Handover Game for Data Transportation over Dynamic UAV Networks with Predictable Channels

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***Abstract*—This paper studies a decentralized transmission strategy for delay-tolerant wireless data transportation over unmanned aerial vehicle (UAV) networks, where a team of UAVs is employed for data transportation as a secondary task without altering the preset courses of the UAVs from their primary tasks. The key novelty yet challenge is to exploit the predicted channel knowledge among the UAVs to optimize the transmission strategy. Much prior work focuses on multi-UAV cooperation from a centralized perspective, or in a distributed manner but requiring intensive message exchange. This paper develops a team strategy following a game-theoretical approach, where the data packets are passed from one node to the other according to the handover time that is negotiated in a fully distributive way. A Handover Game is thus formulated and is proven that the Nash equilibriums (NEs) are the stationary points of an energy minimization problem for coordinated data transportation. A neighbor coordinate response strategy is designed, which is shown to converge faster than a classical asynchronous response in a multi-player game. Numerical experiments show that the proposed scheme substantially reduces transmission energy from classical relay or data ferry schemes.**

***Index Terms*—Handover Game, energy optimization, UAV networks, predictable channels.**

I. Introduction

With the rapid development of Internet-of-Thing (IoT) networks, there is intense pressure on the communication infrastructure to enhance the data collection capability for wireless sensors. As many IoT sensors are battery-powered, they prefer short-range and line-of-sight (LOS) communications for energy-efficient transmission [1]. However, it is not always feasible to deploy base stations (BSs) close enough to all sensors to establish the short-range and LOS condition. To tackle such a dilemma, unmanned aerial vehicles (UAVs) may serve as a good candidate. First, it has been a trend to employ UAVs for cargo delivery, environment monitoring, and so on, which establishes a natural opportunity to employ UAVs as data ferries to assist data collection, data relaying, and data transportation. Second, UAVs experience a better chance for short-range and LOS communications with ground nodes [2].

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We consider employing low altitude UAVs for wireless data collection and transportation as a side task for the UAVs. Specifically, consider a team of UAVs that follow a set of predetermined and fixed courses set by other tasks, where one of the UAVs happens to pass by the source area with sensors requesting communication assistance, and another UAV passes by the fusion center, which is the communication target of the sensors. We propose employing the UAV team as *opportunistic* communication relays to collect data from the source and transport it to the fusion center without altering the preset courses of the UAVs while fulfilling the delay constraint of the transmission. As data transportation is a side task of the UAV team, it is crucial to minimize the energy consumption for the communication. As a key novelty of this work, it is essential to exploit the predicted channel knowledge among the UAVs for optimizing the transmission strategy, because the routes of the UAVs have been predetermined from higher-level tasks.

While there has been much work related to UAV-assisted data collection and multi-hop transmission, it is not yet well-understood how to exploit the trajectory information of the dynamic UAV network to assist delay-tolerant transmission. Most recent work focused on single UAV deployment for enhancing network performance, e.g., for data collection [3], for device-to-device (D2D) relay [4], for coverage enhancement [5]. To provide large-range service support, [6] divided the large service area into multiple small areas and deployed one UAV to serve each small area. However, the lack of cooperation or communication among UAVs limits their performance.

To facilitate the cooperation among UAVs, the instantaneous transmission among UAVs was modeled to optimize network connectivity and multi-UAVs data relaying [7]. To accomplish the delay-tolerant transmission task, [8] weighted the effect of the delay to design transmission policy. Whereas, instantaneous end-to-end transmission on multi-hop link is inefficient in long-distance transmission scenario, since the worst channel dominates its performance. Some work utilizes cache-and-pass topology to design multi-UAVs cooperation strategies, in which the UAV allows to transmit to the target when they are close enough. For example, in [9], a cooperative UAV sense-and-send protocol is proposed for UAV route choice; in [10], a multi-hop delay-tolerance transmission scheduling is designed

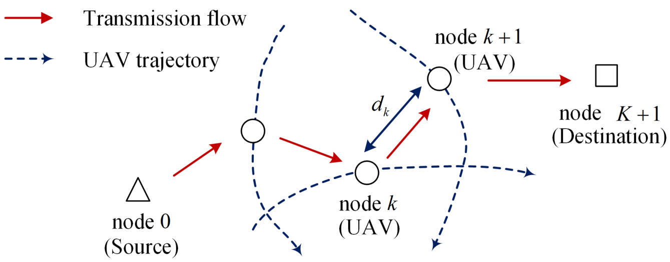

Figure 1. Illustration of data delivery scenario where multiple UAVs establish the relay path between the sensor and the fusion center.

