Maximum Freedom Last Scheduling Algorithm for Downlinks of DSRC Networks

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***Abstract*—This paper proposes a maximum freedom last (MFL) scheduling algorithm for downlinks, from the roadside unit to the onboard unit (OBU), of dedicated short-range communication networks in intelligent transportation systems, to minimize the system handoff rate under the maximum tolerable delay constraint. The MFL scheduling algorithm schedules the service ordering of OBUs according to their degree of freedom, which is determined by factors such as remaining dwell time of service channel, remaining transmission time, queueing delay, and maximum tolerable delay. The algorithm gives the smallest chance of service to the OBU with the largest remaining dwell time, the smallest remaining transmission time, and the largest weighting factor, which is a function of the queueing delay and the maximum tolerable delay. Simulation results show that the MFL scheduling algorithm outperforms the traditional first-come–first-serve and earliest-deadline-first methods in terms of service failure and system handoff rates.**

***Index Terms*—Dedicated short-range communication (DSRC), intelligent transportation system (ITS), scheduling.**

I. INTRODUCTION

INTELLIGENT transportation systems (ITS) are next-generation transportation systems that aim to increase efficiency, convenience, and safety of transportation by enhancing infrastructures and vehicles [1]. The ITS network consists of a backbone network and several access networks to accommodate vehicles with different data transmission capabilities. Among these access networks, a dedicated short-range communication (DSRC) network is a strong candidate for short- to medium-range communication networks for ITS applications [2]. DSRC networks are based on the IEEE 802.11a standard and provide a high-volume and reliable radio link for vehicles and roadside units (RSUs). A DSRC network has two communication modes, namely 1) vehicle-to-roadside (v2r) and 2) vehicle-to-vehicle. This work considers v2r communications, as shown in Fig. 1, in which an onboard unit (OBU) in vehicles communicates with an RSU via a control channel (CCH) and downloads ITS application services from the RSU via a service channel (SCH) [3].

A seamless service is essential for ITS applications in high-mobility environment. A handoff procedure must be executed for service continuity when an OBU roams into the service region of a neighboring RSU, or else the ITS applications are forced to terminate. Chung and Cho proposed a resource management scheme, named double-adjustment soft handoff (DASH), for supporting real-time streaming services in a code division multiple access-based ITS network [4]. When terminals move into handoff regions, DASH schedules network resources and adjusts transmission rates to keep the handoff termination low. As to DSRC network, the handoff latency is longer than the cell dwell time due to its small cell coverage. The handoff latency combines the time to a establish link with the time for back-end signaling. The link-level establishment is the time in which the OBU listens to CCH to discover where the RSU can establish a connection, whereas the back-end signaling time is the time taken to exchange information between the authentication, authorization, and accounting servers and the DSRC network. Therefore, an effective scheduling algorithm for handoffs is essential for the downlinks of DSRC networks.

The handoff problem can be resolved by two methods, namely 1) *reduction of handoff latency* [5], [6] and 2) *reduction of handoff rate* [8]–[10]. Reduction of handoff latency focuses on "proactive caching," which means finding the handoff target and transferring the user profile in advance. Paik and Choi proposed a prediction-based fast handoff scheme that supports broadband wireless access for fast-moving vehicles [5]. The proposed scheme predicts the tendency of a moving pattern of the vehicles and the next-candidate access router for seamless handoff. Shim *et al.* introduced a fast handoff mechanism for wireless Internet Protocol networks, called NeighborCasting, which utilizes neighboring foreign agent information [6]. The NeighborCasting scheme initiates data forwarding to the possible new foreign agent candidates and the link-layer handoff procedure at the same time to minimize handoff latency. Although the above schemes can generally reduce the handoff latency for wireless networks, the handoff latency is still excessively long for DSRC networks when considering mobility and cell coverage. Additionally, the busy back-end signalings for handoff transactions would be a burden to the DSRC networks.

Conversely, reducing the handoff rate is an attempt to reduce the probability of handoff occurrence during the period that OBUs request for the ITS applications from RSUs, which can be achieved by well-designed scheduling algorithms for

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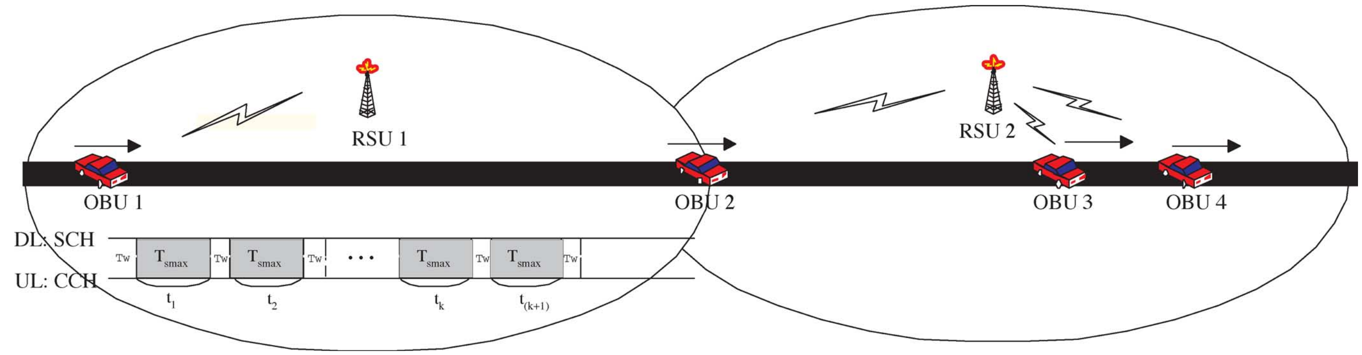

Fig. 1. Illustrative DSRC network.

downlinks in DSRC networks. The DSRC lower layer management and medium access control extension (MACX) specification [7] includes a simple method of the queue selector implementation in the transmission mode based on a first-come–first-serve (FCFS) scheduling algorithm. All queues with the same priority are served according to their arrival time, that is, a transaction datum is served if it arrives earlier than the others. Although easily implemented, this algorithm would perform poorly in DSRC networks due to high handoff rate. A new policy for handoff calls was proposed in [8], which determines the channel priority of the handoff calls in queue according to their dwelling times in the handoff area. An earliest-deadline-first (EDF) algorithm was proposed to handle the handoff requests in [9], where the deadline time (handoff threshold) was calculated based on the speed direction of mobile travel, the cell size, and the type of ongoing mobile traffic. This scheme first serves the mobile with the tightest deadline to reduce the handoff rate. A novel handoff method was proposed for picocellular networks in [10], which adopts the speed and location of mobile hosts to reduce the buffer overhead and achieve seamless connection service.

