Array Antenna for Power Saving of Sensor Nodes in UAV-BS enabled WSN

Hendrik Lumbantoruan and Koichi Adachi
Advanced Wireless & Communication Research Center (AWCC)
The University of Electro-Communications
1-5-1 Chogugaoka Chofu, Tokyo, Japan 182-8585, Email: {hendrik, adachi}@awcc.uec.ac.jp

***Abstract*—Low power consumption communications techniques are required for sensor nodes (SNs) in wireless sensor networks (WSNs) as it is difficult to charge the power supply once deployed. In order to reduce the transmit power of the SNs, an unmanned aerial vehicle-base station (UAV-BS) can be deployed as a mobile data collector. In this paper, we propose a rotational angle division multiple access (RADMA) which is suitable for UAV-BS. In RADMA, a *virtual sector* is formed by an array antenna equipped at the UAV-BS. By rotating the UAV-BS, the multiple virtual sectors are created in order to cover the whole area. By RADMA, the signal collision among the SNs can be avoided by limiting the number of active SNs that are within the virtual sector. Since the received signal power from SNs can be enhanced by the high gain of the array antenna, the SNs can transmit at a higher rate to shorten the transmission time. Thus, the transmission energy can be reduced since the SNs are able to transmit in a shorter time without abundant repetitions. Numerical results validate the effectiveness of the proposed scheme.**

I. INTRODUCTION

Wireless sensor network (WSN) consisting of a large number of sensor nodes (SNs) has become one of the major research issues and promising research interests as it can be deployed to observe or monitor a certain area. As it is not easy to provide the wired power supply for each SN, the SNs are typically powered by a fixed energy source such as a battery. Because it is almost impossible to change or recharge the battery once deployed [1], energy efficient communication schemes are crucial to prolong the network lifetime.

In WSN, the transmissions are carried out in an autonomously distributed manner by using random access schemes such as carrier sense multiple access/collision avoidance (CSMA/CA) rather than a centralized access control [2]. Since each SN transmits in a distributed manner, the probability of signal collision due to the simultaneous transmission from multiple SNs increases proportionally to the number of SNs in the WSN. This signal collision deteriorates the communication efficiency as the packet retransmission is required. Furthermore, as the retransmission consumes the excessive energy at the SNs, it is necessary to avoid the signal collision in order to save the energy consumption of SNs.

In recent years, the use of an unmanned aerial vehicle (UAV) as a base station (BS) has been considered as it can be deployed easily and dynamically at a low cost. UAV-BS provides several advantages. First, the probability to have line-of-sight (LoS) links to ground terminals is higher due to its higher altitude. Second, since UAV-BS can be dynamically placed closer to ground terminals or highly-dense area by leveraging its high mobility, the link distance to each ground terminal can be reduced which can save the transmission energy of all ground terminals [3]. Therefore, using UAV-BS as a mobile data collector for the SNs in WSN is considered as a promising approach to reduce the required transmission power to achieve a certain desired communication quality [4].

For UAV-BS enabled WSN, sleep and wake up mechanism is known to be a useful technique to save the energy consumption of the SNs [5]. In this mechanism, the SNs are in sleep mode by default and become active mode (wake up) after receiving a beacon signal with power bigger than a certain threshold then will return to the sleep mode after finishing the transmission. Due to the highly dynamic wireless channels between the SNs and the moving UAV-BS, which are prone to packet loss [6], the deployment of the UAV should be properly designed to ensure that each SN can transmit its data with low outage probability when it is in its active mode.

This paper proposes a rotational angle division multiple access (RADMA) that avoids the signal collisions among the SNs to achieve reliable and energy-efficient data collection in UAV-BS enabled WSN. The aim is to reduce the energy consumption of SNs while ensuring a target amount of data can be reliably transmitted. By utilizing the UAV-BS an array antenna, a *virtual sector* can be formed by the lobes of the array [7]. The virtual sector can be multiplexed by rotating the UAV-BS horizontally with an appropriate time interval. Signal collisions can be avoided by limiting the communicating SNs within the virtual sector. Further, the channel gain between each SN and UAV-BS can be improved by exploiting the array antenna. Numerical results elucidate the significant energy saving up to 280 times for SNs by the proposed RADMA compared to the conventional method in which an omnidirectional antenna is deployed to cover the whole coverage area at once.

