Delay Efficient D2D Communications Over 5G Edge-Computing Mobile Networks with Power Control

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Abstract—As the development of mobile web, Internet of things, and the 5th Generation (5G) of cellular network, the usage of Device-to-Device (D2D), which is defined as direct communication between two mobile users without traversing the Base Station (BS) or core network, has attracted more and more attentions from both industry and academia. For Device-to-Device (D2D) data offloading, if the same piece of content is available in the vicinity of a device, the piece of content could be directly sourced from one of its neighboring devices. Suppose there are multiple devices which aim to obtain valuable contents via D2D communications, and assume each device has a unit demand, the objective is to seek an interference-aware schedule of D2D communication activities with minimum delay to satisfy all demands. Due to the complicated network topology, and the scheduling hardness of multiple devices, to achieve the optimal arrangement for sourcing the contents via D2D communication is very challenging. In this paper, we consider the problem under the physical interference model with monotone power control. An approximation algorithm under the duty-cycled model is proposed to address the above challenges with theoretically proved the approximation factor which could independent of the period length under the duty-cycled model. Besides, we also theoretically demonstrated the correctness and scheduling efficiency of our proposed algorithm.

Index Terms—D2D communication, latency, SINR, duty cycle.

I. Introduction

5G of wireless networks is aiming to provide fast and reliable connectivity while responding to the continued traffic growth. In the context of Device-to-Device (D2D) communication, a buffering is performed at a small base station or directly at a user terminal. As shown in Figure 1, there are different channel of D2D communication which result in mutiple mode of information exchange. The device can communicate through the eNB (Evolved Node B), or directly communicate with other devices, with the multi-hop transmission, the users can also help each other for the data transmission communication.

With D2D communication, if the same piece of content is available in the vicinity of the device, the content can be directly sourced from one of its neighbouring devices. Naturally, the key problem becomes how to maximize data offloading capacity via D2D communication. However, the capacity maximization is very challenging in this situation due to the complicated environment of D2D communication and multiple roles involved in the conversation.

We study delay efficient D2D communication scheduling with the following challenges. The first challenge is that the D2D is different from the traditional communication link scheduling problem. In the D2D scenario, each node (device) with a demand has a flexibility to choose candidate nodes to source, some nodes may be redundant to satisfy this demand. Thus, the task contains joint scheduling of node-level and link-level scheduling. However, this is not true in the traditional link scheduling scenario.

The second challenge is wireless interference. The wireless interference casts significant effect on communication throughput under any scheduling algorithm. Thus, we need to model and address wireless interference carefully to ensure the efficiency of the proposed algorithm in the actual wireless communication scenario. Compared to various graph-based interference models, e.g., the protocol interference model, the CTS / RTS model, and the K-hop interference model [1], [2], the recent work focus more on the physical interference model [3]–[5]. The physical interference model is much more accurate for capturing interference. Under the physical interference model, a successful transmission also accounts for interference generated by transmitters located far away. This feature greatly differs from that in graph-based interference models.

In the field of wireless communication, for the limited energy characteristics of some IOT devices, some work [6], [7] also studies how to achieve low power consumption. We consider length-monotone power control [8] to achieve energy-efficiency. Each communication link or its corre-

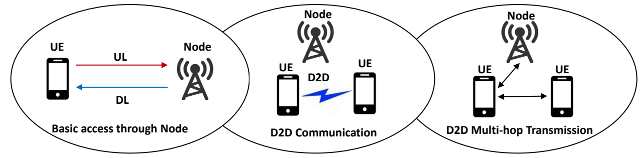

Fig. 1. Models of D2D communication

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sponding sender is assigned with a transmission power that increases with its link length. As a longer communication link requires more transmission power, this power control setting is usually energy-efficient. Note that length-monotone power control is a representative of the oblivious power assignment family where the transmission power of each link only depends on its length.

The fast D2D scheduling problem is described as follows. Given a set of devices, assume each device has a demand to source valuable data from other devices. For the requested data, to satisfy a demand, a node may fetch data from any neighbor that contains the data. We define a node that requests data from other nodes as a retrieving node, for each retrieving node, there may be a subset of neighboring nodes which contain the useful data. As shown in Figure 2, red nodes represent retrieving nodes, blue nodes represent neighbor nodes that have the required data. The circle with radius R represents the wireless communication range of the retrieving node, the retrieving node can obtain data from any neighbor node within the range. The objective is to schedule all nodes and activities of links to satisfy all demands with the minimum schedule length, and the physical interference between wireless communication links should be considered.

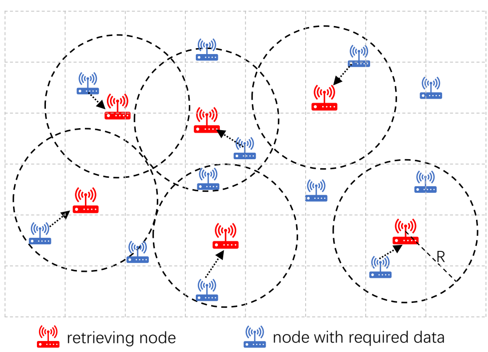


Fig. 2. D2D communication of retrieving nodes

We will address the problem in duty-cycled networks, as the duty cycle mechanism can achieve a reduction in energy consumption. In the duty-cycled networks, radios are controlled on a periodical basis, alternating between active and dormant states. In the active state, nodes can send or receive data, while in the dormant state the nodes switch radios off to save energy. If wireless nodes are active for only a small portion of time and stay dormant for the rest of time, such wireless networks are called low duty-cycled networks, low duty-cycle can reduce energy consumption to a lower level. We will focus on the uncoordinated low duty-cycled model where the active time-slot of each node could be arbitrary. In duty-cycled model, to transmit a data packet, the sender node needs to hold the packet and wait until the receiver node's active time-slot.