ITS data services are categorized into three types [11], namely 1) location-independent services, including music, news, and software programs, 2) location-dependent service with immediate response, including traffic accidents and road condition information, and 3) location-dependent service without immediate response, including travel information. The time limitation is critical for location-dependent services. Even if the ITS information is successfully received, it quickly becomes obsolete. The time limitation depends on the effective service area of the RSUs and the velocity of the OBUs. Accordingly, different maximum tolerable delays are assigned for each OBU.

This paper proposes a novel downlink scheduling algorithm, named maximum freedom last (MFL) scheduling algorithm, for DSRC networks supporting ITS applications to effectively reduce the handoff rate. For OBUs, the MFL algorithm determines the service order and assigns the corresponding data volume according to remaining cell dwell time, remaining transmission time, queueing delay, and maximum tolerable delay. A larger remaining cell dwell time implies a lower OBU service priority. The remaining transmission time of an OBU would be proportional to the requested data volume by the OBU. A larger transmission time implies a higher service priority of the OBU. Additionally, a weighting factor, which is a function of the queueing delay and the maximum tolerance delay, is designed to adjust the service priority. Simulation results show that the MFL scheduling algorithm outperforms the traditional FCFS and EDF methods in terms of the service failure rate and the handoff rate. Moreover, it can achieve highest effective system utilization for the DSRC networks.

The rest of this paper is organized as follows: Section II introduces the system model, which includes the system operation and the system architecture of a DSRC network. Section III presents the downlink scheduling algorithm of the MFL. Simulation results and discussions are presented in Section IV. Finally, conclusions are drawn in Section V.

II. SYSTEM MODEL

This paper assumes that a DSRC network, consisting of RSUs and OBUs, is implemented along roads. An RSU provides downlink data transmission to OBUs that request for ITS applications within its cell coverage region. The radio band of the DSRC network in ITS is located at 5.9 GHz and divided into seven channels. One channel is CCH, which is designed to establish sessions, and the others are SCHs, which are adopted to transmit data. The RSUs apply point coordination function (PCF) mode (polling mode) in SCH to transmit the downlink data to the OBUs. The proposed MFL scheduling algorithm in RSU generates a *service list* and a *data volume assignment table*, where the service list is the polling list and the data volume assignment table stores the information of the corresponding data volume.

A. System Operation

Fig. 2 shows the flowchart of the system operation. Initially, RSU sends a roadside service table (RST) via CCH to announce the service provisioning and awaits a response. OBUs that are interested in the service contend with other OBUs to send OBU service tables (OSTs). If the OSTs are successfully received and accepted, then RSU responses with ACK packets to these OBUs accordingly. The response time duration in which OBUs can send OSTs is defined as the CCH wait time T_w. Additionally, the duration between the two consecutive transmissions that the RSU sends the RST is called a scheduling round. In each scheduling round, the number of OBUs permitted to send OSTs at the response time duration is restricted to γ. The RSU and the granted OBUs then jump to the SCH for the

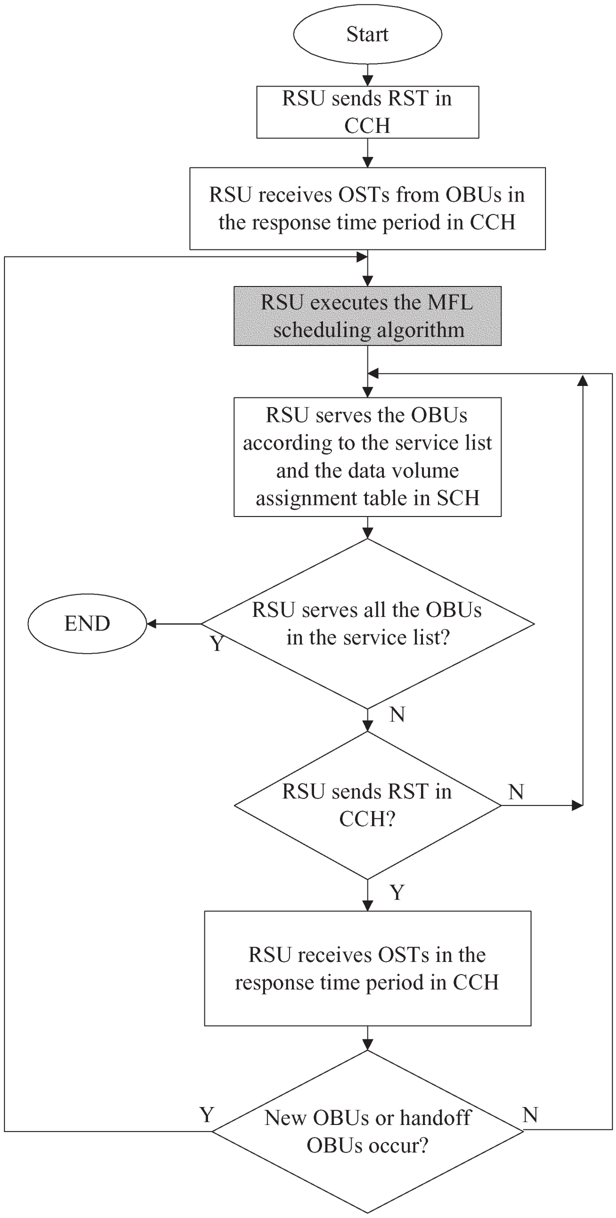

Fig. 2. Flowchart of the system operation.

data transmission of ITS applications. The time duration of SCH is $T_{s,\max}$, which is equal to a scheduling round.

