

Data Aggregation Scheduling in Wireless Networks with Cognitive Radio Capability

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Abstract—Complicated collisions and spectrum uncertainty constrain the usage of Cognitive Radio Networks (CRNs) on heavy transmission and time sensitive applications. On the other hand, data aggregation has been considered as an essential operation in wireless networks. A large amount of effort has been dedicated to the investigation of CRNs and data aggregation in wireless networks. However, the existing literatures rarely concentrate on how to use cognitive radio technique to promote the performance of data aggregation in conventional wireless networks. In this paper, we investigate the Minimum Latency Data Aggregation Scheduling in wireless networks with Cognitive Radio capability (MLDAS-CR) problem. As the first try, an approximation scheduling algorithm based on Integer Linear Programming (ILP) and Linear Programming (LP) is proposed. According to the simulation results, this method performs great, however, it is difficult to theoretically evaluate the solution. Therefore, a heuristic scheduling algorithm with guaranteed latency bound is presented in our further investigation. The performance of the proposed solutions are evaluated through extensive simulations.

I. INTRODUCTION

A report released by Federal Communications Commission (FCC) [1] shows that a large portion of licensed wireless spectrums are underutilized while the number of wireless users has explosively increased in the last decade. In order to alleviate the spectrum shortage and underutilization problem, Cognitive Radio Networks (CRNs) have been proposed. In CRNs, unlicensed users are equipped with cognitive radios which are capable of adapting transmitter parameters based on interaction with their operating environment. Unlicensed users can dynamically access and exploit licensed spectrum holes when the spectrum is unoccupied by licensed users. Therefore, CRNs are called “Next Generation Networks” [2]. Since unlicensed users need to avoid collisions with the ongoing transmissions between both licensed users and other unlicensed users, the spectrum availability is quite limited for unlicensed users. Furthermore, due to the unpredictable activities of licensed users, unlicensed users can only access the licensed spectrum opportunistically. This uncertainty constrains the usage of CRNs on heavy transmission and time sensitive applications. e.g., fast data aggregation in wireless networks.

Data aggregation has been considered as an essential operation in wireless networks. It plays a vital role in the summarized data gathering procedure, such as tracking critical

phenomena in continuous and periodic monitoring applications. During the data aggregation process, raw readings are aggregated and then transferred in the network. Classic aggregation functions such as *sum*, *maximum*, *minimum*, *average* or *count* are widely used. Since data is aggregated at intermediate nodes during the transmission process, both data redundancy and the number of transmissions are reduced. Therefore, data aggregation is an efficient strategy to alleviate energy consumption and medium access contention. A large amount of research on data aggregation can be found in existing literatures, where some of them focuses on energy efficiency (such as [3]) and some others concern about time performance ([4]-[10], for example).

In this paper, we concentrate on the investigation of data aggregation in wireless networks with cognitive radio capability. Instead of investigating CRNs that data transmissions among unlicensed users can only rely on the unstable spectrum holes, we study time efficient data aggregation in a wireless network, where the users in the network are equipped with cognitive radios. As in conventional wireless networks, an unlicensed spectrum is assigned to the network. It is available to the in-network users all the time. Meanwhile, the cognitive radio enables wireless users searching and exploiting the spectrum holes. Since a default working spectrum is always guaranteed, regular data transmission can still be processed if there is no spectrum hole. Furthermore, when extra idle spectrum exists, some users can move to that spectrum, so that alleviate contention on the default spectrum and speed up the transmission procedure.

In this paper, instead of taking unoccupied spectrum holes as our only hope for data transmission, we consider them as our assistant and use them to accelerate the data aggregation process. Particularly, we do not intuitively assume that the spectrum holes are only from the licensed bands as discussed in existing literatures. Literatures on coexistence of heterogeneous wireless systems can be found, such as the coexistence of ZigBee and Wifi studied in [11] and [12]. We could have the faith that with the developed technology in wireless networks, more and more heterogeneous networks can co-exist with each other. Therefore, the investigation of this paper is meaningful for facilitating data aggregation process by taking advantage of unused spectrum resources in other networks.

A large amount of effort has been dedicated to the inves-

tigation of CRNs and data aggregation in wireless networks. Several authors did realize the perspective of introducing cognitive radio capability to improve the performance of wireless networks. For example, [13]-[16] studied issues of wireless networks with cognitive radio capability. In all the above four articles, users can work on a stable unlicensed spectrum or access licensed spectrum opportunistically. The authors of [13] focused on the network performance when CSMA is employed. [14] studied the similar issue as [13] with an additional re-trial phenomenon. "When and how long to perform spectrum sensing" in cognitive radio enabled smart grid is investigated in [15]. The performance of wireless mesh networks with cognitive radio capability is analyzed in [16]. However, the existing literatures rarely concentrate on how to use cognitive radio technique to promote the performance of data aggregation in conventional wireless networks, which is the focus of this paper. The main contributions of our work can be concluded into the following aspects:

- We employ the cognitive radio capability in wireless networks to accelerate data transmission. Subsequently, the Minimum Latency Data Aggregation Scheduling problem in wireless networks with Cognitive Radio capability (MLDAS-CR) is formalized and investigated.
- As the first try, the MLDAS-CR problem is formalized as an Integer Linear Programming (ILP) problem. Considering the hardness of solving an ILP, the optimal solution of its linear programming relaxation is obtained, instead. Subsequently, a rounding algorithm is employed to obtain a feasible solution for the ILP from the optimal solution of the relaxed LP.
- According to the simulation results, we can see that the ILP and LP based method has a good performance, however, it is difficult to theoretically evaluate the solution. Therefore, a heuristic scheduling algorithm with guaranteed latency bound is presented in our further investigation.
- The simulation results verify the performance of the proposed solutions.

The remainder of this paper is organized as follows: The system model and problem formulation are presented in Section II. In Section III, the proposed solutions are discussed in detail, followed by the performance evaluation in Section IV. In Section V, the work of this paper is concluded.

II. SYSTEM MODEL AND PROBLEM FORMULATION

We consider a dense wireless network co-exists with another wireless network who are willing to temporarily release idle spectrum holes. The objective of this paper is to find out how cognitive radio capability can contribute to data transmission in conventional wireless networks. Therefore, for the purpose of distinguishing this work from existing literatures on conventional CRNs, we refer to the two wireless networks as the wireless network and the Auxiliary Network (AN) (the network provides extra spectrum opportunity).

