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Surveillance on-the-road: Vehicular tracking and reporting by V2V communications

Lien-Wu Chen [a,*], Yu-Chee Tseng [b], Kun-Ze Syue [b]

[a] Department of Information Engineering and Computer Science, Feng Chia University, Taichung 407, Taiwan
[b] Department of Computer Science, National Chiao Tung University, Hsinchu 300, Taiwan

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ABSTRACT

Vehicular networks have attracted a lot of attention recently. One potential application of vehicular networks is to use video cameras embedded in vehicles to support video surveillance, which we call "*surveillance on-the-road*". Traditional surveillance systems only rely on fixed stations on the roads to monitor road conditions. With vehicular cameras, deeper and richer road conditions may be tracked. In this paper, we study the related communication issues to support such "on-the-road" surveillance scenarios. We use monitoring and tracking suspicious vehicles (such as stolen cars) on the road through *license plate recognition (LPR)* as an example (our results should be applicable to other scenarios as well). We show how vehicles can work cooperatively through *vehicle-to-vehicle (V2V)* communications to achieve this goal. With a tracking and a reporting modules, our solution does not rely on infrastructure networks. The tracking module allows handoff of a tracking job to neighboring vehicles as necessary and report of suspicious vehicles to nearby police cars. The reporting module can help guide message flows to avoid flooding the network. Simulation results verify the message efficiency of our approach. We also show how our framework can be applied to the developing *WAVE/DSRC (Wireless Access in Vehicular Environments/Dedicated Short Range Communications)* standards.

1. Introduction

Recently, lots of progress has been made in video surveillance due to the advances of video technologies and embedded computing and communications technologies. Many vehicular surveillance applications have been studied, such as vehicle security [1], brake warning [2], and urban monitoring [3]. Traditional surveillance systems only rely on fixed stations on the roads to monitor road conditions. In this paper, we propose to use cameras embedded on vehicles to help the surveillance job, which we call "*surveillance on-the-road*". Therefore, in addition to fixed video cameras, millions of cameras installed on vehicles may help the surveillance job. For example, most vehicles nowadays have rear cameras to assist backward driving. With vehicular cameras, deeper and richer road conditions may be tracked.

In this work, we study the communication issues to support such "on-the-road" surveillance scenarios through *vehicle-to-vehicle (V2V)* communications. We use tracking and reporting suspicious vehicles as an example. Most existing works [4–7] rely on roadside infrastructures to achieve this goal.

We propose an infrastructure-less framework for tracking and monitoring suspicious vehicles by vehicles on the roads. Our solution consists of a tracking module and a reporting modules. The tracking module allows a vehicle

* Corresponding author. Tel.: +886 4 24517250x3759; fax: +886 4 24516101.

E-mail addresses: lwuchen@fcu.edu.tw (L.-W. Chen), yctseng@cs.nctu.edu.tw (Y.-C. Tseng), kzsyue@cs.nctu.edu.tw (K.-Z. Syue).

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to keep tracking an identified suspicious vehicle and handoff its tracking job to neighboring vehicles as necessary. Also, on detecting an intersection, it allows a tracking vehicle to report the intersection passed by the suspicious vehicle to nearby police cars even if it has no digital map information at hand. Note that if vehicles have digital maps installed in their onboard units, an intersection might be detected by the current GPS location and digital maps. Otherwise, the proposed intersection detection scheme will be used to detect an intersection without relying on digital maps.

The reporting module helps find the nearest police car at low message cost without relying on costly roadside infrastructures, such as roadside units (RSUs) and wireless local area network access points (WLAN APs). Instead, it only relies on V2V communications. Note that if both the tracking vehicle and the nearest police car have 3G/3.5G radio interfaces, the discovery for suspicious vehicles might be directly reported to the nearest police car via 3G/3.5G communications. Otherwise, V2V communications will be used to report the discovery as proposed in this work.

On the other hand, we propose to enhance *LPR (licence plate recognition)* capability to a vehicular camera, so a suspicious license number which is to be tracked can be recognized locally *in* a vehicle. This could greatly reduce the communication overhead. Also, there is no need of large amounts of human labors to watch these videos. Only in rare situations, a vehicular camera needs to keep a video clip for future use (such as a proof of evidence). Note that such video clips may be even clearer than those taken by fixed stations. Finally, our work should be applicable to the developing *WAVE/DSRC (Wireless Access in Vehicular Environments/Dedicated Short Range Communications)* standards. We will comment how our work relates to WAVE/DSRC.

Section 2 defines our suspicious vehicle tracking and reporting problem. Section 3 describes our framework to solve this problem. Simulation results are presented in Section 4. Section 5 concludes the paper.

1.1. Related works

For tracking purposes, Ref. [4] presents an architecture for vehicle tracking systems using wireless sensor technologies. RSUs are installed along roads to continuously keep tracking vehicles at regular intervals. These RSUs are connected to the underlying wired infrastructure to receive queries from the central server and reply back with the necessary information. Ref. [5] presents a WLAN-based real time system for vehicle localization. The proposed solution uses a neural network trained with a map of received power fingerprints from WLAN APs surrounding the vehicle. In these two works, however, a large number of RSUs and WLAN APs must be installed on the roadside to provide target information and received signal strengths to vehicles, respectively. Ref. [7] proposes a smart parking scheme in VANETs, which includes tracking stolen vehicles. When a thief drives a stolen vehicle along a road, all pass-by RSUs can detect the parking beacon sent from the moving vehicle. According to the parking lot's identifier in the beacon, the position of the stolen vehicle can be reported to the parking lot. Again, this is also achieved by the deployment of RSUs along roads.