The RSU executes the proposed MFL scheduling algorithm immediately before the start of the service. The MFL algorithm categorizes the OBUs as new, handoff, and ongoing OBUs. New OBUs are the OBUs that have just sent the OSTs in this scheduling round. Handoff OBUs are the OBUs that have just completed the handoff procedure but have not yet listened to the RST. For service continuity, the RSU directly serves the handoff OBUs without any further service requests. The handoff procedure considered in this paper follows the IEEE 802.11f [12]. Ongoing OBUs are the OBUs with unfinished data transmissions. The MFL algorithm generates a service list and its data volume assignment table for the scheduling round. The RSU serves OBUs according to the generated service list and the corresponding data volume assignment table. If the SCH time $T_{s,\max}$ expires during the data transmission, then the transmission is suspended. The OBUs send OBU probes and return to the CCH for channel monitoring. An OBU probe contains information on the current in-process transactions, containing the priority and identification of the ITS application. If no high-priority RST is received after the CCH time T_w expires, then the RSU and OBUs return to the SCH and resume the suspended service. The scheduling round continues until all OBUs in service list are fully served. However, if new OBUs or handoff OBUs request service during the CCH waiting time, then the MFL scheduling algorithm is executed once again to generate a new service list and a data volume assignment table. After all OBUs at the service list are served completely, then the RSU terminates the service procedure and jumps back to the CCH to wait for the next service session.

B. System Architecture

Fig. 3 shows the structure of MACX and the corresponding layer management functions, which are specified in [7], for transmission operations in the RSU of the DSRC network. To transmit DSRC data packets, the queue router route each MACX data unit received by the MACX from the logical link control layer to a dedicated queue by the queue router, where queue i corresponds to ith OBU, $1 \leq i \leq N$, and queue 0 corresponds to CCH. The queue selector with the MFL scheduling algorithm inside serves these queues according to the generated service list and the data volume assignment table. Additionally, the upper layer calculates the assignments of power and data rate, whereas the lower layer processes the queue and timer information [7].

To alternate between CCH and SCH, RSU and all OBUs implement timers with SCH time $T_{s,\max}$ and CCH wait time T_w. As described above, if the SCH transactions in progress cannot be completed before the time $T_{s,\max}$ expires, then MACX suspends the ongoing transmission and returns to CCH for the CCH wait time T_w. The service-incomplete packets are stored in the MACX queues. The proposed MFL scheduling algorithm implemented in the queue selector resumes the transmission service for the incomplete packet according to the service list when T_w expires and MACX returns to SCH.

For the transmission scheduling, RSU collects information from OBUs, including location, direction of movement, and velocity. The MFL scheduling algorithm generates the service list and the data volume assignment table according to the remaining SCH dwell time D_i, the remaining transmission time TX_i, the queueing delay t_i, and the maximum tolerable delay T_i for an OBU, $1 \leq i \leq N$. The service list indicates the transmission order of the OBUs, and the data volume assignment table records the allowed data volumes of the OBUs.

Notably, the remaining SCH dwell time D_i of OBU i is equivalent to its remaining cell dwell time minus the total CCH wait time and its response time within the remaining cell dwell time. Herein, the remaining cell dwell time for each OBU is calculated from its location information, moving direction, and velocity. The remaining transmission time TX_i of OBU i can be calculated by dividing the remaining queue length by the data transmission rate. The maximum tolerable delay T_i of OBU i can be obtained by dividing the effective area range of the request service data by the vehicle velocity of OBU i.

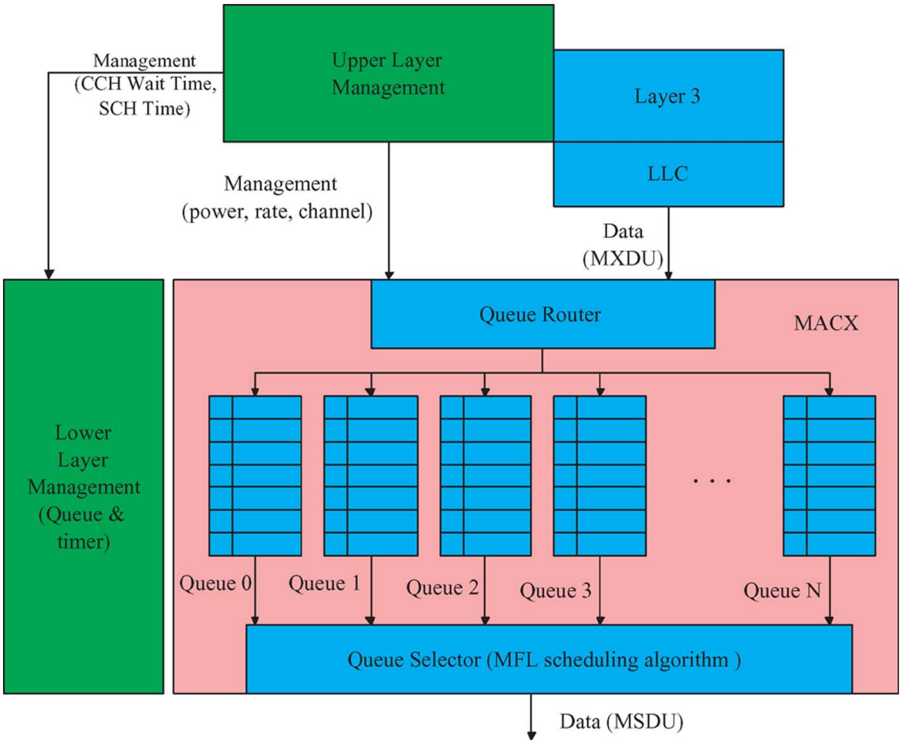

Fig. 3. MACX and the corresponding layer management functions in RSU.

