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The Electromagnetic Compatibility between FAST and Public Mobile Communication Stations and its Cognitive Using Frequency Strategy

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Abstract

To master the electromagnetic environment characteristics around the Five-hundred-meter Aperture Spherical radio Telescope (FAST) and ensure a better ecological environment in the radio-quiet zone of FAST, we analyzed the radiation characteristics of the public communication stations around FAST. By comparing the FAST received signal power from the communication stations and the interference protection threshold of the radio astronomy applications, we found that the total proportion of the communication stations exceeding the radio astronomy protection threshold is 69.01%. Furthermore, to fully protect the regular operation of FAST, we proposed four interference avoidance and frequency coordination strategies based on the cognitive theory. Namely: (1) increasing the operating frequency of the communication station; (2) adjusting the direction of the transmitter antennas; (3) reducing the height of the transmitter antennas; (4) decreasing the transmitting power of the communication station. As a result, the impact on FAST can effectively be reduced, and the FAST's received power from the communication stations will be lower than the radio astronomy protection threshold by using the above mentioned four strategies. Through the analysis of the experiment, the prediction is consistent with the overall trend of the measurement, and using frequency strategies can significantly reduce the signal power at the receiving locations. Furthermore, we construct a quality evaluation system for frequency coordination and analyze the satisfaction of the four strategies under the four criteria. The results show that adjusting the direction of the transmitter antennas has better satisfaction, and the maximum satisfaction is 0.85. The above research results can be further expanded to potentially improve the electromagnetic ecological environment around FAST and support the regular operation of FAST.

Key words: methods: analytical – methods: statistical – telescopes

1. Introduction

Five-hundred-meter Aperture Spherical radio Telescope (FAST) is one of the nine national scientific and technological infrastructures determined by the National Science and Education Leading Group (Nan et al. 2011). The construction of the highly sensitive giant radio telescope was initially designed by Chinese scientists, who thoroughly considered the unique topographic conditions of the karst depression in southern Guizhou, China. FAST is currently the world's largest radio telescope in terms of aperture. It is about 10 times more sensitive than the 100 m telescope in Bonn, Germany, and about 10 times more comprehensive than the Arecibo 300 m telescope in the United States. FAST provides significant support for China to carry out research activities on the nature of dark matter and dark energy, the origin and evolution of the universe, the origin of life in space, and the search for extraterrestrial civilizations, and plays an irreplaceable role in China's national defense construction and security (Nan & Jiang 2017). Since the radio signals emitted by distant objects in the universe are faint, a strict electromagnetic environment is required around radio telescopes to guarantee their monitoring of cosmic signals through sensitive terminal equipment (Li et al. 2009). Therefore, one can master the surrounding electromagnetic environment and reduce the radio interference of radio astronomy services by measuring, analyzing, and evaluating the electromagnetic environment around FAST, which is essential to ensure the regular operation of FAST.

Recently, many researchers have monitored and evaluated the electromagnetic environment around FAST before and after the operation. The purpose of these researches is to ensure better operation of FAST with avoiding radio frequency interference. Li et al. (2019) have systematically described FAST significant scientific application value for deep space exploration, autonomous spacecraft navigation with pulsars, high-resolution microwave survey, and reception systems. Li et al. (2015) provided a scientific basis for the scientific site selection and radio astronomy protection operations through relevant electromagnetic environment tests. Also research on an intelligent monitoring and positioning system to reduce radio frequency interference (RFI) is essential for monitoring, identifying, and positioning RFI sources, which is conducive to strengthening the operation and management of radio-quiet zone (RQZ) (Wang et al. 2020c). Huang et al. (2017) focused on analyzing the electromagnetic transmitting power of visitors' electronic devices, such as tablet computers, digital cameras, and mobile phones, based on the monitoring results of the electromagnetic environment around FAST to assess the interference caused by the visitors' electronic devices to the radio telescope. Zhang et al. (2017, 2020) conducted electromagnetic compatibility studies on FAST during its design, construction, and operation phases. They evaluated the RFI impact on mobile communication stations by conducting RFI tests on mobile communication stations within the core area of FAST (5 km) and proposed permanent communication station shutdown measures to reduce interference from communication stations.

Wang et al. (2021) established a satellite RFI suppression system by studying the interference caused by space satellites to FAST. The system can effectively avoid satellite interference by adjusting the observation band of FAST. Hu et al. (2020) systematically introduced the results of applying radio wave environmental protection at FAST from effective electromagnetic compatibility measures for the radio telescope and the establishment and operation of the RQZ. Zhang et al. (2022) proposed a method to reduce RFI in FAST observations and gave the statistical results of RFI. Qiang et al. (2021) proposed an adaptive threshold RFI detection method based on fused wavelet transform reconstruction and an RFI elimination method based on neighborhood weighted padding based on normalized processing of SBRS observation data. Wang et al. (2020a) quickly and efficiently removed RFI from pulsar data by pseudo-inverse learning autoencoder to meet the demand for real-time processing of FAST data. Zhang et al. (2021) identified RFI in spectral data by combining depthwise separable convolution and residual principles based on the unit neural network method. Wang et al. (2020b) studied the *UHF* signal fading characteristics in the karst landscape environment of the FAST RQZ. They determined the optimal distribution models of channel fading range, fading depth, and fading rate. Yang et al. (2019) validated the applicability of the international radio wave propagation prediction model in the karst region of Guizhou to support the analysis and assessment of the electromagnetic environment around FAST. Most of the above studies focus on electromagnetic environment monitoring and analysis and less on coordinating the utilization of electromagnetic radiated sources around FAST to ensure intersystem compatibility.

To master the FAST operation environment and ensure its regular operation, we will evaluate the energy distribution characteristics of the public mobile communication stations around FAST using the dedicated radio wave propagation and interference analysis model. Compared with the radio astronomy protection requirements, we analyzed whether the public mobile communication stations in the 870–878.6 MHz frequency band cause interference to FAST. In the case of electromagnetic interference (EMI), considering the frequency coordination requirements, we propose the strategies for interference avoidance and using frequency for the public mobile communication stations that need to be coordinated. We construct a quality evaluation system for cognitive using frequency with the analytic hierarchy process.

2. Analysis of EMI Characteristics of Mobile Communication Stations to FAST

2.1. Analysis Object

FAST (106°85E, 25°64N) is located in the Dawodang depression of Kedu Town, Pingtang County, Guizhou Province, about 800 m in diameter. The feeder support system consists of six 100 m high support towers, 6 km scale flexible steel cable systems, and the driving units suspended in the air (Peng et al. 2009). The receiver system is equipped with a multi-band and multi-beam feed covering 70 MHz–3 GHz, with high sensitivity. FAST observes the weak electromagnetic signals sent by celestial bodies in the universe and mainly carries out the observation and research on neutral hydrogen in the universe, the discovery of new pulsars, very-long-baseline interferometry, and extends the deep space communication capability (Li & Duan 2019). To ensure a strict electromagnetic environment around FAST, Guizhou Province promulgated the "Methods for protecting the RQZ of Five-hundred-meter Aperture Spherical radio Telescope." This rule stipulates that the FAST is the center, and the radius is 30 km as the RQZ. As shown in Figure 1, the 5 km range is the core zone, 5–10 km is the intermediate zone, and 10–30 km is the remote zone.

According to the "Interference protection requirements for Five-hundred-meter Aperture Spherical radio Telescope" and ITU-R RA.769, the 870–878.6 MHz stations mainly involve the B03 low-frequency and B04 receivers in FAST. Its interference threshold is

$$P_H = 10\log(0.1kT\Delta f\big/\sqrt{2t\cdot\Delta f}\,) \tag{1}$$

where k is the Boltzmann constant, T is the system noise temperature (K), t is the observing time (s), and Δf is the bandwidth (Hz).

