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COLLABORATIVE BEAMFORMING-BASED WIRELESS POWER TRANSFER CONSIDERING INTERFERENCE SUPPRESSION

TRUYỀN NĂNG LƯỢNG KHÔNG DÂY DỰA TRÊN ĐỊNH DẠNG BÚP SÓNG CỘNG TÁC CÓ XEM XÉT TRIỆT NHIỄU

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ABSTRACT

The goal of the energy-efficient data communication technique known as collaborative beamforming (CB) is to extend the network's transmission range by radiating the power of a cluster of sensor nodes in the direction of the desired base stations or access points (BSs/APs). The main lobe of the CB sample beampattern is independent of the particular node positions; however, the CB average pattern exhibits a deterministic characteristic. The sample beam pattern produced by the CB for a cluster of finitely many collaborative nodes, on the other hand, exhibits sidelobes that are highly dependent on the particular node positions. This paper demonstrates a simple sidelobe control or interference suppression approach that is appropriate for CB in wireless sensor networks. This approach aims to reduce interferences at unwanted BSs/APs while maintaining the main lobe steering the desired BSs/APs. The proposed approach's performance is evaluated in terms of interference suppression ability and the average number of search trials required to select collaborative nodes. Simulation results show that when node selection is employed with CB, interferences can be significantly reduced, and they also agree closely with theoretical results.

Keywords: *Wireless power transfer, collaborative beamforming, node selection, interference suppression.*

TÓM TẮT

Mục tiêu của kỹ thuật truyền thông dữ liệu tiết kiệm năng lượng được gọi là định dạng búp sóng cộng tác (CB: Collaborative Beamforming) là tăng phạm vi truyền dẫn trong mạng bằng cách bức xạ công suất từ một cụm nút cảm biến (nút) theo hướng của các trạm gốc hoặc điểm truy cập mong muốn (BS/APs: Base Stations/Access Points). Búp sóng chính của giản đồ bức xạ mẫu CB độc lập với các vị trí nút biến cụ thể; tuy nhiên, giản đồ bức xạ trung bình CB thể hiện một đặc tính xác định. Mặt khác, giản đồ bức xạ mẫu do CB tạo ra cho một cụm gồm nhiều nút cộng tác thể hiện các búp sóng phụ mà chúng phụ thuộc nhiều vào các vị trí nút cụ thể. Bài báo này trình bày một giải pháp điều khiển búp sóng phụ hay triệt nhiễu đơn giản mà phù hợp với CB trong mạng cảm biến không dây. Giải pháp này nhằm mục đích giảm nhiễu tại các BS/APs không mong muốn trong khi vẫn duy trì búp sóng chính về các BS/APs mong muốn. Tính hiệu quả của giải pháp đề xuất được đánh giá qua khả năng triệt nhiễu và số lần thử nghiệm tìm kiếm trung bình cần thiết để chọn các nút cộng tác. Kết quả mô phỏng cho thấy rằng khi giải pháp lựa chọn nút được sử dụng với CB, nhiễu có thể được giảm đáng kể và giải pháp này cũng phù hợp chặt chẽ với các kết quả lý thuyết.

Từ khóa: *Truyền năng lượng không dây, định dạng búp sóng cộng tác, lựa chọn nút, triệt nhiễu.*

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1. INTRODUCTION

Many wireless sensor network (WSN) applications call for the deployment of sensor nodes across a wide region in order to collect environmental data and transmit it to base stations or access points (BSs/APs). In the context of WSNs, collaborative beamforming (CB) is an energy-efficient communication technique that uses a number of sensor nodes to increase the transmission range. In particular, sensor nodes in one cluster work together as a distributed antenna array and modify the initial phases of their carriers to ensure that the separate signals from different sensor nodes combine well and produce a beam that is specifically directed in the direction of the desired BSs/APs. By doing so, CB can extend the sensor nodes' communication range, and in some situations, it can be thought of as a different communication method from multi-hop relay transmission. However, because WSNs are distributed, CB inherits some difficulties. Specifically, the necessity for distributed methods and the random positioning of sensor nodes. Phase synchronization and information sharing between sensor nodes in a cluster of WSNs are two crucial conditions that must be met to implement CB. Other approaches created in [1] and [2] are based on the time-slotted round-trip carrier synchronization approach, while a synchronization algorithm published in [3] uses a straightforward 1-bit feedback iteration. A medium access control-physical (MAC-PHY) cross-layer CB method, which is based on medium random access, has been presented in [4] to speed up the process of sharing data across all sensor nodes in a cluster from multiple sources. Furthermore, even for the typical CB beampattern, the multiple access strategy of [4] leads to greater sidelobes. All of these factors may result in high interference levels coming from unwanted BSs and APs. Considering the inherently distributed nature of WSNs, sidelobe control must be accomplished with the least amount of data overhead and channel knowledge. Unfortunately, due to their excessive complexity and need for centralized processing, existing sidelobe control methods created for classical array processing [5, 6] cannot be used in the context of WSNs. To implement the centralized beamforming weight calculation in the WSNs, a node or BS/AP must collect the information on the channel and position from each sensor node, significantly raising the corresponding overhead in the network.

