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A novel energy efficient IRS-relay network for ITS with Nakagami-*m* fading channels

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Abstract

In this paper, we have investigated the performance of energy efficiency (EE) for Intelligent Transportation Systems (ITS), which recently emerged and advanced to preserve speed as well as safe transportation expansion via a cooperative IRS-relay network. To improve the EE, the relay model has been integrated with an IRS block consisting of a number of passive reflective elements. We analyze the ITS in terms of EE, and achievable rate, with different signal-to-noise ratio (SNR) values under Nakagami-m fading channel conditions that help the system to implement in a practical scenario. From the numerical results it is noticed that the EE for the only relay, IRS, and proposed cooperative relay-IRS-aided network at SNR value of 100 dBm is 30, 17, and 48 bits/joule respectively. In addition, we compare the impact of multi-IRS with the proposed cooperative IRS-relay and conventional relay-supported ITS. Simulation results show that both the proposed cooperative IRS-relay-aided ITS network and multi-IRS-aided network outperform the relay-assisted ITS with the increase in SNR.

Keywords: Intelligent Transportation Systems; Nakagami-m fading; Energy efficiency; IRS; SNR

1. Introduction

Recently transportation has shown a larger expansion with the massive vehicles as well as the high pace. The speed control and safety management of transportation have raised a challenging task for academia and industry. To address this problem Intelligent Transportation Systems (ITS) have been adopted, where the transportation system is connected with the communication network to control and operate the ITS in such a manner to avoid accidents, and traffic control. And also provide seamless connectivity between the vehicles to share the information that can help to reach the destination in prior time intervals. The work in [1] summarized the previous concepts of many possible ways to operate ITS smoothly with artificial, computation-based approaches in practical implementations. And also proposed the framework consists of multiple artificial transportation systems (ATS), utilized parallelly to manage the traffic as well as control the ITS. A novel architecture for sharing information among vehicles has been developed, allowing congestion and safety to be executed jointly. It will be achieved by the presented architecture, which carries (i) sensor networks established by vehicles in a specific area that share congested road details, (ii) logical features that have been installed in vehicles for predicting practical knowledge, and the overall transportation systems information [2]. Authors in [3] demonstrated the effectiveness of ITS in-emergency situations by combining vehicle-to-infrastructure (V2I) and vehicle-to-vehicle (V2V) technologies. In case of accidents, data has been collected directly from the vehicles, immediate intimation of accident information to the control unit, and based on the intelligence of vehicles primary information of losses has been investigated.

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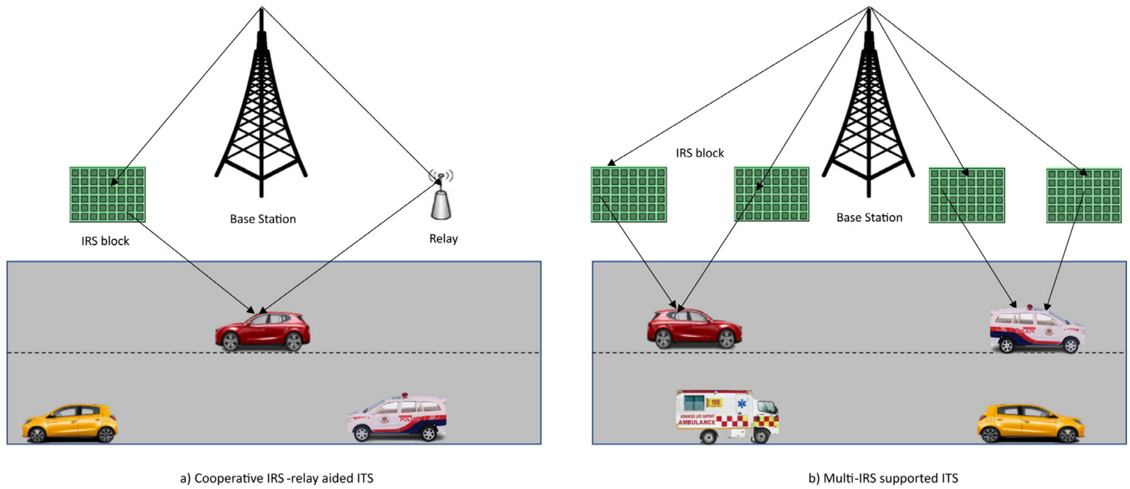

Fig. 1. IRS-relay Aided ITS Network.