According to the above equation, the corresponding parameters and interference thresholds of the FAST receivers are obtained as shown in Table 1.

In the research of the compatibility characteristics between FAST and its surrounding stations, FAST is the receiver, and its antenna radiation pattern (870–878.6 MHz) is shown in Figure 2. During the operation of FAST, the zenith angle changes with the different observation tasks, and the antenna gain toward the incoming wave direction of the station will also

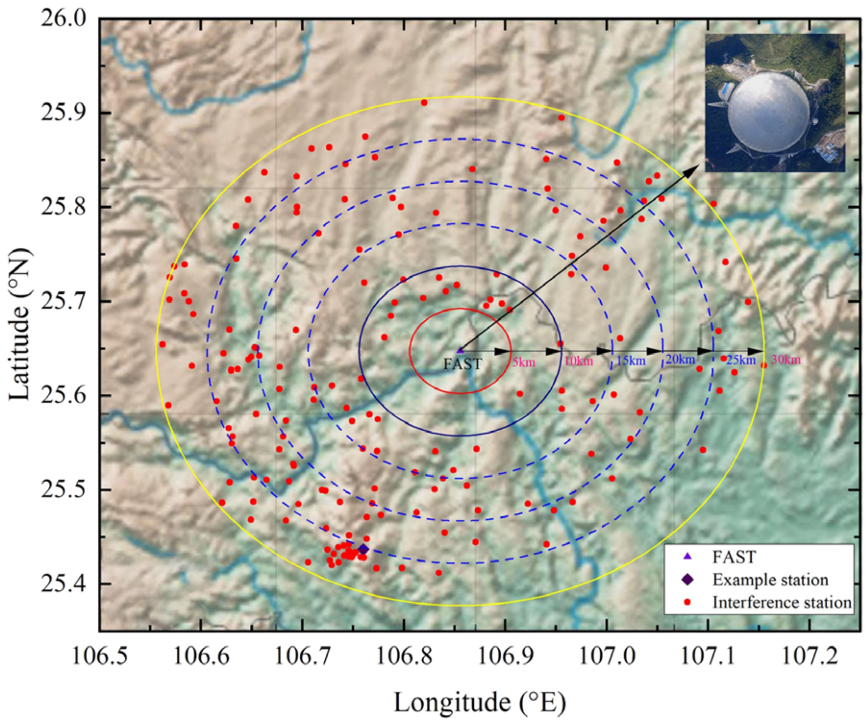


Figure 1. The distribution of FAST and the surrounding stations in the 870–878.6 MHz.

Table 1
Communication Interference Protection Requirements of FAST

	FAST Parameters				Interference Threshold (dBW)
Receiver	Center Frequency (MHz)	Frequency Band (MHz)	Bandwidth (MHz)	System Noise Temperature (K)	
B03	610	270–950	680	60	−195
B04	840	560–1120	560	60	−195

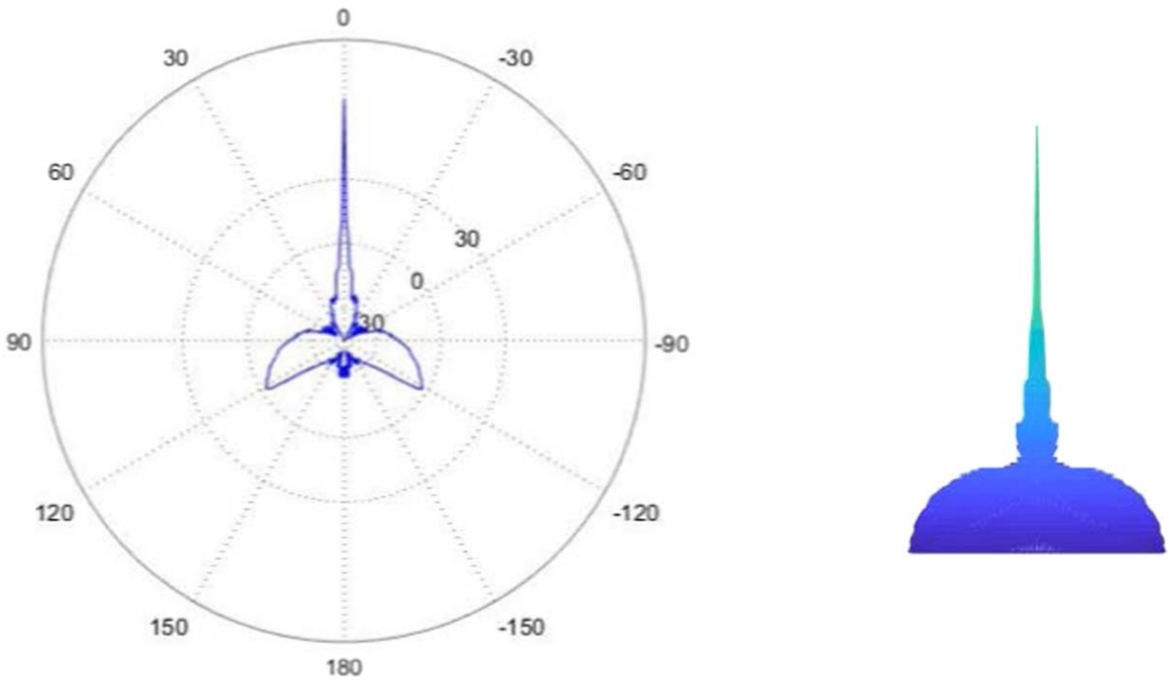
change. Therefore, we calculated the antenna gain against the zenith angle of 0°, 10°, 20°, 30°, and 40°, and azimuth toward the transmitting station and away from the transmitting station, respectively. The transmitters are deployed at communication stations, and its antenna radiation patterns are shown in Figure 3.

2.2. Analysis Method

Here, we chose the deterministic prediction method of radio wave propagation according to the terrain characteristics around FAST (see ITU-R P.2001, for details). The interference propagation mechanism between radio systems on the Earth's surface is considered comprehensively, and the main interference mechanisms include line-of-sight propagation, diffraction propagation, troposcatter propagation, etc. According to the station parameters, the FAST parameters, and the link transmission loss between the station and FAST calculated by the propagation loss prediction method, the received power at FAST is calculated as follows (ITU-R RA.1031).

$$P_r = P_t + G_t - L(d, f, h_t, h_r, e) + G_r \tag{2}$$

where P_t is the transmitting power of the station, G_t is the gain of the station antenna, G_r is the gain of the FAST antenna, and L is the link transmission loss between the interference station and FAST. The loss is a function of transmission distance (d), operation frequency (f), transmitter antenna height (h_t), receiving antenna height (h_r), and radio meteorological parameters (e). The prediction of propagation loss is to perform a comprehensive analysis. The independent models include near-surface propagation model, troposcatter propagation model, and ionospheric sporadic-E propagation model. Finally, the integrated method synthesizes the separate models and predicts the propagation loss between the station and FAST. Especially the predicting process for these independent models is as follows (ITU-R P.2001).



(a) (b)

Figure 2. The FAST antenna radiation pattern with the zenith angle is 0 degrees. (a) Two-dimensional antenna radiation pattern. (b) Three-dimensional antenna radiation pattern.

(1) Near-surface propagation: When the antenna height is low, in the maximum radiated direction along the ground, the near-surface propagation loss L_{sub1} mainly integrated with the free space propagation L_{bfs}, the diffraction propagation L_d, the clear-air effect A_1, and the gaseous attenuation effect L_{gas}.

$$L_{\mathrm{sub1}} = L_{bfs} + L_d + A_1 + L_{\mathrm{gas}} \quad (3)$$

The free-space basic transmission loss is given as a function of path length d_{fs} and frequency f by:

$$L_{bfs} = 92.4 + 20\log(f) + 20\log(d_{fs}) \quad (4)$$

Diffraction propagation is the phenomenon of radio waves bypassing obstacles in the propagation path, and diffraction loss L_d can be calculated as:

$$L_d = L_{dba} + \max\{L_{dsph} - L_{dbs}, 0\} \quad (5)$$

where L_{dsph} is the spherical-Earth diffraction loss, L_{dba} and L_{dbs} are the Bullington diffraction loss for the actual path profile and smooth path profile, respectively.