For reporting purposes, Ref. [6] proposes a searching strategy called ANTS to locate a desired vehicle close to the query user based on the lost ant searching for its nest. ANTS is employed in ShanghaiGrid [8] consisting of a large number of local nodes installed at crossroads, which is responsible for storing vehicle information and accepting queries. However, deploying such local nodes on each intersection requires a dramatic number of RFID readers and wireless APs and thus is costly. More importantly, it may not be practical to construct infrastructure in suburban and rural areas.

For message rebroadcast and contention resolution, most of VANET-specific schemes [9–14] do not consider the difference of vehicles located on intersections and road segments to employ different broadcast and backoff strategies for those vehicles. In addition, the memories of vehicles encountered the target car are not further investigated for cooperative searching on the road.

2. System model

Fig. 1 shows our system model. We use suspicious vehicle tracking and reporting as an example (our results are not limited to such applications). We consider vehicles on the roads, which form vehicular surveillance networks via V2V communications. Each vehicle is equipped with a GPS receiver and some video cameras (one possibility is to install an embedded camera on each corner of the vehicle [15]). These video cameras can help recognize the license plates of the vehicles immediately in front/rear of it. With license plate recognition (LPR) techniques, transmitting license plate images is not always necessary. For identifying suspicious vehicles, the police department may publish a list of license plate numbers to be tracked in a particular region. Then vehicles in that region can try to recognize these plate numbers and keep those video clips when there is a match. We assume that each vehicle has an onboard communication unit, such as a Wi–Fi [16]

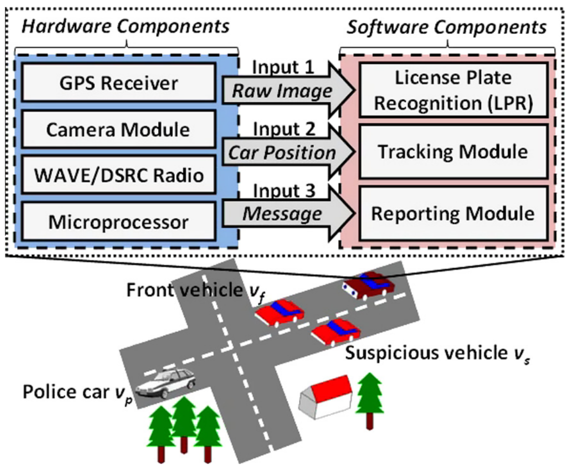

Fig. 1. System model of "Surveillance On-the-Road".

radio interface operating in the ad hoc mode under the same Basic Service Set Identifier (BSSID) or an IEEE 802.11p [17] radio interface operating in the WAVE mode with low connection setup overhead. In the WAVE mode, as long as vehicles operate in the same channel and use the same wildcard BSSID (with all 1 s as its address), two vehicles can immediately communicate with each other upon encountering on the road without having to join a BSS. Vehicles transmit periodical beacons to exchange IDs and positions with neighboring vehicles, and TTL (time to live) is indicated in broadcasting messages to limit their ranges.

For tracking and reporting suspicious vehicles, we formulate the problem as follow. The radio interface on each vehicle has a fixed transmission range R. By LPR, each vehicle i can identify whether the immediate front/behind vehicle v_f/v_b is a suspicious vehicle v_s or not. Below, we use v_f as an example (our framework should be applicable to v_b as well). Vehicle i recognizes v_f's license plate number every t_u and t_n seconds $(t_u < t_n)$ in the urgent mode and normal mode, respectively. Before v_s has been identified, i recognizes the license plate number of its v_f in the normal mode. Once v_f is identified as v_s, i will immediately report this discovery to nearby police cars v_p and switch to the urgent mode to continuously recognize the license plate number of its v_f to keep tracking v_s. In addition, since the tracked v_s cannot change its direction on road segment, the current position of v_s will be reported to v_p on each intersection for reducing the number of reporting messages and maintaining the up-to-date location of v_s. On the other hand, if v_s is not in front of i due to changes of lane or direction, the tracking job will be handoff from i to i's neighboring vehicle which is immediate behind v_s.

Our goal is to design efficient protocols for vehicles to cooperatively track the identified v_s and to report each intersection passed by v_s to v_p during the tracking process. Such reporting messages m_r should be guided to the nearest v_p and delivered through multi-hop forwarding. Through these m_r, v_p can reconstruct the trajectory of v_s and take further actions a.s.a.p. Given such scenarios, we will consider the following four research issues.

1. Tracking handoff: How do we handoff the tracking job to neighboring vehicles as v_s changes its lane or direction so that v_s can be continuous tracked on the road?
2. Intersection detection: How do we detect an intersection without digital maps at hand so that each intersection passed by v_s can be reported to v_p for maintaining the up-to-date location of v_s?
3. Rebroadcast decision: How do we report the location of v_s to nearby v_p such that the number of rebroadcasts of m_r can be minimized?
4. Message guiding: How do we guide the propagation of m_r to the nearest v_p without flooding the network so that the message overhead for reporting can be reduced?

3. Tracking and reporting protocols

In this section, we propose an infrastructure-less framework for the vehicle tracking and reporting problem, which consists of a tracking module and a reporting module, as shown in Fig. 2. First, to keep tracking an identified v_s, we propose a tracking handoff scheme and an intersection detection scheme in Section 3.1. Second, to efficiently deliver reporting messages about v_s to the nearest v_p, we propose a rebroadcast decision, an intersection-guiding search, and a memory-based backoff schemes in Section 3.2. Table 1 summarizes the notations to be used.