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II. System Model

A. System Description

In this section, the proposed communication protocol for UAV-BS enabled WSN is presented. Fig. 1 shows wireless communications system where a UAV-BS is deployed as a mobile data collector to gather information from a WSN consisting of K SNs which generate delay tolerant data packets. The set of SNs is denoted by $\mathcal{K} = \{1, \cdots, K\}$. All SNs with location denoted by $\mathbf{w}_k = (x_k, y_k) \in \mathbb{R}^{2\times 1}$ are randomly and uniformly distributed in the coverage area. Each SN transmits the generated sensing data with an omnidirectional antenna.

B. Rotational Angle Division Multiple Access (RADMA)

The concept of the virtual sector which splits the whole coverage area into partially overlapping areas is shown in Fig. 1. In this paper, all SNs are assumed to be in the sleep mode by default in order to reduce the energy consumption. The SNs will switch back to active mode once received the beacon signal from UAV-BS with signal power bigger than a certain threshold and then the data transmission process is initiated. Since the channel gain within the virtual sector can be higher due to the lobes of the array antenna, only the SNs within the virtual sector will switch back to active mode while others will remain to be in the sleep mode.

In order to give communication opportunity to all SNs within the coverage area, the multiple virtual sectors are created by rotating the UAV-BS horizontally with a certain rotational angle $\theta_{\mathrm{RT}} \in \{0, 2\pi\}$ within a fixed *sector time* T_{sec}, which is given by

$$T_{\mathrm{sec}} = \frac{T_{\mathrm{Round}}}{J}, \tag{1}$$

where T_{Round} is the time for one round [s] and $J = 2\pi/\theta_{\mathrm{RT}}$ is the number of sectors. Note that the choice of T_{sec} has a significant impact on the system performance. On one hand, a longer T_{sec} provides more time for the UAV-BS to serve a certain virtual sector hence the probability for all the SNs within the virtual sector can transmit all the data is increasing. On the other hand, a longer T_{sec} also incurs a larger access delay for SNs existing outside of the virtual sector which is currently being served. Instead of fixing at a certain value, adjusting the sector time $T_{\mathrm{sec},j}$ to the SNs density within the virtual sector is also considered to enhance the network performance, which is given by

$$T_{\mathrm{sec},j} = \frac{K_j}{K} T_{\mathrm{Round}}, \tag{2}$$

where K_j is number of SNs within the jth virtual sector.

The probability that multiple SNs simultaneously transmit the data packet can be lowered as the communicating SNs is limited per each virtual sector. In addition, since the virtual sector is a narrower area compared to the whole communication area, the probability that

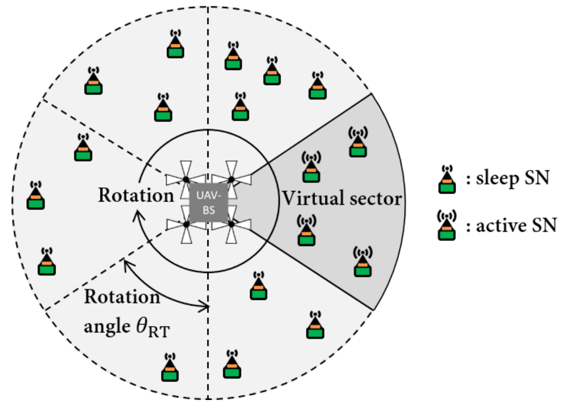

Fig. 1: Virtual sector in UAV-BS WSN using RADMA

each active SN can successfully detect the ongoing transmission is increasing as the active SNs located close to each other can detect the transmit signal of each other. Thus, the probability of signal collision due to hidden-terminal can be reduced. Hence, it is possible to realize the high-efficiency communication system and increase the energy efficiency as a result of avoiding the excessive energy and the retransmission time.

Further, the received signal power from the active SNs can be increased by exploiting the high gain of the array antenna, thus a higher transmission rate can be assigned to shorten the data transmission duration. Hence, a low power communication can be realized as the required transmission power can be reduced proportionally to the shortened transmission time.

C. Channel Model

The channel for each communication link between an SN and UAV-BS is modelled with path-loss and shadowing-loss. For the simplicity, we consider the uplink channel to be a non-fading channel. Since no scatters exist around the UAV-BS, it is reasonable to consider such non-fading uplink channel [8].