In addition, several research studies were conducted on the cooperative ITS in Europe to provide a clear overview of the standardized system guidelines, structures, services, safety, and supervision including other technologies required in ITS [4,5]. As the ITS framework has been connected to several sources, data collection and processing will increase the complexity and it may turn into a data-driven system. Nevertheless, the data may be utilized to create new facilities and services in ITS, in addition to being transformed into usable information. Whereas the recent works in [6] provide a comprehensive survey that illustrates the current issues and research direction to provide the large amount of data required by the ITS [7]. On the other hand, higher data rates for ITS with speed and safe transportation lead to an increase in power consumption. Unlike ITS connected with different technologies, it consists of multiple sources that consume various power levels. To alleviate these constraints many recent advancements have been developed in wireless communication such as 5G and beyond 5G techniques which have been identified as key enabling solutions to design energy-efficient (EE), ITS [8]. The cooperative multiple-input-multiple-output spatial modulation (CMIMO-SM) is used to build the ITS model to reduce overall energy consumption [9,10].

Moreover, to overcome the challenges and address the EE problem, Intelligent Reflecting Surfaces (IRS) have been realized as a promising technology. IRS blocks consist of several passive elements to reflect the incident signal towards the destination [11], which can be deployed in the ITS to improve performance with reduced power consumption. The use of IRS in vehicular mm-wave wireless networks has been envisioned to optimize resource allocation for autonomous vehicles. More recently modern public transportation with IRS features in smart transportation has been investigated to enhance the signal strengths with lower transmission power [12,13]. In fact, the propagation of signals must travel longer distances in ITS, with line-of-sight (LoS) and Non-LoS (NLoS) environments. The authors in [14,15] analyzed IRS-based Internet of Vehicles (IoV) with cybertwin in Nakagami-m fading channel, whereby adjusting m value, channel condition can change from Los to NLoS that is more suitable to evaluate the ITS in a practical scenario [16]. The research described in [17] examines the realm of energy efficiency in outdoor-to-indoor communication systems utilizing dual IRS. The work focuses on ways to improve energy usage optimization and communication efficacy within such systems, where the base station communicates with the user located in an indoor scenario by using a dual IRS model. Prior to this work, we analyzed the EE of an IRS-aided IoT network, and results showed that the proposed hybrid and multiple IRS outperformed conventional relay networks [18]. From the above research works, we noticed that IRS and relays are more useful in ITS to improve the coverage area, resource allocation, and reduce the hardware cost. However, more research is needed on IRS-based or relay-supported ITS to improve the performance in terms of EE. The main aim of the proposed cooperative IRS-relay-aided ITS is to reduce power consumption over long distances and operate the system faster as well as safer mode. In our analysis, ITS network architecture consists of both LoS and NLoS environments with IRS elements, so the Nakagami-m fading will provide a better performance in comparison with conventional methods.

In this paper, we analyze the EE of cooperative IRS-relay assisted ITS and compare the EE in different environments by adopting Nakagami-m fading and the m value can be varied to select the certain fading condition. Furthermore, we examined and realized that multi-IRS has outperformed the relay-aided ITS with reduced power consumption and deployment cost. This work allows us to think about the practical scenario implementation and significance of the cooperative IRS-relay and multi-IRS-aided networks in ITS development. The contributions from the paper are summarized as follows.

- To the best of our knowledge, we are the first to study the deployment of relay-aided, IRS-aided, and cooperative IRS-relay-assisted ITS networks in terms of EE.
- We compare the achievable rate and EE as a function of varying signal-to-noise ratio (SNR) values and with the number of IRS elements in the Nakagami-m fading channel condition. Furthermore, we realized that multiple IRS blocks can be deployed randomly with relays to

increase the EE of the ITS network instead of deploying multiple relays over longer distances.

The rest of the paper is organized as follows. Section 2 presents the system model, which covers the relay, IRS, and the hybrid relay-IRS-aided ITS network. Section 3 focuses on introducing the energy efficiency formulation and performance analysis. Section 4 provides the numerical results, and Section 5, concludes the article with our final remarks.

