Trajectory and Communication Protocol for Efficient Data Collecting in UAV-Enabled WSN

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***Abstract*—A low power consumption and efficient communication scheme is crucial to boost the data collecting effectivity in a WSN (Wireless Sensor Network) with a large number of SNs (Sensor Nodes). To enhance the received signal power and avoid frequent signal collision, RADMA (Rotational Angle Division Multiple Access) has been proposed. In RADMA, a UAV-BS (Unmanned Aerial Vehicle-Base Station) equipped with ULA (Uniformly Linear Array antenna) is deployed as the mobile data collector, To improve the performance of RADMA when serving a larger area, it is required to design an effective trajectory to dynamically deploy the UAV-BS within the area. In this paper, a simple UAV-BS trajectory decision method based on sectorized K-means clustering is proposed to provide uniform QoS (Quality-of-Service) among all SNs. First, the area is sectorized with equal sector size. Then, the initial centroid coordinate of each cluster is randomly generated within each sector area to avoid biased centroids. Finally, the trajectory is formed by connecting the centroids of the SNs clusters. The numerical results have validated that combining RADMA with sectorized k-means clustering-based trajectory enables all SNs to transmit all the data within a predetermined mission time and with low transmission energy.**

I. Introduction

WSN (Wireless Sensor Network) with a large number of SNs (Sensor Nodes) has become one of the major research issues as it can be deployed to monitor a particular area. Because it is difficult to change or recharge the battery once deployed [1], SNs are required to communicate with low power consumption to prolong its battery lifetime. However, many SNs located at edge area may suffer an outage, where the achievable SNR (Signal-to-Noise power Ratio) falls below a certain threshold, due to the long-distance communication link to FC (Fusion Center) located at the center of the area. Therefore, it is required to deploy multiple FCs to provide uniform QoS (Quality-of-Service) among all SNs.

Recently, the use of UAV-BS (Unmanned Aerial Vehicle-Base Station) as FC has been considered as it can be dynamically deployed. Further, UAV-BS can provide several advantages such as the high probability of having LoS (Line-of-Sight) links to SNs due to its high altitude, and the shorter communication distance to each SN by leveraging its high mobility [2]. Therefore, deploying a single UAV-BS as a mobile FC, which moving to several coordinates within the area sequentially to serve all SNs, is considered as a promising approach instead of deploying multiple FCs [3].

In [4], RADMA (Rotational Angle Division Multiple Access) has been proposed. In RADMA, a UAV-BS is equipped with ULA (Uniformly Linear Array antenna) to serve the SNs. The aim is to realize a low power consumption and efficient communication protocol. Due to the high gain of ULA, the received power of SNs, even transmitted with low transmission power, can be enhanced. The main lobe of the ULA can be exploited to form a *virtual sector* [5]. The virtual sector can be multiplexed by rotating the UAV-BS horizontally with an appropriate time interval. As the communicating SNs can be limited within the virtual sector, signal collisions can be avoided. In order to enhance the performance of RADMA when serving a larger area, it is required to design an effective trajectory to dynamically deploy the UAV-BS within the area.

Trajectory design has been a major research area to enhance the performance in UAV-BS enabled communication systems. In [6], UAV-BS trajectory is designed to minimize the maximum energy consumption of all SNs while ensuring the data of each SN is collected reliably within a certain time, which is defined as *mission time*. UAV-BS is able to approach the SNs location if a longer mission time is given but only able to fly straightly from one side to the opposite side if the given mission time is short. This method seems not efficient to serve a large number of SNs as UAV-BS is required to visit all SNs. In [7], UAV-BS trajectory is designed to minimize the mission time while ensuring each GT (Ground Terminal) recovers the file with a certain probability. The GTs are clustered based on the UAV-BS coverage range threshold, then the center of the clusters are defined as the waypoints. This method seems not effective as some clusters may overlap and still requires an additional algorithm to optimize the visiting order of the waypoints.

