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Communication mode selection and game theoretic bandwidth sharing model for D2D relay communication

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ABSTRACT

Device-to-device (D2D) communication plays a crucial role in achieving successful implementation of 5G+ and 6G wireless networks. The selection of the communication mode is a vital parameter that enables the activation of a communication link through D2D relays. Consequently, this selection can be considered the fundamental functionality responsible for activating the communication mode of transmission within any device-to-device communication network. This research paper proposes a communication mode selection scheme based on a hexagonal cellular structure. The scheme holds significant potential for application in various wireless transmission schemes. Additionally, the paper investigates the issue of bandwidth sharing in device-to-device networks. In future wireless systems, device-centric approaches will be widely adopted, necessitating a key focus on spectrum sharing. The proposed scheme not only facilitates wireless users in sharing their available spectrum with others but also allows them to receive financial rewards in return. This cooperative sharing approach fosters collaboration among wireless users. Furthermore, the paper compares the performance of two utility functions for the purpose of bandwidth sharing. The Cobb-Douglas model is utilized to present the proposed bandwidth-sharing scheme between two users. Simulation experiments are conducted to determine the percentage of bandwidth shared by the two users under various scenarios, including a case where both users share 50% of the bandwidth. The results indicate that the optimal utility function is achieved when one user shares 10% of the bandwidth while the other user shares 90%.

1. Introduction

The 5G communication standard offers significantly increased bandwidth capacity to end users compared to previous wireless standards. The forthcoming wireless standard, 6G, is projected to deliver a transmission capacity that is 1000 times greater than that of 5G, accompanied by an end-to-end latency of less than 1 millisecond (Letaief et al., 2019). The 5G wireless standard encounters several significant challenges, including high connection density, high data rates, large traffic volumes, high mobility, and low latency (Feng et al., 2013). These challenges can be addressed by the evolution of wireless standards, which can be achieved through the adoption of various technologies. These technologies include massive multiple-input multiple-output (MIMO) systems, artificial intelligence (AI), visible light communication (VLC), millimeter wave (mmWave) communications, cognitive radios (Khadim et al., 2017; Khan et al., 2016; Shaikh and Altaf, 2013; Shaikh and Tamil, 2015) and device-to-device (D2D) communications (Letaief et al., 2019; Noura and Nordin, 2016). D2D communications provide exciting opportunities to communicate user equipment directly to base stations (Fig. 1) as well as by exploiting the D2D relaying mode of transmission (Fig. 2). The major applications of interest for D2D communication include public safety, disaster management, social networking, data flooding and local data transfer (Corson et al., 2010; Lin et al., 2014). Additionally, there are many features that can be borrowed from cognitive radio (Alam et al., 2017; Khadim et al., 2017; Khan et al., 2019) based wireless systems i.e. spectrum sensing, bandwidth sharing, energy

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optimization, and opportunistic communication to improve the performance of D2D communications. D2D radios may also play a pivotal role in the improvement of operation for the Internet of Things (Khan and Altayar, 2021; Amaonwu et al., 2022; Bello and Zeadally, 2014; Sankar and Srinivasan, 2018). Additionally, Artificial Intelligence can also play a leading role in resource optimization for D2D communication networks (Altaher, 2017; Srinivasulu and Pushpa, 2020; Srinivasulu et al., 2022).