III. MFL SCHEDULING ALGORITHM

The MFL scheduling algorithm attempts to generate a service list and a data volume assignment table to reduce the handoff rate in a DSRC network. The MFL scheduling algorithm focuses on assigning a higher service priority to OBUs with a higher possibility of being served completely. Moreover, among the high-priority OBUs, the one with the highest degree of freedom are served last. The degree of freedom considers factors such as remaining SCH dwell time, remaining transmission time, queueing delay, and maximum tolerable delay of OBUs. An OBU is considered to possess greater freedom if it has a lower transaction time and a longer remaining SCH dwell time. An OBU with larger freedom can tolerate a longer transmission delay, which means that some OBUs may be served before it. Additionally, a weighting factor, which is a function of queueing delay and maximum tolerable delay, is proposed for the MFL scheduling algorithm to adaptively adjust the service priority and avoid the service failure.

The MFL scheduling algorithm comprises four main phases, namely 1) *initialization phase*, 2) *reverse lineup phase*, 3) *transmission time pileup phase*, and 4) *partial service phase*. Fig. 4 shows the flowchart of the proposed MFL algorithm. In the initialization phase, each OBU in a service set A is assigned with its scheduling parameters, which are defined later, and grouped in either the complete service set A_+ or the partial service set A_-. In the reverse lineup phase, a temporary list F is iteratively constructed according to the priority index of the OBUs in A_+. The temporary list F is added to a service list later. After some portion of service time is allocated to OBUs in A_+, the parameters of the OBUs in A_- are then updated in the transmission time pileup phase. Finally, in the partial service phase, all the OBUs in A_- are scheduled, and a complete service list is generated.

A. Initialization Phase

In this phase, the ith OBU from service set A, $1 \leq i \leq N$, is assigned with its scheduling parameters, which are defined as the virtual finish time FT_i and virtual start time ST_i. The time FT_i is equal to D_i, and the time ST_i is equal to $(FT_i - TX_i)$. All the OBUs are categorized as either a complete service set A_+ or a partial service set A_-. If $ST_i \geq 0$, OBU i is grouped into set A_+; otherwise, it is placed into set A_-.

B. Reverse Lineup Phase

If set A_+ is not empty after the initialization phase, then a temporary list F is iteratively constructed by sorting procedure, according to the priority index PI_i of OBU i in the complete service set $i \in A_+$. The priority index of OBU is explained later. In each iteration, the OBU with the highest priority index is chosen, added to the list F, and then eliminated from set A_+. The parameters of the remaining OBUs in A_+ are then recalculated, and the sorting procedure is executed once again. This iterative procedure is not terminated until set A_+ is empty. The details of the sorting procedure are given as follows:

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Define $\{k = 1 \text{ and } FT_i = D_i \ \forall i \in A_+\}$
Step 1: $f_k = \arg\max_{i \in A_+} \{PI_i\}$
Step 2: $ST_{f_k} = FT_{f_k} - TX_{f_k}$
Step 3: $F := F + \{f_k\}$ and $A_+ := A_+ - \{f_k\}$
Step 4: $FT_i = \min\{D_i, \ ST_{f_k}\}$ and $ST_i = FT_i - TX_i$
        $\forall i \in A_+$
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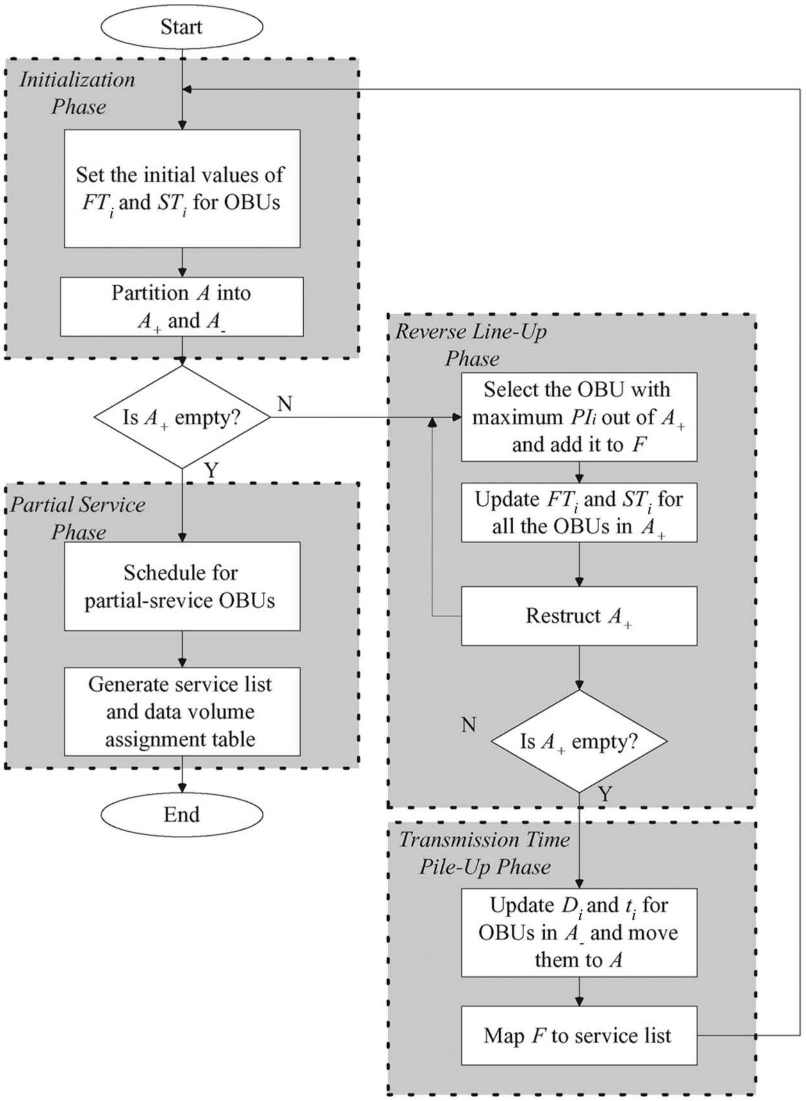


Fig. 4. Flowchart of the MFL scheduling algorithm.