The efficient use of CB in resource-constrained wireless networks, like WSNs, typically bases on several factors, all of which can, fortunately, be met by using workable technologies. Therefore, they can be considered as rational presumptions for using CB. For instance, the beam patterns can be controlled by adjusting the highest excitation currents. when the nodes in CB are supposed to use individual omnidirectional antennas [9 - 12]. References [13] and [14] assume that the BS and nodes are located on the same outdoor plane and that the path losses are equal with all nodes. Furthermore, it is required that the nodes for CB be completely synced to ensure that there is no frequency offset or phase jitter [13]. Nearly all of the earlier research on CB is dependent on the traditional array factor (AF) described in [9]. In addition, there are numerous power consumption models for defining the sensor nodes' power properties, but the WSNs most frequently employ the straightforward distance-based model introduced in [4].

The sample beam pattern produced by the CB for a cluster of finitely many collaborative nodes has sidelobes that are dependent on specific node placements. High-level sidelobes that point in the direction of unwanted BSs or APs can provide intolerable interference. Therefore, by enabling simultaneous multilink CB, sidelobe control in CB can reduce interferences at unwanted BSs/APs. Traditional sidelobe control methods are not appropriate for WSNs and are supported for centralized antenna arrays. In fact, a node or BS/AP must gather the position and information of the channel from every sensor node in order to implement the centralized beamforming weight calculation in the WSNs, considerably increasing the corresponding overhead in the network. This paper shows an interference suppression approach that uses a node selection algorithm to make use of the unpredictability of sensor node locations. Nodes in this approach are equipped with a single half-wave dipole antenna. In WSNs, this approach can be used to create scalable and simple sidelobe control methods appropriate for CB. Low-rate feedback node selection algorithm is used for searching over different node combinations. The typical number of search trials needed to choose the collaborating nodes, and interference suppression ability is used to assess the efficiency of the proposed approach. It has been demonstrated that when node selection is used in conjunction with CB, interferences may be greatly decreased.

2. SYSTEM MODEL

Assume that a wireless sensor network has sensor nodes randomly distributed on a plane as shown in Figure 1. The BSs/APs are designated as $\mathbf{D} = \{d_0, d_1, \dots, d_D\}$ and located outside the coverage of individual nodes in the direction $\varphi_0, \varphi_1, \dots, \varphi_D$. Therefore, the sensor nodes are unable to send data straight to the BS, and sensor nodes must employ CB for uplink transmission.

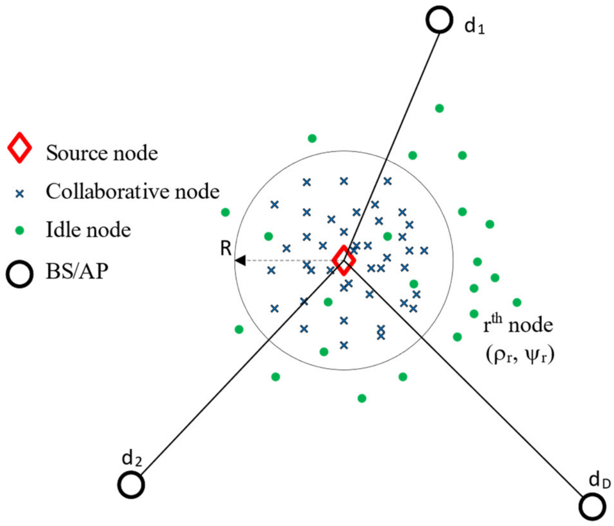

Figure 1. WSN model with multiple BSs/APs [15]

