Optimal Scheduling for Roadside WLANs with Pre-Downloaded Messages

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***Abstract*—In this paper, data dissemination services are discussed in the context of vehicular ad hoc networks (VANETs). In order to improve the efficiency of data dissemination, messages are network coded and pre-downloaded to the local nodes within the roadside WLANs (RS-WLANs) and then scheduled for transmission when a vehicle goes through the coverage area. We investigate the optimal scheduling problem for the pre-downloaded messages when a vehicle travels through a specific trajectory. Based on the given vehicle trajectory, resource allocation model, and message pre-downloading profile, the optimal scheduling problem is mathematically formulated. As the global vehicle trajectory information is required for the problem formulation, the original problem is transformed into a set of subprolems which require only the local information upon each visit of a vehicle to an RS-WLAN. By utilizing the theory of deterministic sequencing and scheduling, an optimal scheduling algorithm is proposed. Simulation results indicate that the proposed scheme can improve the delivery probability while reducing the delivery delay of data dissemination sessions as compared with the legacy random access scheme.**

I. INTRODUCTION

In vehicular ad hoc networks (VANETs), a broad range of applications can be classified as data dissemination services, such as traffic information broadcasting, entertainment content downloading, and commercial advertising [1] [2]. Due to the high cost and low speed of data dissemination through wireless wide area networks (WWANs) such as cellular networks, data dissemination based on roadside units (RSUs) is widely investigated in the existing research following the concept of drive-thru Internet [3]. However, during the initial deployment phase of VANETs with a low market penetration rate, the number of RSUs is expected to be very limited and, as a result, the quality of data dissemination services is likely to be capped.

In order to improve the efficiency of data dissemination, increasing the availability of the RSUs is indispensable. Based on the concept of wireless metropolitan area sharing networks (WMSNs), the APs of the publicly and/or privately owned roadside WLANs (RS-WLANs) can be shared and functions as RSUs [4] [5]. Because of the bandwidth limitation of the wireline connections from the Internet to the RS-WLANs (e.g., in the residential area), a message pre-downloading mechanism can be implemented where messages are pre-downloaded to the RSUs and scheduled for transmission upon the visit of a vehicle. However, with a limited buffer space of an AP, the amount of pre-downloaded messages is generally limited (e.g., restricted to a few megabytes for the MobTorrent scheme [6]). One straightforward solution to this problem is connecting each AP with a local file server as the WiFi-based content distribution community infrastructure (CDCI) [7]. But an extra cost is inevitable for the server deployment. Different from the exiting schemes which only pre-download messages to the AP, some recent research utilizes the buffer space provided by the local nodes within the RS-WLANs to improve message dissemination performance [8] [9]. However, given a set of pre-downloaded messages and the trajectory of a vehicle, how to optimally schedule the pre-downloaded messages still needs to be investigated.

On the other hand, the message delivery performance optimization over a vehicle trajectory has been studied in a few existing research works. In [7], the file retrieval probability is maximized with delay and storage constraints. However, as the messages are only pre-downloaded to the file servers of the APs, the proposed scheme cannot be directly applied to VANETs with RS-WLANs where the wireless channel contention among local nodes is not negligible. In [10], the AP association problem is investigated in VANETs for throughput and fairness improvement in an overlapped coverage area of multiple APs. However, as the storage functionality is not supported by the APs, the proposed scheme cannot be applied to RS-WLANs with pre-downloaded messages.

In this work, we consider a VANET with sparsely located RS-WLANs and investigate the optimal scheduling problem when a vehicle travels through a specific trajectory consists of a set of RS-WLANs pre-downloaded with network coded messages. The objective is to maximize the delivery probability while minimize the delivery delay of the data dissemination sessions. The optimal scheduling problem is mathematically formulated by considering the vehicle trajectory, resource allocation model, and message pre-downloading profile. Based on a transformation of the original problem, an optimal scheduling algorithm is proposed by utilizing the theory of deterministic sequencing and scheduling. The performance of the proposed scheme is evaluated by simulations and compared with the legacy random access scheme.

