distance of the ship from the shore will remain the predetermined constant value. Moreover, assuming the values of the paper parameters, the minimum allowable distance will not be smaller than 100 kilometers for any values of FDR and carrier frequency. This distance will not be smaller than 97 kilometers for any values of FDR and vessels annual numbers, too.

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