Burst traffic on the uplink transmission, with nodes transmitting suddenly while being idle the majority of the time. In fact, the BSs/APs are often able to communicate with one another almost immediately and with little to no latency. Because the BSs/APs can use high-energy transmission, the downlink can be configured more easily and for direct transmission. A cluster of WSN nodes can ignore the power to communicate among the nodes within the network because the nodes are close together. Each sensor node has a single half-wave dipole for both transmission and reception. Each node in a cluster has a unique identification number for identification.

At each time slot, only $K + 1 = \min\{\text{cardinality}(\mathbf{S}), \text{cardinality}(\mathbf{D})\}$ source-destination pairs are allowed to communicate with a set of active source nodes $\mathbf{S} = \{s_0, s_1, \dots, s_s\}$. With source node s_k, the area of coverage is a circle whose amplitude is based on the energy assigned for node transmission to other nodes. Let M^k be a set of nodes within the range of node s_k. The rth collaborative node indicated as $c_r, r \in M^k$ has polar coordinates (ρ_r, ψ_r). The range between the collaborative node c_r and a point (A, ϕ) in the same plane is calculated by Euclidean distance [15]:

$$d_r(\phi) \triangleq \sqrt{A^2 + \rho_r^2 - 2\rho_r A\cos(\phi - \psi_k)} \approx A - \rho_r\cos(\phi - \psi_r) \quad (1)$$

where $A \gg r_k$ in the far-field area. The set of sensor nodes M^k have array factor in a plane can be described as [15]:

$$AF^k(\phi) \triangleq \sum_{r\in M^k} \sqrt{P_r} e^{j\theta_r^k} e^{-j\theta_r(\phi)} \quad (2)$$

where P_r is the transfer energy of the rth node, θ_r^k is the initial phase of the rth sensor carrier frequency, $\theta_r(\phi) = (2\pi/\lambda)d_r(\phi)$ is the phase shift due to spreading at the point (A, ϕ), and λ is the wavelength of the carrier. Then the far-field beam pattern correlating to a set of sensor nodes M^k can be calculated by [15]:

$$BF^k(\phi) \triangleq \left|EF^k \times AF^k(\phi)\right|^2 = \left|EF^k \times \sum_{r\in M^k} \sqrt{P_r} e^{j\theta_r^k} e^{-j\theta_r(\phi)}\right|^2 \quad (3)$$

where $|\cdot|^2$ stands for a complex number's magnitude and EF is the element factor of the antenna. The main lobe of the beampattern is formed toward the direction of d_k while using the information of the node location, the collaborative node c_r, r will synchronize with the initial phase $\theta_r^k(\phi) = -(2\pi/\lambda)\rho_r\cos(\phi - \psi_r)$.

3. THE PROPOSED APPROACH

3.1. Model of CB and corresponding signal

There are two steps including information sharing and the actual CB steps [15] for the node selection process. Information sharing aims to broadcast data to all nodes in the coverage region of the source node. In the first step, the source node s_k sharing the symbol z_k to every node within its coverage area M^k. During the second step, each collaborative node in M^k transmits the signal to d_k:

$$t_r = z_k\sqrt{P_r} e^{j\theta_r^k}, r \in M^k \quad (4)$$

All collaborative nodes in M^k broadcast the signal at an angle ϕ with value [15]:

$$g(\phi) = \sum_k z_k \sum_{r\in M^k} \sqrt{P_r} a_{rk} e^{j\theta_r^k} e^{-j\theta_r(\phi)} + \omega \quad (5)$$

where ω denoted as the additive white Gaussian noise at the direction ϕ. The signal received at the BS/AP d_{k^*} can be calculated as [15]:

$$g_{k^*} \triangleq g(\varphi_{k^*}) = z_{k^*} \sum_{r\in M^k} \sqrt{P_r} a_{rk^*} + \sum_{k\neq k^*} z_k \sum_{r\in M^k} \sqrt{P_r} a_{rk^*}(x_r^{(k^*,k)} - jy_r^{(k^*,k)}) + \omega \quad (6)$$

where $x_r^{(k^*,k)} = R\left\{e^{-j(\theta_r^{k^*} - \theta_r^k)}\right\}$ is real parts, $y_r^{(k^*,k)} = I\left\{e^{-j(\theta_r^{k^*} - \theta_r^k)}\right\}$ is imaginary parts of the complex number, and $u \in \left\{x_r^{(k^*,k)}, y_r^{(k^*,k)}\right\}$ has $m_u = E\{u\} = 0$ and variance $\sigma_u^2 = E\{u^2\} = 0.5$.