This paper proposes a simple trajectory decision method based on sectorized K-means clustering. The aim is to enable the UAV-BS approaches most of the SNs while ensuring the fairness concern. Before executing the K-means clustering, the area is first sectorized exactly with equal size. Then, the initial centroid coordinate of each cluster is randomly generated within each sector area. Thus, this enables clustering without biased centroids. One round trajectory can be simply formed by assigning the UAV-BS to fly to the next centroid within the neighbour sector. Further, RADMA is assigned as the communication protocol to enhance the received signal power and avoid frequent signal collisions. The numerical results have validated that combining RADMA with sectorized k-means clustering-based trajectory enables all SNs can transmit all the data within the mission time and with low transmission energy.

The rest of the manuscript is organized as follows. In Section II, the system model is given. In Section III, the communication protocol is explained. In Section IV, UAV-BS trajectory is described. Finally, some selected simulation results are provided in Section V in order to validate the effectiveness of the proposed method.

II. System Model

A. System Description

A UAV-BS is deployed as a mobile data collector, i.e., FC, to gather information from a WSN consisting of K SNs that generate delay tolerant data packets. The set of SNs is denoted by $\mathcal{K} = \{1, \cdots, K\}$. The 2D (two-dimensional) location of SN $k \in \mathcal{K}$ is denoted by $\mathbf{w}_k = (x_k, y_k) \in \mathbb{R}^{2\times 1}$. All SNs are randomly and uniformly distributed within the coverage area. Each SN transmits the generated sensing data with an omni-directional antenna and a fixed transmission power P_{T}.

B. Channel Model

The communication link between each SN and UAV-BS is modeled with path-loss and shadowing-loss. For the simplicity of the initial stage of this research, the uplink channel is considered to be a non-fading channel. It is reasonable to consider such a non-fading uplink channel as no scatters exist around the UAV-BS [8].

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

$$L_k = \left(\frac{4\pi f_{\mathrm{c}} d_k}{c}\right)^2, \tag{1}$$

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 the UAV-BS can be calculated by

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

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]

$$\psi_{k,\mathrm{dB}} \sim \mathcal{N}(\mu, \sigma_k^2) \tag{3}$$

where,

$$\sigma_k = k_1 \exp(-k_2\theta_k), \tag{4}$$

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.

III. Communication Protocol

In this section, the communication protocols are presented. The transmissions from the SNs are carried out in an autonomously distributed manner based on a random access scheme. To avoid the signal collisions due to the simultaneous transmission of multiple SNs, CSMA/CA (Carrier Sense Multiple Access/Collision Avoidance) is applied. However, the probability of signal collision increases proportionally to the number of SNs in the WSN. This is because as each SN transmits the signal in a distributed manner. This signal collision deteriorates the communication efficiency as the packet retransmission is required. Furthermore, the retransmission consumes the excessive energy at the SNs. Therefore, it is necessary to avoid the excessive signal collision to save the energy consumption of SNs.

A. Conventional Method

UAV-BS is equipped with a single omni-directional antenna to serve the communication area at once. In this protocol, the signal collisions might frequently occur due to the increasing number of SNs served at once.

B. RADMA

UAV-BS is equipped with ULA to serve the SNs. The ULA 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]

$$G_{\mathrm{R},k} = \left|\sum_{n=0}^{N-1} g(\theta_k, \phi_k) \mathrm{e}^{-j2\pi n\Delta \sin\theta_k \cos\phi_k}\right|^2, \tag{5}$$

where N is the number of antenna elements and Δ is the antenna element spacing normalized by the carrier wavelength. $g(\theta_k, \phi_k)$ is the directivity of the antenna element. In this manuscript, a half-wave dipole antenna is used for each antenna element and the directivity $g(\theta_k, \phi_k)$ is given by the following equation [10]:

$$g(\theta_k, \phi_k) = \sqrt{1.64}\cos\left(\frac{\pi}{2}\cos\theta_k\right) / \sin\theta_k. \tag{6}$$