The clear-air effect (A_1) denotes the attenuation due to the combined of clear-air and rain/wet-snow in dB. A_1 is can be given by:

$$A_1 = A_{\mathrm{iter}} \quad (6)$$

where A_{iter} is the iterative procedure that is used to calculate the attenuation of a propagation mechanism for a given percentage of an average year.

Also, the gaseous attenuation of the near-surface propagation mainly includes the total gaseous attenuation under non-rain conditions and the gaseous attenuations due to water vapor under both non-rain and rain conditions, calculated as shown in the following equation. Namely,

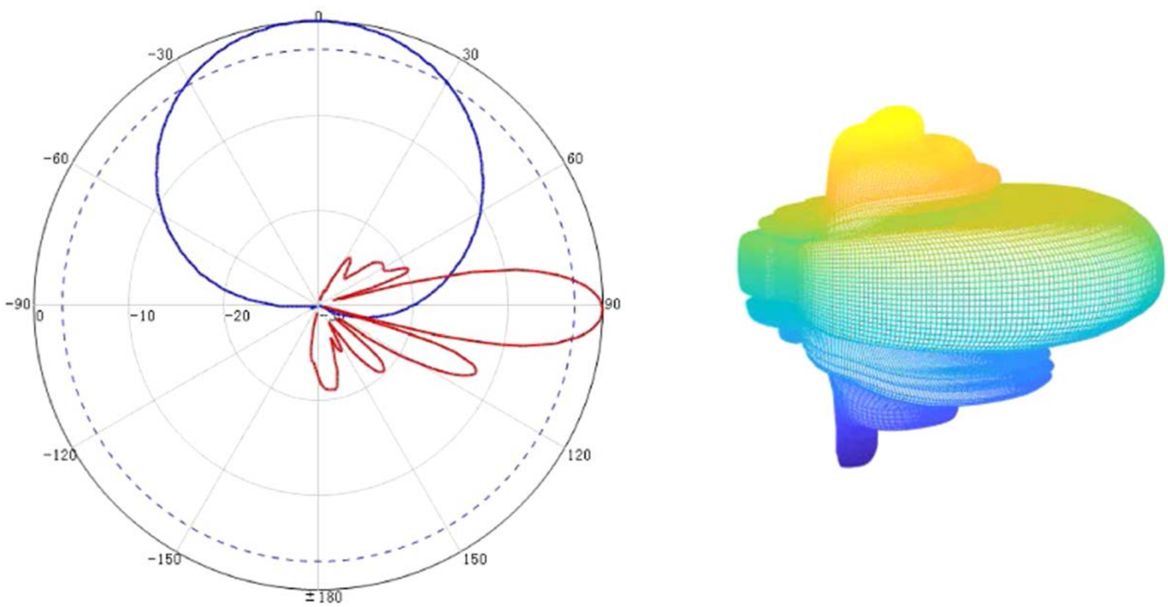
$$L_{\mathrm{gas}} = F_{wvr}(A_{wrsur} - A_{wsur}) + A_{gsur} \quad (7)$$

where F_{wvr} is the coefficient of influence on the water vapor attenuation produced. A_{gsur} is the total gaseous attenuation under non-rain conditions. A_{wrsur} and A_{wsur} are gaseous attenuations due to water vapor under rain and non-rain conditions.

(2) Troposcatter propagation: When radio waves such as ultrashort waves and microwaves are projected on the vortex air mass, the scattering phenomenon caused is troposcatter propagation. The effects considered for troposcatter propagation prediction mainly include the basic transport loss L_{bs}, the attenuation A_2 of rain, snow, precipitation, and the gaseous absorption loss L_{tropgas}.

$$L_{\mathrm{sub3}} = L_{\mathrm{bs}} + A_2 + L_{\mathrm{tropgas}} \quad (8)$$

The basic transmission loss of the troposcatter mainly includes the loss related to frequency and distance, the loss of antenna aperture and medium coupling, and the meteorological and atmospheric loss under different climate zones. The basic transmission loss of the troposphere can be calculated by the



(a) (b)

Figure 3. Antenna radiation patterns of the communication stations. (a) Two-dimensional antenna radiation pattern in the 870–878.6 MHz. (b) Three-dimensional antenna radiation pattern in the 870–878.6 MHz.

following equation.

$$L_{\rm bs} = M + L_{\rm freq} + L_{\rm dist} + L_{\rm coup} - Y_p \text{ dB} \tag{9}$$

where M is the meteorological structure parameter, $L_{\rm freq}$ is the frequency-dependent loss, L_{dist} is the distance-dependent loss, $L_{\rm coup}$ is the loss of antenna aperture and medium coupling, and Y_p is the meteorological structure parameter.

The attenuation of rain, snow, and precipitation of troposcatter propagation: we define the incident distance from the transmitter to the troposphere and the reflection distance from the receiver to the troposphere. The attenuation caused by rain, snow, and precipitation at both distances is calculated by the following equation:

$$A_2 = (A_{2t}(1 + 0.018 d_{tcv}) + A_{2r}(1 + 0.018 d_{rcv}))/(1 + 0.018 d) \text{ dB} \tag{10}$$

where d_{tcv} and d_{rcv} are the propagation path distances from the transmitter and receiver to the troposphere, respectively. A_{2t} and A_{2r} are the precipitation attenuation on the scattering propagation path from the transmitter and receiver to the spatial, respectively.

The gaseous attenuation of troposcatter propagation mainly includes the total gaseous attenuation under non-rain conditions and the gaseous attenuation caused by water vapor under non-rain and rain conditions. It can be expressed as.

$$L_{\rm tropgas} = 0.5(F_{wvrtx} + F_{wvrrx}) \times (A_{wrs} - A_{ws}) + A_{os} + A_{ws} \tag{11}$$

where F_{wvrtx} and F_{wvrrx} are the coefficients of the effect of transmitter and receiver path segments on water vapor attenuation. A_{wrs}, A_{ws} and A_{os} are the gaseous attenuations due to water vapor under rain and non-rain conditions and oxygen, respectively.

(3) Ionospheric propagation by sporadic-E: The modes considered for ionospheric propagation by sporadic-E mainly include 1-hop propagation and 2-hop propagation. Ionospheric propagation by sporadic-E may be significant for long paths and low frequencies. Basic sporadic-E transmission loss, L_{be}, is given by:

$$L_{be} = \begin{cases} L_{bEs1} & L_{bEs1} < L_{bEs2} - 20 \\ L_{bEs2} & L_{bEs2} < L_{bEs1} - 20 \\ -10\log(10^{-0.1 L_{bEs1}} + 10^{-0.1 L_{bEs2}}) & \text{otherwise} \end{cases} \tag{12}$$

where L_{bEs1} is the 1-hop basic propagation loss, and L_{bEs2} is the 2-hop basic propagation loss.