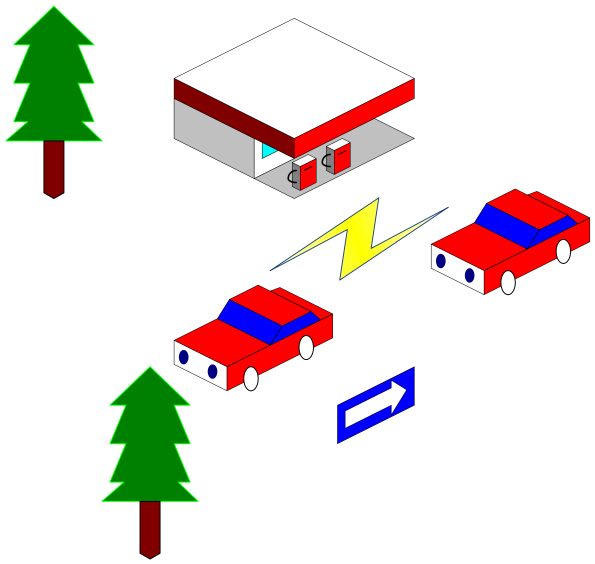

Fig. 1: A case of D2D communication in vehicular environments

The D2D communication device distinguishes itself from cognitive radios and other ad hoc networks, such as WiFi and Bluetooth-based wireless networks, by operating in a licensed spectrum. Cognitive radios, on the other hand, function as devices that opportunistically exploit the spectrum in a secondary manner. This utilization of the spectrum in an opportunistic fashion can be categorized as an unlicensed operation. Hence, while D2D networks predominantly operate within licensed spectrum allocations, cognitive radios, and other ad hoc networks operate in unlicensed fashion.

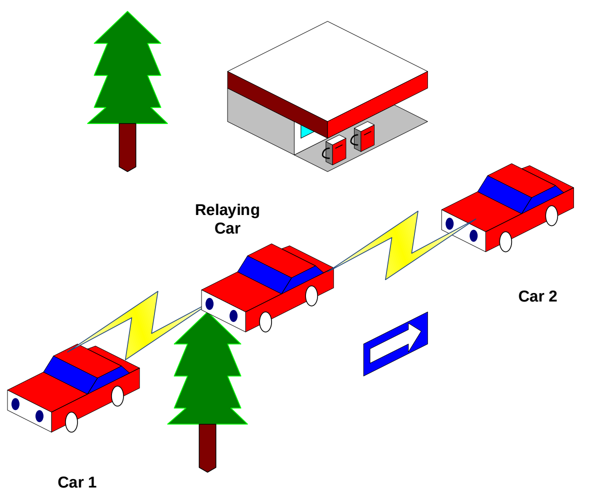

Fig. 2: A case of D2D communication in vehicular environments with relaying concept

There are many differences between D2D and Adhoc network devices. The security features of Adhoc devices are generally quite weak hence, no confidential data such as public safety or critical data can be transmitted over these networks (Wang and Yan, 2017; Ramanathan and Redi, 2002). However, D2D communication typically exploits the licensed spectrum hence that can easily be used for transmission of secure and critical data. Additionally, Adhoc devices typically use unlicensed spectrum in comparison to the licensed spectrum exploited in the D2D networks.

D2D communications are implemented in a manner that eliminates the necessity for intermediate nodes or resources between the communicating nodes. This mode facilitates significant advantages by effectively utilizing key characteristics such as proximity, reuse, hop, and pairing gains, as well as spectral and energy efficiency (Amanuel and Ameen, 2021; Gandotra et al., 2017). The utilization of radio resources for D2D communications encompasses the same spectral resources employed by licensed networks. This approach enhances reuse gain, leading to an overall improvement in spectral efficiency for the network. Consequently, it enables the support of greater integration of services and enhances the grade of service for existing applications. The D2D discovery mode heavily relies on proximity discovery, serving as a trigger for establishing direct communications. However, it can also be utilized as an independent service without enabling the trigger for D2D communications. The discovery process prioritizes fast recovery time and low energy consumption while minimizing additional interference to the wide area network and resource degradation.

Two crucial parameters hold significant importance in D2D communications: the search for a D2D relay partner and the associated payoff for sharing wireless scarce resources, specifically RF bandwidth. In the subsequent section, both of these issues will be emphasized and examined in detail.

1.1. Communication mode selection

The identification of a reliable partner for potential collaboration within the D2D scenario is a crucial step toward the successful implementation of any D2D relay network for wireless communications. In their study, Jiang et al. (2015) conducted an investigation and derived the probability of a D2D user being present and prepared to share the available bandwidth. Moreover, the density of users also plays a significant role in finding a suitable partner for successful sharing, as the effectiveness of relaying primarily depends on this parameter. To facilitate the initiation of communication in D2D relaying, the authors also determined a communication transition threshold specific to the proposed scenario. However, for the sake of simplicity, the circular structure is assumed to be an actual circle, whereas in practice, it should be hexagonal. This assumption is made due to the limitations in accessing many geographical locations when employing a circular structure. Consequently, to accurately demonstrate and model the cellular structure, a hexagonal cellular structure is essential. Therefore, the proposed research will serve as a foundation for addressing various D2D issues within a realistic cellular structure.