A. Network Model

Auxiliary Network (AN): Consider an AN consisting of m Auxiliary Users (AUs) denoted by set $\mathbb{U}_a = \{U_1, U_2, \dots, U_m\}$. The transmission radius and interference radius of an AU are denoted by T_a and I_a , respectively. Let S_a represent the operating spectrum of AUs. Assume the network time is slotted, where the length of a time slot τ_a is long enough for AUs to finish the transmission of a data package. At the beginning of each time slot, AUs make their decisions to stay active (receive or send data) or inactive in the current time slot according to the network protocol. The inactive AUs remain silent for the rest time of the current slot. During each time slot, the active senders follow a two-dimensional Poisson point process X_S with density λ . Apparently, the distribution of the active receiver forms another two-dimensional Poisson point process X_R with the same density λ .

Wireless Network: The considering wireless network consists of n users. Let $\mathbb{U}_r = \{u_1, u_2, \dots, u_n\}$ denote the set of users, among which user $u_b \in \mathbb{U}_r$ wants to get the aggregated information from the network. For $u_i \in \mathbb{U}_r$, its transmission and interference radii are denoted by T_r and I_r , respectively. There is a default working spectrum S_r physically available to all the users all the time. Each $u_i \in \mathbb{U}_r$ is equipped with a single, half-duplex cognitive radio, which is capable of accessing the default spectrum S_r or adapting parameters to access opportunistically appeared spectrum holes on S_a . Assume the time in the wireless network is also slotted, where the length of the time slot τ_r is long enough for a user to monitor the available spectrum conditions and then transmit a data package. Due to the radio limitation, a user can either transmit or receive data, not both, from all directions at one time slot on a specific spectrum. In each time slot t , a user who has data to send can either operate on S_r or opportunistically access S_a in a sensing-before-transmission manner, as long as no collision will be caused to both networks. Particularly, users in the wireless network have equal rights to access S_r . However, S_a can be used by non-AUs if and only if no on-going transmissions in AN will be interrupted. That is, the AUs have absolute priority on S_a .

Unit Disk Graph Interference Model: In this paper, we consider the Unit Disk Graph (UDG) interference Model, which has been widely used in existing literatures. Under this model, the interference range and the transmission range of wireless devices are denoted by equally disks. That is, $T_a = I_a$ and $T_r = I_r$.

B. Problem Formulation

Definition 2.1: Exterior Collision. At time t , given a link $\overrightarrow{u_s u_r}$ ($u_s, u_r \in \mathbb{U}_r$), where sender u_s has data to send to receiver u_r , if the proceeding of this transmission influences or is influenced by at least one on-going transmission in AN, it is said that there exists an exterior collision. Let U_s and U_r be the transmitter and receiver that affect u_r or affected by u_s when an exterior collision is occurred. We have $\|U_s - u_r\| \leq T_r$ or $\|U_r - u_s\| \leq I_a$, and $\|A - B\|$ is the Euclidean distance

between A and B .

Definition 2.2: Interior Collision. Let $\overrightarrow{u_{s_1}u_{r_1}}$ and $\overrightarrow{u_{s_2}u_{r_2}}$ represent two links in the wireless network, where u_{s_1} and u_{s_2} are senders, and u_{r_1} and u_{r_2} are their corresponding receivers. If the concurrent scheduling of the two links at some time t leads to a collision, then the collision is called an interior collision. Similarly, when an interior collision is caused, $\|u_{s_1} - u_{r_2}\| \leq T_r$ or $\|u_{r_1} - u_{s_2}\| \leq T_r$ can be derived, and vice versa.

Based on the network model and definitions, the **Minimum Latency Data Aggregation Scheduling** problem in a wireless network with **Cognitive Radio** (MLDAS-CR) can be formalized as follows:

Given a wireless network denoted by $G = (\mathbb{U}_r, E)$, where $\mathbb{U}_r = \{u_1, u_2, \dots, u_n\}$ is the set of wireless users, and E is the set of links ($\overrightarrow{u_s u_r} \in E$ if $\|u_s - u_r\| \leq T_r$). A user $u_b \in \mathbb{U}_r$ acts as a base station and desires to obtain aggregated data from the network. Users in \mathbb{U}_r are equipped with cognitive radios capable of adapting transmitting parameters as required. A default working spectrum S_r is allocated to \mathbb{U}_r . An AN consists of m AUs operating on spectrum S_a . S_a is open to \mathbb{U}_r if no transmission in the AN is affected. Initially, each user $u_i \in \mathbb{U}_r \setminus \{u_b\}$ generates a data package d_i . For simplicity, let $\mathbb{D} = \{d_1, d_2, \dots, d_n\}$ denote the set of data packages generated in the wireless network, where $d_i (i \neq b)$ is the data generated by user u_i . An MLDAS-CR problem can be defined as a schedule set $\mathbb{S} = \{\mathbb{S}_1, \mathbb{S}_2, \dots, \mathbb{S}_\mathbb{L}\}$, where each \mathbb{S}_t ($1 \leq t \leq \mathbb{L}$) is a set of collision-free links in G who are scheduled at time slot t . Furthermore, to be an MLDAS-CR, the following constraints are required:

- 1) $\forall t$ ($1 \leq t \leq \mathbb{L}$), neither an exterior collision nor an interior collision is caused by any scheduled links in \mathbb{S}_t .
- 2) $\forall t$ ($1 \leq t \leq \mathbb{L}$), given two links $\overrightarrow{u_{s_1}u_{r_1}} \in \mathbb{S}_t$ ($s_1 \neq r_1$) and $\overrightarrow{u_{s_2}u_{r_2}} \in \mathbb{S}_t$ ($s_2 \neq r_2$) scheduled on either S_r or S_a , then $s_1 \neq s_2$, $s_1 \neq r_2$, $s_2 \neq r_1$, and $r_1 \neq r_2$.
- 3) $\forall t_1, t_2$ ($1 \leq t_1, t_2 \leq \mathbb{L}$, $t_1 \neq t_2$), if $\overrightarrow{u_{s_1}u_{r_1}} \in \mathbb{S}_{t_1}$ and $\overrightarrow{u_{s_2}u_{r_2}} \in \mathbb{S}_{t_2}$, then $s_1 \neq s_2$.
- 4) $f(\bigcup_{t=1}^{\mathbb{L}} \{d_{\overrightarrow{u_{s_t}u_b}} | \forall \overrightarrow{u_{s_t}u_b} \in \mathbb{S}_t\}) = f_A(\mathbb{D})$, where $d_{\overrightarrow{u_{s_t}u_b}}$ is the data package received by u_b at time t through link $\overrightarrow{u_{s_t}u_b}$, f_A is the aggregate function and $f_A(\mathbb{D})$ is the aggregated result over \mathbb{D} .
- 5) If $t = \mathbb{L}$, the transmission is $\overrightarrow{u_s u_b}$, and $\bigcup_{t=1}^{\mathbb{L}-1} \{u_{s'} | \overrightarrow{u_{s'}u_{r'}} \in \mathbb{S}_t\} \cup \{u_s\} \cup \{u_b\} = \mathbb{U}_r$.
- 6) $\arg \min_{\mathbb{S}=\{\mathbb{S}_1, \mathbb{S}_2, \dots, \mathbb{S}_\mathbb{L}\}} \mathbb{L}$.