for full channel state information (CSI) and queue state information (QSI) environment. These works developed best-effort multi-hop ferry strategies from the centralized perspective, or in a distributed manner but requiring intensive message exchange; however, such the methods will cause huge communication overload and high computational complexity. Most existing approaches developed for delay-tolerant transmission in sensor networks were based on Markov decision process or dynamic programming [11]. However, existing approaches did not exploit the deterministic trajectories for the dynamic UAV network, and the reinforcement learning assisted solutions usually suffer from high complexity and lack of theoretical insights.

In this paper, we study UAV-team-assisted data collection and transportation for remote sensor nodes with delay tolerance comparable with the travel time of the UAVs passing the target area. The goal is to minimize the communication energy consumption with limited coordination among UAVs. It is found that it is *not* energy-efficient to establish an end-to-end multi-hop UAV relay channel for data flow transmission. Instead, a better relaying strategy is to *cache* the data and *pass* it on to the next UAV until the two UAVs are close enough to each other. Therefore, the key challenge is to design an efficient distributed mechanism to optimize the transmission timing for each UAV. Towards this end, we propose a team strategy, an efficient negotiation process to find the *handover time*.

Our key contributions are made as follows:

- We formulate the handover time negotiation process as a non-cooperative game and prove that the pure strategy Nash equilibrium (NE) always exists, and the NEs are the stationary points of the original problem. A neighbor coordinate strategy is proposed to reach the NE in a distributive way, and is shown to converge faster than a classical asynchronous response for a multi-player game.
- We perform numerical experiments to show that the proposed scheme outperforms real-time relay scheme and equal-interval ferry scheme.

II. System Model

Consider a team of K UAVs that follow a set of preset and fixed courses to fly over an area, where there is a source node that needs to transmit some data to a destination node at a distance. Consider exploiting the UAVs to relay the data from the source node to the destination node, as illustrated in Fig. 1. The total amount of data is S bits, and the tolerable end-to-end delay is T seconds. The UAVs operate at half-duplex model and the transmission order is fixed. Without loss of generality, we assume the source node first transmits to the first UAV, which relays the message to the second UAV, and so on; finally, the Kth UAV relays the data to the destination node. In this paper, we assume the transmission order has been configured by an upper-level strategy that takes into account the chronological order that the UAVs enter the target area; however, the design of such a protocol is out of the scope of this paper.

Denote the position of node k at time t as $\mathbf{x}_k(t)$. The distance between the kth node and the next node, *i.e.*, node $k+1$, is denoted as $d_k(t) = \|\mathbf{x}_{k+1}(t) - \mathbf{x}_k(t)\|_2$. Here, we assume each UAV k only knows the trajectories of its own and its neighbors, *i.e.*, node $k-1$ and node $k+1$. The goal of this paper is to design decentralized transmission strategy for the team of UAVs to minimize their communication energy based on *local* information and coordination. The key novelty yet challenge of the design is to exploit the local information of the complete trajectories $\mathbf{x}_k(t)$ of the UAVs to optimize the team transmission strategy for delay-tolerant data transportation.

A. Channel Model

Assume that the channel gain $g_k(d_k(t))$ from the kth node to the $(k+1)$th node is a deterministic function of distance $d_k(t)$, and hence, can be completely characterized ahead of time, given the preset trajectories $\mathbf{x}_k(t)$. Such distance-dependent channel models are widely adopted in UAV communications [12], since UAV communication links are most likely in LOS condition. For example, the channel gain can be modeled as $g_k(t) = \beta_0 \frac{(d_k(t))^{-\alpha}}{N_0 B}$, where β_0 is a power gain factor, α is the path loss exponent, N_0 is the noise density, and B is the transmission bandwidth.

Let $p_k(t)$ be the power transmitted by the kth node. The instantaneous channel capacity is modeled as

$$c_k(t) = B\log_2(1 + \kappa p_k(t) g_k(t))$$

where κ is a parameter to back off for small-scale fading, digital modulation, and coding loss.

