Maximizing QoS in railway radio networks: leaky cable and ray-tracing for optimal BER on bridges

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Article Info

Article history:

Received Sep 23, 2024
Revised Jul 25, 2025
Accepted Oct 14, 2025

Keywords:

FRMCS
Leaky coaxial cable
QoS
Railway radio coverage
Ray-tracing

ABSTRACT

The future railway mobile communication system (FRMCS) standard is crucial for advancing railway communication and implementing intelligent train control systems. This research focuses on development of an efficient modeling method to evaluate and optimize FRMCS performance on railway bridges, particularly under high-density modulation and radio noise interference. The key aspect of this study involves computer modeling of the deployment of a leaky coaxial cable (LCX) and comparison of its performance to traditional methods of radio coverage modeling. Using the single-slot radiation pattern, we evaluate the quality of radio communication by comparison of the bit error rate (BER) metrics for the Ray Tracing propagation model with and without the use of LCX. The results show that the use of LCX significantly reduces BER values, providing a much clearer and more reliable signal. This improvement is crucial for the safety and reliability of railway operations, ensuring effective communication for train control and reducing the risk of accidents in complex and high-demanding transport networks. This research contributes to the optimization of railway information infrastructure, with the aim of ensuring safe, reliable, and efficient operations.

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1. INTRODUCTION

One of the trends in design and development of the radio communications systems for railways is the exploitation of the future railway mobile communication system (FRMCS) standard, which comes into application after GSM-R and aggregates other LTE-R and 5G-R systems [1]. For the majority of the Eurasian Union railways, it means full migration from analog HF and UHF radio systems [2]. Moreover, the implementation of FRMCS in modern telecommunications provides an opportunity for wider deployment of intelligent transport systems (ITS) [3], [4]. The TDD-LTE as FRMCS-ready technology provides all digitalization procedures as the main element of FRMCS and 5G-R technology and may serve as the foundation for digital solutions, which provide safety, reliability, and accessibility for passengers and companies as users [5]. In general, the FRMCS standard is a modified 5G (R17) protocol and includes such specific features for railways as push-to-talk, vehicle-to-vehicle communication and safety systems [6]. In addition, the FRMCS is used for train movement over state borders in a number of countries, and, therefore, it is more useful than the GSM-R [7]. For example, the FRMCS is introduced to Trans-Siberian railway, which means its usage in the Europe-Asia transcontinental railway radio corridor from the Republic of Korea to the United Kingdom [8], [9].

5G-technology supports many features that can provide high values of quality of service (QoS) parameters for locations with difficult radio operating conditions: multiple-input multiple-output (MIMO), beamforming, adaptive antenna arrays, and others. One of the possible decisions is to deploy the leaky coaxial cable (LCX), which is often deployed in indoor communication systems, for mines and tunnels.

The main objective of this paper is to evaluate the potential of LCX deployment for enhancing radio communication performance over bridge segments in railway networks. Through computer simulations, this study analyzes signal propagation and bit error rate (BER) metrics to determine whether LCX-based systems can support consistent QoS and align with FRMCS modernization requirements. The findings aim to inform early-stage planning and optimization of communication infrastructure prior to physical deployment.

2. RELATED WORK

Wide introduction of trunking digital radio communication systems, which mainly support the movement safety and velocity on railways, is to guarantee communication between dispatchers, train drivers and workers, who maintain the railway infrastructure. Moreover, digital requests also support the work of remote operators and vehicle-to-vehicle applications operation [10]. Meanwhile, the intelligent train control systems should support unmanned train operation, therefore they require high quality of communication infrastructure considering latency, BER, and high mean opinion score (MOS) for audio and video applications [11]. Modern methods of modeling allow making measurement of the QoS parameters before deployment of a real FRMCS system [4].

The LCX is a popular choice when it is necessary to increase the signal power and minimize BER values in areas, which are complicated for the signal propagation, as it was presented in [12], [13]. Its authors conducted their research and modeled the BER rayleigh fading channel, as they simulated and got results for the best slot period (which should be $\lambda/2$) with the minimal BER value. Moreover, there are many researchers which conducted their own research on signal propagation in tunnels in different terrain [14], [15].