Step 5: $A_+ = \{i|ST_i \geq 0\}$ and $A_- = \{i|ST_i < 0\}$
Step 6: If A_+ is not empty, $k := k + 1$ and go to Step 2
Step 7: End ■

In Step 1, OBU f_k with the highest priority index PI_i is chosen out of set A_+. The priority index PI_i of ith OBU is defined as

$$PI_i = FT_i - W_i \times TX_i \tag{1}$$

where W_i is the weighting factor. The weighting factor, which is defined as a function of queueing delay and maximum tolerable delay, is given by

$$W_i = \begin{cases} 1 - \frac{t_i}{T_i}, & \text{if } T_i - (FT'_i + t_i) \text{ is } \geq 0 \\ 1 + \frac{t_i}{T_i}, & \text{if } T_i - (FT'_i + t_i) \text{ is } < 0 \end{cases} \tag{2}$$

where FT'_i is the virtual finish time on the absolute time axis, t_i is the queueing delay, and T_i is the maximum tolerable delay, for the ith OBU. Since the queuing delay consists of the waiting time in CCH as well as the transmission time in SCH, FT_i, FT'_i is calculated by

$$FT'_i = \begin{cases} \left(\left\lfloor \frac{FT_i}{T_{s,\max}} \right\rfloor + 1\right) \times T_w + FT_i, & \text{if } \left\lfloor \frac{FT_i}{T_{s,\max}} \right\rfloor \neq \frac{FT_i}{T_{s,\max}} \\ \left(\left\lfloor \frac{FT_i}{T_{s,\max}} \right\rfloor\right) \times T_w + FT_i, & \text{if } \left\lfloor \frac{FT_i}{T_{s,\max}} \right\rfloor = \frac{FT_i}{T_{s,\max}}. \end{cases} \tag{3}$$

In (2), the weighting factor W_i is larger than unity if the service time (i.e., waiting time + transmission time) of the ith OBU exceeds the maximum tolerable delay; otherwise, it is smaller than or equal to unity. Obviously, an OBU has larger probability to be chosen by the MFL algorithm if its queueing delay is large but still within the maximum tolerable delay. In Step 2, the virtual start time for the chosen OBU f_k (ST_{f_k}) is calculated. At the next sorting iteration, the time ST_{f_k} is considered as the remaining SCH dwell time for all the OBUs in set A_+. Step 3 incorporates OBU f_k into F and removes

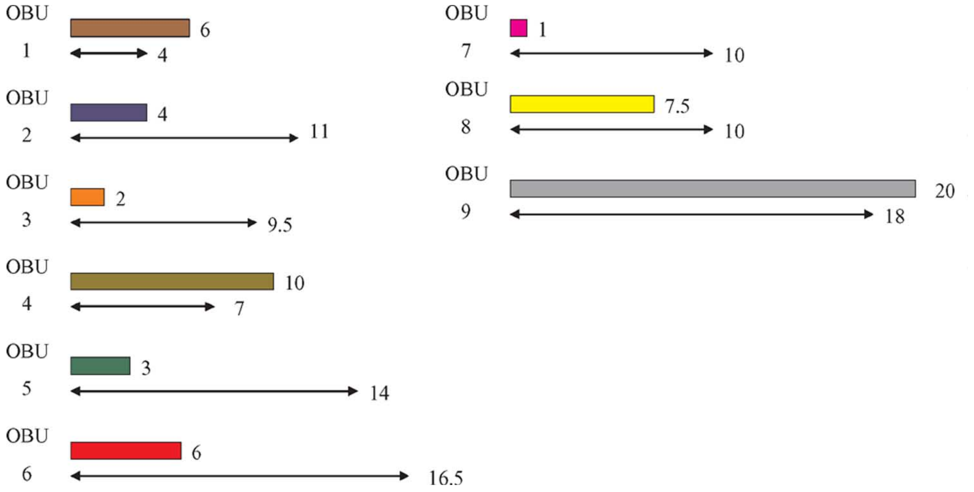


Fig. 5. Example of the MFL scheduling algorithm.

OBU f_k from set A_+. In Step 4, the virtual finish time FT_i and virtual start time ST_i for the ith OBU in set A_+ are updated by

$$FT_i = \min\{D_i, ST_{f_k}\} \tag{4}$$

and

$$ST_i = FT_i - TX_i. \tag{5}$$

To fully serve most OBUs, the algorithm sets the virtual finish time of each OBU as close as possible to its remaining SCH dwell time, which is limited by an upper bound ST_{f_k}, as stated in (4). Additionally, the virtual start time is calculated to check whether any OBU cannot be completely served. In Step 5, all OBUs are repartitioned by the same rule applied in the initialization phase to determine the completely served possibility for OBUs in A_+. Step 6 checks whether all possible completely served OBUs are already chosen. Once set A_+ is empty, the construction of the temporary list F is completed and the transmission time pileup phase is then performed. Otherwise, this phase is reexecuted.

C. Transmission Time Pileup Phase

Parameters of the ith OBU in set A_- are calculated again in the phase because some portion of service time is already allocated to higher priority OBUs. Accordingly, the remaining SCH dwell time D_i is updated by

$$D_i = D_i - \sum_{k \in F} TX_k \tag{6}$$

and the queueing delay t_i (on the absolute time axis) is set by

$$t_i = t_i + \sum_{k \in F} TX_k. \tag{7}$$

The OBUs in the temporary list F are added to the service list by a first-in–last-out rule. The MFL algorithm schedules the completely served OBUs by sorting the service order of OBUs in reverse order, so that the reverse order of list F equals the order of the service list. The algorithm then enters the final phase when all completely served OBUs are scheduled.

D. Partial Service Phase

In this phase, the OBU with the longest remaining SCH dwell time in set A_- is selected. Notably, all the OBUs selected in this phase can be partially served only. This OBU is added to the last place of the service list, and its data volume is given as its remaining SCH dwell time multiplied by the data transmission rate. This step generates the service list and the data volume assignment table as a result.

Additionally, the Appendix includes a proof that the process in the reverse lineup phase can minimize the handoff rate if the queueing delay is negligible. Notably, maximizing the number of OBUs being served results in minimizing the handoff rate. Moreover, in practical implementation, a small guard time could be inserted between FT_i and D_i to accommodate the prediction errors.