Constraint 1 shows MLDAS-CR should be exterior and interior collisions free. No exterior collision guarantees that no interference will be caused to AN, and interior collision free avoids extra delay and congestion caused by retransmission in the wireless network. Since u_i has only one radio, constraint 2 requires u_i can either be a sender or receiver at a particular time slot t , but not both. Constraint 3 indicates the property of data aggregation, that is, each user sends its aggregation result (aggregated data of its own and data received during the MLDAS-CR) only once. The data integrity property is ensured

by constraint 4, where data received by the base station should be the aggregated information of the whole network. At the last time slot, the base station should receive the last transmission from a SU as specified in 5. Constraint 6 denotes that the objective of the MLDAS-CR scheduling \mathbb{S} is to minimize the total transmission latency.

It is known that the Minimum Latency Data Aggregation Scheduling (MLDAS) problem in wireless network is NP-hard without considering the cognitive radio capability. It can be considered as a special case of MLDAS-CR when the AUs in AN are so dense and active that no spectrum holes exist. Therefore, the MLDAS-CR problem is NP-hard.

III. SCHEDULING ALGORITHM FOR MLDAS-CR

In this section, we first introduce the construction of a balanced Connected Dominating Set-based tree, which serves as the routing tree during the data aggregation process. Subsequently, two scheduling algorithms for MLDAS-CR are discussed in detail.

A. Construction of a Balanced Routing Tree

Given a graph, a Connected Dominating Set (CDS) is a connected component with the property that for every vertex on the graph, it is either in the CDS or has some one-hop neighbor in the CDS. This property makes CDS quite suitable for serving as routing infrastructure in wireless networks. However, it is not the case that an arbitrary CDS-based routing tree is efficient for the data aggregation application. In this paper, a Balanced CDS-based Routing Tree (BRT) is employed for the purpose of distributing transmission workload evenly, reducing the delay of users with large degree, and then accelerating the aggregation process.

Definition 3.1: 2-norm. Given a vector $X = (x_1, x_2, \dots, x_n)$, the 2-norm of X is defined as: $|X|_2 = \sqrt{\sum_{i=1}^n |x_i|^2}$.

According to [17], given a vector X as defined in Def. 3.1, $|X|_2$ can be used to measure the balance among all variables x_i ($1 \leq i \leq n$).

Let vector $W = (w_1, w_2, \dots, w_n)$ denote the workload, where w_i represents the load allocates to u_i . Then, $|W|_2$ can be used to measure how balance the workload is distributed among users in \mathbb{U}_r . Especially, the smaller $|W|_2$, the more balance of workload allocation. Initially, $\forall i, w_i = 0$. The construction of BRT can be described as follows:

Step 1: Set the layer of u_b as 0, and build a Breadth First Search (BFS) tree rooted at u_b . Then, search the BFS tree from root to leaves, by layer, mark all the users who form a maximal independent set BLACK.

Step 2: Start at the 2nd layer, mark the parent of BLACK nodes GRAY. Subsequently, for each GRAY node, find a BLACK node from the same layer or one upper layer to be its parent. During this process, update W for BLACK nodes according to their number of GRAY children. If multiple choices are available to a GRAY node, then the BLACK gives minimum $|W|_2$ after allocation will be chosen as its parent.

Step 3: In the last step, the unmarked WHITE nodes are balanced allocated to BLACK nodes. In order to obtain a BRT, a

WHITE node accepts the BLACK in its one-hop neighborhood who can minimize $|W|_2$ as its parent. The details are illustrated in Alg. 1. Finally, from root to leaves, each node updates its layer according to its parent's layer.