There is no simple equation to model signal attenuation in accordance with distance, terrain, buildings and surface materials, therefore the use of computer simulations can provide more benefits than real experiments in terms of time and resources required [16]. In addition, simulations can provide testing the QoS parameters and ability of traffic control applications to function in real environments. Currently, the ray tracing algorithms for radio coverage analysis can be used in order to evaluate QoS parameters for 5G and LTE. These methods also can be used to construct an efficient model for approximate coverage area inside artificial structures in 3D-space [17].

There are approximately 9,000 artificial infrastructural objects in the area of the Asian part of Trans-Siberian Railway, each of them may influence QoS parameters of railway radio link [18]. One of the types of artificial structures to consider is railway bridges, which are numerous along the railways. For Trans-Siberian Railway the main difficulties in modeling of the signal coverage are the terrain conditions and artificial objects of transport system's infrastructure [19].

3. THE PROPOSED METHOD

The bridge deployment of the LCX allows for operation without the use of amplifiers, provided that an extension antenna is used in accordance with the cable's electrical parameters. For railway applications, this is especially important, as it helps to reduce both maintenance complexity and power consumption. The schematic diagram of the proposed implementation of this solution is shown in Figure 1.

Regarding an antenna coverage, the simulation can be conducted using the standard coverage evaluation methods. For the area outside the bridge structure, the longley-rice empirical model was used to account for terrain topography, since ray tracing model in MATLAB is not suitable for long distances or areas without buildings. To address this constraint, a hybrid approach was proposed by dividing the computations for the long-range and close-in regions using an intermediate point. This allows the transformation of coordinates from a geographical to a Cartesian coordinate system be automatized in computer model. This approach also enables the usage of a three-dimensional model of the bridge structure. The signal power evaluation diagram is shown in Figure 2.

The results of ray tracing model application in the computer experiment give the estimates of such QoS parameters as BER, regarding the following:

- modeling transceiver and receiver of the radio system;
- adding noise and jitter;
- modulation and demodulation signals;

– estimating BER.

The proposed method enables accurate modeling of different propagation scenarios, leveraging a combination of empirical models and ray tracing techniques. This hybrid approach allows the realistic evaluation of signal strength and BER to be possible for complex environments, including large infrastructure elements like bridges.