In this work, we first put forward the concept of retrieving node, because the devices are always data demand-oriented, the node always obtains data from its neighbor node with the required data, rather than the traditional fixed sender-receiver mode, so that the node can obtain data nearby, under this model, the transmission can achieve delay efficiency and energy efficiency. Then we design an approximation algorithm for minimizing the delay of schedualing and data transmission under the D2D model. The well formulation of the problem and the theoretical contribution would bring some inspiration to the challenges in D2D communication scenario.

We organize the remaining sections of this paper in the following. Section II provides the system model illustration. Section III detailed presents the approximation algorithm. Section IV provides the analysis of the algorithm performance. Section V shows the results of simulation experiments and analyzes the performance of the algorithm. Section VI presents the literature review. We conclude this paper in Section VII.

II. System and Network Model

There are a set of device nodes in the network. Denote the Euclidean distance between a pair of nodes u and v by $\|\overrightarrow{uv}\|$.

The path loss over a distance l is $\eta \cdot l^{-\kappa}$, where κ is path loss exponent, and η is the reference loss factor. Let ξ be the noise power, and let σ be the SINR threshold for a successful reception. Each device node has a transmission power upper-bounded by P. A link $\overrightarrow{uv}$ can transmit successfully if and only if

$$\frac{P_u \cdot \eta l^{-\kappa}}{\xi + \sum_{w \in I_u} P_w \cdot \|\overrightarrow{wv}\|^{-\kappa}} \geq \sigma \tag{1}$$

Here I_u denotes the set of other simultaneous senders with sender u.

From Equation (1), if I_u is empty, the SINR reduces to signal to noise ratio (SNR), i.e., $\frac{P_u \cdot (\eta \cdot \|uv\|^{-\kappa})}{\xi} \geq \sigma$, thus $\|uv\| \leq \sqrt[\kappa]{\frac{\eta P_u}{\sigma\xi}} \leq \sqrt[\kappa]{\frac{\eta P}{\sigma\xi}}$. Later we assume $R = \sqrt[\kappa]{\frac{\eta P}{\sigma\xi}}$ as the maximum transmission radius.

In a length-monotone power control setting [9], a node u transmits to another node v always at a power that increases with the length of the link. In this work, we will assume the power for link $\overrightarrow{uv}$ is $c\|\overrightarrow{uv}\|^{\beta}$ for some constants $c > 0$ and $0 < \beta \leq \kappa$. This assumption implicitly imposes an upper bound on the distance between a pair of nodes which directly communicate with each other. For a communication link uv, we must have $c\|\overrightarrow{uv}\|^{\beta} \leq P$ and hence we have $\|\overrightarrow{uv}\| \leq (P/c)^{1/\beta}$.

We assume a duty-cycled scenario with a period T, and a duty-cycle $\frac{d}{T}$, where d is the number of active time-slots in a period of T consecutive time-slots. For each node v, let $\kappa(v) = [a_0, a_1, \cdots, a_{T-1}] \in \{0,1\}^T$ be its duty-cycle. Here $\kappa(v)$ is a T-dimensional vector, where each entry a_i is either 0 or 1. The duty-cycle of a node is $\sum_{i=0}^{T-1} a_i/T$. In

TABLE I
Notations

$\overrightarrow{uv}$	Link from node u to node v
$\left\|\overrightarrow{uv}\right\|$	Link length, Euclidean distance, of link $\overrightarrow{uv}$
R	Maximum link length of all links
P	Maximum power for a node
η	Reference path loss factor
κ	Path loss exponent
c, β	Linear power allocation constants
ξ	Noise power
σ	SINR threshold for successful reception

this paper, we simply assume $d = 1$. As shown in Figure 3, both node v_2 and node v_4 are active in the time-slot a_1 of each cycle. Therefore, if physical interference is not considered, v_2 and v_4 can obtain data from their neighbor nodes simultaneously. In a duty-cycled network, a node v will be active and ready for data reception at time t only if $a_k = 1$, where $k \equiv t \mod T$. We assume that a node u can send data packet to node v at time t, if and only if node v is active at time-slot t. In this case, node u should already have the data ready before time t and has been waiting for node v to be active.

A transmission schedule is a set

$$S = \{(I_j, L_j) : 1 \leq j \leq k\}$$

such that I_j is an independent set of retrieving nodes, and L_j is the corresponding set of links and the receiver of each link in L_j is a retrieving node in I_j. In other words, there is a one-to-one mapping between each node in I_j to a link L_j. A transmission schedule is feasible if each subset of links is an independent set with duty-cycle constraint satisfied. k is referred to as the length of the schedule S.