2.3. Analysis Results

We analyzed the 319 logical stations in the 870–878.6 MHz listed in Figure 1. Each station was calculated with five different time probabilities, such as 1%, 10%, 50%, 90%, and 99%, and five zenith angles, such as 0°, 10°, 20°, 30°, and 40°, two types of azimuth angles, such as toward the transmitting station and away from the transmitting station, and the signal power arriving at FAST under different antenna gains of the same station. Moreover, we compared the received power with

Table 2
Received Power and Interference Margin Analysis of FAST

Antenna Gain of Communication Stations/dBi	Interference Path Azimuth/°	Zenith Direction of the FAST Observation/°	FAST Antenna Gain/dBi	FAST Received Power/dBW	Interference Threshold/dBW	Interference Margin/dB	Threshold Exceeded (Y/N)
13.21	⋯	0	−19.41	−173.38	−195	21.62	Y
13.21	201	10	−13.36	−167.32	−195	27.68	Y
13.21	201	20	−7.71	−161.67	−195	33.33	Y
13.21	201	30	−2.35	−156.31	−195	38.69	Y
13.21	201	40	−26.07	−180.04	−195	14.96	Y
13.21	21	10	−24.94	−178.91	−195	16.09	Y
13.21	21	20	−34.15	−188.11	−195	6.89	Y
13.21	21	30	−39.34	−193.30	−195	1.70	Y
13.21	21	40	−35.98	−189.94	−195	5.06	Y

the interference thresholds required by the corresponding receivers, focusing on the upper and lower frequency limits of the frequency band used by the station equipment. In this work, we analyzed 57,420 pieces of data, and 17,794 pieces of data met the requirements, accounting for only 30.99%. The lowest value of transmitting power was reduced by 31.61 dB compared with the protection threshold.

Here, we take the Ma Caozhai intersection station, Yudu Avenue, Luodian as an example. The station is located at (106°.76E, 25°.44N), 25.87 km away from FAST. The transmitting power is 16.2 dBW, and the antenna height is 30 m. According to the collected parameters, we selected the lower limit 870 MHz and the upper limit 878.6 MHz as the transmitting frequencies of the station equipment for analysis. The transmitting height was set to the actual height of the station, and the receiving height was equivalent to 10 m simultaneously. According to the "Interference protection requirements for Five-hundred-meter Aperture Spherical radio Telescope," the interference threshold of the B03 and B04 receiver is −195 dBW. The comparison results of the interference threshold of the B03 and B04 receiver are listed in Table 2. The results show that the FAST received power varies with the zenith direction of the FAST antenna and azimuth between FAST and the communication station at Ma Caozhai intersection, Yudu Avenue, Luodian. It exceeds the interference threshold specified in the "Interference protection requirements for Five-hundred-meter Aperture Spherical radio Telescope." The highest value exceeds 38.69 dB, while the lowest value exceeds 1.7 dB. That is, the FAST receivers can receive the signal of this communication station, which may have specific radio interference to the FAST.

Due to the substantial EMI caused by the communication stations in the core zone of FAST, which is prone to cause nonlinear distortion of the FAST receiver, it has been permanently closed by the local government (see Zhang et al. 2020, for reviews). Therefore, the 870–878.6 MHz stations are distributed outside the core zone (5 km) of FAST, as shown in Figure 1. The analysis results of all 319 stations are summarized. The statistical analysis of the percentage of meeting the interference threshold requirements at different distance ranges is performed according to five distance ranges, including 5–10 km, 10–15 km, 15–20 km, 20–25 km, and 25–30 km, and the results are shown in Figure 4. Generally, the propagation loss is proportional to the propagation distance. That is, the link loss gradually increases as the propagation distance increases between the communication station and the FAST. As shown in Figure 4(a), the proportion of meeting the interference threshold in different distance ranges gradually increases as the propagation distance increases, with the maximum ratio in the 25–30 km range from FAST, accounting for 44.13%, higher 33.52% than that in the 5–10 km range from FAST. Among the data that meets the interference threshold, the proportion in the 25–30 km is 53.78%, which exceeds the total of the other distance ranges. While the proportion in the 5–10 km range is slightly higher than that in the 10–15 km range because the number of stations in the 5–10 km range is nearly twice that in the 10–15 km range, as shown in Figure 4(b). As a result, the communication stations in different ranges lead the EMI to FAST, and the shorter the distance between the communication station and FAST, the more obvious the interference. In order to ensure the stable operation of FAST, it is necessary to take interference suppression methods for the stations.

3. Research of Interference Suppression and Using Frequency Strategy

3.1. Interference Tracing and Cognitive Strategy

The sensitivity limit of most radio astronomy observations is at a flux-density level far below that used for the reception of radiocommunication signals (ITU-R RA.517), and certain signals from ground-based transmitters may sometimes interfere with radio astronomy observations. EMI suppression and improvement of electromagnetic ecological environment around FAST support the regular operation of FAST. If geographical sharing is to be successful, the transmission loss

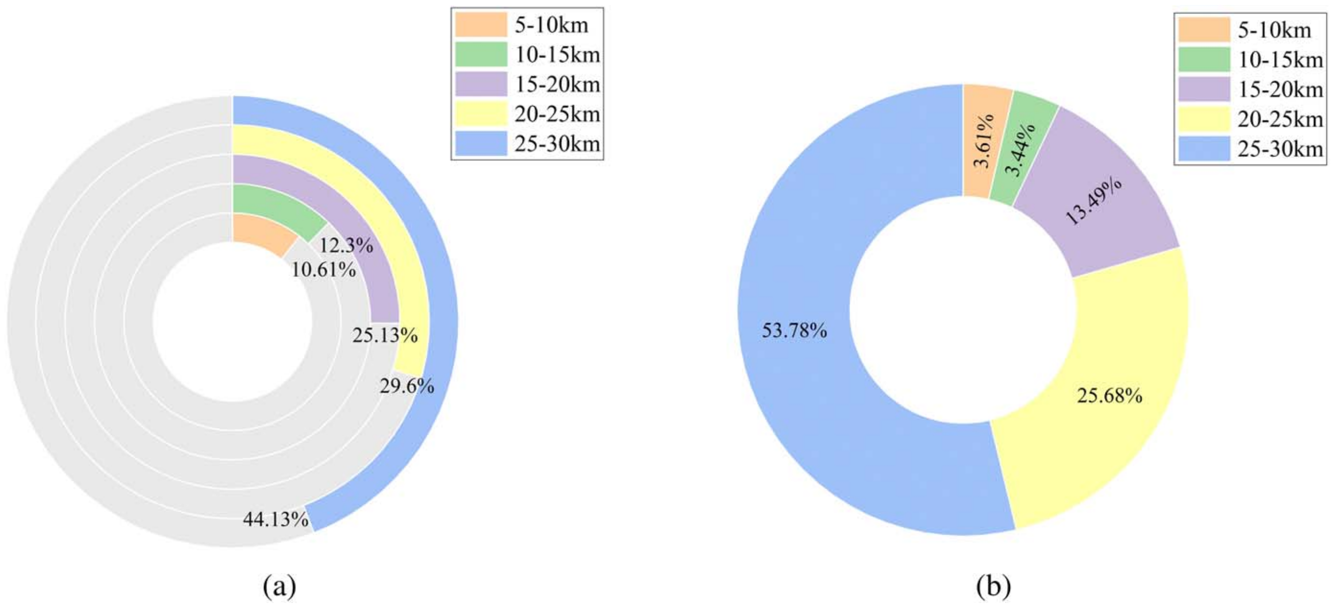


Figure 4. The proportion distribution of meeting the interference threshold at different distance ranges. (a) The station's percentage of meeting the interference threshold in different distance ranges. (b) The station's percentage of meeting the interference threshold in different distance ranges against the total station.

of the interfering transmitter and the interfered-with receiver must be sufficient so that the interference is not considered harmful. For a radio astronomy observation, the received power is integrated over a period of time T to reach a better sensitivity. The received power from interferers during observation may be expressed as follows (ITU-R RA.1031):

$$I = \frac{1}{N}\sum_{i=1}^{N}(P_t(i)\cdot G_t(i)\cdot G_r(i)/L_p(i)) \tag{13}$$

where $L_p(i)$ is the propagation loss at instant i, $P_t(i)$ is the transmitting power level in the radio astronomy service bandwidth at the input to the antenna at instant i (W), $G_t(i)$ is the gain of the transmitting antenna in the direction of the radio astronomy antenna at instant i, $G_r(i)$ is the gain of the radio astronomy antenna in the direction of the transmitter at instant i, N is the number of samples in the integration time T, and I is the interference power in the reference bandwidth at the receiver input averaged over the observation period T (W).