II. SYSTEM MODEL

Consider a network region where isolated RS-WLANs are available for data dissemination services. Data dissemination sessions are pre-downloaded to the local nodes within the RS-WLANs, where each session corresponds to a piece of information such as a flyer of a supermarket which can tolerate a relatively long delay (e.g., up to days). Vehicles roaming in the network region can download the data dissemination sessions when they come into the coverage area of the RS-WLANs. In order to avoid the coupon collector's problem among multiple RS-WLANs, network coding [11] (or erasure coding [1]) based data dissemination is implemented. The messages of each dissemination session are network coded before the pre-downloading to the local nodes. The network coding can be performed on a Galois field with a large size since the decoding delay is much shorter than the inter-contact duration of a vehicle to the RS-WLANs. Under this assumption, each delivered encoded message is innovative with high probability [1]. Suppose a data dissemination session consists of M messages, then the session can be successfully decoded given any M of the encoded messages are received by the vehicle. As in [7], we focus on the message delivery for a single data dissemination session when a vehicle visits the RS-WLANs and do not consider vehicle to vehicle communications in this work. For the wireless communications between the local nodes and the vehicle, we consider the production phase where the local nodes can transmit messages with its maximum transmission rate according to the transmission technology adopted by the RS-WLAN [3] [10]. The wireless transmission during the production phase can be approximated as error free. By utilizing the production phase, high resource utilization can be guaranteed for each RS-WLAN.

The detailed system model is presented in the following subsections. In Subsection II-A, the vehicle trajectory is defined based on the set of RS-WLANs to be visited. For each RS-WLAN on the vehicle trajectory, the resource allocation model for message scheduling is presented in Subsection II-B. In Subsection II-C, the message pre-downloading profile is described for each local node.

A. Vehicle Trajectory

The vehicle trajectory can be defined based on a set of RS-WLANs to be visited by the vehicle and the entering and leaving time of the vehicle to each RS-WLAN. Consider a specific trajectory of a tagged vehicle where the number of RS-WLANs to be visited is K. Within the kth RS-WLAN, the ith local node (denoted by L_{ki}) can facilitate the data dissemination session if and only if it has the pre-downloaded messages and the vehicle can come into its transmission range. Without loss of generality, we do not consider the message delivery from an AP because of its buffer and wireline bandwidth limitation. Denote the group of local nodes within the kth RS-WLAN which can facilitate the data dissemination session as N_k. Then we have

$$N_k = \left\{ L_{ki} | L_{ki} \in \tilde{N}_k, \exists t, \tilde{r}_{ki}(t) < r_{ki} \right\} \tag{1}$$

where $\tilde{N}_k$ is the group of local nodes with pre-downloaded messages in the kth RS-WLAN, while $\tilde{r}_{ki}(t)$ is the distance between the vehicle and local node L_{ki} at time t. In (1), r_{ki} represents the wireless transmission range (of the production phase) of local node L_{ki}. Note that, although the transmission

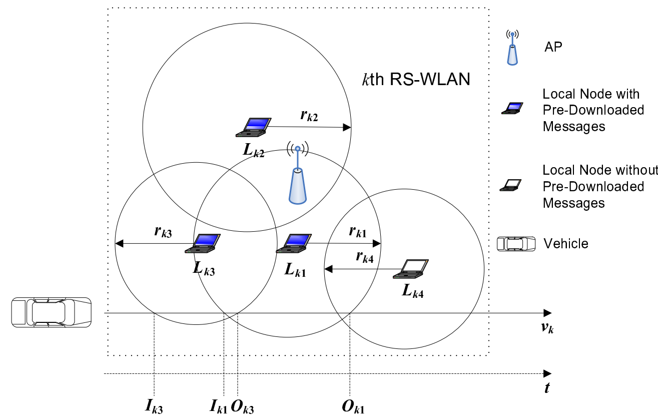

Fig. 1: The visit of a vehicle to the kth RS-WLAN.

rate is the same for all local nodes within the same RS-WLAN according to the transmission technology adopted, the transmission range may be different because of the difference in the transmission power of wireless devices.