2. System model

In the ITS model as shown in Fig. 1, the transportation network is implemented in two different scenarios. Where the ITS has been assisted by the proposed cooperative IRS-relay aided network and later with multi-IRS blocks. In phase-I, ITS has been supported by the cooperative IRS-relay, where both IRS and relay are propagating the signal received from the BS to the intelligent vehicle to provide seamless connectivity with high data rates. In phase-II, multi-IRS blocks are deployed in the ITS instead of relays to enhance the coverage area and EE of the network. For simplicity, we indicate the base station (BS), relay, IRS, and ITS as B, R, I, and v, respectively. The channels between the B to R, R to the v, B to I and I to the v are represented as $h_{BR} \in \mathbb{C}$, $h_{Rv} \in \mathbb{C}$, $h_{BI} \in \mathbb{C}^n$, and $h_{Iv} \in \mathbb{C}^n$, respectively.

All these channels are modeled to follow the Nakagami-m fading. Most of the distributions follow uniform scattering in Rayleigh fading and Rician fading. These two different fading channels are used separately in LoS and NLoS scenarios. However, the Nakagami-m fading channel can be used as Rayleigh as well as Rician by adjusting the parameter m. The parameter m denotes the shape and Ω denotes the spread of the signal. The major advantage of Nakagami-m fading is more suitable for practical measurements. And also depends on the m value scenarios that can change from LoS to NLoS propagation. The Nakagami-m fading probability density function is given as

$$P_R(r) = \frac{2^m r^{(2m-1)}}{\Gamma(m)\Omega^m} e^{-(\frac{m}{\Omega})r^2}, \tag{1}$$

where the parameters

$$m = \frac{(r^2)^2}{(r^2-(r^2))^2}, \qquad \Omega = (r^2), \tag{2}$$

where $\Gamma(m)$ represents the gamma function, m, and Ω are the shape and spread parameters respectively.

2.1. Cooperative IRS-relay aided ITS network

In the first time slot, the relay and IRS receive the transmitted signal from the B. The signal arrived at the relay is given as

$$y_R = \sqrt{P_B}(h_{BR} + (h_{BI}^T \Theta h_{IR})x) + n_R, \tag{3}$$

where P_B is the transmit power at the BS, x denotes the message signal, n_R is the Additive White Gaussian Noise (AWGN) with zero mean and variance σ^2. And $\Theta = diag(n_1 e^{j\theta_1}, n_2 e^{j\theta_2}, ..n_N e^{j\theta_N})$ denotes phase-shift matrix, where in $n_i \in [0,1]$ and $\theta_i \in [0, 2\pi]$ for $i = [1,2,3,\ldots,N]$. The SNR received at the relay is derived as

$$\gamma_R = \frac{P_B|(h_{BR} + (h_{BI}^T \Theta h_{IR}))|^2}{\sigma_R^2}. \tag{4}$$

In the second time slot, relay and IRS elements propagate the message signal x to the user v. The signal received at the v is expressed as

$$y_v = \sqrt{P_R}\{h_{Rv} + (h_{RI}^T \Theta h_{Iv})x\} + n_v, \tag{5}$$

where P_R denotes the transmission power at the relay and n_v is the AWGN at the ITS user v. So the SNR at the user v is obtained as

$$\gamma_v = \frac{P_R|h_{Rv} + (h_{RI}^T \Theta h_{Iv})|^2}{\sigma_v^2}. \tag{6}$$

2.2. Multi-IRS aided ITS network

We have analyzed the EE of a multi-IRS-aided ITS network, where multiple IRS blocks are placed to provide the required coverage to the ITS with less power consumption compared to the relay-aided network.

As in the previous transmission, the signal received from the B at the I is given as

$$y_{I_{(n)}} = \sqrt{P_B}(\sum_{n=1}^{M} h_{BI_{(n)}})x + n_{I_{(n)}}, \tag{7}$$

where $I_{(n)}$, $n_{I_{(n)}}$ denotes the number of IRS blocks with n = 1,2,3,..M and noise at multi-IRS blocks respectively.