From (6), the maximum value of $g(\theta_k, \phi_k)$ can be obtained at $\theta_k = \pi/2$, which is impossible as SN k has to be at the same altitude as UAV-BS. So it is necessary to arrange the antenna elements with a certain tilt angle θ_{tilt} instead of vertical placement. In this manuscript, the tilt angle θ_{tilt} is determined so that the direction of the main beam towards the center of the coverage radius r, which is defined by the half-length of the sector's side. In this case, the tilt angle θ_{tilt} can be written as the following equation:

$$\theta_{\mathrm{tilt}} = \frac{\pi}{2} - \tan^{-1}\left(\frac{r/2}{H_{\mathrm{UAV}}}\right). \tag{7}$$

Substituting (7) into (5) and (6) gives

$$G_{\mathrm{R},k}=\left|\sum_{n=0}^{N-1} g(\theta_k,\phi_k)\mathrm{e}^{-j2\pi n\Delta\sin(\theta_k+\theta_{\mathrm{tilt}})\cos\phi_k}\right|^2, \tag{8}$$

where

$$g(\theta_k,\phi_k)=\sqrt{1.64}\frac{\cos\left(\frac{\pi}{2}\cos(\theta_k+\theta_{\mathrm{tilt}})\right)}{\sin(\theta_k+\theta_{\mathrm{tilt}})}. \tag{9}$$

The concept of virtual sector is introduced in this method. The virtual sector is formed by the main lobe of the ULA beam. Thus, the whole coverage area is split into partially overlapping virtual sectors. In order to give communication opportunities to all SNs within the communication area, the multiple virtual sectors are created by rotating the UAV-BS horizontally with a specific rotational angle $\theta_{\mathrm{RT}}\in\{0,2\pi\}$ within SNs density adjusted *sector time* $T_{\mathrm{sec},j}$, which is given by

$$T_{\mathrm{sec},j}=\frac{K_j}{K}T_{\mathrm{hover}}, \tag{10}$$

where T_{hover} is the hovering time of UAV-BS [s], $J=2\pi/\theta_{\mathrm{RT}}$ is the number of sectors, and K_j is number of SNs within the virtual sector $j=\{1,\cdots,J\}$.

The probability that multiple SNs simultaneously transmit the signal can be lowered as the communicating SNs are limited per each virtual sector. In addition, the high gain of the ULA can enhance the received signal power from the SNs. Thus, the outage probability, where achievable SNR falls below a certain threshold, can be lowered, and a higher transmission rate can be assigned to shorten the transmission duration.

C. Transmission Rate

The received SNR γ_k from SN k at the UAV-BS can be given by

$$\gamma_k=\frac{P_{\mathrm{T}}}{BN_0}\frac{G_{\mathrm{T}}G_{\mathrm{R}}}{L_k\psi_k}, \tag{11}$$

where $P_{\mathrm{T}},G_{\mathrm{T}},B,N_0$ are the transmission power of SN, the transmit antenna gain at SN, the bandwidth, and the noise power spectrum density, respectively. G_{R} is the received antenna gain at UAV-BS, which is determined by the omni-antenna gain for conventional method, and ULA gain $G_{\mathrm{R},k}$ for RADMA. $\psi_k=10^{\psi_{k,\mathrm{dB}}/10}$. Adopting IEEE 802.11 as the wireless access protocol, each SN can transmit its data with different transmission rates adjusting to the channel condition, e.g., SNR.

D. Required Condition for Successful Decoding

Suppose that the SN k is within the virtual sector j. When a signal collision occurs, the received SINR (Signal power to Interference plus Noise power Ratio) SINR_k of SN k at the UAV-BS is given by

$$\mathsf{SINR}_k=\frac{\frac{P_{\mathrm{T}}}{B}h_k}{\frac{P_{\mathrm{T}}}{B}\sum_{k'\in\mathcal{K}_j}h_{k'}I(k,k')+N_0}, \tag{12}$$

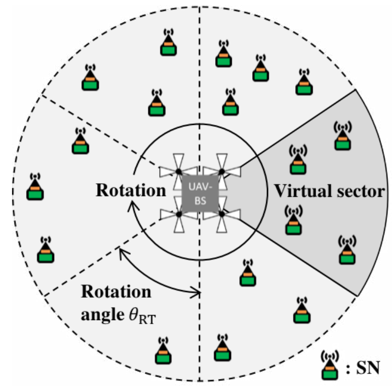

Fig. 1: Virtual sector and rotation concept

where $I(k,k')$ denotes the indicator function indicating that whether the SN k and SN k' can carrier sense with each other, which is given by

$$I(k,k')=\begin{cases}1 & \text{if SN } k' \text{ cannot sense SN } k\\ 0 & \text{otherwise}\end{cases}, \tag{13}$$