In order to effectively avoid EMI from the stations to FAST, the strategies of reducing EMI are studied from two aspects of interference sources and coupling paths, and four perspectives of time domain, frequency domain, spatial domain, and energy domain, using the electromagnetic environment cognitive theory combined with Equation (10), as shown in Figure 5. Time-domain suppression strategies mainly include time-division multiplexing. Frequency-domain suppression strategies mainly include frequency-division multiplexing, frequency-domain filtering, increasing frequency, etc. Spatial-domain suppression strategies mainly include expanding the interference distance, changing the radiated direction, reducing the antenna height, etc. Energy-domain suppression strategies mainly include reducing the transmitting power, reducing the antenna gain, etc. In addition, there are other strategies, such as electromagnetic shielding.

Since the operating time and frequency band of the FAST cover that of the existing mobile communication, it is impossible to achieve time-domain suppression strategies, frequency-division multiplexing and frequency-domain filtering. Since FAST and communication stations are fixed and their equipment has been deployed, it is also impossible to reduce the interference distance and reduce the antenna gain. In addition, electromagnetic shielding is relatively complex, which has been completed in the previous work (Zhang et al. 2017; Hu et al. 2020; Wang et al. 2020c). Therefore, considering the difficulty of coordinating frequency implementation, we carried out four interference suppression strategies: (1) increasing the operating frequency of the communication stations (the propagation loss $L_p(i)$ is increased sequentially), (2) adjusting the direction of the transmitter antennas (the gain of the transmitting antenna $G_t(i)$ gets decreased), (3) reducing the height of the transmitter antennas (another strategy of increasing the propagation loss $L_p(i)$), and (4) decreasing the transmitting power of the stations (the transmitting power level $P_t(i)$ gets decreased). The specific implementation strategy is to analyze whether the received power meets the threshold requirements by comparing the received power and the interference threshold of FAST after adopting four strategies, respectively.

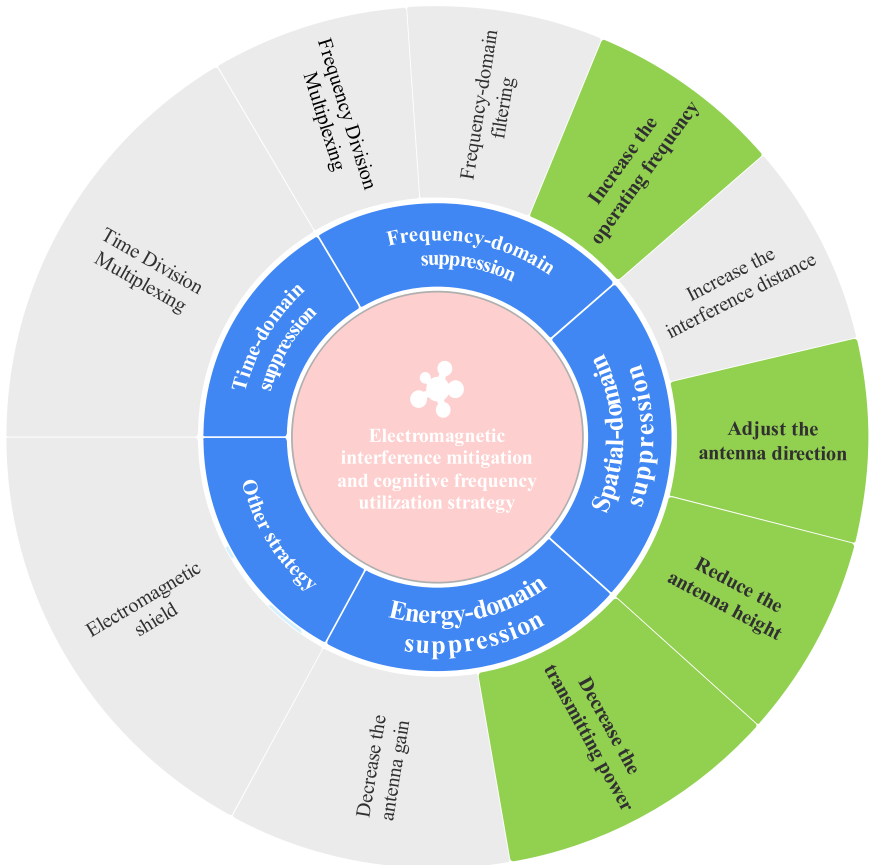


Figure 5. EMI suppression and cognitive using frequency strategy for FAST.

3.2. Evaluation Criteria

An excellent cognitive using frequency strategy has the characteristics of multi-layer, all-around, and quantifiable. In constructing the index system, the comprehensiveness and typicality of the index system are the difficulties and the key points of making the evaluation system when ensuring the evaluation quality and taking into account the refinement of the index system. The basic principle of the analytic hierarchy process is to decompose the evaluation object or system into multi-layer (goal, criteria, and index) (Xu et al. 2013), on which each index is analyzed and made decisions. Therefore, to improve the reliability and feasibility of decision-making, the paper comprehensively considers three aspects of implementation complexity, economic cost, strategic benefit, and communication quality and uses the analytic hierarchy process to score the indicators. As shown in Table 3, we propose a quality evaluation system for cognitive using frequency strategy.

The relevant definitions and calculation methods of the four criterion parameters of implementation complexity, economic cost, strategic benefit, and communication quality are as follows:

1. Complexity parameter (C_1) of implementing this strategy is defined as the percentage of implementation time T_s to the construction cycle T_c of the communication base station, namely:

$$C_1 = T_s / T_c \quad (14)$$

2. Cost parameter (C_2) of implementing this strategy is defined as the percentage of implementation cost E_s to the construction cost E_c of the communication base station, namely:

$$C_2 = E_s / E_c \quad (15)$$

3. Interference probability (C_3) of implementing this strategy is defined as the percentage of data exceeding the threshold B_s in total data B_c after adopting this strategy, namely:

$$C_3 = B_s / B_c \quad (16)$$

4. Mobile communication quality (C_4) of implementing this strategy is defined as the percentage of communication service Q_s to the original communication service Q_c of

Table 3
The Evaluation System of Cognitive Using Frequency Strategy

Goal Layer	Criteria Layer	Index Layer	
Cognitive using Frequency with FAST	Implementation Complexity	Simple	[0, 20%] of the construction period
		Normal	(20%, 40%] of the construction period
		Middle	(40%, 60%] of the construction period
		Difficult	(60%, 80%] of the construction period
		Very difficult	(80%, 100%] of the construction period
	Economic cost	Tiny	[0, 20%] of the construction cost
		Small	(20%, 40%] of the construction cost
		Middle	(40%, 60%] of the construction cost
		Large	(60%, 80%] of the construction cost
		Huge	(80%, 100%] of the construction cost
	Strategic benefit	Excellent	Interference probability is between [0, 20%]
		Good	Interference probability is between (20%, 40%]
		Middle	Interference probability is between (40%, 60%]
		Bad	Interference probability is between (60%, 80%]
		Worse	Interference probability is between (80%, 100%]
	Communication quality	Worse	Communication quality is between [0, 20%]
		Bad	Communication quality is between (20%, 40%]
		Middle	Communication quality is between (40%, 60%]
		Good	Communication quality is between (60%, 80%]
		Excellent	Communication quality is between (80%, 100%]

the communication base station, namely:

$$C_4 = Q_s / Q_c \tag{17}$$

For C_1, C_2, and C_3, the lower the index value, the higher the quality evaluation. On the contrary, the lower the index value of C_4, the lower the quality evaluation. Therefore, for the cognitive using frequency strategy with FAST, the objective attribute vector can be constructed as follows:

$$\boldsymbol{O} = [\mathbf{1} - \boldsymbol{C}_1^N; \mathbf{1} - \boldsymbol{C}_2^N; \mathbf{1} - \boldsymbol{C}_3^N; \boldsymbol{C}_4^N] \tag{18}$$

where N is the number of using frequency strategy.