B. Decentralized Relay Transmission Model

If global information were available, the instantaneous end-to-end capacity of the $(K+1)$-hop decode-and-forward relay channel can be modeled as $\frac{1}{K+1}\min_k\{c_k(t)\}$, where the factor $\frac{1}{K+1}$ assumes the UAVs use shared time-frequency resources and operate in a half-duplex mode. It is not surprising to note that transmitting at the instantaneous end-to-end capacity is inefficient because the performance is dominated by the worst link. Another possibility is to truncate the source package into small pieces, and design cache-and-pass strategy for each sub-packet; thus, multiple links can be activated in the same time frame. However, this strategy requires global coordination among UAVs for interference management and handling the

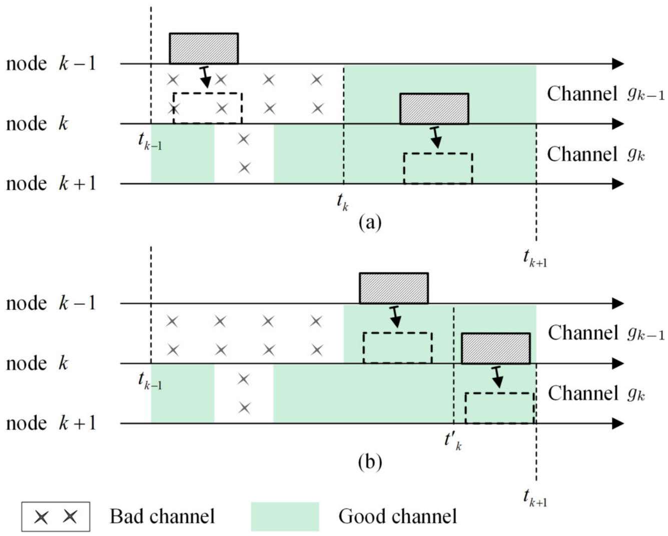

Figure 2. Cache-and-Pass transmission protocol. The handover time t_k in (a) changes to t'_k in (b). (a) is not desired since it requires more energy due to the bad channel utilization, whereas, (b) is better than (a).

causality of data transmission, resulting in high complexity and coordination overhead.

To seek a better trade-off between the performance and the coordination overhead, this paper proposes a *cache-and-pass* protocol, where the entire packet is transmitted sequentially from one UAV to another, and the transmission occurs only when the channel is good enough. This is illustrated in Fig. 2. Specifically, given an end-to-end delay tolerance T, define t_k's with $0 \le t_1 \le t_2 \le \cdots \le t_K \le T$. In our context, t_k is termed as the *handover time*, where node k transmits to node $k+1$ only in the kth *transmission period* $[t_k, t_{k+1})$. For notation convenience, set $t_0 = 0$ and $t_{K+1} = T$.

In this paper, we assume that given the transmission interval $[t_k, t_{k+1})$, node k can get the optimal transmission energy, $E_k^*(t_k, t_{k+1}) \triangleq \min_{p_k(t)} \int_{t_k}^{t_{k+1}} p_k(t)\, dt$, while keeping the full data transmission $\int_{t_k}^{t_{k+1}} c_k(t)\, dt \ge S$. In addition, $E_k^*(t_k, t_{k+1})$ is only related to the handover time, t_k and t_{k+1}, and continuous. One possible solution is Water-filling algorithm. This paper only focuses on the UAV negotiation process for determining the handover time t_k's.

C. Problem Formulation

Given the delay tolerance T, nodes negotiate with their neighbors to determine the handover time t_k's to minimize the total energy consumption, as formulated in the following

$$\mathscr{P}1: \quad \underset{t_1, t_2, \cdots, t_K}{\text{minimize}} \quad E_{\text{tot}} = \sum_{k=0}^{K} E_k^*(t_k, t_{k+1}) \tag{1}$$

$$\text{subject to} \quad 0 \le t_1 \le t_2 \le \cdots \le t_K \le T. \tag{2}$$

Note that the challenge in solving $\mathscr{P}1$ is that global information is not available at the nodes. The remaining part of the paper aims at developing coordination strategy to exploit the predicted channel knowledge $g_k(t)$ in a distributed way.

III. Team Strategy

As it is formulated in Section II, the set of nodes aims at minimizing the global energy consumption in (1), where each node k only has the local information on the channel gain $g_k(t)$ and $g_{k-1}(t)$, *i.e.*, the channels connected to the neighbors of node k. As a result, each node k only has access to the local cost

$$\Lambda_k(t_k, \boldsymbol{t}_{-k}) = E_{k-1}^*(t_{k-1}, t_k) + E_k^*(t_k, t_{k+1}) \tag{3}$$

which contributes to a portion of the global cost in (1). Here, the variable $\boldsymbol{t}_{-k} \triangleq \{t_j\}_{j \ne k}$ is a collection of handover time to be determined by nodes other than k.