In this paper, the SN whose transmitted frame (signal) received by FC first is defined as the desired user. Even when a frame collision occurs, it is assumed that the frame is decodable if the following condition is satisfied.

$$\min\{\mathsf{SINR}_k\}\geq\rho_{\mathrm{th},k}, \tag{14}$$

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

IV. UAV-BS Trajectory

In this section, the UAV-BS trajectory is described. UAV-BS is assigned to temporarily hover at a specific coordinate to serve the SNs located around the coordinate. Then, move to the next coordinate and temporarily hover to serve SNs surround. UAV-BS is set to start to fly from an initial coordinate and required to come back to the initial coordinate within a predetermined time, which is defined as mission time T_{mission}.

A. Circle-Shaped Trajectory

UAV-BS is assigned to fly on a circle-shaped trajectory. The coordinates, where UAV-BS temporarily hovers at, are uniformly spaced on the circle-shaped trajectory. To prioritize the SNs at the edge of the WSN area, the radius of the circle-shaped trajectory is set to $L/3$, where L is the length of the WSN area.

B. K-means Clustering Based Trajectory

The trajectory is formed by the link connection between deployment coordinates. The trajectory coordinates are defined by the centroids of SNs clusters, which means that UAV-BS is required to move from one centroid to other centroids. Therefore, the clustering method and coordinates visiting order will bring a significant impact on the performance. Creating uniform centroids deployment within the area is the key point to provide uniform QoS among all SNs. However, the clustering method that creates uniform centroids gives an extra task to UAV-BS due to its complexity. Thus, it is essential to consider the complexity of the clustering method.

K-means clustering method is considered in this paper. The reason is the simple and computationally light algorithm which is suitable to UAV-BS with limited computing resource. However, the generated cluster depends on the initial centroid. Thus, a biased centroids deployment possibly happens as the centroids of the clusters are randomly initialized. As a consequence, some particular SNs may suffer poor channel conditions due to the long communication link.

The visiting order of the centroids is not a negligible issue due to the randomness of the centroids deployment as UAV-BS is required to fly from an initial coordinate and come back again to the initial coordinate within a predetermined mission time T_{mission}. Thus, an algorithm to find the best visiting order is required to minimize the flying distance. However, applying such additional algorithm may lead tasks increment which is not suitable for a UAV-BS with limited energy and computer resource.

C. Sectorized K-means Clustering Based Trajectory

This trajectory method is the extension version of the K-means clustering based trajectory. Before executing the K-means clustering method, the area is divided into 9 sectors with equal size as shown in Fig. 2. The initial centroid of each cluster is generated randomly within each sector area. Hence, the biased centroids deployment, described previously, can be avoided.

The center sector is not necessarily to be served particularly as the SNs located surrounding the center sector can be served by the UAV-BS when serving around the other 8 sectors. Further, an algorithm to find the best visiting order is unnecessary as UAV-BS is only needed to fly to the next centroid within the neighbour sector. Thus, one round trajectory can be simply formed.

In Fig. 2, an example of SNs clustering generated by K-means and sectorized K-means is shown. Fig. 2 shows that the centroids generated by K-means clustering are biased due to the randomness of the initial centroids. This problem can be solved by sectorized K-means clustering as the initial centroids are generated within each sector. Thus, a uniform QoS among SNs is realizable to be provided by deploying UAV-BS with the trajectory formed by the centroids of sectorized K-means clustering method.

D. Combination of RADMA and Sectorized K-means Based Trajectory

The combination of RADMA as the communication and sectorized K-means clustering based trajectory as the UAV-BS trajectory decision method is considered in this paper. As shown in Fig. 3, the direction of the ULA's main lobe is required to be considered according to the serving location of the UAV-BS. When UAV-BS is serving at the corner sectors, the direction of the ULA's main lobe should be toward the edge of the WSN area to prioritize the SNs located at the edge. However, when the UAV-BS is serving in the inner sectors, the direction of the ULA's main lobe should be towards the center sector to prioritize the SNs located in the center sector.