Given a set of retrieving nodes, and each retrieving node u is associated with a unit data demand, the problem Fast D2D Scheduling seeks a feasible transmission schedule such that the length is the shortest. In other words, the goal is to minimize the total number of time-slot, since we will schedule a batch of nodes in each time-slot. Table I lists major notations.

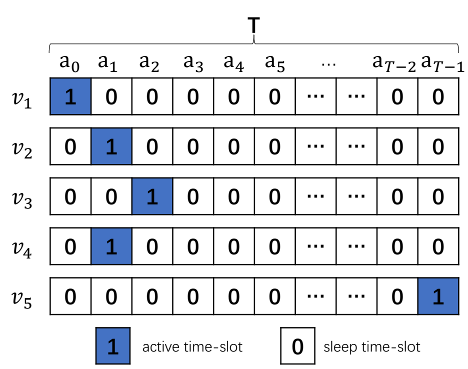


Fig. 3. An example of five nodes with their own active time-slot

III. Approximation Algorithm

We first introduce a concept of strong independent set. Given a collection of retrieving nodes, a subset of retrieving nodes are said to be a strong independent set if for any retrieving node u in this subset, no matter which sender in node u's vicinity transmits the data, all the transmissions are interference-free.

The proposed scheduling algorithm consists of two phases, i.e., node-level and link-level scheduling.

- [Phase I: node-level scheduling] The algorithm first finds a strongly independent set I of retrieving nodes
- [Phase II: link-level scheduling] For each retrieving node u in the strongly independent set I, select a neighboring node s which contains the required data as a sender and form a communication link $\overrightarrow{su}$, assume all corresponding links form a set L.

Based on the definition of physical interference model, if we select a subset of geographically well-separated nodes and let only these corresponding links transmit simultaneously, we can ensure that the interference on each link is bounded. By using this property, we schedule nodes based on a partition scheme of the plane.

We partition the plane into square cells. Each cell has a diagonal length of R which is the maximum link length. Let $\ell = R/\sqrt{2}$ denote the side length of a cell. Let $\mathbb{Z}$ represent the integer set. The vertical line segments $\{x = i \cdot \ell : i \in \mathbb{Z}\}$ and horizontal line segments $\{y = j \cdot \ell : j \in \mathbb{Z}\}$ partition the plane into half-open, half-closed cells of side length ℓ: We call the plane area $[i\ell, (i+1)\,\ell) \times [j\ell, (j+1)\,\ell)$ as cell (i, j). In other words, the plane is partitioned into square cells (i, j) of side length ℓ for $i, j \in \mathbb{Z}$.

Based on a partition of the plane, we define a large-block as a large square which consists of $(K+1) \times (K+1)$ cells. The value of K is set as follows to satisfy the interference constraint.

$$K = \lceil \sqrt{2} \cdot (c_1 + 1) \rceil \tag{2}$$

$$c_1 = \max\{\frac{\kappa - 1}{\kappa - 2} \cdot 2^5 3 \cdot (\frac{\eta}{\sigma} - \frac{\xi}{c})^{-1}, 2\} \tag{3}$$

Algorithm 1 describes how to partition the retrieving nodes in V into multiple subsets, where each subset is an strong independent set of retrieving nodes and the duty-cycle constraint is satisfied. A subset is formed by picking retrieving nodes only from the cells lying in the same relative location of large blocks as shown in Figure 4. In addition, at most one node is picked from each cell under the duty-cycled model.

When constructing a strong independent set, we not only ensure that the difference between the upper and lower bounds of the scheduling length is a constant approximation, but also make the result as close to the optimal solution as possible. Specifically, when generating each independent set, based on the partition scheme firstly, selecting a node with active time-slot d and the same relative position in large blocks, add them to the

Algorithm 1 Fast Duty-Cycled D2D Communication Scheduling

Input: A set of nodes V.
Output: $\{(I_0, L_0), (I_1, L_1), \cdots\}$.
Set K according to Equation (2) .
$t \leftarrow 0$.
while TRUE do
  $d = t \mod T$.
  for $r = 0, \cdots, K$ and $s = 0, \cdots, K$ do
    for $i, j \in \mathbb{Z}$ and the cell $g_{i,j}$ contains nodes from V the active time-slot of the nodes is d; do
      if $i \mod (K+1) = r$ and $j \mod (K+1) = s$ then
        select one node in $g_{i,j}$ and the active time-slot of the node is d.
      end if
    end for
    all the selected nodes form a set $I_t^{'}$.
    for $i, j \in \mathbb{Z}$ and the cell $g_{i,j}$ contains nodes from V the active time-slot of the nodes is d; do
      if node v in $g_{i,j}$ and for every node $v^{'}$ in $I_t^{'}$ have $||vv^{'}|| \geq (c_1+1) \cdot R$ then
        add node v into $I_t^{'}$.
      end if
    end for
    $I_t = I_t^{'}$.
    for $v \in I_t$ do
      select a corresponding sender and form a link l_v.
    end for
    all the links form a set L_t.
  end for
  $V \leftarrow V \setminus I_t$.
  if $V \equiv \emptyset$ then
    exit .
  end if
  $t = t + 1$.
end while
return $\{(I_0, L_0), (I_1, L_1), \cdots\}$.