Suppose the vehicle enters and leaves the transmission rage of local node L_{ki} at time I_{ki} and O_{ki}, respectively, which are given by

$$I_{ki} = \arg\min_t \{\tilde{r}_{ki}(t) \le r_{ki}\} \tag{2}$$

$$O_{ki} = \arg\max_t \{\tilde{r}_{ki}(t) \le r_{ki}\}. \tag{3}$$

In this work, we assume that when a vehicle comes into the coverage area of an RS-WLAN, the entering and leaving times can be perfectly estimated based on the GPS information or signal strength estimation, while evaluating the impact of the estimation error is left for our further work. Then the entering and leaving times of the vehicle with respect to the kth RS-WLAN can be calculated as

$$I_k = \min_{L_{ki} \in N_k} \{I_{ki}\} \tag{4}$$

$$O_k = \max_{L_{ki} \in N_k} \{O_{ki}\}. \tag{5}$$

An illustration of the visit of a vehicle to the kth RS-WLAN is given in Fig. 1, where v_k is the velocity of the vehicle when it visits the RS-WLAN and is assumed to be a constant during the visiting period. The figure illustrates four local nodes within the kth RS-WLAN, i.e., L_{k1}, L_{k2}, L_{k3}, and L_{k4}. The transmission range of each local node is shown by a circle. Local nodes L_{k2} and L_{k4} cannot be used to facilitate the data dissemination service since the transmission range of local node L_{k2} cannot reach the visiting vehicle while local node L_{k4} has no pre-downloaded message. Therefore, we have $N_k = \{L_{k1}, L_{k3}\}$, $I_k = I_{k3}$, and $O_k = O_{k1}$.

B. Resource Allocation Model

For the resource sharing among the local nodes and the vehicle, we assume a reservation based resource allocation for the RS-WLAN [12], where time is partitioned into superframes with equal durations and a fraction ϕ_k of time within each superframe is assigned for the data dissemination service upon a visit of the vehicle under consideration. The reservation parameter ϕ_k depends on the agreement between the vehicle and the RS-WLAN (e.g., the payment agreement [5]). Define the transmission rate from the local nodes within the kth RS-WLAN to the vehicle as R_k^*. Then the equivalent transmission rate for the data dissemination service to the vehicle is $R_k = \phi_k R_k^*$.

Denote the size of each encoded message as Z. Since the duration of a superframe is much shorter than the sojourn duration of a vehicle to an RS-WLAN, we model the message scheduling by a slotted system. The duration of each time slot (τ_k) corresponds to the transmission time of a message within the kth RS-WLAN, i.e., $\tau_k = Z/R_k$. Define $S_k = \{s_{ks}, s_{ks}+1, \cdots, s_{ke}\}$ as the set of time slots of the kth RS-WLAN, where s_{ks} and s_{ke} are the starting and ending slots, respectively, when the vehicle visits the kth RS-WLAN. Since message delivery can only be established when the vehicle comes into the coverage area of the local nodes, we have

$$s_{ks} = \begin{cases} 1, & \text{if } k = 1 \\ s_{(k-1)e} + 1, & \text{otherwise} \end{cases} \tag{6}$$

$$s_{ke} = s_{ks} + \left\lfloor \frac{O_k - I_k}{\tau_k} \right\rfloor \tag{7}$$

where the values of I_k and O_k are given by (4) and (5), respectively. Note that in (6) and (7), no time slot is assigned when the vehicle is out of the coverage area all RS-WLANs.