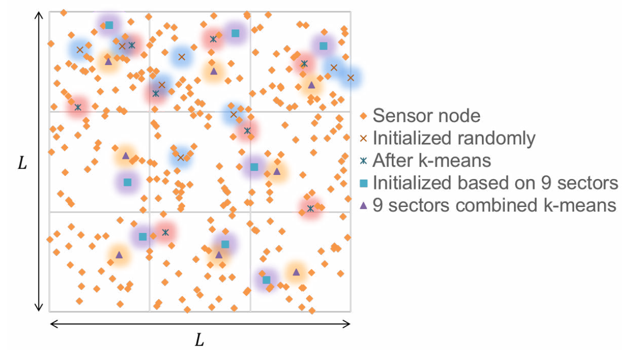

Fig. 2: Sectorized k-means clustering based coordinates

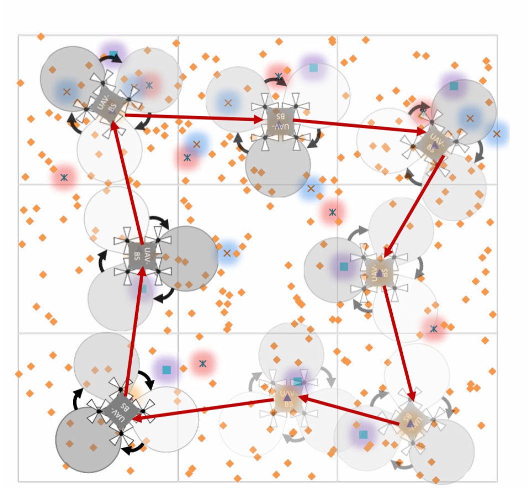
Fig. 3: Combination of sectorized k-means and RADMA

In RADMA, the received signal power of SNs can be enhanced due to the high gain of ULA. Thus, the achievable SNR is still possible to surpass the required SNR threshold even with a large path-loss due to the long communication distance. Hence, SNs are possible to communicate in more than one cluster. When the data transmitting is not completed yet, this method enables the SNs to continue transmitting the data when the UAV-BS moves to the next coordinate to hover.

E. Hovering Time

It is important to note that the assignment of the hovering time T_{hover} of UAV-BS has a significant impact on system performance. On one hand, a longer T_{hover} provides more time for the UAV-BS to serve a particular cluster. Thus, the probability for all the SNs within the cluster can transmit all the data increases. On the other hand, a longer T_{hover} also incurs a more substantial

TABLE I: Computer simulation parameters

Parameters	Values
Coverage area	2000×2000 [m^2]
Number of SNs	$K = 200$
UAV-BS altitude	$H_{\mathrm{UAV}} = 30$[m]
UAV-BS flying speed	$v_{\mathrm{UAV}} = 10$[m/s]
UAV-BS antenna elements	$N = 3$
Normalized antenna spacing	$\Delta = 0.5$
Rotation angle	$\theta_{\mathrm{RT}} = \frac{2\pi}{3}$ [radian]
SN's height	0.1 [m]
SN's antenna gain	$G_{\mathrm{T}} = 0$ [dBi]
SN's transmit power	$P_{\mathrm{T}} = 10$ [mW]
SN's data size	$S = 50$ [Mb]
Carrier frequency	$f_{\mathrm{c}} = 2.4$ [GHz]
Bandwidth	$B = 20$ [MHz]
Noise power density	$N_0 = -174$ [dBm/Hz]
Noise figure	10 [dB]
k_1, k_2, g_1, g_2	10.39, 0.05, 29.06, 0.03
$\mu_{\mathrm{LoS}}, \mu_{\mathrm{NLoS}}$	1, 10 [dB]
α, β	0.6,0.11