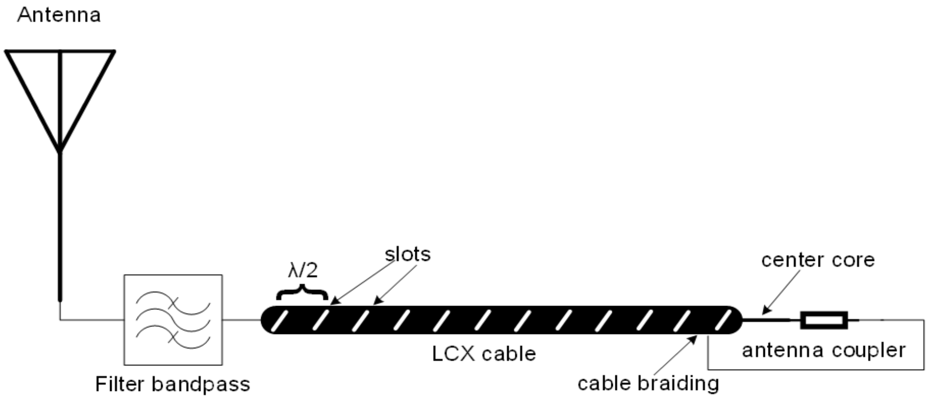


Figure 1. The passive LCX equipment

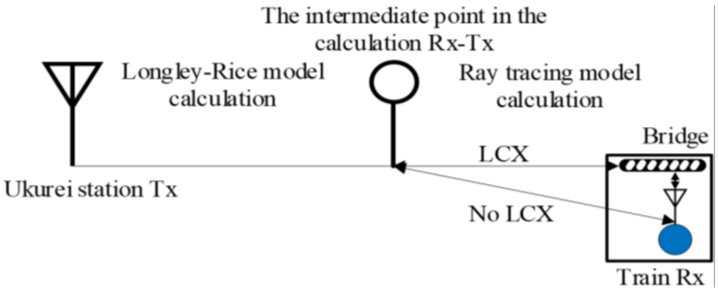


Figure 2. Signal power evaluation diagram

4. DESCRIPTION OF COMPUTER SIMULATION

The Pacific region of Russia is characterized by a high intensity of cargo and passenger train movement, which implies an increased requirements for the reliability and efficiency of railway communication systems. Within a simulated environment a bridge is considered as a typical truss design: with the length of 76 meters, height of 11.4 meters, and width of 7.1 meters. The majority of such bridges is made of metal and is capable of supporting vehicle movement either on the upper or lower level. The LTE-like standards, used within the Russian Railways, i.e., long term evaluation, usually administered in communication systems with time division multiplexing in the frequency band of 1,785-1,805 MHz [20]. This standard is provided by Huawei Company and delivered as a part of Huawei's smart railway solutions drive industry Digitalization [21].

This research is devoted to signal propagation modeling for both approaches: computer models of the antenna and LCX integrated deployment along the bridge and the usage of antennae only. In further computer simulations a Huawei AQU4518R24 directed antenna was considered as a radio system antenna, which is used in railways for the LTE-R and FRMCS applications and installed at the nearest railway station Ukurei at the 10 m mast [22]. The parameters of computer experiments are shown in Table 1.

Table 1. Parameters of computer experiments

Antenna	Radio system parameters
Station – 10 m above the surface	Tx power – 10 W
Train and the LCX system – 5 m above the track	Rx sensitivity – -113 dB
	Frequency – 1,800 MHz

As it was mentioned above, the length between the LCX slots is equal to the half of the wavelength. For the FRMCS, which is used along the Trans-Siberian Railway, it is equal to $8.5 \cdot 10^{-2}$ m. From one of the vendors, Antex, LLC, an antenna diagram for a single slot of the LCX was digitized by antenna diagram editor in [23], and it is shown in Figure 3.

The results of the literature survey demonstrate that a lot of research is devoted to signal propagation in tunnels using the LCX, as in GBSB model for MIMO channel using LCXs in tunnel from Shanghai University [24]. The authors considered the subway and railroad tunnels in [25]. In this paper, which presented MIMO, geometrically based single-bounce (GBSB) for LTE-R, the authors compared LCX-MIMO and dipole MIMO in Ricean coverage model. Using MATLAB's antennae array toolbox, it is possible to model the LCX as a Uniform Linear Array (ULA), as a type of antennae array configuration, where identical antenna elements are evenly spaced along a straight line [26]. These slots as a part of the ULA are shown in Figure 4. Based on the data presented in Figure 4, an analysis was performed and the following radiation pattern was obtained. The radiation pattern of the LCX with ten combined slots is shown in Figure 5.

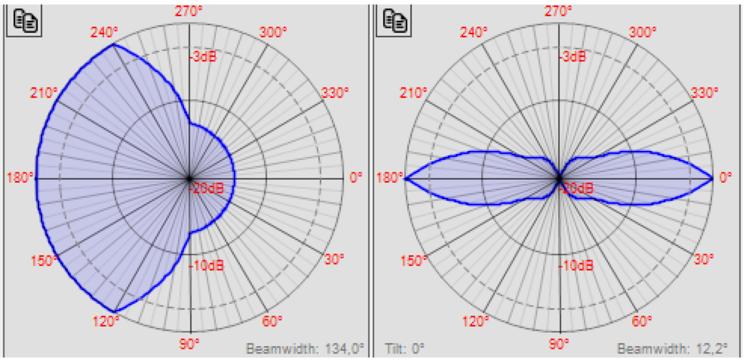


Figure 3. The antenna diagram for a single slot of the LCX [24]