1.2. Pay-off mechanism for sharing the RF bandwidth

Efficiently sharing bandwidth with users necessitates a crucial aspect: the presence of a clear motivation to engage in such activities. Sharing RF bandwidth without any incentives is highly unlikely and impractical. This is attributed to the limited nature of cellular users' resources, such as battery life, bandwidth, finances, and data storage. Consequently, resource sharing is typically driven by individuals who anticipate receiving something in return for their contributions. In this context, various authors have employed different payoff mechanisms to incentivize the sharing of essential wireless resources.

1.3. Research contributions

This paper presents a D2D network model that holds potential for future wireless communication systems. The primary contributions of this research are outlined as follows:

- The successful identification of a D2D partner is a critical task for the effective implementation of a D2D network. However, accurately modeling the cellular structure is necessary for a successful partner search. Previous work by Jiang et al. (2015) derived a model using a circular structure to represent the cellular layout. However, in practical applications, this approach has limited significance as it fails to accurately locate cellular users. In this paper, a hexagonal structure is assumed, and the probability of successfully finding a D2D partner is determined.
- Radio spectrum is a scarce and valuable natural resource. Therefore, sharing bandwidth or any other resources without appropriate compensation is only feasible when users can determine the benefits of such activities. This determination can be achieved through the use of utility functions, such as Nash Equilibrium or best-fit response in game theory. By employing such functions, a desirable number of wireless users can actively search for sharing partners. In this paper, a Cobb-Douglas utility-sharing model is employed for this purpose. Specifically, the Cobb-Douglas model is applied to the case of two users, demonstrating how the additional bandwidth provided by these users can be advertised for sharing purposes. Utilizing a two-user production model offers numerous advantages, as it distributes the burden of resource utilization and allows the two users to request suitable compensation from individuals interested in exploiting the shared bandwidth, as suggested by various authors.

The subsequent sections of this paper are structured as follows. Section 2 provides an analytical derivation of the communication mode selection for a hexagonal cellular structure assumption. In Section 3, the application of the Cobb-Douglas model for a cooperative scenario involving two users is elaborated upon. Furthermore, the historical perspective and the procedural details of its application are presented in this section. Section 4 presents the simulation results and subsequent discussions on the proposed scenario, covering aspects such as the probability of finding a partner in a realistic scenario and the bandwidth sharing case using the Cobb-Douglas model for wireless communications. Finally, in Section 6, the paper is concluded with an outline of future work and potential challenges that lie ahead.

2. Communication mode selection for D2D relaying

In the classic mode of transmission, a User equipment (UE) or mobile station transmits the data directly to a Base station (BS). In the proposed model, it is assumed that the direct link between UE and BS is not progressing well. In such a situation, as the communication link establishment is not possible without a reliable link hence, the BS switches its mode of operation to the D2D communication mode. And the Mobile Station/User equipment transmits to the BS through D2D relaying mode. Fig. 3 shows the typical setup. The hexagon residing inside the larger hexagonal surface is representing the available D2D devices. From these devices, it is assumed that only a selected number of devices can play the role of relaying hence, that quantity is represented through $\pi/2$. And the other area of the hexagonal surface is representing those D2D devices that are not available to relay any information for the proposed setup.

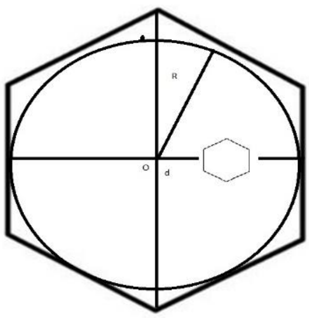

Fig. 3: Setup of D2D communication scenario

Suppose that all the UEs arrive at the proposed cellular area independently and UEs are evenly distributed within the cell. At a certain time, interval t, the user density within the cell is represented through η per unit area. The average number of UEs within the cell then can be calculated as $\frac{3\sqrt{3}\,a^2}{2}$, where a represents the length of each side of the hexagon.