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

access delay for SNs existing outside of the cluster which is currently being served. Instead of fixing to a specific value, adjusting the hovering time $T_{\mathrm{hover},c}$ to the number of SNs K_c within the cluster c is also considered to enhance the network performance, which is given by

$$T_{\mathrm{hover},c} = \frac{K_c}{K} \left(T_{\mathrm{round}} - T_{\mathrm{fly}} \right), \tag{15}$$

where the flying time T_{fly} is the required time to fly from initial coordinate until come back to the initial coordinate after finishing visiting all the coordinates, which is given by

$$T_{\mathrm{fly}} = \frac{L_{\mathrm{round}}}{v_{\mathrm{UAV}}}, \tag{16}$$

where L_{round} is the one round flying distance, which is defined by the total distance from the initial coordinate until back again to the initial coordinate after visiting all coordinates, and v_{UAV} is the flying speed of UAV-BS.

V. Numerical Results

In this section, the numerical results are provided. These results are obtained by executing computer simulation and the system model is reconstructed into C language. SNs $K = 200$ are randomly located within an area with length of side $L = 2000$ [m]. The hovering altitude H_{UAV} and flying speed v_{UAV} are set to 30 [m] and 10 [m/s], respectively. The number of antenna elements N of the ULA at UAV-BS is set to 3, and the normalized antenna elements spacing Δ is set to 0.5. Transmit power P_{T} and antenna gain G_{T} at SN are set to 10 [mW] and 0 [dBi], respectively. All SNs are set to transmit data with size of 50 [Mb]. The carrier frequency is set to $f_{\mathrm{c}} = 2.4$ [GHz] and the bandwidth is $B = 20$ [MHz]. The noise variance is set to $\sigma^2 = -174$ [dBm/Hz] and the noise figure is 10 [dB]. Mission time T_{mission} is taken as a parameter.

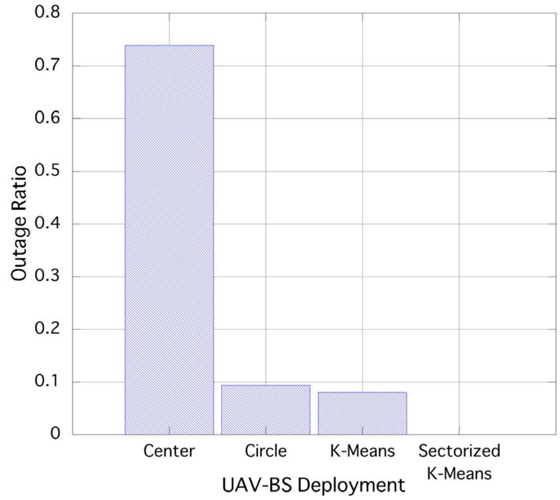

Fig. 4: Outage Ratio vs UAV-BS Deployment

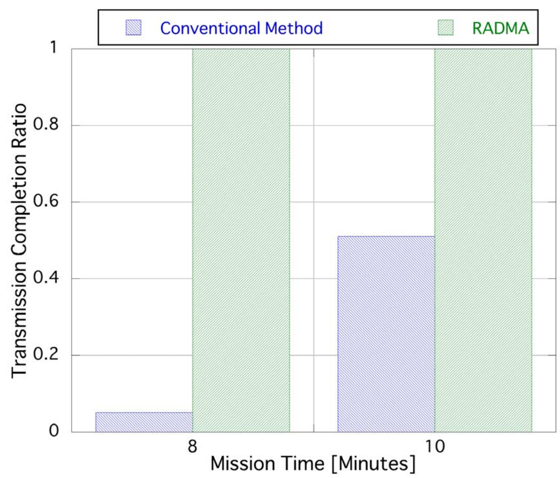

Fig. 5: Completed Transmission Ratio vs Mission Time

First of all, let us evaluate the impact of different UAV-BS deployment on the outage ratio of SNs. In this paper, SN k is considered in outage when the received SNR γ_k of SN k falls below a certain threshold, which is 4 [dB] as shown in TABLE II. Here, the conventional method with an omni-directional antenna is adopted as the communication protocol. The center deployment means that the UAV-BS is deployed at the center of the WSN area. For the dynamic deployments, the number of the trajectory's coordinates is set to 8.