Similarly, the signal received by the ITS user v is derived as

$$y_{vI(n)} = N\sqrt{P_e}(\sum_{n=1}^{M} h_{vI(n)})x + n_{v_{I(n)}}, \tag{8}$$

where $n_{v_{I(n)}}$ represents the Additive White Gaussian (AWG) noise at the user v. The SNR at the multi-IRS blocks and the ITS user v are defined respectively as

$$\gamma_{I(n)} = \frac{P_R|\sum_{n=1}^{M} h_{BI_{(n)}}|^2}{\sigma_{I(n)}^2}, \tag{9}$$

$$\gamma_v = \frac{NP_e|\sum_{n=1}^{M} h_{vI(n)}|^2}{\sigma_v^2 I(n)}. \tag{10}$$

3. Energy efficiency performance with the proposed model

Energy efficiency is defined as the ratio of the sum rate to the total power consumed by the communication network and is formulated as

$$EE = \frac{R_{sum}}{P_{Total}} \text{ bits/J}, \tag{11}$$

where R_{sum} is the sum rate and P_{Total} denotes the total power consumption.

In this proposed cooperative IRS-relay assisted ITS network adopted both the IRS and relay to improve the system performance. Moreover, all the reflecting elements should be well designed to get a higher rate and better performance in terms of EE. Hence we need to calculate the sum rate of both the IRS and relay-aided network as well total power consumed by the cooperative network.

The achievable rate of cooperative IRS-relay-aided ITS is obtained as

$$R_{sum} = \frac{1}{2} log_2\{1 + (\gamma_R, \gamma_v)\}. \tag{12}$$

The energy consumption of the IRS block is determined by the nature and resolution of each reflecting element that properly adjusts the phase shift of the incident signal. Hence the power dissipation of IRS blocks with N-reflecting elements has been denoted as NP_e. Therefore the total power consumption at the IRS block is given as,

$$P_{IRS} = P_B + P_v + NP_e, \tag{13}$$

and the total power consumption at the relay is given as

$$P_{DF} = \frac{P_R}{\nu} + P_v + \frac{1}{2}P_B + P_r, \tag{14}$$

where P_r, P_v, and ν are the power dissipation at the relay, ITS user v, and efficiency of the power amplifier, respectively.

Hence from (13) and (14), the total power utilized by the ITS with the cooperative IRS-relay network is given as

$$P_{Total} = P_{IRS} + P_{DF}. \tag{15}$$

4. Numerical results

Numerical results are presented in this section to analyze the EE performance for the ITS in different scenarios. In both the cases of IRS-aided or relay-aided only networks, we consider that there is no direct connection between the BS and the vehicle. The path loss exponent is fixed to 2.2. The fading channel Nakagami-m parameters are adjusted from 0.5 to 3. For the multi-IRS scenario, the reflection coefficients are selected close to 0.8 for all IRS elements. The velocity has been assumed as 50 km/h, and the direction of the ITS is moving towards the IRS. To find the maximum EE, our simulation setup includes the power dissipation of each IRS element P_e = 3 mW, and $BS = ITS = R$ = 50 mW to implement in the real-time scenario.

Fig. 2 demonstrates the achievable rate versus the SNR values. It can be seen that the rate of cooperative IRS-relay-aided ITS achieved better performance compared to the remaining two scenarios as only-IRS and only-relay-aided network. And it is clearly observed that when SNR is increasing, the rate also increases. The achievable rate for IRS and cooperative IRS-relay-aided ITS at SNR 50 dBm are 22 b/s/Hz, and 27 b/s/Hz however with a relay-aided network it is 5 b/s/Hz.

Results in Fig. 3 compare the EE of the proposed cooperative IRS-relay with the IRS, relay-aided ITS network with fixed IRS elements by varying the SNR. As we can see, the noticeable differences observed in the figure, the cooperative IRS-relay aided ITS reaches a maximum EE of 55 bits/J at the SNR value of 110 dBm. Whereas only IRS and relay-aided ITS network gained the highest EE around 22 bits/J and 30 bits/J. However further increments in SNR values have affected the EE and it started decreasing after the 110 dBm.