Algorithm 1: Balanced Allocation

input : The tree gets from step 2
output: BRT

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1 for each  $w_i$  do
2    $w_i = 0$ ;
3 for each unmarked node  $u_i$  do
4   mark in WHITE;
5   check all neighbors in BLACK denoted as set  $NB(i)$ ;
6   if  $u_j \in NB(i)$  and the allocation of  $u_i$  to  $u_j$  achieves the
   minimum increase of  $|W|_2$  then
7     set  $u_j$  as  $u_i$ 's parent;
8     update  $w_j$  accordingly.

```

Since the maximum number of WHITE nodes is $n - 1$, and the number of black nodes in a white node's one-hop neighborhood is no more than 5 (Lemma 4), therefore, the running time of Alg. 1 is $O(n)$. Based on the construction of BRT, the following lemma holds:

Lemma 1: All the BLACK users are in even layers. All GRAY users are in odd layers. Each GRAY user has a BLACK parent and at least one BLACK child. The BLACK and GRAY users form a CDS. Any WHITE user is leave on the BRT and has a BLACK parent.

Particularly, in order to intuitively show links on BRT, we transfer G to $G^B = \{U_r, \{E^B, E\}\}$, where E^B contains the links on the BRT. For simplicity, we only consider the directed links from children to parents in E^B , while ignore links in the opposite direction. The reason is that data in the network is aggregated only from bottom (children) to top (parent) on the BRT.

B. Scheduling Algorithm Based on LP

In this subsection, a mathematical model is employed to formalize the MLDAS-CR problem. According to the formalization, a scheduling algorithm based on Linear Programming (LP) is discussed in detail.

We define two scheduling variables R_{ij}^t and A_{ij}^t as:

$$R_{ij}^t = \begin{cases} 1, & \text{if link } \overrightarrow{u_i u_j} \text{ is scheduled on } S_r \text{ at time } t \\ 0, & \text{otherwise} \end{cases}$$

and,

$$A_{ij}^t = \begin{cases} 1, & \text{if link } \overrightarrow{u_i u_j} \text{ is scheduled on } S_a \text{ at time } t \\ 0, & \text{otherwise} \end{cases}$$

Variable Y_{ij} is used to indicate the AUs' activity around link $\overrightarrow{u_i u_j}$, where

$$Y_{ij}^t = \begin{cases} 1, & \text{if schedule } \overrightarrow{u_i u_j} \text{ at } t \text{ cause exterior collision} \\ 0, & \text{otherwise} \end{cases}$$

To be specific, at time t , $Y_{ij}^t = 1$ if there is at least one receiver in AN active in u_i 's interference range or one sending activity is detected within u_j 's transmission range at t .

Let $Q_i^t = 1$ indicate that u_i has obtained data from all its children at t , Otherwise, $Q_i^t = 0$. Apparently, the Q variable of any WHITE node on the BRT is 1.

Due to the constraint of half-duplex radio, a user can active as a sender or receiver but not both on a particular spectrum at a particular time. Therefore, at a specific time t , for an arbitrary user u_a on BRT, it may keep silent or play one role on S_a or S_r , that is:

$$\sum_{\overrightarrow{u_a u_i} \in E^B} R_{ai}^t + \sum_{\overrightarrow{u_i u_a} \in E^B} R_{ia}^t + \sum_{\overrightarrow{u_a u_i} \in E^B} A_{ai}^t + \sum_{\overrightarrow{u_i u_a} \in E^B} A_{ia}^t \leq 1 \quad (1)$$

On the other hand, to prevent re-transmission and unnecessary energy consumption from transmission collision, a scheduled link cannot interrupt or be interrupted by any on-going transmission in both networks. That is, the scheduling of link $\overrightarrow{u_s u_r} \in E^B$ cannot result in exterior or interior collision.

For a particular time t , to avoid interior collision, InEq. (2) is required.

$$R_{sr}^t + \sum_{u_i \in NB(u_r), \overrightarrow{u_i u_j} \in E^B} R_{ij}^t \leq 1 \quad (2)$$

and, on the other hand, to avoid interference with the activities in AN,

$$A_{sr}^t + \sum_{u_i \in NB(u_r), \overrightarrow{u_i u_j} \in E^B} A_{ij}^t \leq 1 \quad (3)$$

where $NB(u_i)$ is the set of one-hop neighbor of u_i in the wireless network.

According to InEq. (2) and (3), the following constraint specifies the property that a confliction-free scheduling plan should have.

$$R_{sr}^t + A_{sr}^t + \sum_{u_i \in NB(u_r), \overrightarrow{u_i u_j} \in E^B} (R_{ij}^t + A_{ij}^t) \leq 1 \quad (4)$$

Furthermore, link $\overrightarrow{u_s u_r} \in E^B$ can be scheduled on S_a if and only if S_a is available, i.e.,

$$A_{sr}^t \leq 1 - Y_{sr}^t \quad (5)$$

Since a node needs to wait for all its children for aggregating data, for $\overrightarrow{u_s u_r} \in E^B$,

$$R_{sr}^t \leq Q_s^t, A_{sr}^t \leq Q_s^t \quad (6)$$

With the purpose of ultimately utilizing spectrum holes on S_a and reducing spectrum competition on S_r , the utility function of scheduling $\overrightarrow{u_s u_r} \in E^B$ at t is defined as:

$$f_{sr}^t = R_{sr}^t + (\alpha d_s + \beta l_s + 1) A_{sr}^t \quad (7)$$

where d_s and l_s are the degree and layer of u_s , respectively. Two variables α and β are used to adjust the weight of the two properties according to demand.

Based on the above constraints, we can conclude the MLDAS-CR problem as:

$$\begin{aligned}
& \text{Maximize} && \frac{1}{L} \sum_{t=1}^L \sum_{\overrightarrow{u_s u_r} \in E^B} f_{sr}^t \\
& \text{subject to} && \sum_{\overrightarrow{u_a u_i} \in E^B} R_{ai}^t + \sum_{\overrightarrow{u_i u_a} \in E^B} R_{ia}^t \\
& && + \sum_{\overrightarrow{u_a u_i} \in E^B} A_{ai}^t + \sum_{\overrightarrow{u_a u_i} \in E^B} A_{ia}^t \leq 1 \\
& && R_{sr}^t + A_{sr}^t + \sum_{u_i \in NB(u_r), \overrightarrow{u_i u_j} \in E^B} (R_{ij}^t + A_{ij}^t) \leq 1 \\
& && A_{sr}^t \leq 1 - Y_{sr}^t \\
& && R_{sr}^t \leq Q_s^t \\
& && A_{sr}^t \leq Q_s^t \\
& && 1 \leq t \leq L, \in R_{sr} \in \{0, 1\}, A_{sr} \in \{0, 1\}, L \in \mathbb{N}
\end{aligned}$$

where L is assumed to be the length of the scheduling time.

Even though the introduced objective function and constraints formalize the MLDAS-CR problem to a 0-1 Integer Linear Program (ILP), we are in a dilemma to find a scheduling plan based on the formalization. The major difficulty we are facing is that the activity Y_{sr}^t for link $\overrightarrow{u_s u_r} \in E^B$ at time t is unpredictable. There is no way we can get the information of Y_{sr}^t until time t .

Therefore, instead of solving the problem considering continuous time, we switch to find optimal scheduling for each time slot. That is, at a particular time t , given Y_{sr}^t for any $\overrightarrow{u_s u_r} \in E^B$, how can we make the best decision so that we can get the maximum number of links scheduled? In this case, we only care about links in E^B denoted as $E^{B'}$ that have not been scheduled yet. For simplicity, in the description below, t is removed from the superscript. Then we have:

$$\begin{aligned}
& \text{Maximize} && \sum_{\overrightarrow{u_s u_r} \in E^{B'}} f_{sr} \\
& \text{subject to} && \sum_{\overrightarrow{u_a u_i} \in E^{B'}} R_{ai} + \sum_{\overrightarrow{u_i u_a} \in E^{B'}} R_{ia} \\
& && + \sum_{\overrightarrow{u_a u_i} \in E^{B'}} A_{ai} + \sum_{\overrightarrow{u_a u_i} \in E^{B'}} A_{ia} \leq 1 \\