A. The Game Formulation

The distributed structure of the cost and information naturally leads to a game for the handover time

$$\mathcal{G}: \quad \underset{t_k}{\text{minimize}} \quad \Lambda_k(t_k, \boldsymbol{t}_{-k}) \tag{4}$$

$$\text{subject to} \quad t_{k-1} \le t_k \le t_{k+1} \tag{5}$$

for all $k \in \mathcal{K}$, where $\mathcal{K} = 1, 2, \cdots, K$ is the set of nodes (players of the game). Denote $\boldsymbol{\mathcal{T}}$ as the set of possible combinations of the transmission space, $\mathcal{T}_k = [t_{k-1}, t_{k+1}]$ as the strategy space of node k, and $\boldsymbol{\mathcal{T}}_{-k}$ as the set of possible combinations of the transmission space of all nodes except for node k, such that the constraint $0 \le t_1 \le t_2 \le \cdots \le t_K \le T$ holds.

The notation of NE of $\mathcal{G}$ is defined as follows.

Definition 1. (Nash Equilibrium). A set of handover time $\boldsymbol{t}^* = (t_1^*, t_2^*, \cdots, t_K^*)$ is called an NE (in pure strategies) if and only if (iff) the following holds:

$$\Lambda_k\left(t_k^*, \boldsymbol{t}_{-k}^*\right) \le \Lambda_k\left(t_k, \boldsymbol{t}_{-k}^*\right), \forall t_k \in \mathcal{T}_k, \forall k \in \mathcal{K}.$$

The NE in the Handover Game is a handover time allocation profile $\{t_k\}$ for all the nodes in the network that none of the nodes can benefit from changing its own handover time unilaterally. The Handover Game $\mathcal{G}$ can be interpreted as each node "persuading" its neighbors to bring it more transmission time, at the same time, trying to minimize its own energy cost. The notion of the NE thus characterizes the situation where the nodes reach an agreement on the handover time allocation.

To study the existence and property of the NE, we exploit the notion of *potential game* defined as follows.

Definition 2. (Exact potential game). A game is called an exact potential game, if there exists a function $\psi : \boldsymbol{\mathcal{T}} \to \mathbb{R}$ such that for all $k \in \mathcal{K}$, for all $\boldsymbol{t}_{-k} \in \boldsymbol{\mathcal{T}}_{-k}$, and for all $t'_k,\ t''_k \in \mathcal{T}_k$, the following equation holds:

$$\psi(t'_k, \boldsymbol{t}_{-k}) - \psi(t''_k, \boldsymbol{t}_{-k}) = \Lambda_k(t'_k, \boldsymbol{t}_{-k}) - \Lambda_k(t''_k, \boldsymbol{t}_{-k}).$$

Moreover, the function ψ is called a potential function.

In an exact potential game, the change in the utility of a node due to its own strategy deviation results in exactly the same amount of change in the potential function.

$$\frac{d}{d\boldsymbol{t}}\psi=\begin{pmatrix}\frac{d}{dt_1}\psi\\ \frac{d}{dt_2}\psi\\ \vdots\\ \frac{d}{dt_K}\psi\end{pmatrix}=\begin{pmatrix}\frac{d}{dt_1}\sum_{k=0}^{K}E_k^*\left(t_k,t_{k+1}\right)\\ \frac{d}{dt_2}\sum_{k=0}^{K}E_k^*\left(t_k,t_{k+1}\right)\\ \vdots\\ \frac{d}{dt_K}\sum_{k=0}^{K}E_k^*\left(t_k,t_{k+1}\right)\end{pmatrix}=\begin{pmatrix}\frac{d}{dt_1}\left(E_0^*\left(t_0,t_1\right)+E_1^*\left(t_1,t_2\right)\right)\\ \frac{d}{dt_2}\left(E_1^*\left(t_1,t_2\right)+E_2^*\left(t_2,t_3\right)\right)\\ \vdots\\ \frac{d}{dt_K}\left(E_{K-1}^*\left(t_{K-1},t_K\right)+E_K^*\left(t_K,t_{K+1}\right)\right)\end{pmatrix}=\begin{pmatrix}\frac{d}{dt_1}\Lambda_1\left(t_1,\boldsymbol{t}_{-1}\right)\\ \frac{d}{dt_2}\Lambda_2\left(t_2,\boldsymbol{t}_{-2}\right)\\ \vdots\\ \frac{d}{dt_K}\Lambda_K\left(t_K,\boldsymbol{t}_{-K}\right)\end{pmatrix} \tag{6}$$

It turns out that the Handover Game $\mathcal{G}$ is an exact potential game.