In the given scenario, let D(d) represents the UEs in the D2D available region of interest. The probability that UE can find a D2D device within its EDCA is a function of binomial distribution with parameters $\left\{\frac{3\sqrt{3}\,a^2}{2}\eta, \frac{D(d)}{\frac{3\sqrt{3}\,a^2}{2}}\right\}$, in these parameters, D (d)/(area of the hexagon) denotes the probability then an arbitrary device is located within the active area. Hence, D (d) can be represented as:

$$D(d) = \left(\frac{3\sqrt{3}\,a^2}{2}\right)\left(\frac{\cos^{-1}(A0/d)}{\pi}\right) = A0^2\cos^{-1}(A0/d) \quad (1)$$

where, A0 represents the apotheosis of the hexagonal cell. As a result, the probability that UE can find m number of D2D devices within its active area is given by,

$$\omega(m) = \left(\binom{\frac{3\sqrt{3}\,a^2}{2}}{m}\right)\left(\frac{A0^2\cos^{-1}(A0/d)}{\left(\frac{3\sqrt{3}\,a^2}{2}\right)}\right)^m\left(1-\frac{A0^2\cos^{-1}(A0/d)}{\left(\frac{3\sqrt{3}\,a^2}{2}\right)}\right)^{\frac{3\sqrt{3}\,a^2}{2}\eta-m} \quad (2)$$

$$1-\omega(0)=\omega(0)$$

$$\left(1-\frac{A0^2\cos^{-1}(A0/d)}{\left(\frac{3\sqrt{3}\,a^2}{2}\right)}\right)^{\frac{3\sqrt{3}\,a^2}{2}\eta-m} \geq 0.5 \quad (3)$$

In Eqs. 2 and 3, d denotes the distance between BS and the pairing node of D2D. In this formula, the minimal value of η that satisfies the given equation is set as the D2D relaying mode transition threshold η_0. Whenever a UE wants to start D2D.

3. Cobb-Douglas model for bandwidth sharing

In this section, it is assumed that the D2D users are sharing the RF bandwidth with other users. This improves the optimization of wireless resources. To achieve this, the Cobb-Douglas utility function is used. The Cobb-Douglas represents the relationship between inputs ad output. This popular econometric model has the advantage of using hypothesis testing and computation of confidence intervals for testing the reliability of estimation (Goldberger, 1968). Additionally, this model also estimates the marginal contribution of each input to the collective output from all the users. The Cobb-Douglas utility function is also used in manufacturing industry estimation algorithms for production functions. It was also used initially in the manufacturing industry in the USA (Zellner et al., 1966).

In this paper, it is assumed that the two D2D users combine their bandwidth resources to share with other users. In this context, the quantity of user 1 is controlled through a parameter represented through α whereas the quantity of user 2 is controlled through user 2 which is controlled by β. In such a way, that α+β=1. The Cobb-Douglas utility function is represented in Eq. 1. The resources are combined due to the reason that the users share only a part of their bandwidth with other users in return for financial gains and the rest of the bandwidth is utilized by themselves for their use. Hence, the two members of the D2D network combine their resources to have an attractive option for others. It is assumed that all the users exploiting the wireless bandwidth will always pay for the resource. And this financial payout will be distributed fairly between the users sharing the resource in proportion to the amount of bandwidth shared.

$$Y = AL^{\alpha}K^{\beta} \quad (4)$$

where, Y shows the total outcome i.e. bandwidth that is available to be shared with other users. This band with is accumulated by two users which are represented through L and K. The powers of the input show the amount of bandwidth shared by a typical user in the wireless D2D communication scenario. The A shows the total factor output. Additionally, the Cobb-Douglas function can also be transformed as a log-linear function Eq. 5.

$$Log\,Y = A + \alpha\,Log\,L + \beta\,Log\,K \quad (5)$$

4. Simulation results and discussion

The following simulation results demonstrate the effective use of the proposed D2D communication system simulation. Fig. 4 assumes that there are two users who are sharing bandwidth. A portion of each user is 50%. The amount of bandwidth with user 1 is 5 units whereas the bandwidth share of user 2 is also assumed as 5 units. Furthermore, Fig. 5 demonstrates the utility function for the case with user 1 sharing 0.3 and user 2 sharing 0.7 quantity of its bandwidth. Fig. 6 demonstrates the utility sharing of User 1 with 0.1 quantity and User 2 with 0.9 quantity of its bandwidth. Fig. 7 demonstrates the utility function of the proposed setup in relation to the bandwidth shared by user 1.