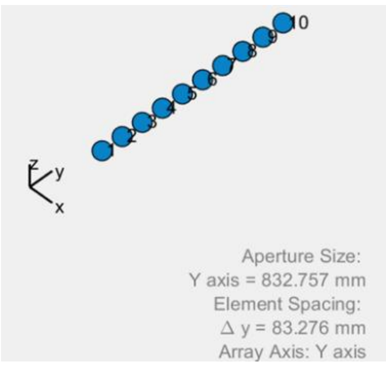


Figure 4. The parameters of computer model of the LCX as a ULA

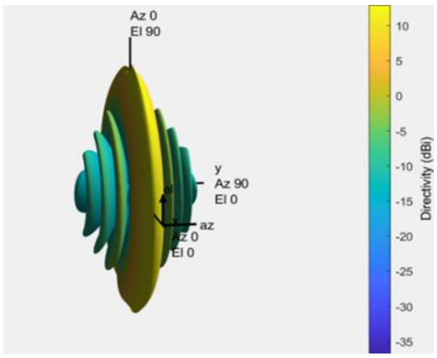


Figure 5. The radiation pattern of ten LCX slots combined

In order to evaluate the values of parameters of the LCX system, also the longley-rice modeling was used. The longley-rice model is recommended to be applied for signal strength prediction in case of rough and uneven terrain. It allows estimating losses of power along signal propagation, regarding many factors such as the distance between a transmitter and receiver, frequency, height of antennae, buildings and rough terrain. The model is based on statistical methods for probability estimation for signal power, registered at the receiver [27]. The main equation for the signal propagation is as follows:

$$L = L_{fs} + L_d + L_{tr} + L_{ol}, \tag{1}$$

where L_{fs} – the free space losses, L_d - the diffraction losses, L_{tr} – the tropospheric losses, L_{ol} – the losses due to other causes. This model is based on empirical data and it is widely used for estimation of the cellular networks' coverage [27].

Further the following may be considered for the simulation. The ray tracing method can be applied to model the non-light of sight propagation and reflections from the bridge structural elements (almost all of the railway bridges are made of metal) [28]. The ray tracing technique, implemented in MATLAB, works using the method of incident and reflected rays (SBR), which allows to evaluate the approximate number of propagation trajectories with a geometric range [29]. These results allow conducting further research, while using the LCX systems in order to increase the values of QoS parameters in artificial structures such as bridges, overpasses and crossing of railroad tracks and pipelines.

The obtained simulation results may be used to evaluate the model of a channel especially for LTE-R/FRMCS implementation. The channel model should maximize compliance with the FRMCS standard. Therefore, a model was developed using low density parity check (LDPC) and digital keying as QAM. The LDPC is a class of block-code method for mistakes detection and correction using parity check. The LDPC consists of:

- A code word, $c = [c_1, c_2, \ldots, c_n]$, where n is the code word length;
- An information word, $u = [u_1, u_2, \ldots, u_k]$, where k is the information word length, $k<n$;
- A control matrix H with the size of $m \times n$, where $m=n-k$, and it satisfies the condition

$$H \cdot c^T = 0, \tag{2}$$

- Where c^T is the transposed vector of the code word. The code word c is obtained from a generating matrix G that is related with matrix H [30].
  The coding process uses the expression:

$$c = u \cdot G. \tag{3}$$

The decoding of LDPC-codes is made by solution of a linear equations system and by evaluating the matrix H. In addition to keying in the FRMCS standard using orthogonal system of channel dividing (OFDM) with 256 subcarrier. OFDM supports the efficient usage of frequency resource [31].

5. RESULTS AND DISCUSSION

The computer modeling results for both antenna and LCX coverage on the bridge are presented below, along with a discussion of their impact on signal quality and system performance. The longley-rice coverage evaluation model works to the nearest point of the bridge, as it is shown in Figure 6.