Proposition 3. *Game $\mathcal{G}$ is an exact potential game with a potential function given by $\psi\left(\boldsymbol{t}\right)=\sum_{k=0}^{K}E_k^*\left(t_k,t_{k+1}\right)$.*

Proof: Given arbitrary t_k', $t_k''\in\mathcal{T}_k$ and $\boldsymbol{t}_{-k}\in\boldsymbol{\mathcal{T}}_{-k}$, then the deviating value of the function ψ is

$$\begin{aligned}&\psi\left(t_k',\boldsymbol{t}_{-k}\right)-\psi\left(t_k'',\boldsymbol{t}_{-k}\right)\\ =&E_{k-1}^*\left(t_{k-1},t_k'\right)+E_k^*\left(t_k',t_{k+1}\right)+\sum_{i\neq k-1,k}E_i^*\left(t_i,t_{i+1}\right)\\ &-E_{k-1}^*\left(t_{k-1},t_k''\right)-E_k^*\left(t_k'',t_{k+1}\right)-\sum_{i\neq k-1,k}E_i^*\left(t_i,t_{i+1}\right)\\ =&\left(E_{k-1}^*\left(t_{k-1},t_k'\right)+E_k^*\left(t_k',t_{k+1}\right)\right)\\ &\qquad-\left(E_{k-1}^*\left(t_{k-1},t_k''\right)+E_k^*\left(t_k'',t_{k+1}\right)\right)\\ =&\Lambda_k\left(t_k',\boldsymbol{t}_{-k}\right)-\Lambda_k\left(t_k'',\boldsymbol{t}_{-k}\right).\end{aligned}$$

This shows that, when node k switches from action t_k' to action t_k'', the change in the function ψ equals the change in the cost Λ_k of that player. Thus ψ is a potential function of $\mathcal{G}$ and the proposed Handover Game $\mathcal{G}$ is an exact potential game. ■

The exact potential game leads to the existence of a pure NE as shown in the following result.

Proposition 4. *(Existence of the NE). There always exists a pure strategy NE for the game $\mathcal{G}$.*

Proof: For each player k, its strategy profile $\mathcal{T}_k$ is $[t_{k-1},t_{k+1}]$, which is compact. Therefore, the Cartesian product of compact set, $\boldsymbol{\mathcal{T}}$, is compact. In addition, ψ is continuous since function $E_k^*\left(t_k,t_{k+1}\right)$ with respect to (w.r.t.) t_k and t_{k+1} is continuous. As a result, potential game $\mathcal{G}$ always has a pure strategy according to [13, Theorem 2.3]. ■

Note that the potential function is exactly the objective function of problem $\mathscr{P}1$. Denote the set of optimal solutions t_k's to $\mathscr{P}1$ as $\boldsymbol{\mathcal{P}}$. The following proposition shows that the relationship between the NEs of $\mathcal{G}$ and the solution to $\mathscr{P}1$.

Proposition 5. *(Connection between the NE and the solution to $\mathscr{P}1$). i) If $\boldsymbol{t}^*\in\boldsymbol{\mathcal{P}}$, then $\boldsymbol{t}^*$ is an NE of $\mathcal{G}$; ii) Suppose that the potential function ψ is differentiable. If $\boldsymbol{t}^*$ is an NE of $\mathcal{G}$, then $\boldsymbol{t}^*$ is a stationary point of $\mathscr{P}1$.*

Proof: Suppose that $\boldsymbol{t}^*=(t_1^*,t_2^*,\cdots,t_K^*)$ is one of the minimizers for problem $\mathscr{P}1$. Thus for all $\boldsymbol{t}'\in\boldsymbol{\mathcal{T}}$, we have $\psi\left(\boldsymbol{t}^*\right)\leq\psi\left(\boldsymbol{t}'\right)$. This suggests that for all player k, there is no better strategy, otherwise, $\boldsymbol{t}^*$ is not a minimizer because the change in the function ψ equals to the change in the cost function Λ_k. Thus we have that $\boldsymbol{t}^*$ must be an NE of $\mathcal{G}$.