In particular, we consider a free-space path-loss model for the link between the SN k and the UAV-BS, which is given by

$$L_k = \left(\frac{4\pi f_{\mathrm{c}} d_k}{c} \right)^2, \tag{3}$$

where f_{c} is the carrier frequency $[\mathrm{Hz}]$ and c is the speed of light $[\mathrm{m/s}]$. The distance d_k between SN k and UAV-BS can be written as

$$d_k = \sqrt{\|\mathbf{w}_{\mathrm{UAV}} - \mathbf{w}_k\|^2 + H_{\mathrm{UAV}}^2}, \tag{4}$$

where $\mathbf{w}_{\mathrm{UAV}} \in \mathbb{R}^{2\times 1}$ and H_{UAV} are the 2D location and the altitude of UAV-BS, respectively.

The log-normally distributed shadowing loss ψ_k [dB] can be written as [9]

$$\psi_{k,\mathrm{dB}} \sim \mathcal{N}(\mu, \sigma_k^2) \tag{5}$$

where

$$\sigma_k = k_1 \exp(-k_2 \theta_k), \tag{6}$$

with μ and σ^2 are the mean and the variance of the shadow fading, respectively. k_1 and k_2 are constant values which depend on environment. $\theta_k = \sin^{-1}(H/d_k)$ is the elevation angle of the UAV-BS and SN k.

The UAV-BS is equipped with a uniform linear array antenna (ULA) with N antenna elements being separated by a uniform distance Δ, where Δ is the antenna element spacing normalized by carrier wavelength. The antenna gain towards the signal transmitted from SN k with a direction of arrival (DoA) ϕ_k respect to the array antenna axis is given by the following equation [10]

$$G_{\mathrm{R},k} = \left| \sum_{n=0}^{N-1} g(\theta_k, \phi_k) \mathrm{e}^{-j2\pi n \Delta \sin\theta_k \cos\phi_k} \right|^2, \qquad (7)$$

where $g(\theta_k, \phi_k)$ is the directivity of the antenna element. In this manuscript, the antenna element used in the array antenna is half-wave dipole antenna and the directivity $g(\theta_k, \phi_k)$ is given by the following equation [10]:

$$g(\theta_k, \phi_k) = \sqrt{1.64} \cos\left(\frac{\pi}{2}\cos\theta_k\right) / \sin\theta_k. \qquad (8)$$

From (8), the maximum value of $g(\theta_k, \phi_k)$ can be obtained at $\theta_k = \pi/2$, which is impossible as the UAV-BS is required to be deployed at the same altitude as SN k. So it is necessary to arrange the antenna elements with a certain tilt angle θ_{tilt} instead of vertical placement to maximize the use of the beam of the antenna element. In this manuscript, the tilt angle θ_{tilt} is settled so the main beam is facing towards the center of the coverage radius as shown in Fig. 2. In this case, the tilt angle θ_{tilt} can be written as the following equation:

$$\theta_{\mathrm{tilt}} = \frac{\pi}{2} - \tan^{-1}\frac{r/2}{H_{\mathrm{UAV}}}. \qquad (9)$$

Substituting (9) into (7) and (8) gives

$$G_{\mathrm{R},k} = \left| \sum_{n=0}^{N-1} g(\theta_k, \phi_k) \mathrm{e}^{-j2\pi n \Delta \sin(\theta_k + \theta_{\mathrm{tilt}}) \cos\phi_k} \right|^2, \qquad (10)$$

$$g(\theta_k, \phi_k) = \sqrt{1.64} \frac{\cos\left(\frac{\pi}{2}\cos(\theta_k + \theta_{\mathrm{tilt}})\right)}{\sin(\theta_k + \theta_{\mathrm{tilt}})}. \qquad (11)$$

Finally, the channel gain h_k between UAV-BS and SN k can be given as

$$h_k = \frac{G_{\mathrm{T}} G_{\mathrm{R},k}}{L_k \psi_k}, \qquad (12)$$

where G_{T} is the transmit antenna gain of SN k and $\psi_k = 10^{\psi_{k,\mathrm{dB}}/10}$.