& && R_{sr} + A_{sr} + \sum_{u_i \in NB(u_r), \overrightarrow{u_i u_j} \in E^{B'}} (R_{ij} + A_{ij}) \leq 1 \\
& && A_{sr} \leq 1 - Y_{sr} \\
& && R_{sr} \leq Q_s \\
& && A_{sr} \leq Q_s \\
& && R_{sr} \in \{0, 1\}, A_{sr} \in \{0, 1\}
\end{aligned}$$

Solving the ILP for time t is still at least NP-hard. However, a Linear Program (LP) is polynomial-time solvable. Therefore, a natural choice is to derive an LP by relaxing the constraints $R_{sr} \in \{0, 1\}, A_{sr} \in \{0, 1\}$ to $0 \leq R_{sr}, A_{sr} \leq 1$. Instead of solving the ILP, the optimal solution of LP can be obtained by an LP solver. After that, a rounding algorithm (as shown in Alg. 2) is employed to get a feasible solution for the ILP. Based on the output of Alg. 2, all the links with $A_{sr} = 1$ can be

scheduled on S_a , and links with $R_{sr} = 1$ should be scheduled on S_r . Then, we can obtain a data aggregation scheduling for

Algorithm 2: Rounding Algorithm

input : Optimal solution from LP
output: Feasible solution for ILP

- 1 Sort the input by non-descending order denoted as $\mathcal{L} = \{\overrightarrow{u_{s_1} u_{r_1}}, \overrightarrow{u_{s_2} u_{r_2}}, \dots\}$;
- 2 **while** $\mathcal{L} \neq \emptyset$ **do**
- 3 **for the ordered unmarked links in** \mathcal{L} **do**
- 4 **if** $Y_{sr} = 0$ **then**
- 5 mark $\overrightarrow{u_s u_r}$, set $A_{sr} = 1, R_{sr} = 0$;
- 6 **for all the links conflict with** $\overrightarrow{u_s u_r}$ **in** \mathcal{L} **do**
- 7 mark $\overrightarrow{u_{s'} u_{r'}}$, set $A_{s'r'} = R_{s'r'} = 0$;
- 8 **else**
- 9 mark $\overrightarrow{u_s u_r}$, set $A_{sr} = 0, R_{sr} = 1$;
- 10 **for all the links conflict with** $\overrightarrow{u_s u_r}$ **in** \mathcal{L} **do**
- 11 mark $\overrightarrow{u_{s'} u_{r'}}$, set $A_{s'r'} = R_{s'r'} = 0$;

MLDAS-CR by iteratively solving the LP problem according to the dynamic network condition, the details are presented in Alg. 3.

Algorithm 3: SLP (Scheduling based on LP)

input : $G^B = \{\mathbb{U}_r, \{E^B, E\}\}$
output: Schedule $\mathbb{S} = \{\mathbb{S}_1, \mathbb{S}_2, \dots, \mathbb{S}_L\}$

- 1 $t = 0$;
- 2 **for each user** $u_i \in \mathbb{U}_r$ **do**
- 3 **if** u_i is WHITE **then**
- 4 set $Q_i^t = 1$;
- 5 **else**
- 6 set $Q_i^t = 0$;
- 7 **while** E^B is not empty **do**
- 8 $t++$;
- 9 **for each link** $\overrightarrow{u_s u_r} \in E^B$ **do**
- 10 sense spectrums, and set Y_{sr}^t accordingly;
- 11 solve the formulated LP;
- 12 call Alg. 2;
- 13 **for each** $R_{sr}^t = 1$ or $A_{sr}^t = 1$ **do**
- 14 **if** $R_{sr}^t = 1$ **then**
- 15 schedule $\overrightarrow{u_s u_r}$ on S_r ;
- 16 **else**
- 17 schedule $\overrightarrow{u_s u_r}$ on S_a ;
- 18 $\mathbb{S}_t = \mathbb{S}_t \cup \{\overrightarrow{u_s u_r}\}$;
- 19 remove $\overrightarrow{u_s u_r}$ from E^B ;
- 20 **for each user** $u_i \in \mathbb{U}_r$ **do**
- 21 update Q_i^t accordingly;

C. Scheduling with Expected Delay Guarantee

As shown in Section III-B and IV, a feasible scheduling policy based on the LP can be derived and its performance is good. However, it is difficult to theoretically show that

how well the feasible solution is. In this subsection, we focus on scheduling algorithm with expected delay guarantee. Meanwhile, the algorithm should be easy to implement.

According to Lemma 1, links in E^B can be classified into three types: the sender u_s is WHITE and the receiver u_r is BLACK, u_s is BLACK and u_r is GRAY, and u_s is GRAY and u_r is BLACK. For simplicity, let l_{wb} , l_{bg} , and l_{gb} denote the three kinds of links, respectively.

Definition 3.2: Interior Interference Link Set. Given $\overrightarrow{u_s u_r} \in E^B$, the Interior Interference Link Set (IILS) of $\overrightarrow{u_s u_r}$, denoted as \mathbb{I}_{sr} , is defined as all the links in E^B active on S_r or S_a which will cause interior collision if $\overrightarrow{u_s u_r}$ is scheduled on the same spectrum (S_r or S_a , accordingly). Furthermore, $|\mathbb{I}_{sr}|$ is defined as the *interference degree* of link $\overrightarrow{u_s u_r}$, which is the total number of links that may interfere with $\overrightarrow{u_s u_r}$ in the wireless network.

Given link set \mathcal{L} , the *conflict graph* of \mathcal{L} denoted by $C[\mathcal{L}]$ is an undirected graph on \mathcal{L} in which there is an edge between two links if they cannot be scheduled simultaneously without collision. Then, given a link set \mathcal{L} , the interference degree of $\overrightarrow{u_s u_r}$ is equal to its degree on $C[\mathcal{L}]$, and \mathbb{I}_{sr} is $\overrightarrow{u_s u_r}$'s one-hop neighbor on $C[\mathcal{L}]$.

The FFS algorithm (Alg. 4, Alg. 5), which based on the BRT constructed in Section III-A, can be concluded into two stages:

Stage 1: All the links of type l_{wb} are scheduled. A link $\overrightarrow{u_s u_r}$ in E^B is said *ready* to be scheduled if the sender u_s has received data from all of its children. Since the WHITE users have no children, they are ready for transmission. Firstly, links of type l_{wb} are sorted in a non-decreasing order according to their interference degrees. For simplicity, let $\mathcal{L}_{wb} = \{\overrightarrow{u_{s_1} u_{r_1}}, \overrightarrow{u_{s_2} u_{r_2}}, \dots, \overrightarrow{u_{s_w} u_{r_b}}\}$ denote the set of sorted links. Subsequently, a first-fit scheduling policy is employed to schedule the sorted links in \mathcal{L}_{wb} . To be specific, links in \mathcal{L}_{wb} are considered in order from $\overrightarrow{u_{s_1} u_{r_1}}$ to $\overrightarrow{u_{s_w} u_{r_b}}$. For a link $\overrightarrow{u_{s_i} u_{r_i}}$, check its spectrum availability and collision status, and then schedule the link whenever a transmission opportunity exist. Alg. 4 shows this stage in detail.

Stage 2: Iteratively schedule links of type l_{bg} and l_{gb} . Let $E^{B'}$ denote the set of unscheduled links in E^B after Stage 1. The scheduling conducts iteratively, where the ready l_{bg} links are scheduled in even iterations, and the ready l_{gb} links are scheduled in odd iterations. During each iteration, ready links are sorted in non-decreasing order according to their interference degree. After that, a first-fit scheduling policy is applied to arrange the scheduling plan. The detailed pseudocode is shown in Alg. 5. According to Alg. 5, we can see that each "iteration" may consist of several time slots, and the length of different "iterations" may be different. That depends on the required time for scheduling the ready links under consideration.

In the following part, we analyze the latency of the proposed FFS algorithm.

Lemma 2: The expected number of spectrums available to a link in the wireless network is $1 + e^{-\pi\lambda(T_r^2 + T_a^2)}$, where T_r and T_a are the transmission radius for users in the wireless network

Algorithm 4: FFS-S1 (First-Fit Scheduling Stage 1)