Under the differentiable hypothesis, the derivative of function ψ can be presented by (6). Suppose that $\boldsymbol{t}^*=(t_1^*,t_2^*,\cdots,t_K^*)$ is an NE of $\mathcal{G}$. Thus $\forall k\in\mathcal{K}$, we have $\frac{d}{dt_k}\Lambda_k\left(t_k,\boldsymbol{t}_{-k}\right)\big|_{t_k=t_k^*}=0$ because the best response must locate in the stationary points rather than the boundary where the utility value is infinity. Thereby, the derivative of the potential function $\frac{d}{d\boldsymbol{t}}\psi\,|_{\boldsymbol{t}=\boldsymbol{t}^*}=\boldsymbol{0}$. In other words, $\boldsymbol{t}^*$ is a stationary point of $\mathscr{P}1$. ■

Therefore, in an ideal case where the potential function has a unique stationary point, searching for the NE is equivalent to solving problem $\mathscr{P}1$.

B. Neighbor Coordinate Response

Here, we derive a distributed strategy to reach an NE. Assume that each node k updates its strategy t_k via a *better response*

$$\pi_k\left(\boldsymbol{t}\right)=\left\{t_k^\star\in\mathcal{T}_k:\Lambda_k\left(t_k^\star,\boldsymbol{t}_{-k}\right)<\Lambda_k\left(t_k,\boldsymbol{t}_{-k}\right)\right\}; \tag{7}$$

or the *best response*

$$\pi_k\left(\boldsymbol{t}\right)=\left\{t_k^\star\in\mathcal{T}_k:t_k^\star=\arg\min_{t_k\in\mathcal{T}_k}\Lambda_k\left(t_k,\boldsymbol{t}_{-k}\right)\right\} \tag{8}$$

based on the updated strategy passing from its neighbors.

However, under such a distributed mechanism, the game is not guaranteed to converge. For example, it may happen that two nodes simultaneously update their strategy, and it takes time for their updated strategies to propagate to all the other nodes in the game. It is known that such a scenario may lead to the oscillation between two solutions. On the other hand, sequential update is known to converge to an NE of a potential game [13], and it can be implemented in a distributive way using tokens passing from one node to another. However, the sequential update is highly inefficient as the number of nodes grows. Therefore, the challenge here is to design a distributed mechanism that guarantees convergence to an NE while being more efficient than sequential updates.

With such a goal, we develop a distributed strategy based on the notion of *independent group*.

Definition 6. (Dependent node and independent group): Node k depends on node j if the strategy t_j of node j affects the response $\pi_k\left(\boldsymbol{t}\right)$ of node k. An independent group under game $\mathcal{G}$ is a set of nodes that none of them depends on the other.

Proposition 7. *(Independent groups): In game $\mathcal{G}$, the set of odd-number nodes forms an independent group, and the set of even-number nodes forms another independent group.*

Proof: Denote the odd-number-node set as $\mathcal{K}_1$ and the even-number-node set as $\mathcal{K}_2$. Given any odd-number node $k\in$

$\mathcal{K}_1$, the variable t_j, $j \in \mathcal{K}_1$, does not appear in either the objective (4) or the constraint (5) when node k computes its strategy. This is because the only strategies that can affect the response $\pi_k(\boldsymbol{t})$ of node k are t_{k-1} and t_{k+1}, which do not belong to odd-number nodes. Thus, the set of odd-number nodes forms an independent group. Similarly, we have the set of even-number nodes forms another independent group. ■

Based on the property of independent groups, we propose the following *neighbor coordinate* strategy:

- Each update is associated with a token n, indicating the nth update from node k, and the tuple $\left(t_k^{(n)}, n\right)$ is passed to the neighbors when the nth update is computed;
- For each odd-number node, compute the $(n+1)$th round response only when both its neighbors finish the nth round response;
- For each even-number node, compute the $(n+1)$th round response only when both its neighbors finish the $(n+1)$th round response.

It is efficient because ideally half of the nodes can compute their updates in parallel. It also avoids the potential convergence issue from parallel update, because the token passing mechanism guarantees that if the strategies of two nodes depend on each other, the two nodes are not allowed to update simultaneously.