C. Message Pre-Downloading Profile

Based on the definition of vehicle trajectory and resource allocation model, the message pre-downloading profile can be described by considering each local node within an RS-WLAN on the vehicle trajectory. For a given local node L_{ki}, the set of pre-downloaded messages is denoted by $\bar{M}_{ki}$. Then the set of pre-downloaded messages within the kth RS-WLAN which can facilitate the data dissemination session is given by $\bar{M}_k = \bigcup_{L_{ki} \in N_k} \bar{M}_{ki}$. We further define $\bar{M} = \bigcup_{k\in\{1,\cdots,K\}} \bar{M}_k$ as the set of all encoded messages pre-downloaded to the RS-WLANs on the vehicle trajectory which can possibly be scheduled for transmission. Since network coding based message pre-downloading is implemented, in order for the data dissemination session to be delivered on the vehicle trajectory, it should be guaranteed that $|\bar{M}| \geq M$.

For each encoded message, a releasing time and a deadline should be assigned according to the coverage area of each local node. For a local node $L_{ki} \in N_k$, let $g_{ki}(s) = I_{ki} + \tau_k \cdot (s - s_{ks})$ denote the starting time of slot s, then the releasing time slot (S_{kim}^R) and deadline time slot (S_{kim}^D) of encoded message m ($m \in \bar{M}_{ki}$) are given by

$$S_{kim}^R = \arg\min_{s\in S_k} \{g_{ki}(s) > I_{ki}\} \tag{8}$$

$$S_{kim}^D = \arg\min_{s\in S_k} \{g_{ki}(s+1) + \tau_k > O_{ki}\}. \tag{9}$$

III. Problem Formulation

The objective of message scheduling for RS-WLANs with pre-downloaded messages is to maximize the session delivery probability and minimize the session delivery delay when a vehicle goes through a specific trajectory. In this section, we focus on the delay minimization problem and it will be shown in Subsection IV-B that the delivery probability maximization problem is inherently solved by solving the delay minimization problem. According to the discussions in Subsection II-C, we consider $|\bar{M}| \geq M$ and sufficient RS-WLANs are available on the vehicle trajectory for session delivery.

Define the message scheduling scheme over the vehicle trajectory as

$$A = \left\{a_{kms} | k \in \{1, \cdots, K\}, m \in \bar{M}, s \in S\right\} \tag{10}$$

where

$$a_{kms} = \begin{cases} 1, & \text{if pre-downloaded message } m \text{ is} \\ & \quad \text{scheduled on time slot } s \\ & \quad \text{by the } k\text{th RS-WLAN} \\ 0, & \text{otherwise.} \end{cases} \tag{11}$$

In (10), $S = \bigcup_{k\in\{1,\cdots,K\}} S_k$ is the set of all time slots over the vehicle trajectory. Obviously, no more than M encoded messages should be delivered to the vehicle since the data dissemination session can be successfully decoded upon the reception of M encoded messages. Therefore, for a feasible scheduling scheme, we have $\sum_{k\in\{1,\cdots,K\}} \sum_{m\in\bar{M}} \sum_{s\in S} a_{kms} = M$.

Define T_A as the delivery delay of the data dissemination session for a given scheduling scheme A. Since network coding is implemented for message dissemination, by considering the delivery delay of M encoded messages, we have

$$T_A = I_{k_d} + \tau_{k_d} \cdot (s_d - s_{k_d s}) \tag{12}$$

where k_d and s_d represent the RS-WLAN and time slot, respectively, at which the Mth encoded message is delivered, and are given by

$$k_d = \arg\max_{k\in\{1,\cdots,K\}} \{a_{kms} = 1\} \tag{13}$$

$$s_d = \arg\max_{s\in S} \{a_{kms} = 1\}. \tag{14}$$

Then the session delivery delay minimization problem (Problem P1) can be formulated as

Problem P1:

$$\min_{A} \quad T_A \tag{15}$$

subject to

$$\sum_{k\in\{1,\cdots,K\}} \sum_{m\in\bar{M}} \sum_{s\in S} a_{kms} = M \tag{16}$$

$$S_{kim}^R \leq s \leq S_{kim}^D, \ \forall a_{kms} = 1, m \in \bar{M}_{ki}, \\ L_{ki} \in N_k, k \in \{1, \cdots, K\} \tag{17}$$

$$\sum_{k\in\{1,\cdots,K\}} \sum_{s\in S} a_{kms} \leq 1, \forall m \in \bar{M} \tag{18}$$

$$\sum_{k\in\{1,\cdots,K\}} \sum_{m\in\bar{M}} a_{kms} \leq 1, \forall s \in S \tag{19}$$

where condition (17) holds since each message can only be scheduled when a vehicle comes into the transmission range of a local node where this message is pre-downloaded. Condition