current independent set, this approach can ensure that the difference between the upper and lower bounds of the proposed algorithm is a constant approximation, because the upper bound of the maximum number of nodes scheduled by each unit is constant, and our algorithm schedules at least one node that meets the requirements in each cell, so our solution is only one constant away from the optimal solution. Then add other nodes that meet the constraints of duty-cycle and SINR into the set, that is, from the unselected nodes, select the nodes whose active time-slot is d and whose distance from all nodes in the current set is greater than $(c_1+1) \cdot R$, add the qualified nodes one by one, so as to complete a strong independent set. The distance index $(c_1+1) \cdot R$ will be explained and

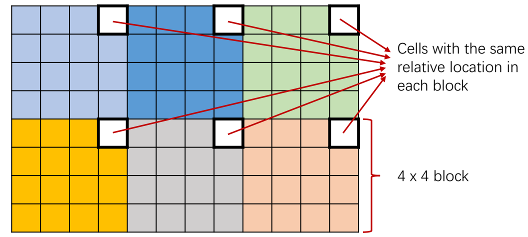


Fig. 4. Build independent sets by dividing Large Blocks

analyzed in the next section. Adding a greedy strategy can make as many nodes as possible join the same independent set, and ultimately reduce the number of independent sets.

As shown in Lemma 1, we can ensure that all the nodes selected to a subset form an independent set and they are active at their assigned time-slot under the duty-cycled model, and hence can transmit simultaneously, under the physical interference model, i.e., the SINR at the receiver node of each link is larger than the threshold σ.

Assume the total number of subsets is l. The l subsets can be scheduled to transmit within l time-slots. Note that the total number of time-slots needed by Algorithm 1 depends on the maximum number of retrieving nodes located in a large block with the same active time-slot.

IV. Performance Analysis

Firstly, we prove that under our model, considering constraints of SINR and duty-cycle, the problem of retrieving nodes scheduling is NP-hard, then we verify the correctness of the proposed algorithm, i.e., each subset of links output by the proposed algorithm is an independent set.

Different from the general link scheduling, we propose a new scheduling model. The previous scheduling problem has a fixed link set, for the link set $L = \{l_1, l_2, ..., l_n\}$, each link has a fixed pair of sending node and receiving node, focusing on the scheduling of the determined link set. But this model focuses on the retrieving nodes with data requirements, which is a new type of node. We assume that the collection of retrieving nodes to be scheduled is $V = \{v_1, v_2, v_3, ..., v_n\}$. We pay more attention to the retrieving node than the sending node, because each node obtains the required data through D2D transmission, the retrieving node can always obtains data directly from one of its neighbor nodes. Lemma 2 proves that as long as the distance of the requesting node is far enough, no matter where the corresponding sender of this node is, it will not be interfered by the transmission of other nodes, so it can be transmitted successfully. We mainly focus on the correctness and performance of the proposed approximate algorithm.

Lemma 1: Under duty-cycle model with considering SINR constraint, the scheduling problem of retrieving nodes is NP-hard.

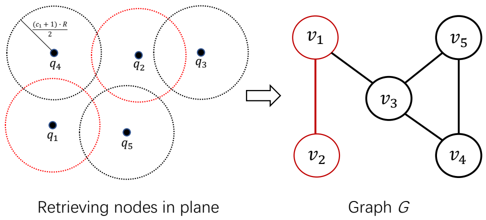


Fig. 5. A case of using the retrieving nodes scheduling problem to solve the clique cover problem

Proof: Prove that the problem is NP. A problem is NP if it can be verified as a feasible solution in polynomial time. For any solution in this problem, for the current time-slot t, to check whether the scheduled retrieving nodes are active at the moment, which requires $O(n)$ time. Secondly, checking whether all nodes scheduled at the same time can meet the SINR index σ requires $O(n^2)$ time. We can verify the feasible solution of the problem in polynomial time, so the problem is NP.

Then we reduce the clique cover problem to the scheduling problem of retrieving nodes to prove that this problem is NP-complete. The clique cover problem was proved to be NP-complete by Karp in his work [10]. The clique cover problem can be described as follows: Given a graph $G = (V, E)$, $V = \{v_1, v_2, ..., v_n\}$, divide graph G into several cliques and minimize the number of cliques, clique is a simple undirected graph with all of the possible edges, also known as a complete graph. Suppose the input to a clique cover problem is a graph G with $V = \{v_1, v_2, ..., v_n\}$ and $E = \{e_1, e_2, ..., e_m\}$, The desired output is the minimum number of k sets $\{s_1, s_2, ..., s_k\}$, each set contains several vertices of a complete graph, and any two sets in the k sets have no intersection, the union of all sets is V,that is:

$$s_i \cap s_j = \emptyset, (i \neq j)$$

$$s_1 \cup s_2 \cup ... \cup s_k = V.$$

In the scheduling problem of retrieving nodes, the input is a node set $Q = \{q_1, q_2, ..., q_n\}$, the coordinate of node q_i and the active time-slot d_i of each node. We consider the active time-slot of each retrieving node and the physical interference of transmission to finally obtain the minimum k sets, all nodes in one set can be scheduled simultaneously to obtain data from neighbor nodes with required data. For SINR constraint, we believe that as long as the euclidean distance between two retrieving nodes is greater than or equal to $(c_1+1)\cdot R$, it can be considered that the respective transmissions of the two retrieving nodes will not affect each other and can be successfully transmitted. This is the conclusion drawn by Lemma 2, we will demonstrate in detail later. Therefore, for the simultaneous scheduling, it needs to satisfy two conditions: the same active time-slot and the euclidean distance is greater than or equal to the safe distance $(c_1 + 1) \cdot R$.