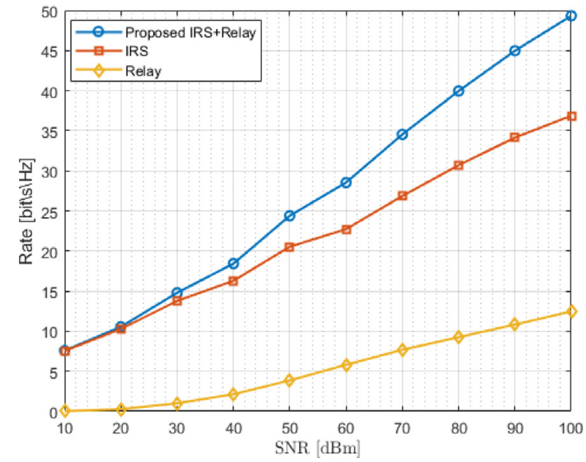

Fig. 2. Rate versus SNR.

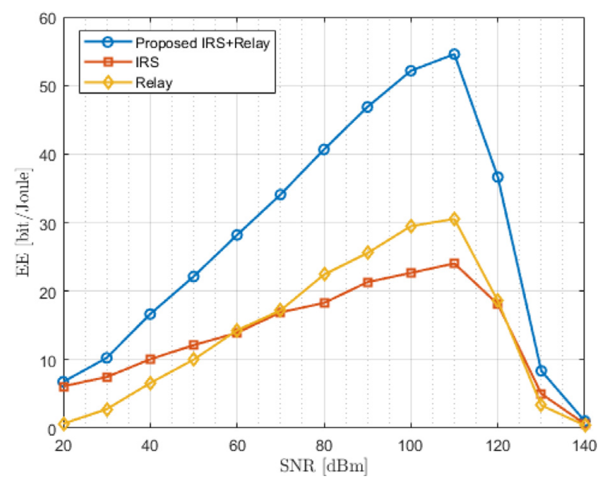

Fig. 3. EE vs. SNR with fixed N.

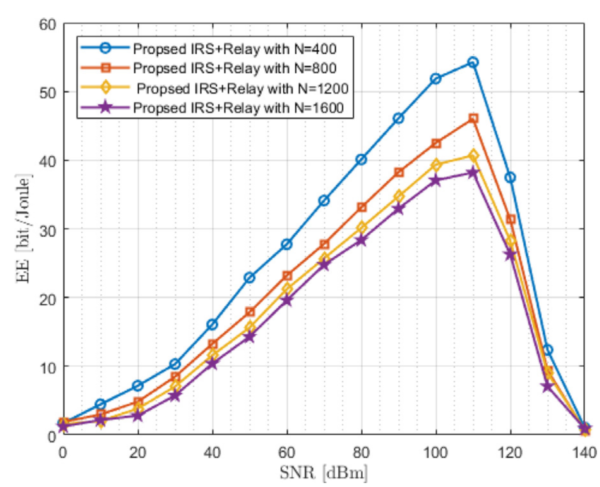

Fig. 4. EE vs. SNR by varying the N.

Fig. 4 illustrates the impact of EE versus SNR with the range of IRS elements deployed in ITS. In this simulation setup power dissipation of each IRS element has been considered to obtain the EE, due to this reason the EE is decreased

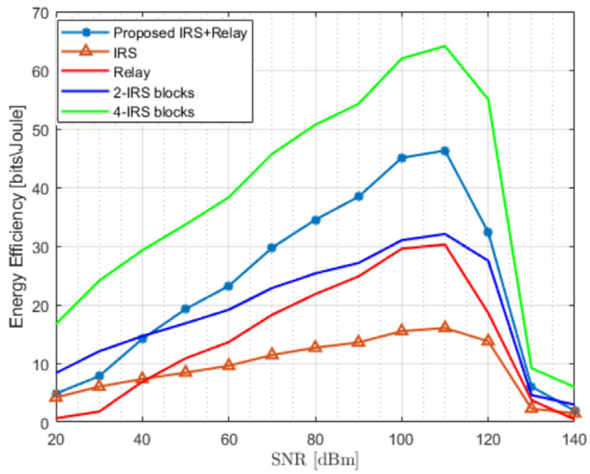

Fig. 5. EE vs. SNR with multiple IRS blocks.