Fig. 7 demonstrates the utility function for a Cobb-Douglas Utility function that involves the case of two users sharing the bandwidth. The maximum total utility function is produced when the portion of one of the users becomes 10% while having the second one's part as 90%. Additionally, other cases are also plotted for comparison purposes so that the effective utility can be compared with different scenarios. The comparison done in the present case includes both devices sharing 50%, one of the devices sharing 90%, 80%, 70%, and 10%.

Fig. 8 illustrates the utility function derived from a Cobb-Douglas Utility function, specifically focusing on the scenario where two users share the available bandwidth. The plot reveals that the maximum total utility function is achieved when one user's share constitutes 10% of the total bandwidth. It is noteworthy that this case yields results consistent with those obtained in Fig. 8, albeit the graph is generated based on user 2's utility function. In the present analysis, a comparison is conducted, encompassing scenarios where both devices share 50% of the bandwidth, as well as cases where one of the devices shares 90%, 80%, 70%, and 10% of the total bandwidth.

Fig. 9 demonstrates the utility function for a Cobb-Douglas Utility function involving two users' functionality. The portion distribution, in this case, varies significantly, hence showing the overall utility of two users. The user 1's portion in this case is 50%, 20%, 30%, 60%, and 90% respectively.

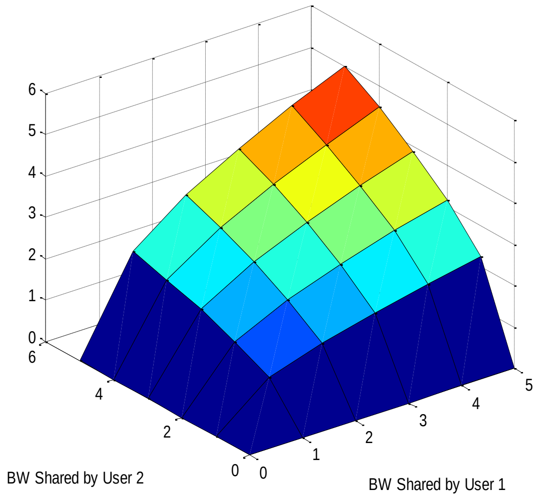

Fig. 4: Cobb-Douglas utility function with a share of 0.5 from each user for sharing purpose

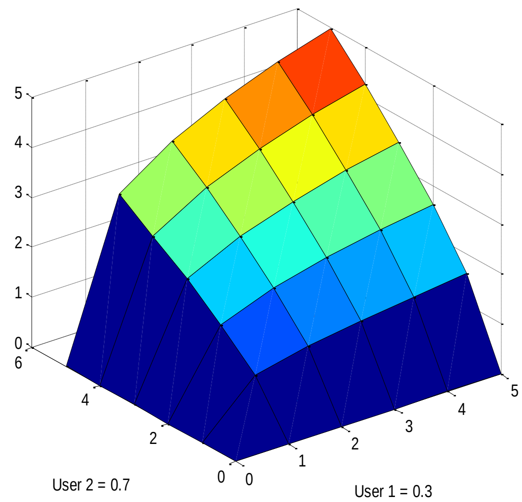

Fig. 5: Cobb-Douglas utility function with a share of 0.3 from user 1 and 0.7 from user 2

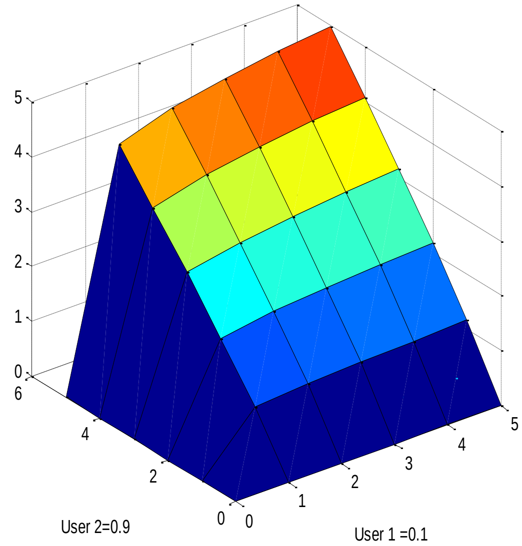

Fig. 6: Cobb-Douglas utility function with a share of 0.1 from user 1 and 0.9 from user 2