3.1. Tracking module

We consider that vehicles use their onboard cameras to conduct surveillance in a cooperative manner, which we call *vehicular surveillance networks*. Through its onboard camera, each vehicle i can take snapshots on its v_f. i retrieves this license plate number and compares it against a database of suspicious plate numbers provided by the police department (through the Internet or nearby police cars). When a suspicious vehicle v_s is identified, i will continuously take snapshots on v_s. Note that to avoid privacy leakage, the suspicious plate numbers from the police department could be the values returned by a hash function. Similarly, the recognized plate number of v_f could be calculated using the same hash function and compared without knowing the actual plate number. For cooperative tracking, we design a tracking handoff scheme to pass the tracking job to a vehicle immediately behind v_s due to changes of lane/direction. In addition, for maintaining the up-to-date location of v_s, we design an intersection detection scheme to report the current position of v_s to v_p on each intersection during the tracking process. Note that since the tracked v_s cannot change its direction on road segment, the position of v_s is only reported on each intersection for reducing the number of reporting messages to v_p.

3.1.1. Tracking handoff scheme

If vehicle i detects its v_f as v_s during the normal mode, i will switch to the urgent mode and continuously track v_s. Once i becomes unable to track v_s during the urgent mode, i will broadcast a tracking handoff message m_h to neighboring vehicles. Vehicles receiving m_h will switch to the

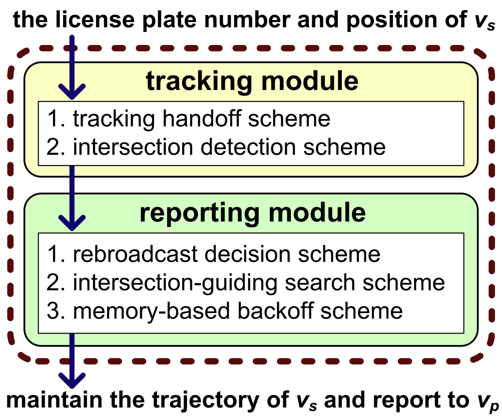

Fig. 2. Tracking and reporting modules.

Table 1
Summary of notations.

Notation	Definition
v_s	The identified suspicious vehicle, such as a stolen car
v_f	The immediate front vehicle
v_p	The police car for dealing with v_s
m_h	The tracking handoff message sent to neighboring vehicles
m_r	The reporting message sent to nearby v_p
d_r	The reporting direction of m_r
d_g	The guiding direction of m_r
N_i	The neighboring vehicles of vehicle i
s_H	The sector with angle θ_H located on the head of a vehicle
s_T	The sector with angle θ_T located on the tail of a vehicle
s_R	The sector with angle θ_R located on the right of a vehicle
s_L	The sector with angle θ_L located on the left of a vehicle
s_C	The corresponding sector for d_r
t_u	The LPR interval in the urgent mode
t_n	The LPR interval in the normal mode
t_i	The passing time from vehicle i met v_p to now
τ	The small integer for the first backoff window
ρ	The number of backoff classes
T	The valid duration of the memory for v_p

urgent mode and continuously check if it can detect the missed v_s. The neighboring vehicle j which detects v_s will take over the tracking job from i without replying any acknowledgment message to i, and all other neighboring vehicles will go back to the normal mode after a threshold (tracking handoff timer). Similarly, once j becomes unable to track v_s, it will repeat the above procedure. Note that if there is no neighboring vehicle that can take over the tracking job, the current tracking job is terminated and a new tracking process will be started again when another vehicle k detects its v_f as the missed v_s during the normal mode. In Fig. 3, for example, A is a tracking vehicle in the urgent mode and B is a suspicious vehicle tracked by A. Once A becomes unable to track B, A will broadcast m_h to C and D. C and D will switch from the normal mode to the urgent mode for detecting B. On one hand, since C has detected B, the tracking job is handoff from A to C. On the other hand, after the tracking handoff timer expires, D will switch back to the normal mode.

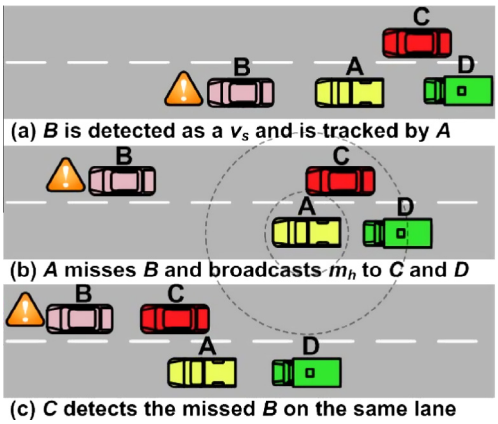

Fig. 3. An example of handoff a tracking job to neighboring vehicles as necessary.

3.1.2. Intersection detection scheme

Since vehicles driving on the roads will transmit periodical beacons to exchange IDs and positions with neighboring vehicles, each vehicle i can maintain the up-to-date locations of its neighboring vehicles N_i based on received beacons (we consider only moving vehicles, not including parked cars). According to the positions of N_i, we remove nearby N_i within a certain distance δ from i (depending on the average width of road segments) and divide N_i into four parts, which are located on i's head sector s_H, tail sector s_T, right sector s_R, and left sector s_L with angles $\theta_H, \theta_T, \theta_R$, and θ_L, respectively. We set $\theta_H = \theta_T, \theta_R = \theta_L$, and $\theta_H = 180^\circ - \theta_R$, where θ_H and θ_T can be determined based on the average width of road segments. In Fig. 4(a), for example, the radius of the inner circle is equal to δ and the radius of the outer circle is equal to the distance from vehicle A and the farthest N_A.

To detect if i is located on intersection, we check whether there is any N_i in s_H, s_T, s_R, or s_L of i. If there is N_i in either s_R or s_L, i is located on intersection. If there is no N_i in s_R and s_L, i is located on road segment. The basic concept is that only when i is located on intersection, it might receive beacons from N_i in its s_R or s_L. In Fig. 4, for example, vehicle B detects that it is located on intersection because there are N_B in its s_R and s_L whereas vehicle A, C, D, and E detect that they are located on road segment since there is no neighboring vehicles in their s_R or s_L. Note that the moving directions of neighboring vehicles in s_R or s_L can be also used for intersection detection in addition to their positions.