D. Transmission Rate

The received signal power to noise power ratio (SNR) from SN k at UAV-BS can be given by

$$\gamma_k = \frac{P_{\mathrm{R},k}}{N_0} = \frac{P_{\mathrm{T}}}{BN_0} \frac{G_{\mathrm{T}} G_{\mathrm{R},k}}{L_k \psi_k}, \qquad (13)$$

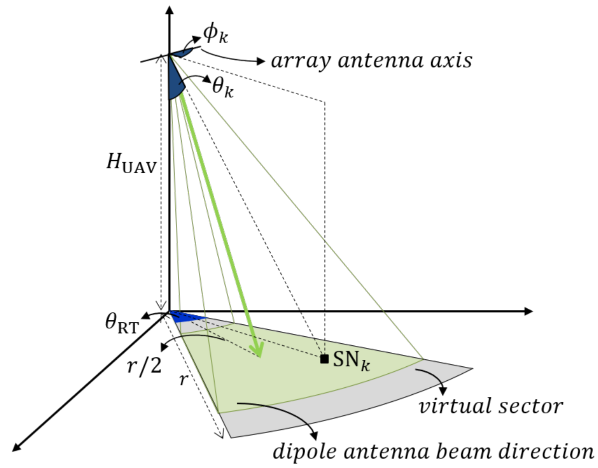

Fig. 2: Arranging antenna element with tilt angle θ_{tilt}

where P_{T}, B, N_0 are the constant transmission power of each SN, the bandwidth, and the noise power spectrum density, respectively. From (13), the achievable SNR can be increased as the receive antenna gain $G_{\mathrm{R},k}$ is higher when using array antenna compared to omniantenna.

Adopting IEEE 802.11 as the wireless access protocol, each SN can transmit its data with different transmission rates adjusting to the channel condition (SNR). Due to the increased SNR, it is possible for SNs to transmit with higher transmission rate. The required SNR range for each transmission rate will be shown in the next section. Further, the outage probability is lowered as the high SNR can surpass the required minimum SNR for reliable communication.

E. Required Condition for Successful Decoding

Suppose that the SN k is within the jth virtual sector. When a signal collision occurs, the received signal power to interference plus noise power ratio (SINR) SINR_k of SN k in the UAV-BS is given by

$$\mathsf{SINR}_k = \frac{\frac{P_{\mathrm{T}}}{B} h_k}{\frac{P_{\mathrm{T}}}{B} \sum_{k' \in \mathcal{K}_j} h_{k'} I(k, k') + N_0}, \qquad (14)$$

where $I(k, k')$ denotes the step function indicating that whether SN k can sense the transmit signal of SN k'. In this paper, the threshold of the signal power that can be sensed is set to -97 [dBm]. $I(k, k')$ is given by

$$I(k, k') = \begin{cases} 1 & \text{if SN } k' \text{ cannot sense SN } k \\ 0 & \text{otherwise} \end{cases}, \qquad (15)$$

In this paper, we define the SN whose frame (signal) is received by UAV-BS first as the typical SN. When a frame collision occurs, it is assumed that the frame of typical SN is decodable if the following condition is satisfied.

$$\min\{\mathsf{SINR}_k\} \geq \rho_{\mathrm{th},k}, \qquad (16)$$

where $\rho_{\mathrm{th},k}$ is the required SNR threshold to define the achievable transmission rate of SN k.

TABLE I: Computer simulation parameters

Parameters	Values
Coverage area	60×60 [m^2]
Number of SNs K	30
SN's antenna gain G_T	0 [dBi]
SN's transmit power P_T	0.5 [mW]
SN's data size S	100 [KB]
UAV-BS's position (x, y, z)	$(30, 30, 20)$ [m]
Number of BS antenna elements N	3
Normalized antenna spacing Δ	0.5
Rotation angle θ_RT	$60, 120$ [°]
Carrier frequency f_c	2.4 [GHz]
Bandwidth B	20 [MHz]
Noise power density N_0	-174 [dBm/Hz]
k_1, k_2	10.39, 0.05
μ	1 [dB]

TABLE II: Transmission rate & the required SNR range

SNR range [dB]	Transmission rate [Mbps]
4≤SNR<6	1
6≤SNR<8	2
8≤SNR<10	5.5
10≤SNR<12	18
12≤SNR<16	24
16≤SNR<20	36
20≤SNR<21	48
21≤SNR	54