Convert the input of the clique cover problem into the input of the scheduling problem. We first establish the correspondence between the vertices and nodes of two problems, for each vertex in V, if it is the first vertex v_1, generate a corresponding node q_1 on the two-dimensional plane arbitrarily, and set the active time-slot. If there is an edge between vertex v_i and a vertex v_j that has been converted, a corresponding node q_i that satisfies $||q_iq_j|| \geq (c_1 + 1) \cdot R$ is generated on the plane, and the active time-slot is the same as q_j, if there is no edge between vertex v_i and a vertex v_j , let q_i satisfies $||q_iq_j|| < (c_1 + 1) \cdot R$, when all vertices are converted, n nodes with active time-slot distributed on the two-dimensional plane are obtained. When we find the solution to the scheduling problem of retrieving nodes, it is assumed that we get k node sets, each node set contains the retrieving nodes capable of simultaneous transmission, and accordingly, each set corresponds to each clique in the clique cover problem.

As shown in Figure 5, for retrieving nodes distributed on the plane, we can solve the clique cover problem by solving the scheduling problem. In this case, we assume that the active time-slot of the nodes on the left side of the Figure 5 are the same, so we do not need to consider the time-slot, but only the distance between nodes. For each node, there is a circle with the node as the center and the radius of $\frac{(c_1-1)\cdot R}{2}$. If two circles intersect, it means that the distance between the nodes is less than $(c_1 + 1) \cdot R$, so it is not considered to put these two nodes into the same independent set. For a complete graph, there are edges between each two vertices, this means that the corresponding nodes in the plane have the same active time-slot, and the distance is greater than or equal to $(c_1 + 1) \cdot R$, so these nodes can be scheduled at the same time. When we get the scheduling length, we can also get the solution of the minimum clique cover of the graph G.

We prove that the clique cover problem can be reduced to scheduling problem of retrieving nodes, and the classical clique cover problem has been proved to be NP-complete. Therefore, the scheduling problem is NP-complete as well, i.e., NP-hard problem.

Lemma 2: Suppose there is a set of receiving nodes with mutual distance at least $(c_1+1)\cdot R$, no matter where the corresponding senders are, all the transmissions are interference free.

Proof: For any two links l_j and l_k, we know $\|r_kr_j\| \geq (c_1+1)\cdot R$. From triangular inequality, $\|I_kI_j\| \geq (c_1-1)\cdot R$. Therefore, disks D_i of radius $\frac{(c_1-1)\cdot R}{2}$ around senders in I_i do not intersect. Then the sender set in I_i is partitioned into concentric rings $Ring_k$ $(k = 0, 1, \cdots, +\infty)$ of width $c_1 \cdot R$ around the receiver r_i, each ring $Ring_k$ contains all senders $I_j \in \mathcal{S}_i^+$, for which $k \cdot (c_1 \cdot R) < \|I_jr_i\| \leq (k+1)\cdot(c_1 \cdot R)$. The first ring $Ring_0$ does not contain any sender. Consider all senders $I_j \in Ring_k$ for some integer $k > 0$, all disks of radius $\frac{(c_1-1)\cdot R}{2}$ around each sender I_j

must be located entirely in an extended ring $Ring_k$ of area

$$\begin{aligned} A(Ring_k) = [((k+1)\cdot c_1 \cdot R + \frac{(c_1-1)\cdot R}{2})^2 - \\ (k \cdot c_1 \cdot R - \frac{(c_1-1)\cdot R}{2})^2] \cdot \pi \\ = (2k+1)\cdot 2c_1(c_1-1)\cdot R^2 \cdot \pi \\ < (2k+1)\cdot 2c_1^2 \cdot R^2 \cdot \pi \end{aligned}$$

Since disks D_i of area $A(D_i) = (\frac{(c_1-1)\cdot R}{2})^2 \cdot \pi$ around senders in S_i^+ do not intersect, we can use an area argument to bound the number of senders inside each ring. The total interference by senders located in $Ring_k$ ($k \geq 1$) is bounded by

$$\begin{aligned} I_{Ring_k}(l_i) &\leq \sum_{I_j \in Ring_k} I_{I_j}(l_i) \leq \frac{A(Ring_k)}{A(D_i)} \cdot \frac{P}{(kc_1R)^\kappa} \\ &\leq \frac{(2k+1)}{k^\kappa} \cdot \frac{P}{R^\kappa} \cdot \frac{8c_1^2}{c_1^\kappa (c_1-1)^2} \\ &\leq \frac{1}{k^{\kappa-1}} \cdot \frac{P}{R^\kappa} \cdot \frac{2^5 3}{c_1^\kappa} \end{aligned}$$

where the last inequality holds since $k \geq 1 \Rightarrow 2k+1 \leq 3k$ and $c_1 \geq 2 \Rightarrow c_1 - 1 \geq c_1/2$. Summing up the interferences over all rings yields

$$\begin{aligned} I_{I_i}(l_i) &< \sum_{k=1}^{\infty} I_{Ring_k}(l_i) \leq \sum_{k=1}^{\infty} \frac{1}{k^{\kappa-1}} \cdot \frac{P}{R^\kappa} \cdot \frac{2^5 3}{c_1^\kappa} \\ &< \frac{\kappa-1}{\kappa-2} \cdot \frac{P}{R^\kappa} \cdot \frac{2^5 3}{c_1^\kappa} \\ &< c \cdot \frac{\kappa-1}{\kappa-2} \cdot \frac{2^5 3}{c_1^\kappa} \end{aligned}$$

where the last inequality holds since $\kappa > 2$.