3.2. Reporting module

Once v_s is identified by vehicle i, the discovery should be reported to the nearest v_p. If both i and v_p have 3 G/3.5 G radio interfaces, the discovery might be directly reported to v_p via 3 G/3.5 G communications. Otherwise, V2V communications will be used to report the discovery to v_p as to be discussed below. After the nearest v_p receives m_r reported by i, it can take less time to arrive at the position of v_s and take further action. Although flooding is an intuitive search scheme that can always find the nearest v_p, it causes a huge amount of network traffic and thus makes its scalability low. Message m_r contains the discover's ID, v_s's position and license number, and a sequence number. To reduce the message overhead for reporting m_r to nearby v_p, we design a rebroadcast decision, an intersection-guiding search, and a memory-based backoff schemes to minimize the number of rebroadcasts.

3.2.1. Rebroadcast decision scheme

In this scheme, vehicles decide whether they rebroadcast m_r according to their positions, m_r's reporting direction d_r, and the corresponding sector s_C for d_r. In Fig. 4(b), for example, sender A is located on s_T of receiver B so that d_r is from s_T to s_H and thus s_C for d_r is s_H. Accordingly, s_C for d_r of C, D, and E are s_R, s_T, and s_R (i.e., shaded areas in Fig. 4(c)–(e)), respectively. The rebroadcast decision is made as follows.

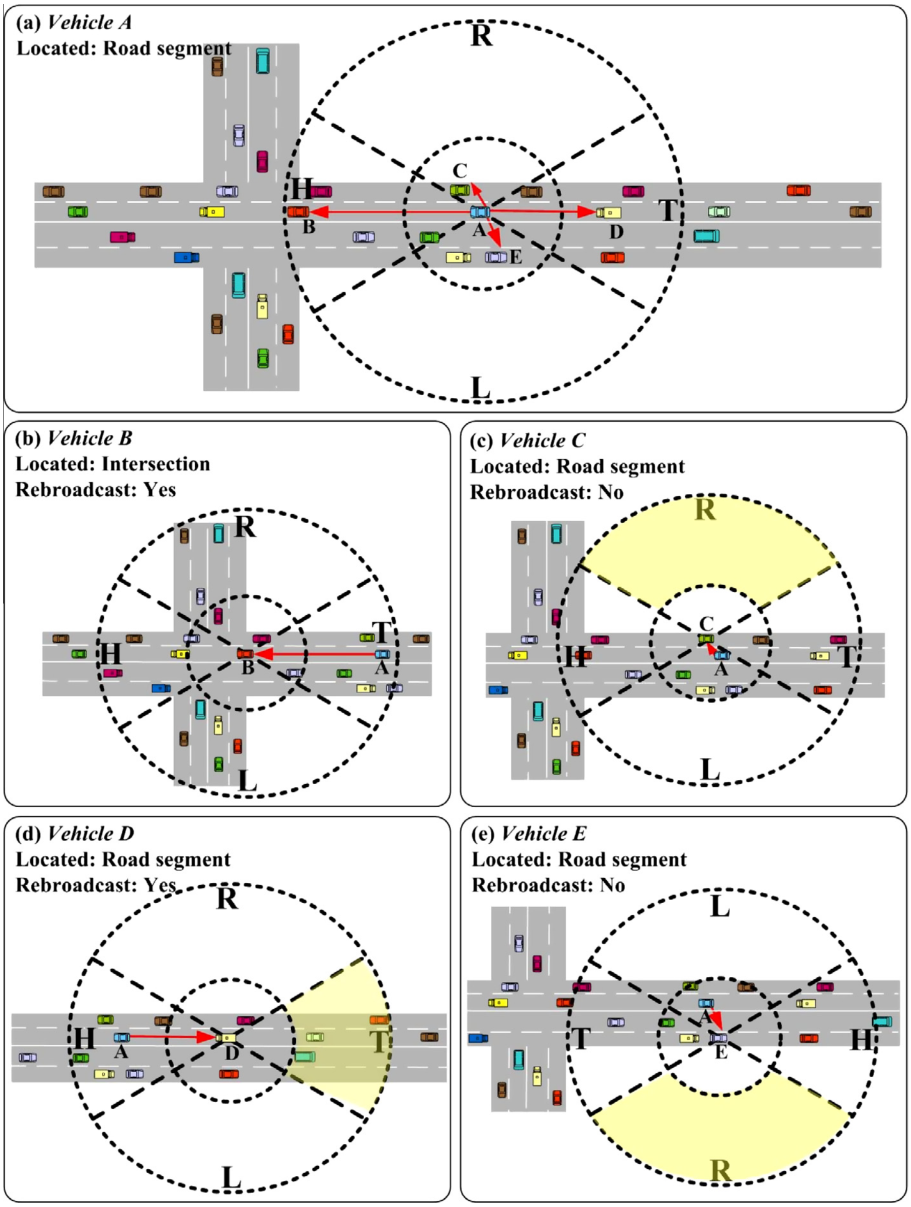

Fig. 4. Rebroadcast decisions based on neighboring vehicle distributions.

1. When vehicle j receives m_r sent by vehicle i, j will first detect if it is located on intersection. If so, j will rebroadcast m_r immediately. Otherwise, it will detect s_C for d_r and then check if there is any N_j in s_C.
2. If there is N_j in s_C, j will rebroadcast m_r. Otherwise, j will discarded m_r to avoid unnecessary rebroadcasts since there is no N_j that can help rebroadcast.