III. Numerical Results

Computer simulation parameters are shown in table I. We consider a WSN consisting of 30 SNs and each SN is required to transmit a data packet with the size of 100 [KB]. The SNs are randomly and uniformly distributed within an area of 60×60 [m^2] and the UAV-BS is deployed at an altitude of 20 [m] at the center of the coverage area. IEEE 802.11g is adopted as the random access protocol from the SNs to the UAV-BS. The carrier frequency f_c is 2.4 [GHz] and the bandwidth B is 20 [MHz]. The transmit antenna gain G_T of each SN is set to 0 [dBi] and the transmission power P_T is set at a fix value of 0.5 [mW]. The number of antenna elements N equipped at the UAV-BS is 3 and the normalized antenna elements spacing Δ is 0.5. In order to validate the effectiveness of the proposed method when rotating the UAV-BS with a big and a small rotational angle, the rotation angle θ_RT of UAV-BS is set to 60 and 120 [°]. We assume that SN selects the $j^\star$ virtual sector for packet transmission with $j^\star = \arg\max_j P_{\mathrm{d},j,k}$ where $P_{\mathrm{d},j,k}$ is defined as the received beacon signal power at sector j by SN k.

The assignment of the transmission rate adjusting to the channel condition (SNR) is shown in table II. In this research, the required minimum SNR for transmission is 4 [dB]. Thus, even if a certain SN has been switched to active mode, it is considered to be in the outage condition if the achievable SNR falls below 4 [dB].

For performance comparison, the performance where the UAV-BS equipped with an omnidirectional antenna covering the whole coverage area at once is taken as the existing conventional method. The 360 [°] rotation angle in the results corresponds to the conventional method.

Fig.3 shows the outage probability performance. The proposed method can suppress the outage probability to 0% for the case of $\theta_\mathrm{RT} = 60$ [°]. This is because the SNR of each SN increases due to the high gain of the array antenna, thus the probability of falling below the required minimum SNR can be lowered. However, for the case of rotating the UAV-BS with a larger θ_RT, e.g., $\theta_\mathrm{RT} = 120$ [°], the average outage probability increases as some SNs may not obtain sufficient antenna array gain while UAV-BS rotates.

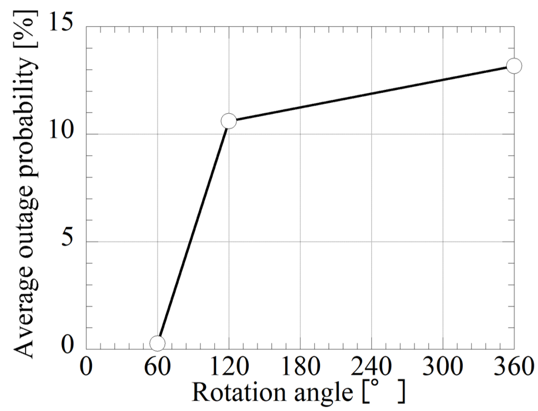

Fig. 3: Outage probability performance

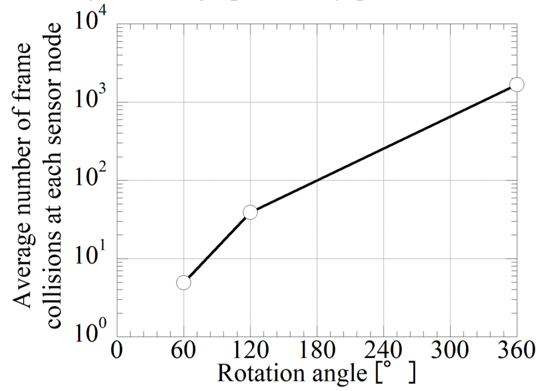

Fig. 4: Average number of frame collisions

Fig.4 shows the average number of frame collisions for each SN until the packet transmission is completed. The proposed method can suppress the number of frame collisions significantly due to the capability of limiting the number of the communicating SNs at a certain time and reducing the hidden terminal problem. When rotating the UAV-BS with a smaller θ_RT, the number of active SNs existing in each virtual sector can be further reduced. Thus, the probability for satisfying the required condition for successful decoding shown in (16) increases due to the capability of reducing the number of interference signals. Hence, the proposed method has a better performance in avoiding the frame collisions when the θ_RT is set to 60 [°] rather than 120 [°].