Proposition 8. *(Convergence): The neighbor coordinate update with better or best response converges to an NE of $\mathcal{G}$.*

Proof: Denote the odd-number-node set and the even-number-node set as $\mathcal{K}_1$ and $\mathcal{K}_2$. According to neighbor coordinate strategy, the response policy for odd-number node $k \in \mathcal{K}_1$ can represent as $t_k^{(n+1)} \in \pi_k\left(t_{k-1}^{(n)}, t_{k+1}^{(n)}\right)$, and for even-number node $k \in \mathcal{K}_2$ can represent as $t_k^{(n+1)} \in \pi_k\left(t_{k-1}^{(n+1)}, t_{k+1}^{(n+1)}\right)$. This suggests that for an arbitrary nth update, the neighbors will not response simultaneously but in a sequential way, however the nodes in a set, $\mathcal{K}_1$ or $\mathcal{K}_2$, can response parallelly. An extreme case is that all odd-number nodes update simultaneously then all odd-number nodes update simultaneously. According to Proposition 7, $\mathcal{K}_1$ and $\mathcal{K}_2$ are two independent groups. Thus there is no interdependent among updates in each set. In other words, the utility deviate of the nth update is non-positive for all nodes when one group finishes the nth-round better or best response. Then, according to Proposition 3, the objective value deviate is also non-increasing for each group updates, and monotonically decreasing w.r.t. the update-round n before reaching the equilibrium.

In addition, the objective function is bounded below, always greater than zero. As a result, when n goes to infinity, the value of the objective function on the strategy $\boldsymbol{t}^{(n)}$ converges to some constant number. In other words, when n goes to infinity, the benefits of deviating their strategies go to zero for all nodes $k \in \mathcal{K}$. Thus nobody has intention to deviate its strategy, and the strategies keep constant, *i.e.*, $\lim_{n\to\infty} \boldsymbol{t}^{(n)} = \boldsymbol{t}^{\star}$. Thus the group sequential response converges to an NE. ■

Therefore, the neighbor coordinate strategy, on the one hand, speeds up the update process by partial parallel update, which is faster than sequential update; on the other hand, can convergence to an NE, which simultaneous update does not guarantee. Also, no global coordination is required; the local node only needs to collect the nearby handover time to do the response.

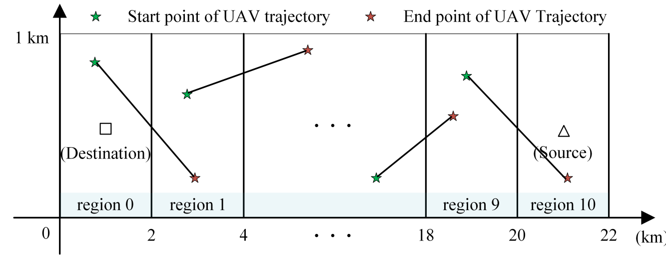

Figure 3. Illustration of UAV-team-assisted data collection scenarios generating.

IV. NUMERICAL RESULTS

Consider a 22 km × 1 km region that is partition into 11 regions there are 10 UAVs travel between adjacent regions as shown in Fig. 3. The trajectories of the UAVs are generated randomly across two adjacent regions. The destination is at a fixed location in the center of the first region. The source locates uniformly at random in region 1 to 10. For a source located in region K, you select a team of UAVs that has their trajectory covering from region 0 to K to deliver the data. The goal is to transmit the data generated by the source to the destination through K UAVs within the delay tolerance threshold T. The following results are based on the transmission requirement with size $S = 100$ Mbits and with delay tolerance 5 s $\leq T \leq 25$ s. The total bandwidth $B = 10$ Mhz with noise power spectrum density $N_0 = -169$ dBm/Hz, and power gain factor is $\beta_0 = -50$ dB, back-off factor is $\kappa = -10$ dB. All experimental results are the averaged more than 500 of independent runs.

We evaluate the proposed scheme with comparison to the following baselines: (i) real-time relay: The UAVs relay the data from the source to the destination directly. As a result, the instantaneous end-to-end capacity of the $(K+1)$-hop relay channel becomes $\frac{1}{K+1}\min_k\{c_k(t)\}$; (ii) equal-interval ferry: the UAVs transmit the data one by one using the fixed equal time interval, $t_k = k \cdot \left(\frac{T}{K+1}\right)$, $k \in \mathcal{K}$.

Fig. 4 shows the total energy consumption over different delay tolerances. It is shown that the transmission energy consumption using the proposed handover time negotiation strategy is always better than the real-time relay and the equal-interval ferry strategies, and the performance superiority is noticeable when relatively sensitive to delay. Likewise, in Fig. 5, our scheme performs better with different distances between source and destination.