Similarly, after vehicle k receives m_r from j, k will repeat above procedures. In Fig. 4, for example, vehicle B and D decide to rebroadcast m_r because B is located on intersection and there is N_D in s_C of D (i.e., s_T), respectively, whereas vehicle C and E decide not to rebroadcast m_r since there is no N_C and N_E in their s_C for d_r (i.e., s_R). Note that the reception of m_r with the same sequence number serves as an implicit message to prevent other vehicles received m_r competing again. Therefore, if vehicle B rebroadcasts m_r received from vehicle $A, N_A \bigcap N_B$ will not rebroadcast A's m_r.

3.2.2. Intersection-guiding search scheme

Based on the rebroadcast decision scheme, we further design an intersection-guiding search scheme for guiding m_r to the nearest v_p. In our scheme, each vehicle i will record the position as it meets v_p (through the beacon broadcast by v_p). When i receives m_r, it will specify the guiding direction d_g in m_r according to its memory for v_p. m_r will be rebroadcast to the recorded position of v_p in i's memory (if the memory is still valid). Thus, m_r can be guided on intersection by vehicles' memory for v_p, so the flooding of m_r can be avoided and the number of rebroadcasts of m_r can be reduced. Note that the valid duration of the memory for v_p is bounded by a predefined threshold T (which is set to 30 s in our simulation). Thus, the up-to-date position of v_p can be updated by the vehicle with the freshest memory (based on the scheme proposed in Section 3.2.3). Even if m_r might be initially guided by the memory not fresh enough, the message can still be guided to v_p since the transmission speed of packets is much faster than the moving speed of vehicles. We illustrate an example in Figs. 5 and 6 as follows.

1. In Fig. 5, vehicle A identifies its v_f as v_s and broadcasts m_r to the nearest v_p. There are four intersections traveled by m_r, where vehicle B is located on the first intersection, vehicle C and D are located on the second intersection, vehicle E is located on the third intersection, and v_p is located on the fourth intersection.
2. On the first intersection, as shown in Fig. 6(a), vehicle B detects that it is located on intersection and m_r is from s_T (i.e., from A to B). In addition, B did not meet v_p before. So B will decide to rebroadcast m_r without specifying d_g (i.e., denoted by "broadcast to: s_C" instead of "s_H", "s_T", "s_R", or "s_L"). Thus, other vehicles located on the first intersection will decide their own d_g by themselves as receiving m_r from B.
3. On the second intersection, as shown in Fig. 6(b), vehicle C detects that it is located on intersection and m_r is from s_H (i.e., from B to C). In particular, C met v_p 10 s ago. So C will guide m_r to its s_L, which is closest to the recorded position of v_p 10 s ago. Thus, only N_C in s_L of C will help rebroadcast m_r sent by C. N_C in s_H, s_T, and s_R will discard m_r immediately because d_g in m_r has been specified to s_L (i.e., denoted by "broadcast to: s_L"), where d_g specified by C is the relative direction between the position of C and the past position of v_p in the memory of C.
4. On the third intersection, as shown in Fig. 6(b), and (d), vehicle E detects that it is located on intersection and m_r is from s_H (i.e., from D to E). Based on the memory for v_p of C, m_r will be rebroadcast to s_R of E. However, E met v_p 5 s ago, which is more up-to-date than C. So m_r is guided to s_L of E according to the memory for v_p of E. Therefore, v_p can receive m_r in the next rebroadcast.

3.2.3. Memory-based backoff scheme

In the IEEE 802.11p standard, the Enhanced Distributed Channel Access (EDCA) originally provided by IEEE 802.11e is employed for prioritizing channel access [18]. It is accomplished by using different channel access parameters for each packet priority and there are four access categories defined for background (AC_BK), best effort (AC_BE), video (AC_VI), and voice (AC_VO) traffic. A backoff scheme is adopted in EDCA, which consists of Arbitration Interframe Space Number (AIFSN) and a random backoff timer. AIFSN is a fixed waiting time in unit of slot, whereas the backoff timer is a random waiting time selected from a Contention Window (CW). The CW size is initially set to CW_{min} and doubled until reaching CW_{max} after each transmission collision. The default EDCA parameter set of IEEE 802.11p is shown in Table 2. In our scheme, m_r is assigned to AC_VO with the smallest AIFSN and a memory-based backoff timer.

To reduce the number of rebroadcasts of m_r, we design a memory-based backoff scheme. It facilitates receivers

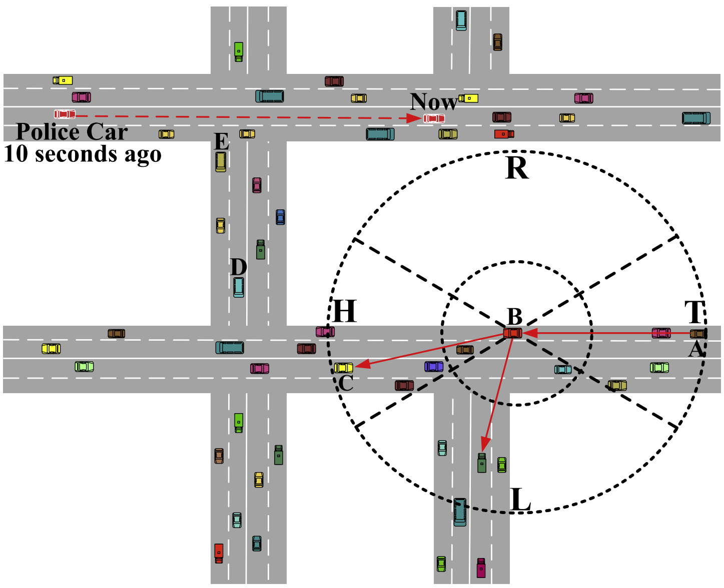

Fig. 5. Reporting the suspicious vehicle discovery to nearby police cars.