On the other hand, for a link l_i to transmit, we have

$$\frac{P_u \cdot \eta l^{-\kappa}}{\xi + \sum_{w \in I_u} P_w \cdot \|\overrightarrow{wv}\|^{-\kappa}} \geq \sigma$$

Thus, we have

$$\sum_{k=1}^{\infty} I_{Ring_k}(l_i) \leq \frac{P_u \cdot \eta l^{-\kappa}}{\sigma} - \xi = \frac{c\eta}{\sigma} - \xi$$

By setting

$$c \cdot \frac{\kappa-1}{\kappa-2} \cdot \frac{2^5 3}{c_1^\kappa} \leq \frac{c\eta}{\sigma} - \xi$$

We have $c_1 = \max\{\frac{\kappa-1}{\kappa-2} \cdot 2^5 3 \cdot (\frac{\eta}{\sigma} - \frac{\xi}{c})^{-1}, 2\}$. This concludes the proof.

Corollary 1: Under the duty-cycled model, suppose I is a retrieving node subset obtained by Algorithm 1, i.e., I contains at most one node from the cell at the relative location (k_1, k_2) in each large block. Here two nonnegative integers k_1 and k_2 are at most K. Then, I is an independent set under the SINR constraint.

Proof: In Algorithm 1, the mutual distance of receiving nodes is at least $(c_1+1)\cdot R$. The corollary follows based on Lemma 2.

We then calculate the approximation ratio of the proposed algorithm. The main idea is as follows: we first estimate the number of time-slots needed for Algorithm 1 and derive an upper-bound. Then, we compute a lower bound which is the minimum number of time-slots required for any algorithm to schedule links lying inside a single large block, which is a lower bound for the length of any schedule to complete all link transmissions. By comparing the upper bound and the lower bound, we can calculate the approximation ratio.

Based on the partition scheme, let B denote the maximum number of retrieving nodes from V lying inside any cell with the same active time-slot in the duty-cycle model. Therefore, we have the following lemma on the upper bound of the number of time-slots needed for Algorithm 1.

Lemma 3: The retrieving node scheduling based on the proposed algorithm needs at most $(K+1)^2 \cdot B \cdot T$ time-slots.

Proof: As shown in line 3 of Algorithm 1, after each $(K+1)^2 \cdot T$ iterations of the while loop, the retrieving nodes lie inside each cell with a certain active time-slot would decrease by at least one. Thus, the number of iterations for the while loop is at most B. In total, Algorithm 1 outputs at most $(K+1)^2 \cdot B \cdot T$ retrieving node subsets, and hence the retrieving node scheduling needs at most $(K+1)^2 \cdot B \cdot T$ time-slots.

Next, we calculate the lower bound that is the minimum possible length for any algorithm.

Let

$$\omega = \left\lceil \frac{2^\kappa P}{\sigma^2 \xi} + 1 \right\rceil.$$

Lemma 4: Under the duty-cycled model, there are at most ω retrieving node receiving concurrently in any independent set I.

Proof: For all $i, j \in \mathbb{Z}$, we denote V_{ij} to be the set of nodes in V lie in cell (i,j). Let $I_{ij} = I \cap V_{ij}$. Assume $a = (u,v)$ be the shortest corresponding link with $v \in I_{ij}$, consider any link $a' = (u', v')$ in I_{ij} other than a, the distance between the sender u' and v satisfies

$$\|u'v\| \leq \|u'u\| + \|uv\| \leq \left\|\sqrt{2}\ell\right\| + \|uv\| \leq 2R,$$

The SINR at a from all other links in I_{ij} is at most

$$\begin{aligned} &\frac{c\|a\|^\beta \cdot \eta \|a\|^{-\kappa}}{\sum_{a' \in I_{ij} \setminus \{a\}} c\|a'\|^\beta \cdot \eta \|u'v\|^{-\kappa}} \\ &\leq \frac{\|a\|^{-\kappa}}{\sum_{a' \in I_{ij} \setminus \{a\}} \|u'v\|^{-\kappa}} \leq \frac{r^{-\kappa}}{(|I_{ij}|-1)(2R)^{-\kappa}} \end{aligned}$$

Here r is the shortest possible length of a link. As $P_u \cdot \eta l^{-\kappa} \leq P_u$, we have $r = \eta^{-\kappa}$. Since $\frac{r^{-\kappa}}{(|I_{ij}|-1)(2R)^{-\kappa}} \geq \sigma$, we have $|I_{ij}| \leq \frac{2^\kappa}{\sigma} \frac{R^\kappa}{r^\kappa} + 1 < \frac{2^\kappa}{\sigma} \frac{P}{\sigma\xi} + 1 = \frac{2^\kappa P}{\sigma^2 \xi} + 1$.