The difference in the environment of the base station will lead to the preference degree of the above three criteria, which directly affects the satisfaction of the final selection strategy. Here, we define the subjective preference weight of these strategies as follows:

$$\boldsymbol{W} = [\boldsymbol{w}_1^N; \boldsymbol{w}_2^N; \boldsymbol{w}_3^N; \boldsymbol{w}_4^N] \tag{19}$$

where $\sum_{k=1}^{4} \boldsymbol{w}_k^N = \mathbf{1}$, N is the number of using frequency strategy.

According to the subjective preference weights and objective attribute vectors, the satisfaction of the strategy based on the weighted average method can be obtained by:

$$S = \boldsymbol{W}'\boldsymbol{O} \tag{20}$$

where the maximum value of the satisfaction S is 1, and "$'$" denotes the transpose operator for the subjective preference weight vector.

3.3. Analysis and Discussion

3.3.1. Using Frequency Strategy Analysis

To analyze the above EMI suppression and using frequency strategies qualitatively, we still take the Ma Caozhai intersection station, Yudu Avenue, Luodian as an example and analyze the received power at FAST before and after adopting the strategies. Because the 30° azimuth angle has the maximum interference margin in Table 2, the power analysis results at this azimuth angle are shown in Table 4.

(1) Strategy 1: Increasing the operating frequency. The frequency range of the transmitting signal of this station is 870–878.6 MHz, which is upgraded to 2110–2130 MHz and selecting 2120 MHz as the center frequency to analyze the channel characteristics and the received power after updating the frequency. The results show that: the proportion of meeting the interference threshold increases from 0.00% to 23.33%. Furthermore, after increasing the operating frequency, the maximum value of exceeding the threshold power is reduced to 30.27 dB. Therefore, increasing the operating frequency has a significant effect on reducing the station's interference to FAST.

(2) Strategy 2: Adjusting the direction of the transmitter antenna. This station uses the antenna in the direction of FAST, and the station antenna gain is 13.21 dBi now. If changed to transmit back to FAST, the antenna gain is −13.00 dBi. Compared with the original operation station parameters, the results show that: the proportion of meeting the interference threshold increases from 0.00% to 67.78%, and the maximum of exceeding the threshold power is reduced to 12.48 dB after

Table 4
Received Power Optimization Statistics Under Four Different Strategies

Optimization Strategy		Parameter Change		The Maximum Value above Threshold/dB		
		Current Parameters	Optimization Parameters	Current Parameters	Optimization Parameters	Lifting Value
Strategy 1	Increase the operating frequency	Frequency: 870–878.6 MHz	Frequency: 2110–2130 MHz	38.69	30.27	8.42
Strategy 2	Adjust the antenna direction	Antenna gain: 13.21 dBi	Antenna gain: −13.00 dBi	38.69	12.48	26.21
Strategy 3	Reduce the antenna height	Antenna height: 30 m	Antenna height: 5 m	38.69	38.46	0.23
Strategy 4	Decrease the transmitting power	Transmitting power: 16.2 dBW	Transmitting power: 6.2 dBW	38.69	28.69	10.00
Integrated Strategy		ALL	ALL	38.69	−6.17	44.86

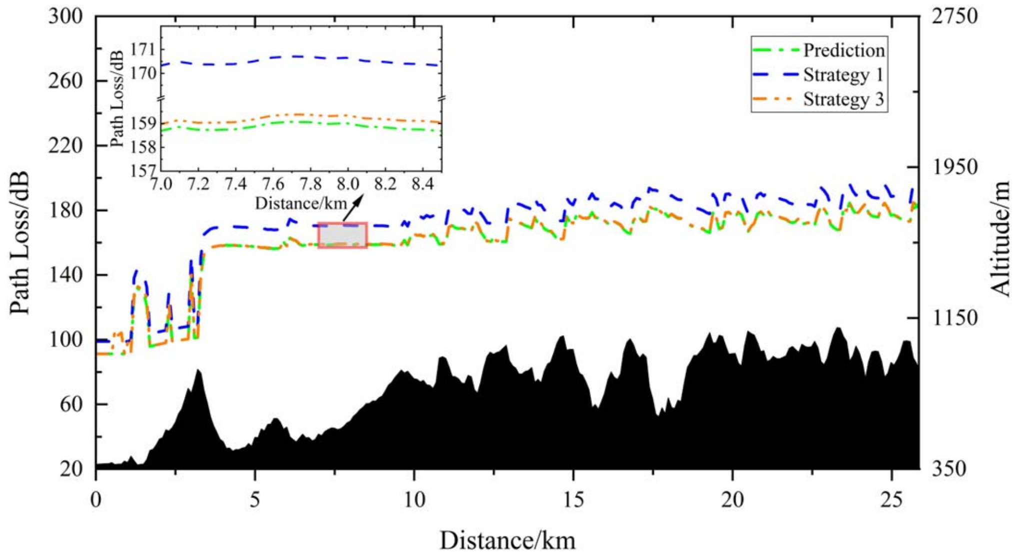


Figure 6. Path loss vs. distance before and after optimization with strategy.

adopting the method of the back to the FAST transmitting direction. Taking this strategy can significantly reduce the influence of the station on FAST.

(3) Strategy 3: Reducing the height of the transmitter antenna. The antenna height of the station is 30 m now, low to 5 m, and analyze the channel characteristics and received power after the antenna parameters are updated. The results show that: the proportion of meeting the interference threshold increases from 0.00% to 1.11%, and the maximum exceeding threshold power is reduced to 38.46 dB after losing the antenna height. As a result, it shows that the effectiveness of this method is not apparent for this station.

(4) Strategy 4: Decreasing the transmitting power of the station. The transmitting power of this station is 16.2 dBW now, which reduces to the minimum transmit power of 6.2 dBW, and the received power of FAST is updated. The results show that: the proportion of meeting the interference threshold increases from 0.00% to 33.33%, and the maximum value of exceeding threshold power is reduced to 28.69 dB. Therefore, decreasing the station's transmitting power can significantly reduce the influence of the station's signal on FAST.

In conclusion, reducing the antenna height and increasing the operating frequency have an apparent impact on the propagation loss. The path loss at 50% time probability versus propagation distance is shown in Figure 6. It is seen that the propagation loss is relatively tiny where the distance is less than 7 km from the Ma Caozhai intersection station, Yudu Avenue, Luodian, especially at the higher altitudes. In comparison, the propagation loss is relatively large in the low-lying areas of the valley and tends to grow with the increase in distance. Reducing the antenna height has a more negligible effect on the path loss, while increasing the operating frequency significantly affects the path loss. Thus, the signal power reaching the FAST's receiver can reduce to meet the requirements of the interference threshold. As a result, within 3 km, reducing the antenna height leads to significant fluctuations in path loss. It may be that the change in antenna height impacts the reflection propagation mode at short distances, and the impact can be ignored in long-distance communication.