3.2. Node selection in sidelobe control

From the set of nodes M^k choose a subset N^k of collaborative nodes in each source node's coverage area in order to obtain the appropriate sidelobes and beamform data symbols to d_k. Note that a set of collaborative nodes $N^k \subset M^k$ to each source-destination pair $s_k - d_k$. A cluster of nodes can test the nodes to determine which ones to include in this collaborative set. By sending only one 'approve/reject' bit per cluster of nodes, the system's data overhead will be reduced. The source node s_{k^*} has M nodes in the coverage area, select $N \le M$ node to participate in collaborative nodes, and the number of nodes that will be examined in each trial be $L \le N$. The process to choose nodes will follow two steps below [15]:

Step 1: Selection. Source node s_{k^*} will share the *select message* with all nodes in the coverage region M^k and select a set L^{k^*} randomly of L applicant nodes from M^{k^*}

Step 2: Test. After assigning the set of subsets L^{k^*} collaborative nodes transmit a checking message containing the desired BS/AP ID to the desired destination d_{k^*}. At this step the received interference-to-noise ratio (INR) η was measured at all unwanted destination d_k $\forall k \neq k^*$ which has different IDs of BSs/APs. If $\eta > \eta_{thr}$, The candidate set L^{k^*} will receive a reject messenger. If all $\eta \le \eta_{thr}$, no reject message sent back and after wait time, the subset L^{k^*} is accepted and each node in L^{k^*} save IDs of the source node s_{k^*} and the destination d_{k^*}. This set L^{k^*} do not join in the next trials to avoid overlap.

This process is repeated until N/L candidate sets have been accepted. The collected set of accepted collaborative node N^{k^*} and source node s_{k^*} sent an end message. With the obtained set, finally, the optimized pattern can be obtained with nulls imposed in the direction of interferences.

4. EXPERIMENTAL RESULTS

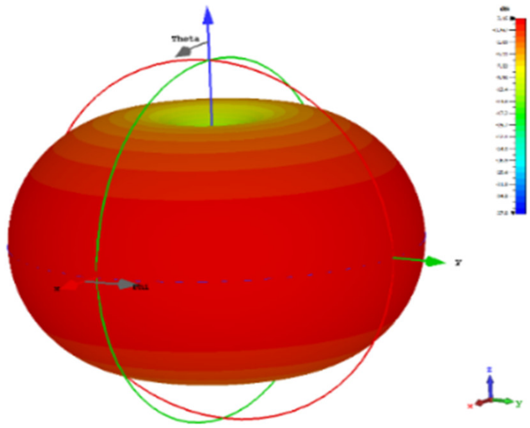

Figure 2. The 3D pattern of a half-wave dipole antenna

This section demonstrates the interference suppression ability of the proposed approach and verifies the accuracy of the analytical expressions that are derived. Unless otherwise stated, the following setup is taken into account throughout this section. Assume that the sensor nodes are distributed over a plane with radius $R = 2\lambda$. The source node's coverage region has $M = 512$ sensor nodes in it. The candidates for collaborative nodes are $N = 256$. The quantity of selection sensor nodes in a cluster $L = 32$, the value of threshold at the unwanted BSs/APs is $\eta_{thr} = 10\text{dB}$. The direction of desired and unwanted BSs/APs will be set in each scenario. Each node is equipped with a single half-wave dipole antenna whose 3D pattern is shown in Figure 2. The effectiveness of the proposed approach is confirmed by averaging the results of 100 independent simulations.

4.1. Interference Suppression Ability

This subsection considers the reference pattern as the pattern computed by the analytical expressions in [15]. Three scenarios are evaluated to prove the efficiency of the proposed approach.