Since there exists one cell that contains B retrieving nodes with the same active time-slot in the duty cycle model, by Lemma 4, this fact immediately implies a lower bound on the number of time-slots required for any algorithm to schedule links lying inside a large block. Thus

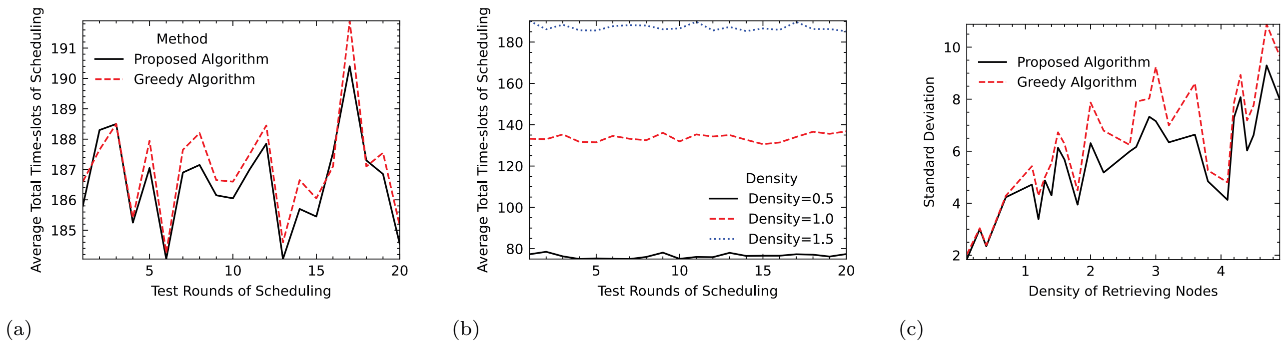


Fig. 6. Schedule length under the same density(a), different densities(b) and standard deviation under different densities

we obtain a lower bound for any algorithm to schedule all nodes in V.

Corollary 2: Under the duty-cycled model, any valid schedule for fast offloading scheduling has a length of at least $\frac{B}{\omega} \cdot T$.

Theorem 1: The approximation ratio of our algorithm for fast offloading scheduling is at most $(K+1)^2\omega$.

Proof: The duty-cycle-aware schedule from our algorithm has a length of at most $(K+1)^2 \cdot B \cdot T$ by Lemma 3. At the same time, any valid schedule for fast offloading scheduling has a length of at least $\frac{B}{\omega} \cdot T$. Thus the approximation ratio of the proposed algorithm can be bounded by $(K+1)^2 \cdot \omega$.

V. Numerical Results

In this section, we present our simulation results. Although we have characterized the worst case performances of the proposed algorithms in terms of approximation bound on the lantecy, we will study the average performance of the proposed algorithm via simulation results.

We randomly deploy a set of nodes in a two-dimensional plane, evaluate proposed algorithm and compare it with a greedy scheduling method. In the greedy method, each time we greedily select retrieving nodes as long as the selected retrieving nodes does not conflict to the retrieving nodes already selected. Specifically, We randomly select nodes, as long as the active time-slot is same and the distance from the nodes in the current set is greater than or equal to $(c_1+1) \cdot R$, the node will be added to the current set.

We consider two scenarios to simulate D2D transmission in reality. The density of nodes is closely related to the interference between communications. Generally, the greater the density, the more communication nodes in the unit area, which will lead to the more complex interference in wireless transmission, and the number of nodes that can be scheduled at the same time-slot will change. Firstly, we present the average latency of the proposed algorithm and the greedy method when the nodes density in the deployment plane are fixed. Secondly, we present the average reward of the proposed algorithm and the greedy method when the density in the deployment plane increases.

Random nodes are constructed in a two-dimensional plane, and divides the plane into several cells with side length of 1.

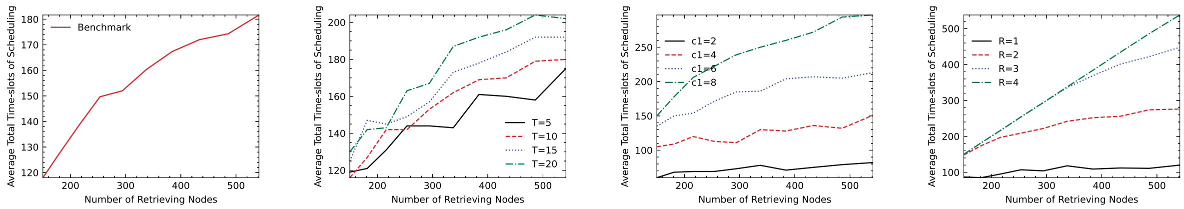
First scenario is to keep the density unchanged. The fixed density is 1.5 nodes per cell, other parameter settings: $R = \sqrt{2}, T = 10, c_1 = 5$,and the size of the plane is $20 * 20$. Under this condition, we conduct 20 rounds of experiments, randomly generate nodes 10 times in each round of experiments, and calculate the average value of each round. Compare the scheduling length between the proposed algorithm and the greedy algorithm, the result is shown in Figure 6(a).