The power difference D_{power} between the received signal and the interference threshold of FAST with different strategies under different zenith angles is demonstrated in Figure 7. The result shows that the received power from the communication station at Ma Caozhai, Yudu Avenue, Luodian to FAST is reduced by adopting strategies such as increasing the operating frequency, backward the transmitter antenna, reducing the antenna height, and decreasing the transmitting power, respectively. Among them, strategy 2 significantly reduces the received power, strategies 1 and 4 have weaker effects than 2, strategy 3 can be negligible. The analysis result of the FAST's received power under the integrated strategy is shown in Figure 8. The received power at different zenith angles and directions of the receivers meets the interference threshold after adopting the integrated strategy. Strategy 2 contributes most to the integrated strategy, and strategy 3 contributes almost negligibly. The interference threshold is met when four strategies are adopted at the zenith angle of the 30° toward the transmitting station. The maximum excess value is only −6.17 dB, which is much higher than other azimuths. Otherwise, only strategies 1 and 2 can meet the interference threshold. Therefore, integrated strategies 1 and 2 adopted can

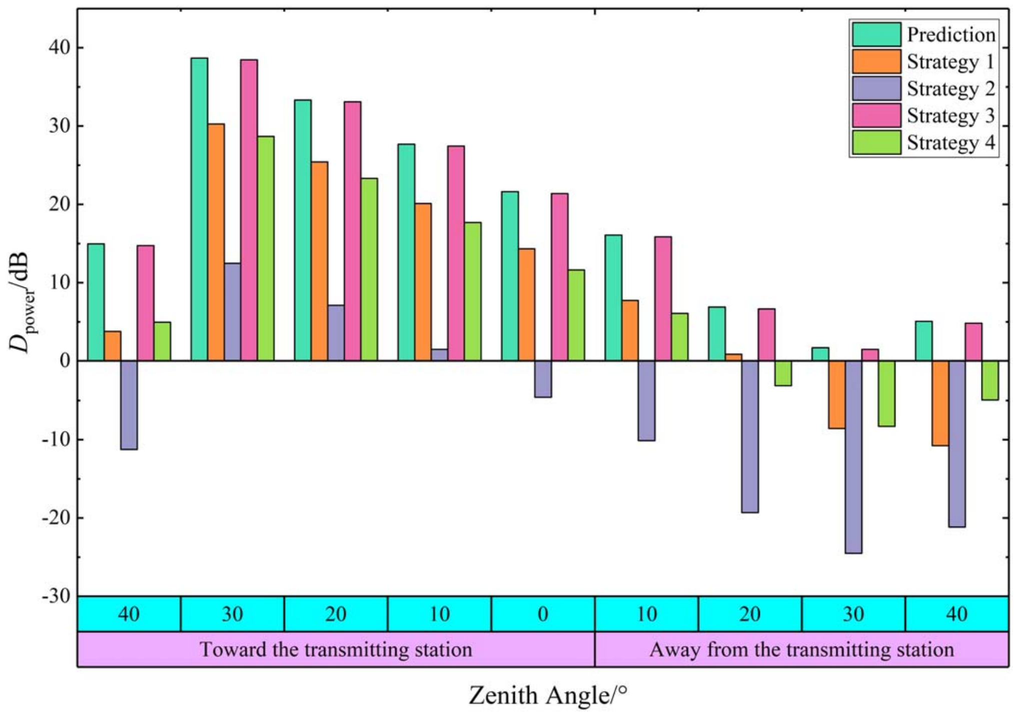


Figure 7. The power difference between FAST's received signal and the threshold under different strategies.

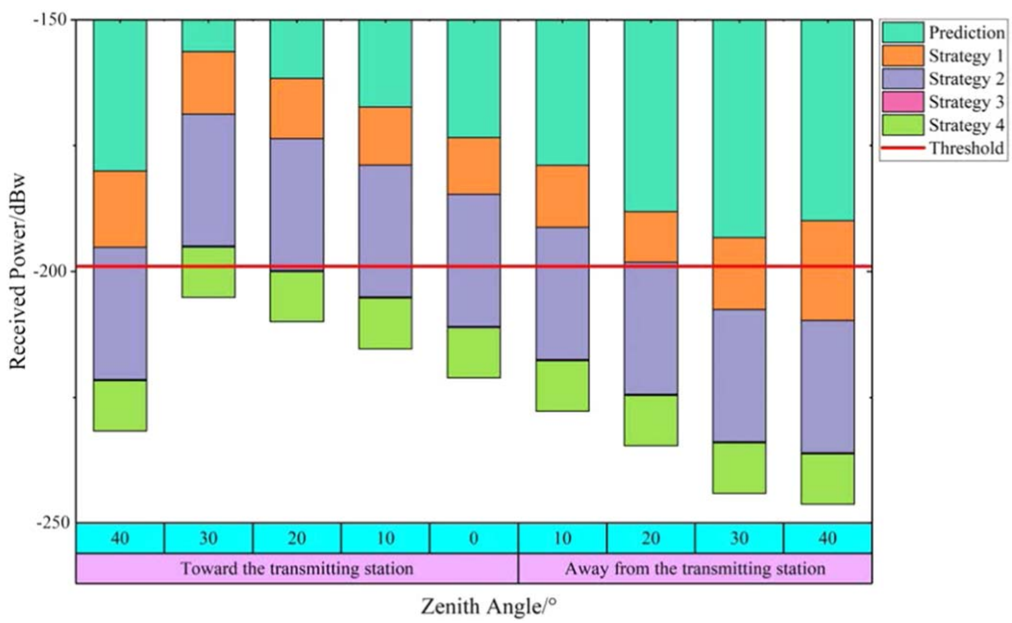


Figure 8. Received power of the FAST receivers under the integrated strategy.

effectively avoid the station's EMI on the regular observation of FAST.

In addition, the five communication stations are randomly selected for RFI analysis at different distances and directions from FAST in the FAST's RQZ. In Table 5, the percentage of the prediction value that meets the interference threshold shows an increasing trend with the increase of the propagation distance, but the increment is relatively slow. Compared with

Table 5
RFI Analysis of the Communication Stations Under Different Distances and Strategies

Station Number	Geographic Coordinates	Link Distance/km	Percentage of Meeting the Interference Threshold/%					
			Prediction	Strategy 1	Strategy 2	Strategy 3	Strategy 4	Integrated strategy
1	(106.°90E, 25.°69N)	6.44	0.00	0.00	33.33	0.00	0.00	66.67
2	(106.°96E, 25.°59N)	12.49	0.00	22.22	33.33	0.00	0.00	77.78
3	(106.°87E, 25.°48N)	19.53	11.11	44.44	55.56	11.11	33.33	100.00
4	(106.°63E, 25.°63N)	22.86	11.11	44.44	77.78	11.11	33.33	100.00
5	(106.°96E, 25.°89N)	28.69	22.22	44.44	77.78	22.22	33.33	100.00

Table 6
Comparative Analysis of Prediction and Measurement in Strategy 1

Receiver Location Parameters		Communication Link		Received Power/dBm		Error/dB
Geographic Coordinates	Frequency/MHz	Distance/km	Antenna Azimuth/°	Prediction	Measurement	
(106.°96E, 25.°59N)	874.2	0.90	7.22	−79.86	−86.30	6.44
	1895			−92.33	−95.60	3.27
	Difference /dB			12.47	9.30	3.17

the prediction value, the improvement of strategy 3 has no effect, while the other three strategies have better effects. Among them, the proportion of strategy 2 has increased the most, with a maximum of 66.67%. After the link distance is beyond 20 km from FAST, the integrated strategy can fully meet the interference threshold requirements of the FAST receiver.

Here, we take station 2 in Table 5 as the transmitter station for experimental communication and set up the signal receiving locations around the station to carry out the prediction and experiment analysis on the radio wave propagation characteristics of the public mobile base station signal. The primary measurement equipment includes a signal and spectrum analyzer and a receiver antenna, where the signal and spectrum analyzer adopts the FSV 3013 of R&S, and the receiver antenna is the VULB 9162 of SCHWARZBECK. The signal and spectrum analyzer uses the mean value detection method and takes the median value of the field strength to record during the data collection measurement.