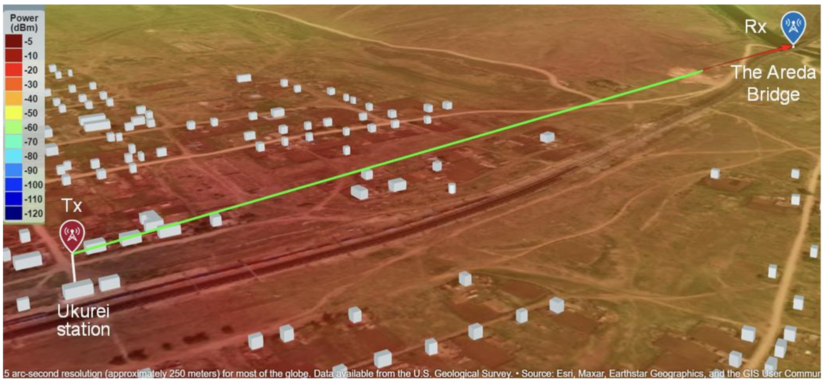
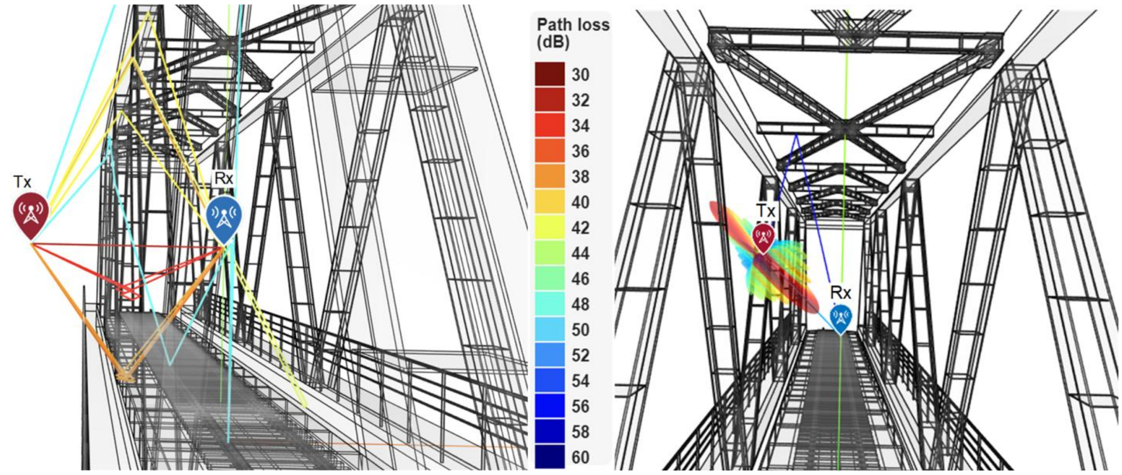


Figure 6. The signal coverage modeling results using the longley-rice empirical model

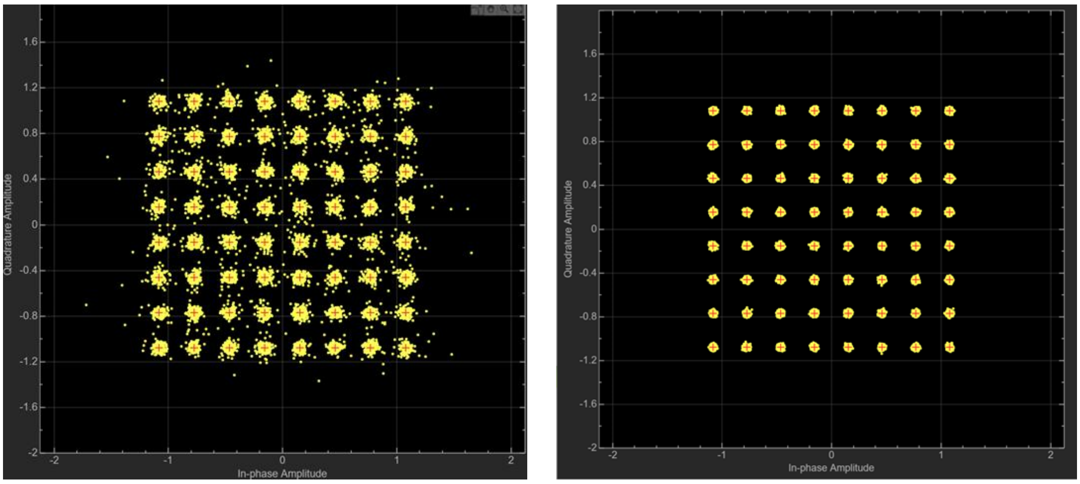
Then the transmitter parameters were input to the ray tracing model. At this step the location coordinates were transformed to the Cartesian coordinate system and the LCX antenna diagram was used, which was obtained previously. The results of computer simulation of the ray tracing model for a bridge presented at Figure 7. Figure 7(a) depicts the simulation results of signal propagation along the bridge without LCX. Here the signal is transmitted along the bridge elements and the rays, reflected from the metal parts, can be visualized. The same model can be used in order to simulate the signal propagation for the bridge with the LCX radiation pattern (Figure 1) deployed. The simulation results for the latter case show ability to transmit the signal inside a bridge better. The ray reflections for this case are shown in Figure 7(b).