Take Fig. 5 as an illustrative example. In the figure, the arrow axis represents the remaining SCH dwell time, and a color bar represents the required transmission time for an OBU. In the initialization phase, OBUs 2, 3, 5, 6, 7, and 8 are in A_+, and OBUs 1, 4, and 9 are in A_-. OBU 5 has a longest virtual start time ST_i, so it is placed in the temporary list F for the first round in the reverse lineup phase. Then, update ST_i for all the OBUs in A_+. Applying the rules, OBUs 7 and 3 are chosen in the second and third rounds. After the third round, OBU 8 has a negative virtual start time, so it is pushed to A_-. In the fourth round, OBU 2 is placed in list F, and OBU 6 is shifted to A_-. Now that all A_+ is empty, the reverse lineup phase is closed. In the transmission time pileup phase, the OBUs in the temporary list F are placed in the service list in first-in–last-out order. After recalculation, only OBUs 6 and 9 have positive remaining SCH dwell time. The MFL goes back to initialization phase to arrange the two OBUs. Just follow the rules, and the service list is finally done. The service list and data volume assignment table are shown in Table I.

IV. SIMULATION RESULTS

In the simulations, the MFL algorithm was compared to the conventional FCFS [7] and EDF [9] methods. Three performance indexes, namely 1) system handoff rate, 2) service

TABLE I
SCHEDULED OUTPUT

Service list					
OBU 2	OBU 3	OBU 7	OBU 5	OBU 6	OBU 9
Data volume assignment table					
4R	2R	1R	3R	6R	2R

TABLE II
SYSTEM PARAMETERS OF THE DSRC SIMULATION ENVIRONMENT

System Parameters	Value
d	400 m
μ_n	2/sec
α	1.1
k	variable
m	10000
M	1000 bytes
V_{min}	60Km/hr
V_{max}	120 Km/hr
$T_{s,max}$	100 ms
T_w	5 ms
T_r	1050 ms
r	4
R	18 Mbps
p	9

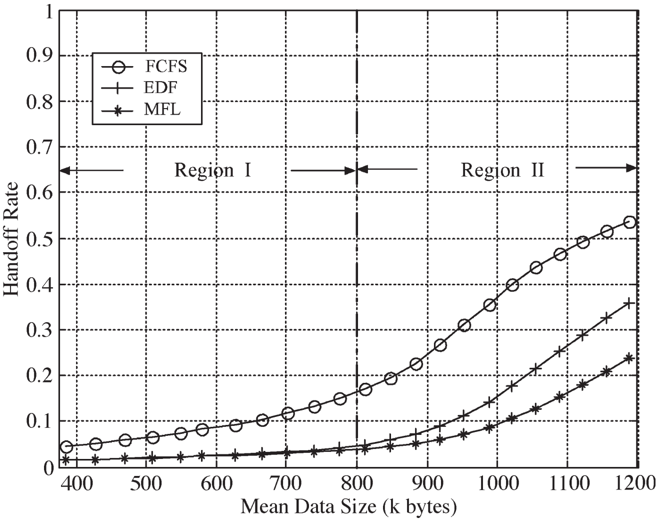


Fig. 6. System handoff rate.

failure rate, and 3) system utilization, were measured. Due to limited system capacity, some OBUs could not complete their transmission request within their dwell time in a cell, causing handoff requests. The system handoff rate R_{sh} is defined as

$$R_{\mathrm{sh}} = \frac{N_{\mathrm{ps}} + N_u}{N_{\mathrm{cs}} + N_{\mathrm{ps}} + N_u} \tag{8}$$

where N_{ps} is the number of partially served OBUs, N_u is the number of completely unserved OBUs, and N_{cs} is the number of completely served OBUs in the DSRC network. A request that cannot be completed within the maximum delay tolerance of an OBU is regarded as a service failure. The service failure rate R_{sf} is defined as

$$R_{\mathrm{sf}} = \frac{N_{\mathrm{sf}}}{N_{\mathrm{srd}}} \tag{9}$$

where N_{sf} is the number of OBUs with service failures, and N_{srd} is the number of all the OBUs accepted by RSU and is equal to $N_{\mathrm{cs}} + N_{\mathrm{ps}} + N_u$. Two system utilization are defined, namely 1) the measured system utilization SU_m, which is the proportion of the average RSU data transmission time over the SCH time frame, and 2) the effective system utilization SU_e, which is the proportion of successful reassembled RSU data transmissions over the SCH time frame. The SU_e is obtained by

$$SU_e = SU_m \times (1 - R_{\mathrm{sf}}). \tag{10}$$

A. Simulation Environment

A six-lane highway environment is simulated, where the vehicles (OBUs) move in either direction with moving speed V, uniformly ranging from $V_{\min}$ and $V_{\max}$, with no abrupt U-turns. RSUs are uniformly installed all along the highway, and the distance between two successive RSUs equals d. The radio propagation is calculated by the long-term fading channel model, which combines free-space loss with exponent number 4 and log-normal fading with standard deviation 8 [13]. Additionally, the process of new OBUs sending OSTs to respond to an RST is modeled as a Poisson process with a mean arrival value μ. For RSU, the repeat period of RST transmission is T_r. The number of probes between two RSTs is p. As to the MAC service data unit (MSDU) packet, the data size is M, and the number of a burst data requested by an OBUs is N_p, which is modeled as a truncated Pareto distribution given by

$$f_{N_p}(n_p) = \begin{cases} \frac{\alpha k^{\alpha}}{n_p^{\alpha+1}}, & m > n_p > k \\ \beta, & n_p = m \end{cases} \tag{11}$$

where m is the maximal allowed number, k is the minimal allowed number, α is the parameter for Pareto distribution, and β is the probability that $n_p \geq m$. The value of β can be calculated by

$$\beta = \int_{m}^{\infty} f_{N_p}(n_p) dn_p = \left(\frac{k}{m}\right)^{\alpha}, \qquad \alpha > 1. \tag{12}$$

Three ITS data service types were considered in the simulations. An effective distance was assigned with respect to the transmission characteristics of the ITS services. A location-dependent service with immediate response was simulated as a small-range service with an effective distance of 500 m; a location-dependent service without immediate response service was simulated as a mid-range service with an effective distance of 1000 m, and a location-independent service was simulated as a long-range service with an effective distance of 2000 m. The traffic portion for each type was the same in our simulation. Details of the system parameters are shown in Table II.