The signal and spectrum analyzer collected effective signals of 869.7–877.6 MHz and 1886–1904 MHz during the measurement. Therefore, we choose the frequency points at 874.2 MHz and 1895 MHz in the two frequency bands for using frequency strategy analysis. The received powers of prediction and measurement are shown in Table 6. The prediction error of received power is 6.44 dB at 874.2 MHz and 3.27 dB at 1895 MHz, which shows that the prediction effect of the higher frequency band is better. After comparative analysis, the prediction can better meet the measurement, and the overall trend is consistent. The results meet the acceptable requirements of prediction accuracy of radio wave propagation. When the receiver signal frequency increases from 874.2 MHz to 1895 MHz, the received power of the prediction decreases by 12.47 dB, the measurement decreases by 9.30 dB, and the error is 3.17 dB, indicating that increasing the operating frequency of the communication station can effectively reduce the receiver signal power. Therefore, the measurement results show that strategy 1 will effectively reduce the received signal power of FAST.

3.3.2. Strategy Evaluation

Here, four strategies are used to analyze the station's EMI to FAST. So, the $N = 1, 2, 3, 4$ represent increasing the operating frequency of the communication station, adjusting the direction of the transmitter antennas, reducing the transmitter antennas' height, and decreasing the transmitting power of the communication station, respectively. If the operating frequency of the communication station increases, the communication equipment will be replaced because the frequency range will be upgraded from 870–878.6 MHz to 2110–2130 MHz. The other three strategies can be implemented with only manual operations, without replacing the communication equipment. So, we can estimate the objective attribute vector by the expert system (Qian & Xu 2008). We estimate the implementation complexity $\boldsymbol{C}_1^N = [0.10, 0.10, 0.10, 0.10]$ by investigating the installation and debugging time of communication equipment and the construction period of communication base stations. By the cost of communication equipment and labor cost and the construction cost of the communication base station,[4] the

[4] Please refer to Technical standard for mobile communication base station engineering (GB/T 51431–2020) issued by the MIIT(China), for details.

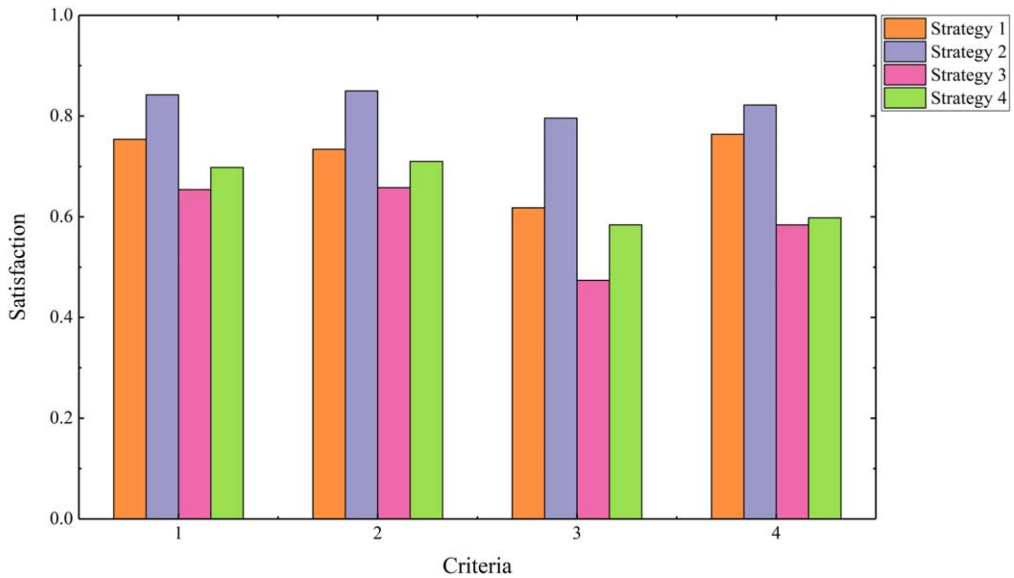


Figure 9. Satisfaction of the four strategies under each criterion.

estimated economic cost $C_2^N = [0.20, 0.06, 0.08, 0.04]$. According to Figure 7, we can calculate the strategy benefits $C_3^N = [0.78, 0.33, 1.00, 0.67]$. Increasing the operating frequency will hardly affect the user's communication experience. Changing the direction of the transmitter antennas will slightly affect the communication quality. Reducing the station antenna's height will affect the communication coverage of the base station. Decreasing the transmitting power of the station will affect the communication range and user signal quality. Therefore, we estimate the communication quality $C_4^N = [0.95, 0.80, 0.55, 0.40]$. Finally, the objective attribute vector $\boldsymbol{O}$ is

$$\boldsymbol{O} = \begin{bmatrix} 0.90, 0.90, 0.90, 0.90 \\ 0.80, 0.94, 0.92, 0.96 \\ 0.22, 0.67, 0.00, 0.33 \\ 0.95, 0.80, 0.55, 0.40 \end{bmatrix} \tag{21}$$

To analyze the satisfaction of each strategy under different criteria, we have given the maximum value of the subjective preference weights of four criteria in turn. Here, the maximum weight is 0.4 for the four criteria in turn, and the rest weights are 0.2, respectively. Then, the corresponding weight $\boldsymbol{W}$ is

$$\boldsymbol{W} = \begin{bmatrix} 0.40, 0.20, 0.20, 0.20 \\ 0.20, 0.40, 0.20, 0.20 \\ 0.20, 0.20, 0.40, 0.20 \\ 0.20, 0.20, 0.20, 0.40 \end{bmatrix} \tag{22}$$

According to Equation (20), we calculate the satisfaction of different strategies under each criterion, as shown in Figure 9. It is found that strategy 2 has the highest satisfaction under each criterion, and the maximum satisfaction is 0.85 at the economic cost. The satisfaction of strategies 1 and 4 is a close second. Strategy 3 has the lowest satisfaction under each criterion, and the minimum satisfaction is 0.47 at the strategic benefit. The maximum satisfaction difference between strategy 2 and 1 on the strategic benefit is 0.18, which indicates that strategy 2 has the better anti-interference ability. Based on the above four criteria, especially in terms of anti-interference ability, strategy 2 can be selected as the method of using frequency strategy, which can satisfy each criterion in a balance.

4. Conclusions

This paper focuses on the EMI from the public mobile communication stations around FAST to the radio astronomical telescope. We use the deterministic radio wave propagation prediction method combined with the "Interference protection requirements for Five-hundred-meter Aperture Spherical radio Telescope" for EMI analysis. The results show that the stations with 870–878.6 MHz around FAST have EMI to FAST under the current conditions. To protect the electromagnetic environment around FAST and fully guarantee the regular scientific output of FAST, we propose four using frequency strategies to avoid interference. Namely: increasing the operating frequency of the communication station, adjusting the direction of the transmitter antennas, reducing the height of the transmitter antennas, and decreasing the transmitting power of the communication station. The proportion of the stations exceeding the interference protection threshold of FAST is significantly reduced after adopting the above strategies. Through the measurement experiment, the prediction results can better meet the measurement results, the prediction error meets the requirements of radio wave propagation prediction accuracy, and using frequency strategies can effectively reduce the signal power of the receiving positions. In addition, we construct a quality evaluation system including four criteria of implementation complexity, economic cost, strategic benefit, and communication quality. Through the satisfaction analysis of the four strategies under the four criteria, the results show that adjusting the direction of the transmitter antennas can better meet the criterion. This research provides a meaningful reference for the operation of FAST and the coordination of frequency usage in the RQZ.

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