A Solicitation-based IEEE 802.11p MAC Protocol for Roadside to Vehicular Networks

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***Abstract*— Recently, vehicular networks have begun to attract much attention in industry as well as academia. In particular, IEEE 802.11-based solutions for vehicular networks are also investigated by IEEE 802.11p. As the original IEEE 802.11 standard is designed only for little mobility, the IEEE 802.11p working group should address important issues such as frequent disconnection and handoff. We first introduce new challenges with which IEEE 802.11p is faced, and then propose a new solicitation-based operation mode for IEEE 802.11p, in which the transmissions of data frames are initiated only by users. Throughput analysis reveals that our proposal achieve the high and stable throughput, irrespectively of the number of contending and moving-away stations.**

I. Introduction

Over the past few years, vehicular networks have begun to attract much attention in industry as well as academia. Federal Communications Commission (FCC) allocated 5.850-5.925 GHz band to promote safe and efficient highways, which is intended for vehicle-to-vehicle and vehicle-to-infrastructure communications. In this spectrum, the emerging radio standard for Dedicated Short-Range Communications (DSRC) [1] is a short- to medium-range communication service that supports both public safety and private operations in roadside to vehicle and inter-vehicle communication environments. Car manufacturers, e.g., Audi, BMW and DaimlerChrysler, also formed a Car2Car communication consortium [2], in which the prototype development for inter-vehicle communications are underway.

Recently, IEEE 802.11-based solutions for vehicular networks are also investigated by IEEE 802.11p [5]. IEEE 802.11p Wireless Access in the Vehicular Environment (WAVE)[1] defines amendments to IEEE 802.11 to support Intelligent Transportation Systems (ITS) [3] applications. This includes data exchanges between high-speed vehicles and between the vehicles and the roadside infrastructure in the licensed ITS band of 5.9 GHz. The WAVE Mode Basic Service Set (WBSS) in IEEE 802.11p enhances IEEE 802.11 MAC functions for rapidly changing communication environments. Stations (STAs) in WAVE mode become members of a WBSS in one of two ways, either as a WBSS provider or as a WBSS user[2].

STAs in WAVE mode typically move much faster than legacy 802.11 STAs in infrastructure or ad-hoc BSS mode. Thus, it is the most important issue that STAs in WAVE join the vehicular network and transmits/receives data as quickly as possible. For this purpose, WBSSs do not require MAC sublayer authentication and association prior to being allowed to transmit data. In a WBSS, a WBSS user only needs to receive the WBSS announcement of a WBSS provider before commencing transmissions.

The remainder of this paper is organized as follows. In Section II, we first introduce a brief overview of the IEEE 802.11p draft, and point out new challenges with which IEEE 802.11p is faced in Section III. Then, in Section IV, a solicitation-based IEEE 802.11p MAC protocol is proposed to address those challenges. Section V analyzes and compares the throughput of original and solicitation-based IEEE 802.11p MAC protocols. Finally, we conclude this paper in Section VI.

II. IEEE 802.11p

According to the current IEEE 802.11p draft [5], it aims at providing the minimum set of specifications required to ensure interoperability between wireless devices attempting to communicate in potentially rapidly changing communications environments and in situations where transactions must be completed in a timeframe, much shorter than that of infrastructure or ad-hoc 802.11 networks. Due to these rapidly changing communication environments, the WBSS provider and user should be ready for communications as quickly as possible.

The WBSS provider first transmits WAVE Announcement action frames, for which the WBSS users listen. That frame contains all information necessary to join a WBSS. Unlike infrastructure and ad-hoc 802.11 BSS types, the WAVE users do not perform *authentication* and *association* procedures before participating in the WBSS. To join the WBSS, only configuring according to the WAVE Announcement action frame is required. In addition, a STA in WAVE mode shall

[1] IEEE 802.11p is based on the higher layer standard, IEEE 1609 (Family of Standards for WAVE).