Scenario 1: Assume $D = 4$ unwanted BSs/APs located in the direction $\varphi_1 = -50°, \varphi_2 = -20°, \varphi_3 = 20°, \varphi_4 = 50°$, and the desired BSs/APs at the direction $\varphi_0 = 0°$. Figure 3 shows the comparison among the reference pattern, the optimized pattern with node selection (the proposed approach), and the pattern without node selection. It determines that at the directions of unwanted BSs/APs, the optimized pattern with node selection has the lowest sidelobes, otherwise, without node selection, the pattern's sidelobes are uncontrollable. Besides, Figure 4 shows the beampatterns of the multilink collaborative with node selection. The results indicate that each beampattern suppressed power radiated in the directions of unwanted BSs/APs (interferences). Both figures show that the main lobe is maintained and steered toward the desired directions while controlling the sidelobe levels.

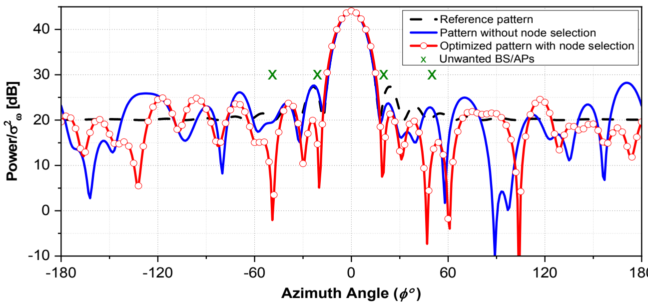

Figure 3. Beampatterns with four unwanted BSs/APs

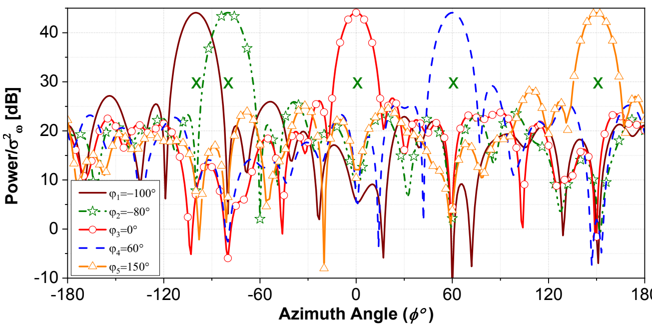

Figure 4. Multilink beampatterns with BSs/APs at different directions

Scenario 2: This scenario assumes interferences emerging in the range $\phi \in [100°; 150°]$. The optimized pattern with node selection and the reference pattern are shown in Figure 5. In this case, the optimized beam pattern is able to achieve low sidelobes in the range of interferences while maintaining the main lobe.

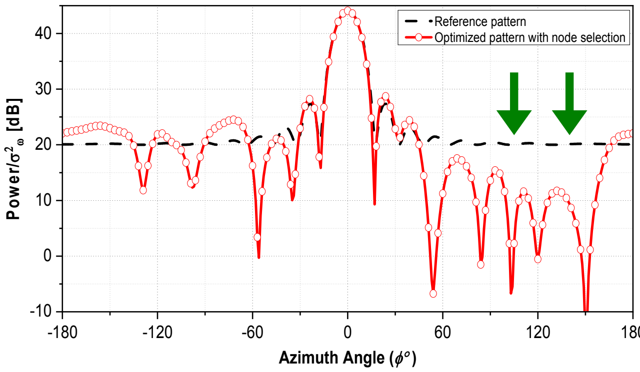

Figure 5. Beampatterns with interference in the range $\phi \in [100°; 150°]$

Scenario 3: In addition to being constrained to a fixed direction as in the aforementioned scenarios, the main lobe of the proposed approach can also be steered. Assume 4 unwanted BSs/APs are located closely on two sides of the largest peak and the main lobe is steered toward $\varphi_0 = -20°$. Figure 6 shows that beam pattern with node selection can suppress interference levels at unwanted BSs/APs directions while preserving the main lobe and sidelobes in the other directions.