Fig. 4 clearly shows that the outage ratio can be lowered by deploying the UAV-BS according to the sectorized K-means clustering based trajectory. The reason is that the UAV-BS can reach all the SNs while keeping fairness among SNs. Thus, this trajectory method will be assigned to present the performances comparison of conventional method and RADMA further.

Next, the probability that the SNs can complete the data transmission within mission time $T_{\text{mission}} \in \{8, 10\}$ [mins] is shown in Fig. 5. As can be seen from Fig. 5, all SNs can complete the data transmission within T_{mission} by combining RADMA as the communication protocol and sectorized K-means clustering based trajectory as the UAV-BS trajectory decision method. The reason for this performance improvement is because the SNs can transmit the data at a higher data rate due to the enhanced received signal power by the high gain of ULA, and the capability to transmit the data within multiple clusters.

In Fig. 6, the signal collision ratio occurred during the transmission is shown. Signal collision ratio is defined as the ratio of the collided transmission's number and the total transmission's number. Fig. 6 shows that the signal collision ratio is lower when applying RADMA compared to the conventional method. This is because the number of communicating SNs can be limited as each cluster is served per each virtual sector in RADMA.

In Fig. 7, the average required transmission energy of each SN to complete the data transmission is shown. It can be seen from Fig. 7, the average required transmission energy can be suppressed by applying RADMA compared to the conventional method. The reason is that the SNs can complete the data transmission within a shorter time due to the high transmission rate and low retransmission frequency due to the capability to communicate effectively.

VI. Conclusion

A low power consumption and efficient communication scheme is crucial to boost the data collecting effectivity in a WSN with a large number of SNs. First, RADMA has been introduced as the communication protocol to enhance the received signal power and avoid frequent signal collisions. Then, the combination of RADMA and sectorized k-means clustering based trajectory is proposed to ensure a target amount of data from all SNs can be reliably collected within the predetermined mission time. The numerical results have verified that the proposed trajectory decision method enabled the UAV-BS to suppress the outage ratio. Further, by combining this trajectory method with RADMA, all SNs are enabled to transmit all the data within the mission time and with low transmission energy.

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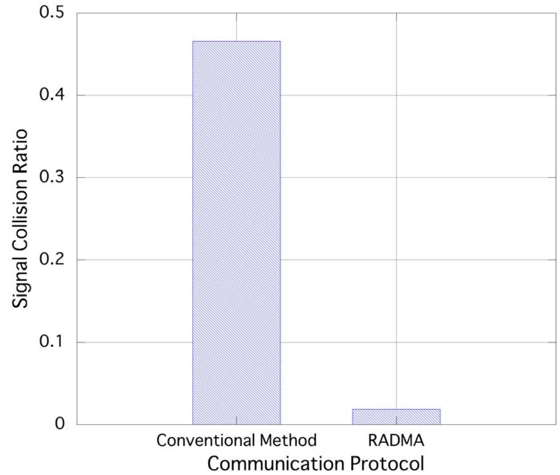

Fig. 6: Collision Ratio vs Communication Protocol

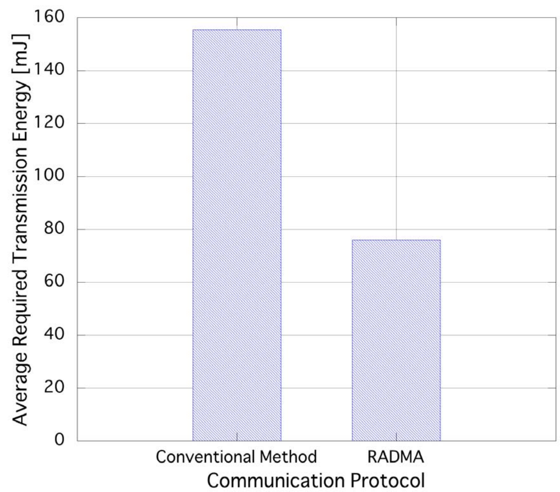

Fig. 7: Transmission Energy vs Communication Protocol

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