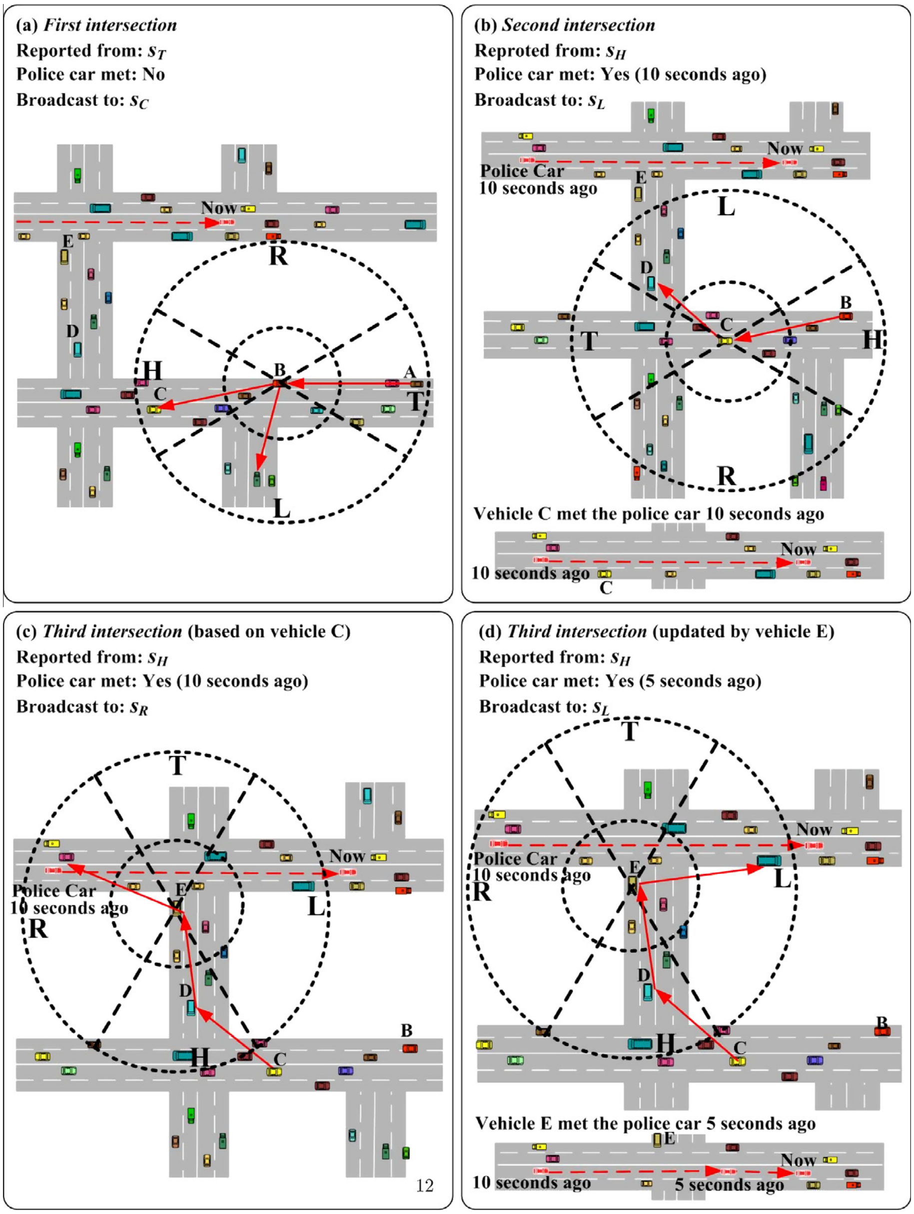

Fig. 6. Example of the intersection-guiding search scheme.

Table 2
Default EDCA parameter set.

AC	CW_{min}	CW_{max}	AIFSN
AC_BK	aCW_{min}	aCW_{max}	9
AC_BE	$(aCW_{min}+1)/2-1$	aCW_{min}	6
AC_VI	$(aCW_{min}+1)/4-1$	$(aCW_{min}+1)/2-1$	3
AC_VO	$(aCW_{min}+1)/4-1$	$(aCW_{min}+1)/2-1$	2

met v_p more recently to rebroadcast at earlier time. When vehicle i receives m_r, i first decides to rebroadcast m_r or not. If i decides to rebroadcast m_r, a backoff timer will be assigned to i based on the passing time t_i from i met v_p to now. If i never met v_p before, t_i will be set to ∞. A smaller t_i will give a smaller backoff timer BT_i, as defined below:

$$BT_i = \begin{cases} [0, 2^{\tau+1}-1] & 0 < t_i \leqslant \frac{1}{\rho}T \\ [2^{\tau+1}, 2^{\tau+2}-1] & \frac{1}{\rho}T < t_i \leqslant \frac{2}{\rho}T \\ \vdots & \\ [2^{\tau+\rho-1}, 2^{\tau+\rho}-1] & \frac{\rho-1}{\rho}T < t_i \leqslant \infty \end{cases}, \tag{1}$$

where τ is a small integer, ρ is the number of backoff classes, and T is the valid duration of the memory for v_p. Thus, this gives receivers met v_p more recently higher priorities to rebroadcast.

Table 3
Simulation parameters.