(18) holds since each encoded message can be delivered at most once, otherwise, a wireless transmission is established to deliver a duplicated message and the radio resource is underutilized. Condition (19) holds since for each time slot, at most one encoded message can be delivered.

IV. The Optimal Scheduling Algorithm

We can observe that in problem P1, global information in terms of the set of RS-WLANs on the vehicle trajectory and speed of the vehicle upon each visit is required. However, the information is usually unavailable a priori for a vehicle, and thus a problem transformation is indispensable to acquire an optimal scheduling scheme. In this section, we first transform problem P1 into a group of subproblems which only require the local information upon each visit of a vehicle to an RS-WLAN, and prove the optimality in Subsection IV-A. Then an optimal scheduling algorithm is proposed in Subsection IV-B based on the theory of deterministic sequencing and scheduling. In Subsection IV-C, the complexity of the proposed algorithm is discussed, where we can also observe that even if the global information can be fully predicted, the computational complexity of solving problem P1 directly is still prohibitive, which further confirms the necessity of the problem transformation.

A. Problem Transformation

In order to avoid the requirement of the global information, we transform problem P1 into a group of subproblems. Suppose that by visiting a sequence of d ($d \geq 2$) RS-WLANs, the pre-downloaded data dissemination session is delivered. We define the RS-WLANs in the set $\{1, \cdots, (d-1)\}$ as the intermediate RS-WLANs while the dth RS-WLAN as the delivery RS-WLAN. The problem transformation is based on the following theorem:

Theorem 1. *With network coding based message pre-downloading, when a vehicle visits an intermediate RS-WLAN, maximizing the number of delivered messages upon its current visit corresponds to a minimal session delivery delay.*

The proof of Theorem 1 is given in the Appendix.

Based on Theorem 1, we can transform problem P1 into subproblems P2 and P3 as follows:

Subproblem P2: (for each intermediate RS-WLAN k)

$$\max_{\substack{a_{kms} \\ m \in \bar{M}_k \\ s \in S_k}} \quad \sum_{m \in \bar{M}_k} \sum_{s \in S_k} a_{kms} \tag{20}$$

$$\text{subject to} \quad S^R_{kim} \leq s \leq S^D_{kim}, \ \forall a_{kms} = 1, m \in \bar{M}_{ki}, \; L_{ki} \in N_k \tag{21}$$

$$\sum_{s \in S_k} a_{kms} \leq 1, \forall m \in \bar{M}_k \tag{22}$$

$$\sum_{m \in \bar{M}_k} a_{kms} \leq 1, \forall s \in S_k \tag{23}$$

where the intermediate RS-WLAN can be determined by comparing the number of remaining messages in the data dissemination session and the maximum number of messages that can be delivered within the currently visited RS-WLAN. Denote M^*_i as the set of delivered messages at a previous intermediate RS-WLAN i ($1 \leq i \leq k-1$) according to the optimal scheduling algorithm. We have

$$M^*_i = \left\{ m | a_{ims} = 1, s \in S_i, m \in \bar{M}_i \right\}. \tag{24}$$

Then the kth RS-WLAN is an intermediate RS-WLAN if and only if $\sum_{i=1}^{k} |M^*_i| < M$, where M^*_k can be calculated by solving subproblem P2.