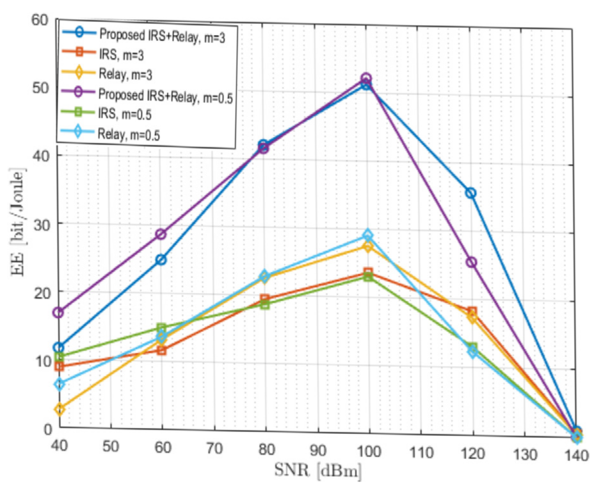

Fig. 6. EE vs. SNR with different *m* values.

with an increase in the number of IRS elements. It is clearly noticed that maximum EE reaches 55 bits/J with $N = 400$ and later gradually it decreases. For other cases with $N =$ [800, 1200, 1600] the maximum EE is attained to 45 bits/J, 42 bits/J, and 38 bits/J respectively. Due to a large number of IRS elements the power dissipation factor, P_e also increases which declines the EE of the network.

Fig. 5 investigated the EE versus SNR with cooperative IRS-relay and multi-IRS-aided ITS. For the multi-IRS case, all the IRS blocks are deployed with a fixed number of elements as $N = 400$. Evidently, the multi-IRS-aided ITS has shown better performance in terms of EE for all the SNR values. It is clearly observed that the 4-IRS blocks-aided network outperforms the conventional IRS, relay, and proposed network with the EE of 65 bits/J, whereas the cooperative IRS-relay aided ITS network gained the EE of 48 bits/J. From this analysis, we realized that the multi-IRS can help the ITS in certain scenarios with reduced power consumption and hardware cost.

Fig. 6 describes the performance of EE versus SNR by varying the Nakagami-*m* parameter with $m = 0.5$ and $m = 3$. The performance analysis shows the impact of m for all

Table 1
The EE of Proposed IRS-relay aided ITS network.

	$m = 0.5$			$m = 3$		
SNR (dBm)	60	100	120	60	100	120
EE (bits/J) proposed cooperative	28	52	25	25	50	36
EE (bits/J) only relay	12	29	12	12	28	18
EE (bits/J) only IRS	14	24	14	11	25	19

three scenarios IRS, relay, and proposed cooperative IRS-relay-aided ITS network. From these results, we realized that EE increased for both the m values and decreased gradually for high SNR. More specifically the EE of the IRS, relay, and IRS-relay network are increased till the SNR value reaches 100 dBm, and later it is decreased. Moreover, it is good to know that the EE for $m = 3$ is better than $m = 0.5$ even after the SNR value of 100 dBm. From this analysis, it is justified that the Nakagami-*m* fading condition can be used in different scenarios with the m value for the lower and higher SNR values to improve the EE depending upon the channel conditions. And we have presented the EE of the proposed network with different *m* values in Table 1.

5. Conclusion

This paper analyzed the achievable rate and EE with IRS, relay, and cooperative IRS-relay-aided ITS. Initially, we calculated the rate versus SNR, later we analyzed the performance of ITS in terms of EE in various environments such as only IRS or relay and cooperative IRS-relay aided ITS with fixed as well as varying IRS elements. In this Nakagami-*m* fading channel conditions are adopted, where by adjusting the *m* factor we can change one scenario to another that is more suited to real-time implementations. Finally, we compared the EE of the proposed cooperative IRS-relay-aided ITS with the multi-IRS network. Simulation results show that EE is enhanced with the proposed cooperative IRS-relay-aided ITS as well as with the multi-IRS model.

CRediT authorship contribution statement

Shaik Rajak: Performed simulations, Written the initial draft, Designed and formulated the ideas and were responsible for the completion of the manuscript. **Inbarasan Muniraj:** Critically examined/monitored each step of the work. **Poongundran Selvaprabhu:** Critically examined/monitored each step of the work. **Vinoth Babu Kumaravelu:** Critically examined/monitored each step of the work. **Md. Abdul Latif Sarker:** Worked on the accuracy and integrity of work. **Sunil Chinnadurai:** Designed and formulated the ideas and were responsible for the completion of the manuscript. **Dong Seog Han:** Reviewed and helped in the implementation part.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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