```

input :  $G^B = \{\mathbb{U}_r, \{E^B, E\}\}$ 
output: Schedule  $\mathbb{S} = \{\mathbb{S}_1, \mathbb{S}_2, \dots, \mathbb{S}_t\}$ 
1  $t = 0$ ;
2 Sort links in  $E^B$  of type  $l_{wb}$  in non-decreasing order according
  to their interference degree;
3  $\mathcal{L}_{wb} = \{\overrightarrow{u_{s_1} u_{r_1}}, \overrightarrow{u_{s_2} u_{r_2}}, \dots, \overrightarrow{u_{s_w} u_{r_b}}\}$  denote the set of sorted
  links;
4 while  $\mathcal{L}_{wb} \neq \emptyset$  do
5    $t++$ ;
6   for each link in  $\mathcal{L}_{wb}$  do
7     if  $\mathbb{I}_{s_i r_i} = \emptyset$  then
8        $\lfloor$  schedule  $\overrightarrow{u_{s_i} u_{r_i}}$  on  $S_a$ ;
9     else if  $\mathbb{I}_{s_i r_i} = \emptyset$  then
10       $\lfloor$  schedule  $\overrightarrow{u_{s_i} u_{r_i}}$  on  $S_r$ ;
11  for each scheduled link  $\overrightarrow{u_{s_i} u_{r_i}}$  do
12     $\mathbb{S}_t = \mathbb{S}_t \cup \{\overrightarrow{u_{s_i} u_{r_i}}\}$ ;
13    remove  $\overrightarrow{u_{s_i} u_{r_i}}$  from  $E^B$  and  $\mathcal{L}_{wb}$ ;
```

Algorithm 5: FFS-S2 (First-Fit Scheduling Stage 2)