Fig.5 shows the CDF (Cumulative Distribution Function) of the required transmission time. The fixed T_sec for each θ_RT is set at a certain value so that all the SNs within each virtual sector can transmit all the data packet. As a consequence, there are some stagnant spots as the sector time is fixed regardless to the number of

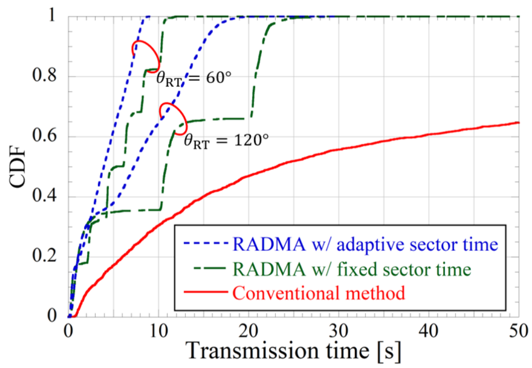

Fig. 5: CDF of the transmission time

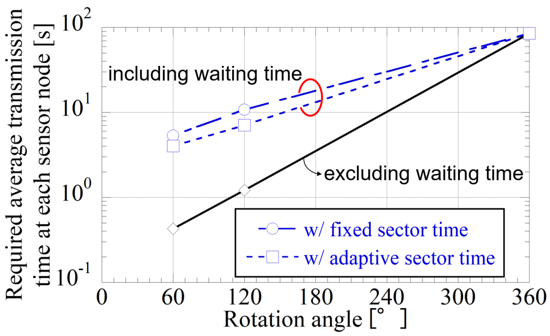

Fig. 6: Required transmission time

SNs within the virtual sector. On the other hand, the waiting time of each SNs to be served and the required time for one round can be shortened by adjusting the sector time to the SNs density within each virtual sector.

Fig.6 shows the required average transmission time to transmit the data packet. The proposed method can shorten the required transmission time compared to the conventional method even when taking into account the waiting time to be served. This is because the number of retransmissions can be reduced as shown in Fig.4 and the SNs can transmit at a higher transmission rate. When rotating the UAV-BS with a smaller θ_{RT}, the possibility that all active SNs communicate within the virtual sector where the antenna gain becomes the maximum increases, thus the proposed method shows better performances in shortening the transmission time when the θ_{RT} is set to 60 [°] rather than 120 [°].

Fig.7 shows the required average transmission energy to transmit the data packet. Even each SNs transmits with a constant transmit power, the proposed method can suppress the transmission energy. This is because the transmission energy is proportional to the transmission time, thus the transmission energy can be reduced as the result of the shortened transmission time.

IV. Conclusion

In this paper, we have proposed a multi-access scheme RADMA by leveraging the high mobility UAV-BS and evaluated it by a computer simulation. By splitting the whole coverage area into the overlapping *virtual sector*, the number of active SNs randomly accessing UAV-BS can be reduced, thus can avoid the signal collision and

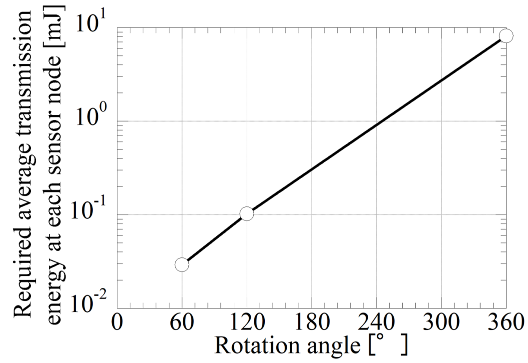

Fig. 7: Required transmission energy

hidden terminal problem. Furthermore, as the achievable SNR can be enhanced, the outage probability can be lowered and the transmission time can be shortened due to a higher transmission rate can be assigned. Thus, the energy consumption can be reduced as the result of the shortened transmission time. For the case of $\theta_{\mathrm{RT}} = 60$ [°], the simulation results have elucidated that the proposed RADMA can reduce the outage probability to 0%, the number of frame collisions to 1/320 times, and the transmission energy to 1/280 times compared to the conventional method. Hence, the proposed RADMA enables the SNs to communicate with high efficiency and low energy consumption.

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