Next, consider the delivery RS-WLAN. The data dissemination session is delivered at the dth RS-WLAN if and only if $\sum_{i=1}^{d-1} |M^*_i| < M \leq \sum_{i=1}^{d} |M^*_i|$. Obviously, minimizing the session delivery delay is equivalent to minimizing the delivery delay of $(|M| - \sum_{k=1}^{d-1} |M^*_k|)$ messages at the dth RS-WLAN. Define $S_{d\delta} = \{s_{ds}, \cdots, \delta\}$ as the set of time slots in the dth RS-WLAN ended with the time slot δ. Then, the delivery delay minimization problem within the dth RS-WLAN is given by

Subproblem P3:

$$\min_{\substack{a_{dms} \\ m \in \bar{M}_d \\ s \in S_d}} \quad |S_{d\delta}| \tag{25}$$

$$\text{subject to} \quad S^R_{dim} \leq s \leq S^D_{dim}, \ \forall a_{dms} = 1, m \in \bar{M}_{di}, \; L_{di} \in N_d \tag{26}$$

$$\sum_{m \in \bar{M}_d} \sum_{s \in S_d} a_{dms} = |M| - \sum_{k=1}^{d-1} |M^*_k| \tag{27}$$

$$\sum_{s \in S_d} a_{dms} \leq 1, \forall m \in \bar{M}_d \tag{28}$$

$$\sum_{m \in \bar{M}_d} a_{dms} \leq 1, \forall s \in S_d. \tag{29}$$

By solving subproblems P2 and P3, we can obtain the optimal scheduling scheme A^* with the minimun session delivery delay T_{A^*}. Note that upon the visit of a vehicle to the kth RS-WLAN, only the related scheduling variables ($a_{kms}, m \in \bar{M}_k, s \in S_k$) are updated, while the other scheduling variables are kept unchanged.

B. Optimal Scheduling Algorithm

Based on the definition of releasing time slot and deadline time slot in (8) and (9), subproblems P2 can be classified as a job scheduling problem with unit processing time and integer releasing times and deadlines [13]. According to the theory of deterministic sequencing and scheduling [14], the optimal scheduling scheme which maximizes the number of delivered messages is determined by the earliest-deadline-first (EDF) algorithm. With the EDF algorithm, for each time slot, the message with the earliest deadline is scheduled for transmission. The detailed algorithm is omitted here because of space limitation. For subproblem P3, it can be solved based on an exhaustive search on δ, while for each iteration, the optimal scheduling scheme is still determined by the EDF algorithm. The optimal scheduling scheme is given by Algorithm 1. In line 2, the EDF algorithm is performed for the set of messages $\bar{M}_d$ and the resulting scheduling scheme is A' with the set of delivered messages in the dth RS-WLAN being M'_d. In line 5, the EDF algorithm is performed based on the updated deadline slots given by line 4.

Algorithm 1 Optimal Scheduling Algorithm for the Delivery RS-WLAN

Input: M, M_k^* $(1 \le k \le d-1)$, $\bar{M}_d$, S_{dim}^R, S_{dim}^D $(m \in \bar{M}_{di},\ L_{di} \in N_d)$

Output: A^*

1: $a_{dms} = 0,\ \forall m \in \bar{M}_d, \forall s \in \{s_{ds}, \cdots, s_{de}\}$;
2: $(A', M'_d) \leftarrow EDF(\bar{M}_d)$;
3: **for** $\delta = s_{de} - 1, s_{de} - 2, \cdots, s_{ds}$ **do**
4: $\quad S_{kim}^D \leftarrow \min\left\{S_{kim}^D, \delta\right\}$;
5: $\quad (A'', M''_d) \leftarrow EDF(\bar{M}_d)$;
6: $\quad$ **if** $|M''_d| < M - \sum_{k=1}^{d-1} |M_k^*| = |M'_d|$ **then**
7: $\qquad$ Break;
8: $\quad$ **end if**
9: $\quad A' \leftarrow A''$, $M'_d \leftarrow M''_d$;
10: **end for**
11: $A^* \leftarrow A'$;
12: **return** A^*;

Note that although the optimal scheduling algorithm is proposed for session delivery delay minimization, it also maximize the session delivery probability when the number of RS-WLANs is limited since the number of messages delivered at each intermediate RS-WLAN is maximized.