[2] A WAVE mode STA that announces the presence of a WBSS is termed a WBSS provider, and a WAVE mode STA that joins a WBSS announced by a WBSS provider is termed a WBSS user.

generate a CCA (Clear Channel Assessment) report[3] in response to a CCA request to know the time-varying channel state precisely.

III. Problem Statement

The IEEE 802.11p standard, which is underway, should address important issues such as frequent disconnection, mobility and the time-varying channel condition, which are the inherent characteristics of vehicular networks. To make an effective IEEE 802.11p standard, we need to tackle the following challenges.

A. Stateless Channel Access

Since there are no authentication and no association in a WBSS, it is unlikely that the WBSS provider keeps track of connectivities with WBSS users. For example, when a WBSS user moves out of a WBSS provider's coverage, the WBSS provider cannot know whether the WBSS user exists in its WBSS or not due to the absence of the de-association process. In such environments, if the WBSS provider has a frame destined for the WBSS user in its buffer, it continues to transmit the frame until the number of retransmissions reaches a predefined threshold. Moreover, in a multi-rate WBSS the WBSS provider, in the absence of ACK frames, may use a lower bit-rate since it deems that the distance between the WBSS provider and user is getting farther or the radio condition becomes poorer, which results in the severe waste of the wireless channel.

B. Caching for Handoff

A WBSS user frequently moves from one WBSS to another while exchanging data because its speed can be high. Therefore, IEEE 802.11p needs to support fast handoff among multiple WBSS providers. In Inter-Access Point Protocol (IAPP) [6], proactive caching is suggested to reduce signaling delay in re-association process when a mobile STA changes its associated AP. However, it cannot be used because there is no association process in IEEE 802.11p, which means that a different approach is needed.

C. Opportunistic Frame Scheduling

While a WBSS user moves within a WBSS, radio link conditions between a WBSS provider and WBSS users are highly dynamic since a high velocity causes a large and fast variation of the channel conditions. Moreover, in such environments with diverse types of obstacles, e.g., buildings, towers and underground passages, the WBSS users frequently experience temporary disconnectivities to the WBSS provider. Therefore, data transmissions have to take place depending on the channel state in an opportunistic manner. In addition, the bit-rate should be determined timely, based on the instantaneous state of the wireless channel to deal with its rapid change.

[3] For infrastructure and ad-hoc BSSs, it is optional for an STA to generate a CCA report in response to a CCA Request. Both messages are defined in IEEE 802.11v [7].

IV. The Proposed Algorithm

In this section, we propose a new operation mode called *WBSS User Initiation Mode* (W-UIM) and a new concept called *WBSS-Area* which is a virtual group of adjacent WBSSs to address new challenges. We assume that WBSS providers share a wired roadside backbone which provides enough link bandwidth.

A. WBSS User Initiation Mode

In W-UIM, a WBSS provider just announces the presence of a WBSS but cannot initiate transmitting data destined for WBSS users. Instead, all data transmissions are initiated by WBSS users. For this purpose, we introduce a new *WAVE-poll* frame of which the format is shown in Fig. 1. In a WAVE-poll frame, the *WAVE mode* field represents whether W-UIM is enabled or not, and the *PHY Tx Rate* field recommends a bit-rate at which the WBSS provider transmits data, depending on the WBSS user's channel state.

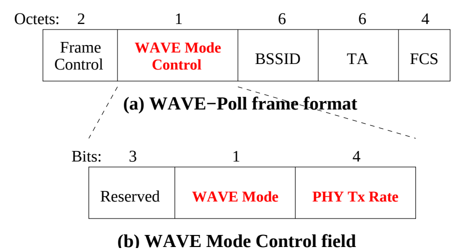


Fig. 1. Format of a WAVE-Poll frame.