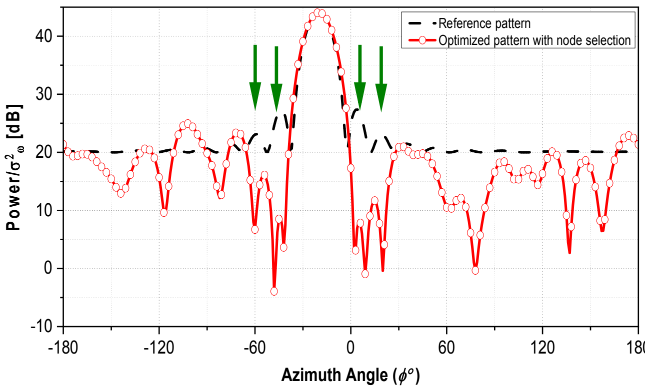

Figure 6. Beampatterns with the main lobe steered toward $\varphi_0 = -20°$

4.2. Average Number of Iterations

This subsection demonstrates the effect of INR threshold parameter changes in the scope $\eta_{thr} = [0; 30]$ dB and the different sizes of candidate nodes $L \in \{16, 32, 64, 128\}$. This demonstration is shown in Figure 7 which indicates that the average value of iterations is inversely proportional to both thresholds and the number of candidate nodes. The curves for the average number of iterations obtained using the analytical expression in [15] are in good agreement with the simulation findings, as seen in the figure. The value of iterations for unchanged N can be modified by L, which means that the number of iterations decreases when L increases.

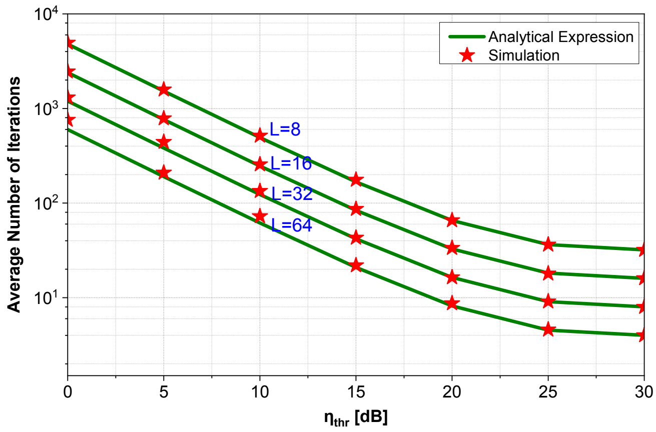

Figure 7. The average number of iterations versus η_{thr} for different values of subsets I

Next, the impact of the quantity of unwanted BSs/APs $D \in \{1, 2, 3\}$ on the performance of the proposed approach is considered. Figure 8 shows the relative of the average number of iterations and the threshold when changing values of D. If D increases the number of iterations increases dramatically at the low threshold η_{thr}. At a high threshold, however, the number of iterations does not change too much when changing the number of unwanted BSs/APs. Finally, it is clear that there is good agreement between the results of the simulation and the analysis.

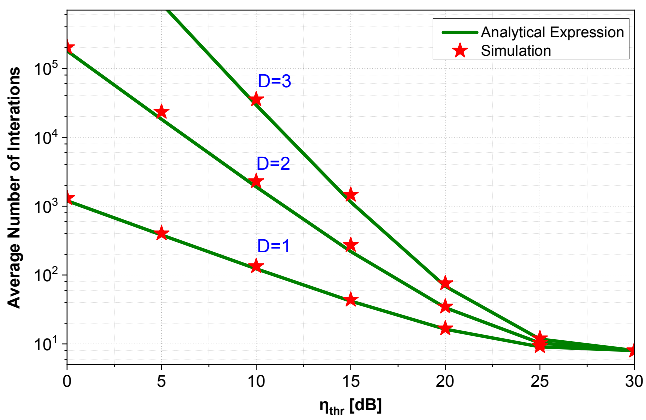

Figure 8. The average value of iterations and η_{thr} for different numbers of BSs/APs

5. CONCLUSION

In the context of WSNs, this paper presented a method for multilink CB sidelobe control. The analytical and simulation results indicate that the proposed approach or the multilink CB with node selection is superior to the multilink CB without node selection in terms of interference suppression capabilities. At the unwanted BSs/APs, optimized patterns can achieve low sidelobes. Experimental results also show the relative between the average number of iterations and the threshold value η_{thr} when changing the number of nodes to be tested in each experiment or changing the number of unwanted BSs/APs.

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THÔNG TIN TÁC GIẢ

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