C. Complexity Analysis

For the EDF algorithm, the complexity of calculating the optimal scheduling scheme is O$(\alpha \log \alpha)$, where α is the number of pre-downloaded messages [13] [14]. For problem P2, since there are $(d-1)$ intermediate RS-WLANs, the complexity of calculating the optimal scheduling scheme is O$\left(\max_{1\le k\le d-1}\left\{|\bar{M}_k| \log |\bar{M}_k|\right\}\right)$. For problem P3, since each iterative search on δ embeds an EDF algorithm, the complexity of solving problem P3 is O$\left(|S_d||\bar{M}_d| \log |\bar{M}_d|\right)$. Therefore, the overall complexity of the proposed scheduling algorithm is O$\left(\max\left\{\max_{1\le k\le d-1}\left\{|\bar{M}_k| \log |\bar{M}_k|\right\}, |S_d||\bar{M}_d| \log |\bar{M}_d|\right\}\right)$.

For comparison, consider that the vehicle trajectory can be fully predicted based on the route plan of the vehicle and the traffic condition on each road. Then, problem P1 can be solved directly by applying Algorithm 1. However, the complexity is $O\left((\sum_{k=1}^{d} |S_k|)(\sum_{k=1}^{d} |\bar{M}_k|) \log(\sum_{k=1}^{d} |\bar{M}_k|)\right)$, which is prohibitive when the number of RS-WLANs on the vehicle trajectory is large. This result indicates that the problem transformation in Subsection IV-A is indispensable.

V. Numerical Results

In this section, numerical results are presented to evaluate the proposed optimal scheduling algorithm. For the vehicle trajectory, the deployment of the RS-WLANs is determined by a set of parameters: the distance from the AP to the road, the coverage distance of each RS-WLAN, the transmission range of the local nodes (for the production phase), and the number of local nodes within each RS-WLAN. Note that the coverage area of each RS-WLAN is considered to be a circle according to the coverage distance with the AP located at the center. The number of pre-downloaded messages at each local node is Poisson distributed. The wireless communication capability of each RS-WLAN follows the IEEE 802.11b standard [3] [15]. The default values of system parameters used in the simulations are shown in Table I.

TABLE I: Values of system parameters used in simulation.

Parameter	Value
Road length	5 km
Distance from the AP to the road	Uniform$[10, 20]$ m
Coverage distance of an RS-WLAN	Uniform$[20, 30]$ m
Transmission range of local nodes (for the production phase)	Uniform$[30, 60]$ m
Number of local nodes within each RS-WLAN	Poisson[3]
Vehicle speed (v_k)	60 km/h
Size of encoded message (Z)	100 kbytes

The average session delivery delay and session delivery probability versus the average number of pre-downloaded messages at each local node are shown in Fig. 2 and Fig. 3, respectively. For Fig. 3, we choose $K = 2$ as an example, while for Fig. 2, we set $K = 10$ so that the session delivery probability is close to 1 for different values of M. We can see that, with the increase of the average number of pre-downloaded messages, the average session delivery delay decreases while the session delivery probability increases. The reason is that, with more pre-downloaded messages, more messages are available for scheduling and the probability for the buffer of a local node to be empty is lower. For a longer data dissemination session with more messages, the average session delivery delay increases while the session delivery probability decreases since a vehicle needs to visit more RS-WLANs in order achieve session delivery. Compared with the legacy random access scheme, the proposed scheduling scheme can improve both performance metrics since the characteristics of the message pre-downloading are taken into account. Moreover, the performance improvement is more significant when the network resource is limited, i.e., for a longer data dissemination session and less pre-downloaded messages at each local node.

VI. Conclusion

In this paper, we investigate the problem of optimal scheduling for RS-WLANs with pre-downloaded messages. The optimal scheduling problem is mathematically formulated and solved based on the theory of deterministic sequencing and scheduling. Compared with the legacy random access scheme, the proposed scheduling algorithm can achieve higher session delivery probability while reducing the average session delivery delay.