B. Simulation Results

Fig. 6 shows the system handoff rate versus the mean data size for the three algorithms. In the figure, the axis of the mean data size is divided into two regions, namely 1) Region I, which represents the light load condition with a mean data

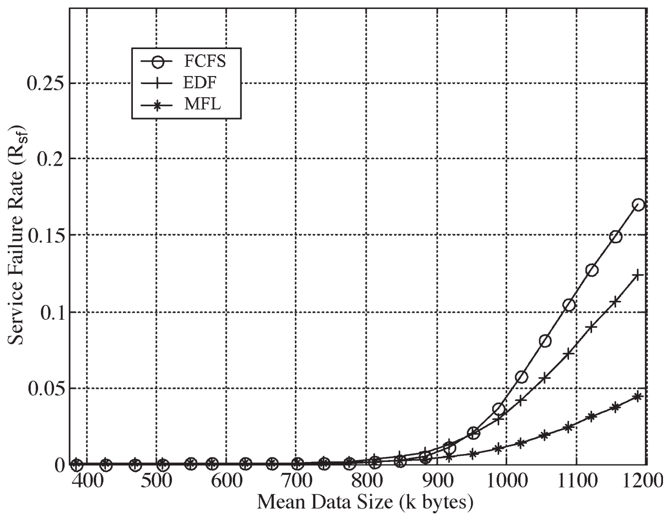
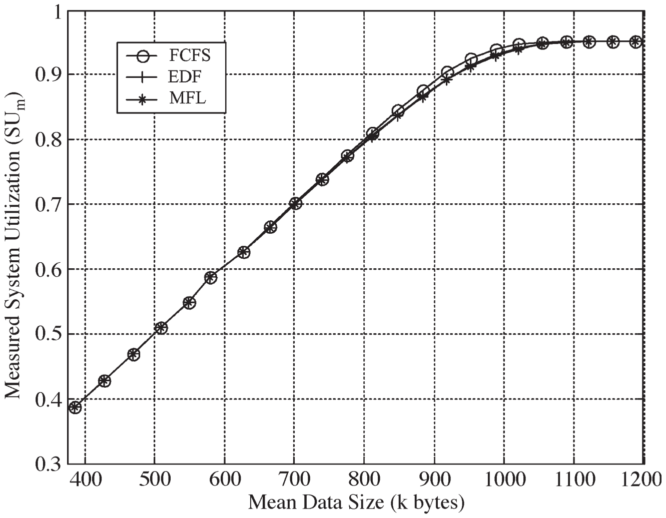


Fig. 7. Service failure rate.

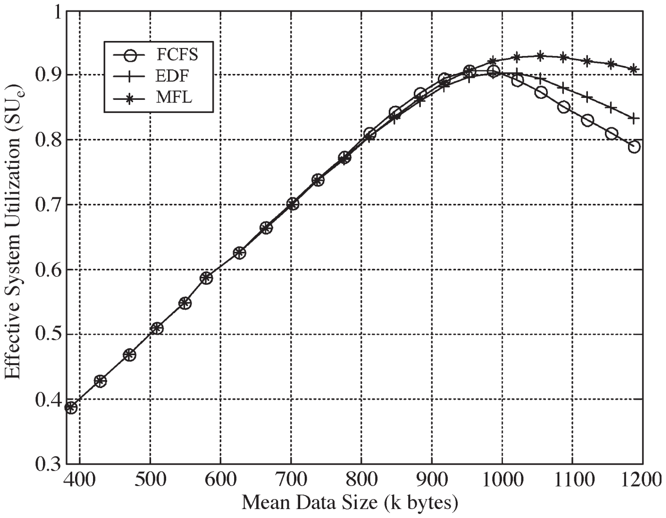
size of 400–800 kB, and 2) Region II, which represents the heavy load condition with a mean data size of 800–1200 kB. Simulation results show that, in Region I, FCFS yielded a system handoff rate higher than EDF and MFL, whereas MFL and EDF had almost the same system handoff rate because FCFS made the service order without considering the remaining SCH dwell time and the remaining transmission time of OBUs. Additionally, the remaining transmission time is much less than the remaining SCH dwell time when the system load is light. In this case, the MFL scheduling algorithm is mostly determined by the remaining SCH dwell time, which is equivalent to that of the EDF. In Region II, simulation results show that the MFL algorithm has the lowest system handoff rate because the remaining transmission time of OBUs is shortened accordingly when the mean data size becomes larger. An OBU with a tighter remaining transmission time is granted a higher service priority by the MFL algorithm and, therefore, has a higher probability of being completely served before it roams outside the service region of the RSU. Consequently, the handoff rate is reduced.

Fig. 7 shows the service failure rate versus the mean data size for the three algorithms. MFL has a smaller service failure rate than FCFS and EDF. This result has two reasons: First, MFL can achieve the lowest system handoff rate so that service failure probability of OBUs declines significantly. The other one is that MFL determines the transmission order according to the transmission state of OBUs. The MFL algorithm assigns a higher probability of serving to an OBU that has a longer queueing delay and is closer to the maximum tolerable delay. Conversely, EDF and FCFS do not consider this factor, and the service of their OBUs, which have longer queueing delays, are terminated when the packet size rises.

Fig. 8(a) and (b) depicts the measured system utilization SU_m and the effective system utilization SU_e versus the mean data size of the three algorithms, respectively. Obviously, the three methods achieve almost the same measured system utilization SU_m because RSU transmits packets for OBUs while the transaction queues are not empty; consequently, the system utilization performance does not change, whatever algorithm is applied. Notably, ITS data are segmented into smaller packets and then are transmitted over the DSRC network. The data can be correctly reassembled only if all the smaller packets are received without dropping. As shown in Fig. 8(b), the MFL algorithm achieves the highest effective system utilization SU_e among the three algorithms because it has the lowest service failure rate, as revealed in Fig. 7.



(a)



(b)

Fig. 8. System utilization. (a) SU_m. (b) SU_e.