We also analyzes the convergence with the response rounds, as shown in Fig. 6. For keeping the results of simultaneous response strategy satisfying constraint (2), the smooth technique is used, that is, $t_k^{(n+1)} = \vartheta t_k^* + (1-\vartheta)\, t_k^{(n)}$, where t_k^* is the best response in $(n+1)$ round, and $\vartheta \in (0, 0.5)$ is update ratio.

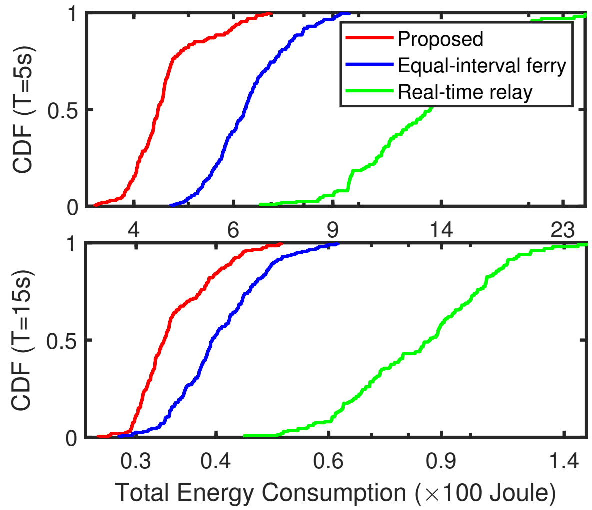

Figure 4. Total energy consumption over different delay tolerances.

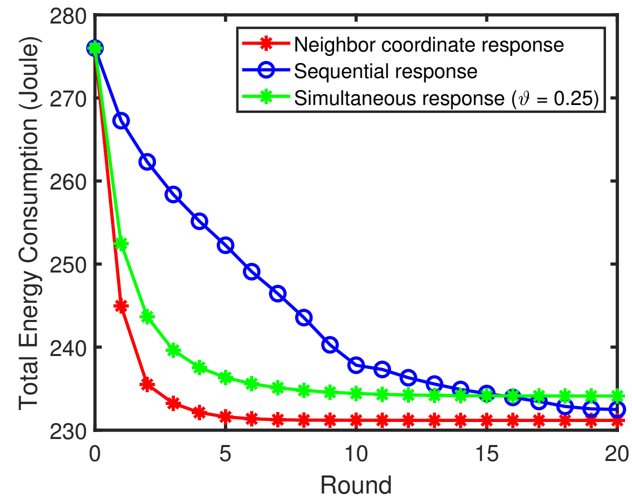

Figure 6. Performance improvement with the round of response.

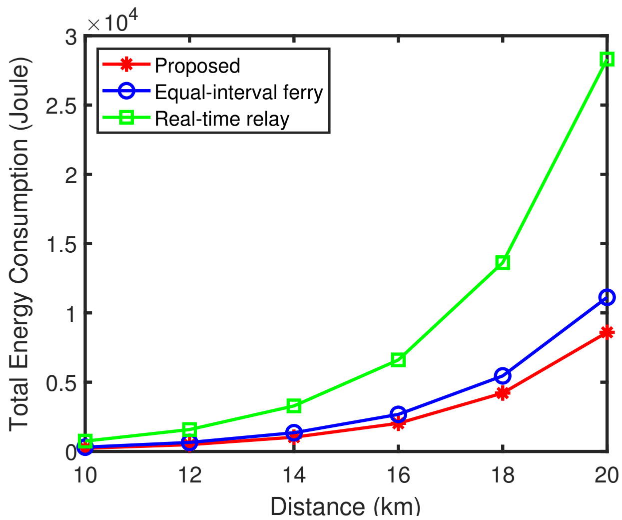

Figure 5. Total energy consumption with different source-destination distances.

It is shown that the proposed neighbor coordination response strategy can converge with the faster speed, almost reaching convergence after 6 rounds of response.

V. Conclusion

This paper proposed a distributed mechanism to negotiate the handover time for better usage of the channel. The core idea is to construct a potential game, where the potential function is exactly the objective of the energy minimization problem. Numerical results show that the proposed mechanism brings significant performance improvement. In addition, the proposed neighbor coordinate response strategy, speeding up an overall response while keeping the convergence to an NE, makes the mechanism implementable in practice. In the future, we are going to design for multi-source scenarios, and design the upper-level strategy to determine the transmission order.

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