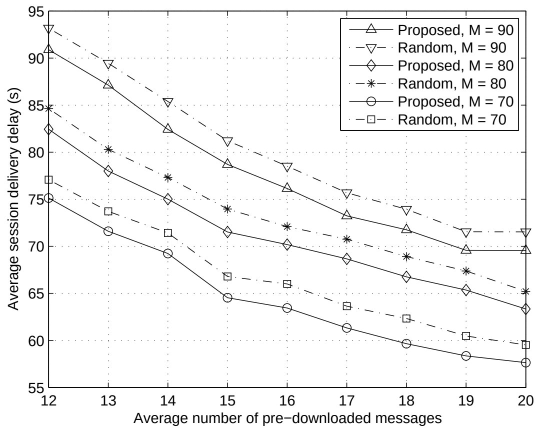

Fig. 2: Average session delivery delay versus the average number of pre-downloaded messages at each local node.

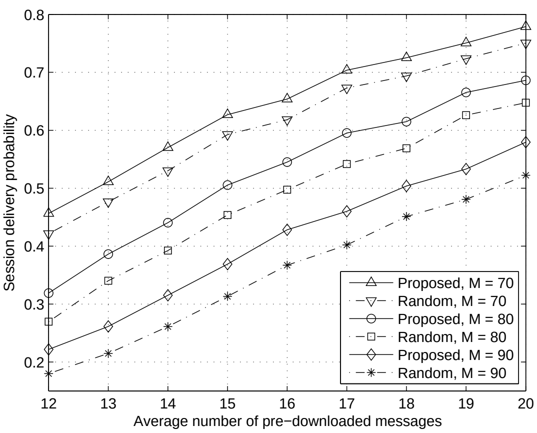

Fig. 3: Session delivery probability versus the average number of pre-downloaded messages at each local node.

In our further work, we will study the feasibility of message scheduling during the non-production phase where the wireless transmission is highly unreliable. Moreover, the impact of vehicle to vehicle communications on data dissemination based on RS-WLANs needs further investigation.

Appendix
Proof of Theorem 1

Proof: Theorem 1 can be proved by contradiction. Obviously, there are two cases for the delivery of the Mth ($M \geq 2$) message: 1) the $(M-1)$th and Mth messages are delivered on time slots s_{M-1} and s_M, respectively, when the vehicle visits the dth RS-WLAN; 2) The Mth message is delivered on time slot s_M when the vehicle visits the dth RS-WLAN while the $(M-1)$th message is delivered on time slot s_{M-1} when the vehicle visits the $(d-1)$th RS-WLAN. For both cases 1) and 2), we have $s_{M-1} < s_M$ since the transmission of each message takes one time slot.

For case 1), suppose the optimal scheduling scheme is A^* while the number of delivered messages at an intermediate RS-WLAN k ($1 \leq k \leq d-1$) is not maximized. Obviously, we have $T_{A^*} = I_d + \tau \cdot (s_M - s_{ds})$. Then we can design another policy A' based on A^* by increasing the number of delivered messages at intermediate RS-WLAN k by one and removing the message delivered on time slot s_M. Since network coding based message pre-downloading is implemented with each encoded messages being innovative, the data dissemination session is delivered on time slot s_{M-1}, which results in a session delivery delay $T_{A'} = I_d + \tau \cdot (s_{M-1} - s_{ds})$. Since $s_{M-1} < s_M$, we have $T_{A'} < T_{A^*}$. For case 2), the proof is similar to that of case 1). However, by adopting the new scheduling policy A', the new session delivery delay is $T_{A'} = I_{d-1} + \tau \cdot (s_{M-1} - s_{(d-1)s})$. Since $T_{A'} \leq O_{d-1} < I_d$ for the isolated RS-WLANs considered in this work, we have $T_{A'} < T_{A^*}$. Thus the scheduling policy which does not maximize the number of delivered messages at the intermediate RS-WLANs is not optimal. ■

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