(a) (b)

Figure 7. The results of computer simulation of ray tracing model (a) within the bridge without LCX and (b) with MATLAB's LCX radiation pattern

After computing thed QAM-64 signal parameters, the received signal quadrature diagrams were obtained, which are shown in Figure 8. When analyzing the results of signal propagation without LCX, which are shown in Figure 8(a), they have wider range and, therefore, increase BER values. Consecutively, in this case the probability of successful transmission is lower. The simulation results for the case with the LCX usage are shown in Figure 8(b), where the radius of the signal spread in QI-diagram is smaller and the probability of correct data reception is higher.



(a) (b)

Figure 8. Signal-code constructions of keying QAM-64: (a) without LCX and (b) with LCX

There are four LDPC codewords per frame and 50 OFDM symbols per frame for BER value estimation in the signal propagation model for the railway bridge. The comparison of the BER simulation results is shown in Figure 9. It illustrates the fact, that the usage of the LCX with passive antenna increases QoS parameters such as BER for QAM modulation of the radio signal in challenging and complicated conditions.

In accordance with the simulation results, the proposed method of using LCX cables shows its efficiency because of BER values' decrease. Moreover, the proposed methods for computer simulation proposed in this paper may be applied for signal propagation modeling along the similar objects like bridges and tunnels, where the FRMCS standard is used regardless of restrictions, such as avaliable frequencies and the previously deployed radio subsystems.

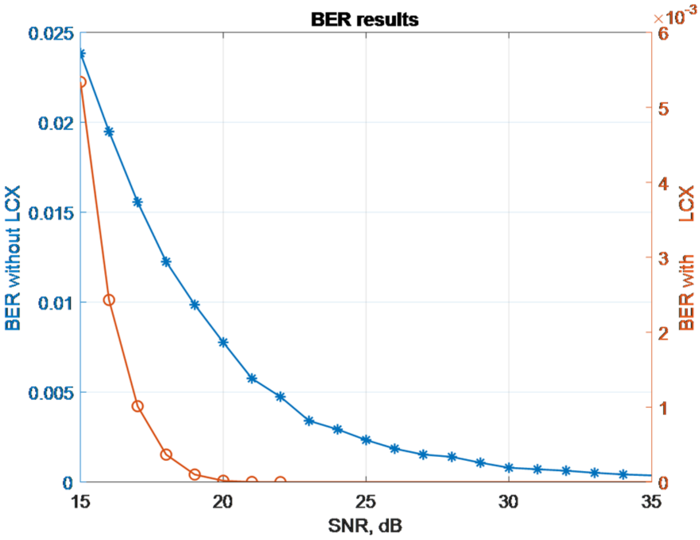


Figure 9. The simulation results BER for QAM-64

6. CONCLUSIONS

The usage of the LCX technology in radio systems for artificial structures such as bridges has proven to be an efficient and cost-effective solution. Moreover, the results of this research can serve as a preliminary analysis tool for evaluating QoS parameters and signal coverage before deployment of the railway radio systems along areas with numerous artificial structures.

Future work will focus on the empirical validation of LCX-based antenna systems through laboratory and field experiments designed to replicate the simulation scenarios presented in this study. These simulations also provide a practical framework for proactive optimization of QoS support measures in radio networks along bridges prior to physical deployment, enabling better planning and real-environment performance prediction. Ultimately, the proposed approach demonstrates that the LCX technology can make the FRMCS deployment more adaptable, scalable, and effective across diverse terrains and infrastructure types, outperforming existing communication solutions.

FUNDING INFORMATION

This research is supported by the “Priority 2030” – the National Program of the Russian Federation.

AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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Ponomarchuk Yulia	✓	✓			✓	✓	✓			✓	✓	✓		✓

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors state no conflict of interest.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author, [MS], upon reasonable request.

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