```

input :  $G^B = \{\mathbb{U}_r, \{E^{B'}, E\}\}$ 
output: Schedule  $\mathbb{S} = \{\mathbb{S}_{t+1}, \mathbb{S}_{t+2}, \dots, \mathbb{S}_L\}$ 
1  $t = t + 1, iter = 0$ ;
2 while Not all scheduled do
3   if  $iter \% 2 = 0$  then
4     Sort ready links in  $E^{B'}$  of type  $l_{bg}$  in non-decreasing
5     order according to their interference degree;
6     let  $\mathcal{L}_{bg} = \{\overrightarrow{u_{s_1} u_{r_1}}, \overrightarrow{u_{s_2} u_{r_2}}, \dots, \overrightarrow{u_{s_b} u_{r_g}}\}$  denote the set
7     of sorted links;
8     while  $\mathcal{L}_{bg} \neq \emptyset$  do
9       for each link in  $\mathcal{L}_{bg}$ : from  $\overrightarrow{u_{s_1} u_{r_1}}$  to  $\overrightarrow{u_{s_b} u_{r_g}}$  do
10        if  $\mathbb{I}_{s_i r_i} = \emptyset$  then
11           $\lfloor$  schedule  $\overrightarrow{u_{s_i} u_{r_i}}$  on  $S_a$ ;
12        else if  $\mathbb{I}_{s_i r_i} = \emptyset$  then
13           $\lfloor$  schedule  $\overrightarrow{u_{s_i} u_{r_i}}$  on  $S_r$ ;
14        for each scheduled link  $\overrightarrow{u_{s_i} u_{r_i}}$  do
15           $\mathbb{S}_t = \mathbb{S}_t \cup \{\overrightarrow{u_{s_i} u_{r_i}}\}$ ;
16          remove  $\overrightarrow{u_{s_i} u_{r_i}}$  from  $E^{B'}$ ;
17         $t++$ ;
18      else
19        repeat step 4 to 15 but replace links of  $l_{bg}$  with  $l_{gb}$ ;
20       $iter++$ ;
```

and AN, respectively.

Given a connected graph $G = \{V, E\}$, let $G[U]$ denote a subgraph of G induced by $U \subseteq V$, Δ and δ are the maximum and minimum degree of G , respectively. The inductivity of G is defined as $\delta^*(G) = \text{MAX}_{U \subseteq V} (G[U])$.

Lemma 3: Given a non-decreasing ordering $O = \langle o_1, o_2, \dots, o_n \rangle$, let d_i denote the degree of o_i , it is proved that a first-fit coloring policy in smallest-degree-last ordering uses at most $1 + \delta^*$ colors, where $\delta^* = \text{MAX}_{1 < i < n} |d_i|$ [6].

Lemma 4: Let C represent a disk of radius r , and U is a

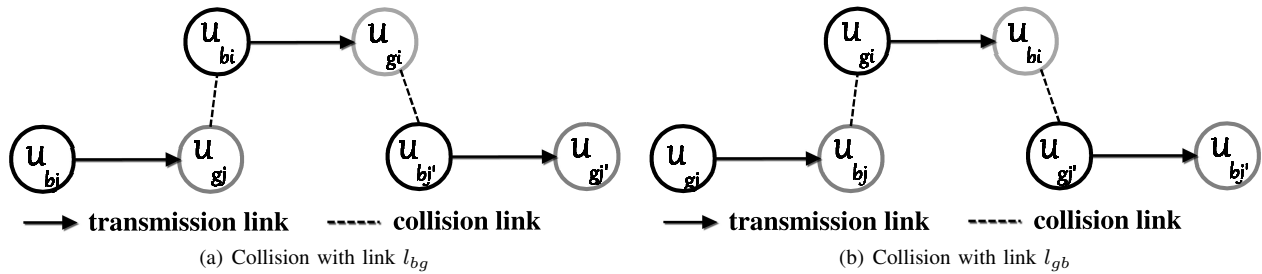


Fig. 1. Example of Collision.

set of points with mutual distance at least 1, then the number of points with mutual distance at least 1 on the disk is upper bounded by $\frac{2\pi}{\sqrt{3}}r^2 + \pi r + 1$, that is, $|U \cup C| \leq \frac{2\pi}{\sqrt{3}}r^2 + \pi r + 1$ [6].

Lemma 5: The expected latency for FFS-S1 is upper bounded by $\frac{5\Delta}{1+e^{-\pi\lambda(T_r^2+T_a^2)}}$, where Δ is the maximum degree of G .

Proof: According to Alg. 4, in FFS stage 1, all links of type l_{wb} are scheduled. The algorithm employ a first-fit scheduling based on the ordering of links' interference degree. Let \mathcal{L}_{wb} denote the set of l_{wb} links. Then, the latency is upper bounded by $\delta^*(C[\mathcal{L}_{wb}]) + 1$ (Lemma 3), where $\delta^*(C[\mathcal{L}_{wb}])$ is the inductivity of \mathcal{L}_{wb} 's conflict graph. Furthermore, $\delta^*(C[\mathcal{L}_{wb}]) = \text{MAX}_{\overrightarrow{u_s u_r} \in \mathcal{L}_{wb}} |\mathbb{I}_{w_i b_i}|$, which is the maximum degree of $C[\mathcal{L}_{wb}]$. Assume the abstraction of $l_{w_i b_i}$ is the vertex with maximum degree in $C[\mathcal{L}_{wb}]$, where the degree is equivalent to the number of links that conflict with $l_{w_i b_i}$. Based on the network model and interference model specified in Section II-A, link $\overrightarrow{u_s u_r}$ that cannot be scheduled simultaneously with $l_{w_i b_i}$ have the property that $\|l_{w_i} - u_r\| \leq T_r$ or $\|l_{b_i} - u_s\| \leq T_r$. Since only l_{wb} links are scheduled in FFS stage 1, for any conflicting link $l_{w_j b_j}$, we have $\|l_{w_i} - l_{b_j}\| \leq T_r$ or $\|l_{b_i} - l_{w_j}\| \leq T_r$, where $\|l_{w_i} - l_{b_j}\| \leq T_r$ contains the BLACK users in u_{w_i} 's one-hop neighborhood, and $\|l_{b_i} - l_{w_j}\| \leq T_r$ specifies u_{b_i} 's one-hop WHITE neighbors. According to Lemma 4, a WHITE user may have at most 5 BLACK one-hop neighbors, where one of them is its parent based on the construction of the BRT. If Δ denotes the maximum degree of G and G^B , then, for each BLACK node, it has at most Δ WHITE neighbors. Therefore, $|\mathbb{I}_{w_i b_i}| \leq 4 * \Delta + \Delta - 1 = 5\Delta - 1$. According to Lemma 3, 5Δ spectrums are needed to color the links. Since we only have $1 + e^{-\pi\lambda(T_r^2+T_a^2)}$ spectrum available, the iteration we need to finish the scheduling is $\frac{5\Delta}{1+e^{-\pi\lambda(T_r^2+T_a^2)}}$. ■

Lemma 6: The expected latency for FFS-S2 is at most $\frac{44D+1}{1+e^{-\pi\lambda(T_r^2+T_a^2)}}$, where D is the diameter of the wireless network.

Proof: The proof of stage 2 is similar to Lemma 5, we concentrate on finding the inductivity of the conflict graph for the link set in each iteration. Since the algorithm performs iteratively, the latency can be derived based on the following two propositions.

Proposition 1: The latency for the even iteration is at most

$$\frac{22}{1+e^{-\pi\lambda(T_r^2+T_a^2)}}.$$

Proposition 2: The latency for the odd iteration is upper bounded by $\frac{22}{1+e^{-\pi\lambda(T_r^2+T_a^2)}}$ if $u_{b_i} \neq u_b$, and $\frac{23}{1+e^{-\pi\lambda(T_r^2+T_a^2)}}$, otherwise.

Finally, based on the construction of the BRT, the maximum number layer of the BRT is upper bounded by $2D$, where D is the diameter of the wireless network (the hops between the farthest two users in the wireless network). According to Alg. 5, Case 1 and case 2 will alternatively run at most D iterations, respectively. Therefore, the expected latency for stage 2 is $\frac{44D+1}{1+e^{-\pi\lambda(T_r^2+T_a^2)}}$. ■

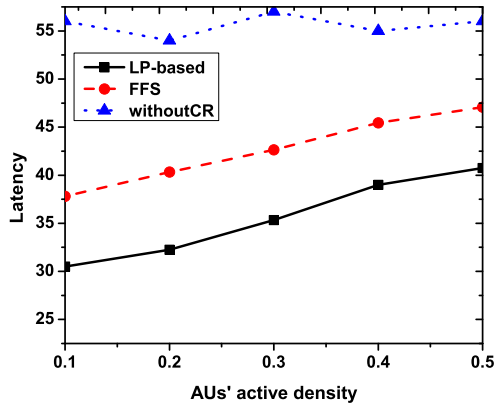
Theorem 1: The expected latency for the proposed first-fit scheduling algorithm is $\frac{5\Delta+44D+1}{1+e^{-\pi\lambda(T_r^2+T_a^2)}}$, where Δ and D are the maximum degree and diameter of the wireless network, respectively.