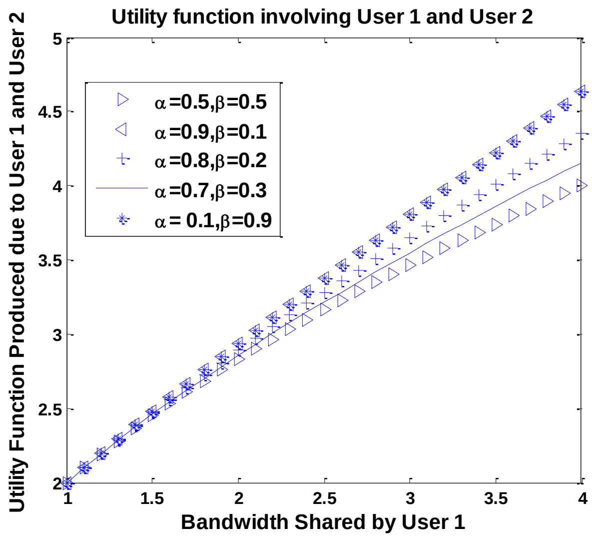

Fig. 7: Utility function in relation to user 1 bandwidth

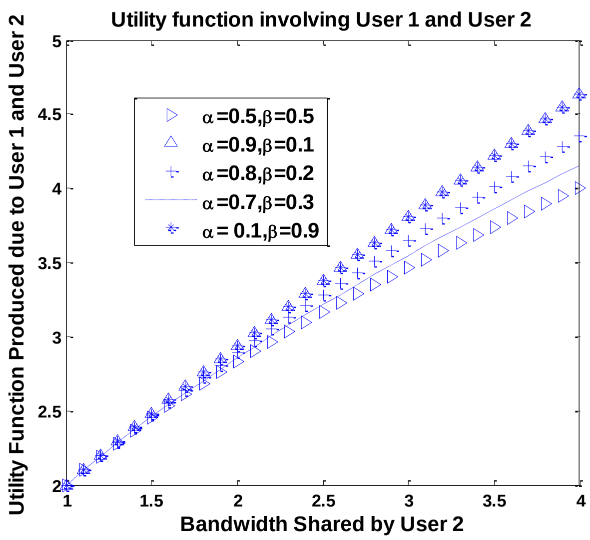

Fig. 8: Utility function in relation to user 2 bandwidth

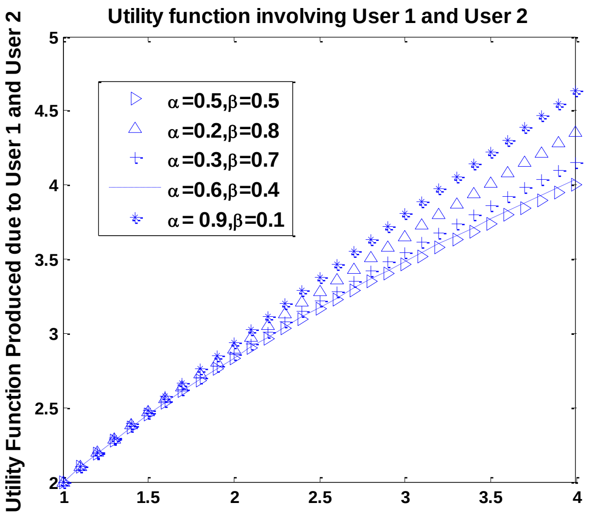

Fig. 9: Utility function in relation to user 1 bandwidth

5. Conclusion

In conclusion, this research paper focused on the investigation of a D2D network for communication mode selection. Analytical results were derived specifically for a hexagonal cellular cell configuration, which holds significant relevance for future wireless communication systems. Additionally, a utility function based on the Cobb-Douglas model was introduced to optimize bandwidth allocation for D2D communication users. As a direction for future work, it is recommended to further optimize the utility function under various cellular communication constraints by employing game theory methodologies.

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Compliance with ethical standards

Conflict of interest

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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