V. Concluding Remarks

In this paper, an MFL scheduling algorithm is proposed for the downlinks of DSRC networks in ITS. Considering the small coverage of RSU and the high mobility of OBU in the DSRC network, the design goal of the proposed MFL algorithm is to minimize the system handoff rate, while the effective system utilization is maximized. The MFL algorithm gives the smallest chance of service to the OBU with the largest remaining SCH dwell time, the smallest remaining transmission time, and the highest weighting factor constituted by both the queueing delay and maximum tolerable delay. The algorithm mainly comprises four phases, namely 1) initialization phase,

2) reverse lineup phase, 3) transmission time pileup phase, and 4) partial service phase. Simulation results show that the MFL algorithm outperforms the traditional FCFS and EDF methods in terms of lower service failure rate, smaller system handoff rate, and higher effective system utilization. The lower handoff rate relieves the workload of back-end signaling in the DSRC network, enabling the network to support ITS applications in a real-time fashion.

APPENDIX

The process in the reverse lineup phase can serve the maximum number of completely served OBUs.

Proof: In the following, denote N as the number of OBUs in the list A_+, "$(\cdot)'$" as the process using other scheduling policy, and "$n(U_i)$" as the number of OBUs that satisfied the condition $U_i \geq 0$.

1) Basis of Induction: $k = 1$ is the first iteration of the reverse lineup phase. The correctness that RSU can serve the maximum number of completely served OBUs for $k = 1$ is proved in the following.

When $k = 1$, we have

$$\begin{aligned} &FT_i = D_i \\ &\quad f_1 = \arg\max_i \{FT_i - TX_i\}, (f_1)' \neq f_1 \qquad \forall i \in A_+, ST_i \geq 0 \\ &ST_{f_1} = (FT_{f_1} - TX_{f_1}) \geq (FT_{(f_1)'} - TX_{(f_1)'}) = ST_{(f_1)'}. \end{aligned}$$

Then, we divide the relation of ST_i, $ST_{(f_1)'}$, and D_i into three cases as follows:

1) If $ST_{(f_1)'} \leq ST_{f_1} \leq D_i$, then

$$\begin{aligned} FT_i &= \min\{ST_{f_1}, D_i\} = ST_{f_1} \\ (FT_i)' &= \min\left\{ST_{(f_1)'}, D_i\right\} = ST_{(f_1)'}. \end{aligned}$$

We can derive

$$n(FT_i - TX_i) \geq n\left((FT_i)' - TX_i\right).$$

2) If $ST_{(f_1)'} \leq D_i \leq ST_{f_1}$, then

$$\begin{aligned} FT_i &= \min\{ST_{f_1}, D_i\} = D_i \\ (FT_i)' &= \min\left\{ST_{(f_1)'}, D_i\right\} = ST_{(f_1)'}. \end{aligned}$$

We can derive

$$n(FT_i - TX_i) \geq n\left((FT_i)' - TX_i\right).$$

3) If $D_i \leq ST_{(f_1)'} \leq ST_{f_1}$, then

$$\begin{aligned} FT_i &= \min\{ST_{f_1}, D_i\} = D_i \\ (FT_i)' &= \min\left\{ST_{(f_1)'}, D_i\right\} = D_i. \end{aligned}$$

We can derive

$$n(FT_i - TX_i) \geq n\left((FT_i)' - TX_i\right).$$

Therefore, the result for $k = 1$ is proved.

2) Inductive Hypothesis: We assume that, when $k = x$, the result is correct for $1 < x < N - 1$.

3) Inductive Step: If the result is correct when $k = x$, we prove the result is correct for $k = x + 1$.

When $k = x + 1$ for $1 < x < N - 1$, we can obtain

$$\begin{aligned} f_{k+1} &= \arg\max_i \{FT_i - TX_i\} \\ (f_{x+1})' &\neq f_{x+1} \qquad \forall i \in A_+, ST_i \geq 0 \\ ST_{f_{x+1}} &= \left(FT_{f_{x+1}} - TX_{f_{x+1}}\right) \\ &\geq \left(FT_{f_{(x+1)'}} - TX_{f_{(x+1)'}}\right) \\ &= ST_{(f_{x+1})'}. \end{aligned}$$

Then, we divide the relation of $ST_{f_{x+1}}$, $ST_{f_{(x+1)'}}$, and D_i into three cases as follows:

1) If $ST_{(f_{x+1})'} \leq ST_{f_{x+1}} \leq D_i$, then

$$\begin{aligned} FT_i &= \min\left\{ST_{f_{x+1}}, D_i\right\} = ST_{f_{x+1}} \\ (FT_i)' &= \min\left\{ST_{(f_{x+1})'}, D_i\right\} = ST_{(f_{x+1})'}. \end{aligned}$$

We can derive

$$n(FT_i - TX_i) \geq n\left((FT_i)' - TX_i\right).$$

2) If $ST_{(f_{x+1})'} \leq D_i \leq ST_{f_{x+1}}$, then

$$\begin{aligned} FT_i &= \min\left\{ST_{f_{x+1}}, D_i\right\} = D_i \\ (FT_i)' &= \min\left\{ST_{(f_{x+1})'}, D_i\right\} = ST_{(f_{x+1})'}. \end{aligned}$$

We can derive

$$n(FT_i - TX_i) \geq n\left((FT_i)' - TX_i\right).$$

3) If $D_i \leq ST_{(f_{x+1})'} \leq ST_{f_{x+1}}$, then

$$\begin{aligned} FT_i &= \min\left\{ST_{f_{x+1}}, D_i\right\} = D_i \\ (FT_i)' &= \min\left\{ST_{(f_{x+1})'}, D_i\right\} = D_i. \end{aligned}$$

We can derive

$$n(FT_i - TX_i) \geq n\left((FT_i)' - TX_i\right).$$

Therefore, the result for $k = x + 1$ is proved. ■

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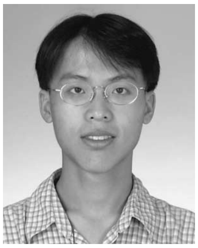

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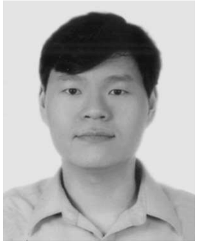

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