The proof of theorem 1 can be directly derived from Lemma 5 and Lemma 6.

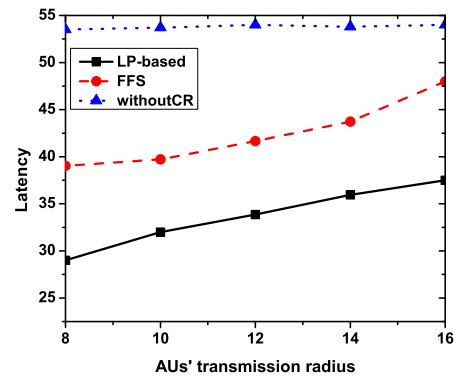
IV. PERFORMANCE EVALUATION

In this section, we evaluate the performance of our proposed scheduling algorithms with respect to different network parameters. To keep consistency with Section II, the same notations are used in this section. To be specific, let m, n denote the number of AUs and wireless users, respectively; T_a (respectively, T_r) is the transmission radius of AUs (respectively, wireless users). At each time slot, the active senders and receivers in the AN follow Poisson Distribution with density λ . The network configuration is initially set up as: $A = 100 * 100$, $m = 100$, $n = 400$, $T_a = T_r = 1.5$, and $\lambda = 0.3$. For simplicity, the utility function for LP is defined as $f_{sr}^t = R_{sr}^t + 1.2 * A_{sr}^t$, where users are encouraged to use the auxiliary spectrum if allowed. In the simulation, in order to verify the influence of different parameters on the proposed algorithms, we adjust one of the parameters per time while keep the rest unchanged. Particularly, the performance of our proposed algorithms are compared with the SAS algorithm. SAS is a sequential aggregation scheduling algorithm based on CDS- aggregation tree and first fit coloring scheduling algorithm proposed in [6]. It is the algorithm we can find in existing literature with the best latency bound $15R + \Delta - 4$, where R is the network radius and Δ is the maximum degree. For comparison, in SAS, we assume only S_r is available.

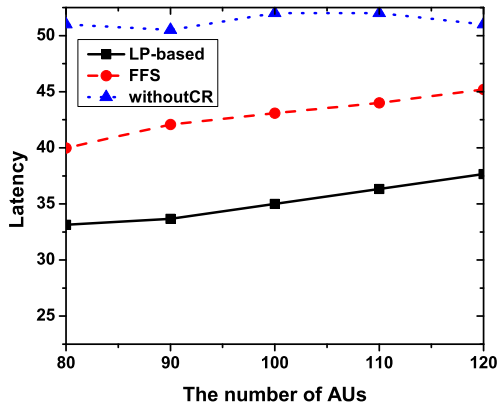
The results are shown in Fig. 2, where the impacts of AUs are evaluated in Fig. 2(a) and Fig. 2(c), and the influence



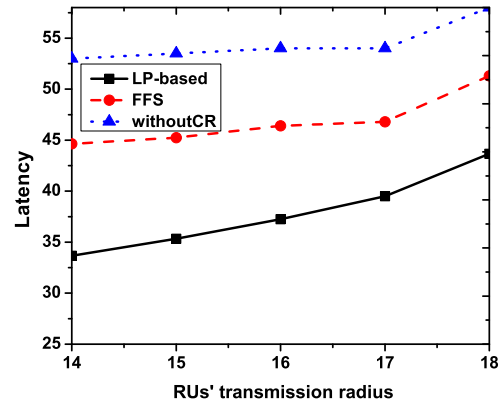
(a) Impact of AUs' active density



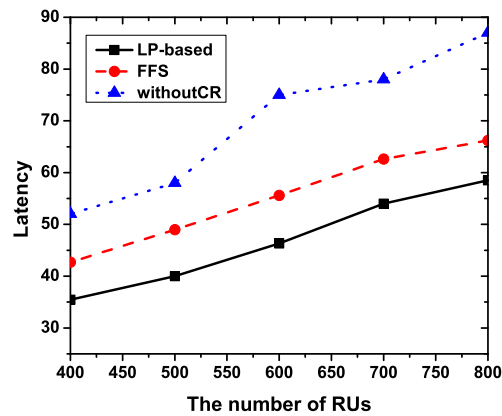
(b) Impact of AUs' transmission radius



(c) Impact of AUs' population



(d) Impact of RUs' transmission radius



(e) Impact of RUs' population

Fig. 2. Performance Evaluation.

of RUs are tested in Fig. 2(d) and Fig. 2(e). For simplicity, “LP-based” is used to represent the algorithm proposed in Section III-B, “FFS” refers to the first-fit scheduling algorithm introduced in Section III-C, and “withoutCR” refers to the SAS algorithm. The performance of “LP-based” and “FFS” is compared with the performance of “withoutCR”. According to the results shown in Fig. 2, the performance of the proposed algorithms outperform the comparison algorithm in all aspects, which clearly shows the advantage of cognitive radio capability. Since “LP-based” and “FFS” seek transmission opportunity on both S_a and S_r , the delay for the two algorithms is shorter than “withoutCR” which only relies on S_r . Particularly, “LP-based” generates the scheduling plan based on an optimum algorithm, which achieves a better time performance compared with “FFS”. Furthermore, because the scheduling of “withoutCR” has nothing to do with S_a , so that changes on the AN does not affect the time performance of “withoutCR”.

The performance of the three algorithms with respect to the change of AUs’ active density is evaluated in Fig. 2(a). With the increasing of active AUs’ density, more senders and receivers are active in the AN at each time slot, which results in a higher risk of exterior collisions. In order to avoid collision, the number of links which are scheduled on S_a at the same time slot decreases, therefore, more time is required to finish the data aggregation. Fig. 2(b) shows that the augment of AUs’ transmission radius causes a longer scheduling delay. The reason is that, a larger transmission radius forms a bigger interference range. The increased interference range prevents more users scheduled on S_a if an AU is active at a particular time, hence, leads to more delay. Similar to the above two scenarios, AUs’ population has a negative influence on the time performance of “LP-based” and “FFS” (as shown in Fig. 2(c)). The growth of AUs’ population introduces more active AUs into AN, so that enlarge the effect of exterior collisions, which results in more delay in the end.

We verify the influence of RUs’ transmission radius and population in Fig. 2(d) and Fig. 2(e), respectively. In Fig. 2(d), we can see that the latency increases with the increasing of RUs’ transmission radius. The reason is similar to the influence of AUs transmission radius. It has no relation with the exterior collision, however, about the interior collision instead. The change of transmission radius may influence BRT, however, the increased transmission radius has more negative effect on enlarging the interference range of RUs, which results in an reduction of the number of RUs that can be scheduled concurrently. Therefore, more time is needed. Since the exterior interference which comes from AN and the interior interference that comes from other wireless users are inevitable, so that the number of RUs that can be scheduled collision-free at each time slot is limited. Therefore, the latency increases with the growth of RUs’ population. Particularly, both RUs’ transmission radius and population affect the network condition on S_r , that is why we can see the same trend on “LP-based”, “FFS”, and “withoutCR”.

V. CONCLUSION

In this paper, we investigate the Minimum Latency Data Aggregation Scheduling in wireless networks with Cognitive Radio capability (MLDAS-CR) problem. As the first try, a scheduling algorithm based on Integer Linear Programming (ILP) and Linear Programming (LP) is proposed. Since getting the optimal solution of an LP is time and resource consuming, another efficient algorithm based on a balanced routing tree is presented. Theoretical analysis shows that the later proposed algorithm has a guaranteed latency bound. The simulation results verify the performance of the proposed solutions.

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