Parameter	Value
MAC protocol	IEEE 802.11a
Radio model	Two-ray ground
Routing protocol	Broadcast forwarding
Reporting message size	128 bytes
Beacon interval	1 s
Tracking handoff timer	10 s
Transmission range	300 m
Number of vehicles	250–1750 vehicles
Vehicle speed	40–60 km/h

On the other hand, an implicit inhibition strategy [13] is adopted to eliminate redundant m_r. Specifically, the reception of m_r with the same sequence number serves as an implicit message to prevent i from competing again. On receiving such a rebroadcasting, i will remove the message in its waiting queue. Furthermore, to improve reliability, a vehicle sending m_r will set its backoff timer to $2^{\tau+\rho}$ and try to overhear any rebroadcasting from any neighboring vehicle. If it cannot overhear any such rebroadcasting, it will back off to 0 and rebroadcast m_r again with a new sequence number.

4. Performance evaluation

We simulate the proposed framework by QualNet 5.0 [19] with some modifications. Basic parameters used in our simulation are summarized in Table 3. A 5-km^2 urban area consisting of 25 1-km^2 building blocks with 250, 500, 750, 1000, 1250, 1500, and 1750 vehicles is simulated, as shown in Fig. 7. All vehicles are uniformly placed on each road segment and their moving directions are randomly selected from right-turn, left-turn, and go-straight on each intersection. Both the suspicious car and the police car are randomly chosen. We set $t_u = 1$ s, $t_n = 10$ s, $\delta = 10$ m, $\theta_H = 60^\circ, \tau = 1, \rho = 3$, and $T = 30$ s. We compare our scheme against the traditional flooding method and the intelligent broadcast method [9,13] that avoids redundant rebroadcasts by implicit acknowledgements. The main performance indices are total number of reporting messages, packet collision rate, and average reporting delay to the police car. Each simulation is repeated 100 times and then we take the average value.

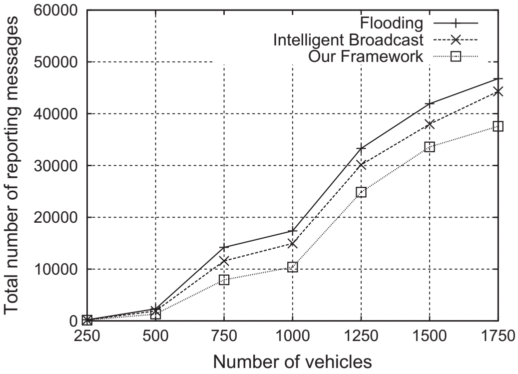

Fig. 8. Comparison of total number of reporting messages.

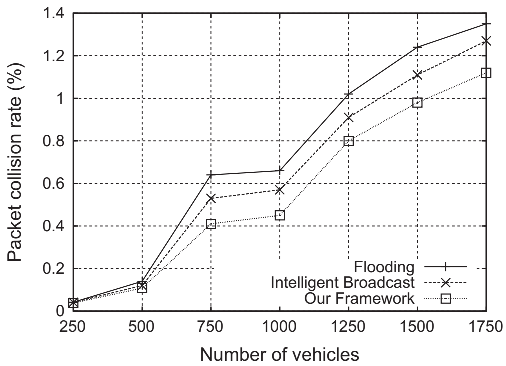

Fig. 9. Comparison of packet collision rate.

Fig. 8 illustrates the total numbers of reporting messages under different numbers of vehicles. We can observe that our scheme has the lowest number of reporting messages. This is because our scheme could guide reporting messages on intersections so that they are only rebroadcast to one of road segments based on the memory for the police car. On the contrary, the flooding scheme and the intelligent broadcast scheme will rebroadcast reporting messages to all road segments on intersections so that their total numbers of reporting messages are much more than ours.

Fig. 9 shows the packet collision rate under different numbers of vehicles. It can be observed that our scheme

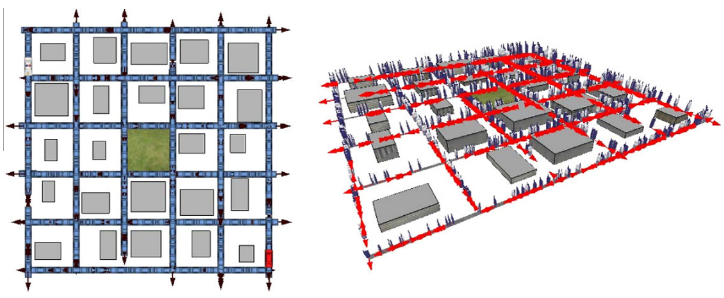

Fig. 7. Manhattan topology used in the experiments.

still outperforms flooding and intelligent broadcast. The reason is similar to what is discussed earlier. In addition, our memory-based backoff scheme further reduces the packet collision rate because we prioritize reporting messages. For irregular road geometry, some intersections are randomly selected to assign the go-straight moving direction all the time to each vehicle passing them. The similar results are obtained that our scheme has the lowest number of reporting messages and the lowest packet collision rate under different numbers of vehicles.

Fig. 10 shows the average reporting delay to the police car for various penetration rates of vehicles equipped with onboard communication units on the roads as the total number of vehicles is 1750. With 14.2% and 28.5% penetration rates, the numbers of communicated vehicles are too less to report the discovery to the police car. As the penetration rate increases, our approach has the similar reporting delay (and reporting success ratio) to flooding and intelligent broadcast while keeping the message cost low. In particular, when there is 100% of vehicles broadcasting periodical beacons every second, our approach slightly outperforms flooding and intelligent broadcast due to its less number of reporting messages. On the other hand, Fig. 11 shows the handoff success rate of our tracking handoff scheme under different numbers of vehicles and tracking handoff timers. The number of vehicles and their handoff timers are varied from 250 to 1750 vehicles and 5 to 30 s, respectively. With more vehicles and larger timers, the handoff success rate can increase from 13% to 97%.