Figure 6(a) shows that the average total number of time-slot obtained by the proposed algorithm is smaller than that of the greedy algorithm. And always remember that our algorithm can ensure that the difference between the upper and lower bounds of the result is constant approximation, and the worst result will not be terrible. In addition, the distance $(c_1+1) \cdot R$ used in the greedy algorithm is also obtained from our proposed method.

Second scenario is to change the node density. Keeping the area of the two-dimensional plane unchanged, and make the density different, then obtain the average total time-slots of nodes scheduling. In order to show the stability of the proposed algorithm, we also calculate the standard deviation of the experimental results under different densities, the results are shown in Figure 6(b) and Figure 6(c).

The results indicates that the total scheduling length increases with the increase of density. As mentioned earlier, total number of time-slots needed by Algorithm 1 depends on the maximum number of retrieving nodes located in a large block with the same active time-slot, which is just related to density of nodes. Figure 6(c) also shows that with the increase of density, the proposed algorithm has better stability in solving the minimum scheduling length, and the results are not prone to large fluctuations for randomly distributed nodes.

Finally we study the influence of each factor on the



(a) (b) (c) (d)

Fig. 7. Schedule length of benchmark and under different T, R and c_1

experimental results. Under the same conditions, we will randomly generate a specified number of nodes 10 times, use the proposed algorithm to obtain the scheduling length results. Taking the case of $R = \sqrt{2}, T = 10, c_1 = 5$ and $density = 1.5$ as the benchmark, we get results under different node numbers when T, R and c_1 change respectively and others remain unchanged. All the results obtained are shown in Figure 7(a) to Figure 7(d).

Comparing the experimental results, we can observe a certain trend, results are approximately positively correlated with the three parameters. After more experiments, we found that different values of c_1 have a relatively large impact on the experimental fluctuation.

Through the above experiments, we prove the effectiveness of the proposed algorithm for retrieving nodes scheduling problem, and study the key factors affecting the scheduling performance, which can provide an effective solution for node deployment and node scheduling of D2D communication in practice.

VI. Literature review

A. Fast duty-cycled Scheduling and D2D communication scheduling

Delay efficient wireless communication scheduling [11]–[13] has been studied in the literature. However, the above works do not consider the duty cycle constraint.

There are extensive work on delay efficient duty-cycled wireless scheduling in multi-hop wireless networks. For example, [14], [15] studied data aggregation, [16], [17] studied broadcast scheduling, and [18], [19] studied gossiping scheduling respectively. To the best of our knowledge, the only two results on delay efficient duty-cycled scheduling that have approximation ratios independent of the duty-cycled period length are [20], [21]. [20] studied delay efficient duty-cycled beaconing scheduling. [21] studied delay efficient duty-cycled multi-flow scheduling. For the strategy of solving the wireless link scheduling problem, some recent work applies machine learning or neural network to D2D communication scheduling. In [22], SVM based on graph kernel is used to learn the link characteristics in the network, and the problem is regarded as a binary classification problem. In [23], the graph neural network is used to describe the distributed network topology information, and the greedy algorithm is combined to solve the maximum weighted independent set problem.

Existing works on deterministic and combinatorial algorithm design for delay efficient wireless scheduling do not consider a D2D communication with traffic offloading scenario. In [24], Lei et al. proposed an optimization framework and formulate a general queuing model for delay-aware resource control with bursty traffic.

Regarding maximizing network capacity, In [25], Lee et al. studied maximizing the spatial reuse of radio resources by allowing the simultaneous transmission of D2D links on the same resources. In [26], Jiang et al. studied the problem of maximizing cellular traffic offloading via D2D communication.

B. Physical Interference Model with Monotone Power

In [27], the scheduling problem without power control under physical interference model, where nodes are arbitrarily distributed in Euclidean space, has been shown to be NP-complete. A greedy scheduling algorithm with approximation ratio of $O(n^{1-2/(\Psi(\kappa)+\epsilon)}(\log n)^2)$, where $\Psi(\kappa)$ is a constant that depends on the path-loss exponent κ, is proposed in [28]. Notice that this result can only hold when the nodes are distributed uniformly at random in a square of unit area.

In [27], the authors proposed an algorithm with a factor $O(g(L))$ approximation guarantee in arbitrary topologies, where $g(L) = \log \vartheta(L)$ is the diversity of the network. In [29], an algorithm with approximation guarantee of $O(\log \Delta)$ was proposed, where Δ is the ratio between the maximum and the minimum distances between nodes. Obviously, it can be arbitrarily larger than $\vartheta(L)$. Recently, there are a lot of work [30], [31] on finding the maximum independent set of links.

Halldorsson et al. [32] presented a robustness result, showing that constant parameter and model changes will modify the minimum length link scheduling result only by a constant. [33] studied the scheduling problem under power control respectively.

VII. Conclusions

In this paper, we studied duty-cycle-aware fast D2D communication scheduling problem. We consider this problem with length-monotone power control and propose the concept of retrieving node according to the data requirements of wireless network equipments. Under the duty-cycled and physical interference model, we try to obtain the method of minimizing the scheduling length. We designed an approximate scheduling algorithm for the problem and demonstrate the efficiency of the proposed algorithm by simulation experiments.

In the future, we plan to develop constant approximation, i.e., asymptotically optimal, scheduling algorithms for the problem under uniform transmission power and arbitrary power control settings.

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