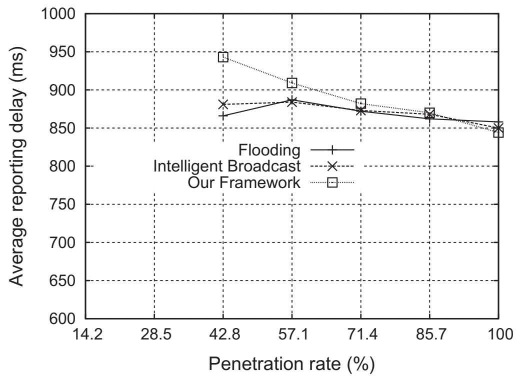

Fig. 10. Comparison of average reporting delay to the police car.

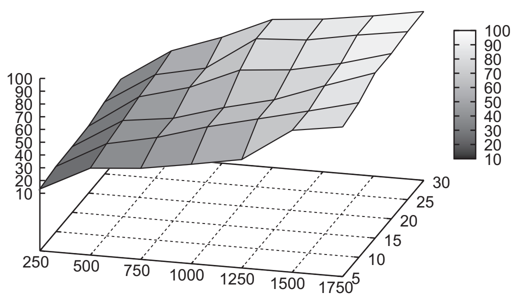

Fig. 11. Handoff success rate under different numbers of vehicles and tracking handoff timers.

Consequently, our proposed approach can achieve the lowest number of rebroadcasts and packet collision rate while keeping the reporting delay as low as flooding and intelligent broadcast. It is leading to more efficient use of wireless bandwidth in vehicular networks. In other words, adopting our approach can both avoid the overhead of reporting messages wasting bandwidth due to unnecessary rebroadcasts and prevent reporting messages from transmission collisions caused by serious packet contention.

5. Conclusion

This paper proposes "Surveillance On-the-Road" that integrates surveillance technologies with WAVE/DSRC communications to support vehicle tracking and reporting applications. We use monitoring and tracking suspicious vehicles as an example and design an infrastructure-less framework consisting of a tracking and a reporting modules. Vehicles can work cooperatively through V2V communications to achieve this goal. The tracking module can handoff a tracking job to neighboring vehicles as necessary and report suspicious vehicles to nearby police cars. The reporting module can help guide message flows to avoid flooding the network. In the paper, we mainly focus on how to design the vehicular tracking and reporting by V2V communications. The mathematical analysis for those proposed schemes will be further investigated in our future work. Simulation results show that our approach outperforms existing works in the message efficiency.

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Lien-Wu Chen received his B.S. and M.S. degrees both in Computer Science and Information Engineering from the Fu-Jen Catholic University and the National Central University in 1998 and 2000, respectively. He was a Research Assistant at the Institute of Information Science, Academia Sinica (Jan. 2001–Feb. 2009). He obtained his Ph.D. in Computer Science and Information Engineering from the National Chiao-Tung University in December of 2008. He joined the Department of Computer Science, National Chiao-Tung University as Postdoctoral Research Associate in Feb. 2009, and qualified as Assistant Research Fellow in Feb. 2010. He is currently an Assistant Professor since Feb. 2012 in the Department of Information Engineering and Computer Science, Feng-Chia University. His research interests include wireless communication and mobile computing, especially in Mobile Ad Hoc and Sensor Networks.

Dr. Chen has published 40 journal/conference papers and has 25 approved/filed patents. Among those patents, the technologies for file transfer, application execution, and goods data searching methods based on Augmented Reality and Cloud Computing have been transferred to Acer Incorporated in Jan., June, and Nov. 2011, respectively. He was a guest researcher at the Industrial Technology Research Institute (Feb. 2009–Dec. 2009) and Chief Executive Officer at the RFID Resource Center, National Chiao-Tung University (Apr. 2009–Mar. 2011). Dr. Chen received the Outstanding Demo Award (1st author) at IEEE MASS 2009, the Best Paper Award (1st author) at WASN 2010, the Audience Award (2nd prize) at ESNC 2011, the Best Paper Award (1st author) at MC-2012, the Prototyping Award (Stars prize) at ESNC 2012, the Best Paper Award (1st author) at WASN 2013, the Best Demo Award (1st author) at MC-2013, and the Best Paper Award (1st author) at NCS 2013. He is an honorary member of Phi Tau Phi Scholastic Honor Society, a lifetime member of IICM, and a member of ACM and IEEE.

Yu-Chee Tseng got his Ph.D. in Computer and Information Science from the Ohio State University in January of 1994. He was/is Chairman (2005–2009), Chair Professor (2011–present), and Dean (2011–present), Department of Computer Science, National Chiao Tung University, Taiwan. Dr. Tseng is a Y.Z. Hsu Scientific Chair Professor. Dr. Tseng received Outstanding Research Award (National Science Council, 2001, 2003, and 2009), Best Paper Award (Int'l Conf. on Parallel Processing, 2003), Elite I.T. Award (2004), and Distinguished Alumnus Award (Ohio State University, 2005), and Y.Z. Hsu Scientific Paper Award (2009). His research interests include mobile computing, wireless communication, and sensor networks. Dr. Tseng is an IEEE Fellow. He serves/served on the editorial boards of IEEE Trans. on Vehicular Technology (2005–2009), IEEE Trans. on Mobile Computing (2006–2011), and IEEE Trans. on Parallel and Distributed Systems (2008–present).

Kun-Ze Syue received his B.S. and M.S. degrees both in Computer Science and Information Engineering from the Chinese Culture University and the National Chiao Tung University in 2005 and 2010, respectively. Before obtaining the M.S. degree, he has ever worked as a software programmer and majored in user interface design (Nov. 2006–May 2008). He is currently a Research & Development Senior Engineer since Aug. 2010 at Alpha Networks Inc., Taiwan.

He received the Outstanding Demo Award at the 6th IEEE International Conference on Mobile Ad-hoc and Sensor Systems (MASS 2009). His research interests include vehicular ad hoc networks and wireless sensor networks.