If a STA receives a new WBSS announcement, the STA becomes a WBSS user by joining the WBSS by configuring according to the WBSS announcement. Then, the WBSS user transmits a WAVE-poll frame in which the *WAVE Mode* field is set to 1 to inform the WBSS provider that its operation mode is W-UIM. In addition, the WBSS user records an appropriate bit-rate in the *PHY Tx Rate* field of the WAVE-poll frame, depending on the channel state of the latest transmission of the WBSS provider. The WBSS user has to transmit a WAVE-poll frame whenever it wants to receive data from the WBSS provider. The *WAVE Mode* fields in all WAVE-poll frames should be set to 1 while the WBSS user is in W-UIM.

The WBSS provider which receives the WAVE-poll frame with the *WAVE Mode* field set to 1 transmits the data destined for the WBSS user in its buffer only if the WBSS user requests data via a WAVE-poll frame. If the WBSS provider receives the WAVE-poll frame successfully, it operates as follows.

- If the WBSS provider has a backlogged data destined for the WBSS user in its buffer, it transmits the data at the bit-rate specified in the WBSS-poll frame after SIFS. The WBSS user which receives the data replies with an ACK frame after SIFS (See the right sub-figure in Fig. 2).
- If the WBSS provider has no backlogged data destined for the WBSS user in its buffer, it directly transmits an ACK frame after SIFS (See the left sub-figure in Fig. 2). This ACK frame means the successful reception of the WAVE-poll frame.

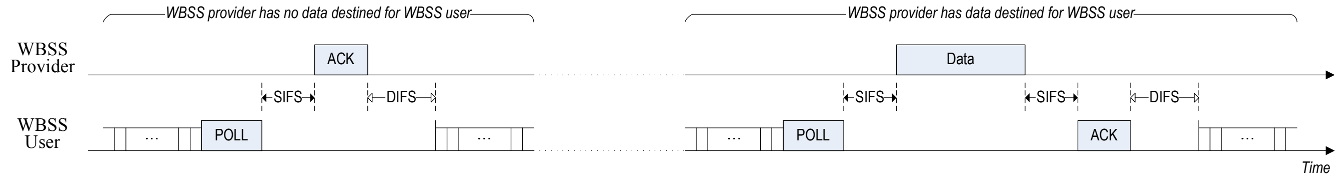


Fig. 2. Solicitation-based data transmissions in W-UIM.

As shown in Fig. 3, if a data frame destined for the WBSS user cannot be ready during SIFS, the WBSS provider will first transmit an ACK frame corresponding to the WAVE-poll frame, and then transmit the data frame after SIFS. This data transmission sequence is optional for less powerful WBSS providers.

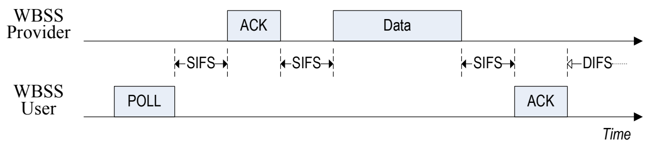


Fig. 3. Optional data transmission sequence.

In order to utilize the wireless channel efficiently, the WBSS user had better request data transmissions to the WBSS provider when its channel state is good[4] because the transmissions of data frames can be completed with less air-time due to a higher bit-rate. Nevertheless, the retransmissions of the frames are still needed because the frames may be lost due to the fluctuating channel state. In W-UIM, the retransmission of the lost data frame is also initiated by the WBSS user via an additional WAVE-poll frame. This is to eliminate the situation that WBSS users, which move out of the WBSS during data transmissions, will cause unnecessary retransmissions.

If a WBSS user does not move or has a very low speed, the W-UIM may cause non-negligible overhead by many WAVE-poll frames. Thus, a WBSS user can optionally turn the W-UIM off by transmitting a WAVE-poll frame of which the *WAVE Mode* field is set to 0. When the WBSS provider receives the WAVE-poll frame with the *WAVE Mode* field reset, it can directly transmit data destined for the WBSS user without waiting for any WAVE-poll frame.

B. Dynamic WAVE-Area

In W-UIM, adjacent WBSS providers can form a caching and forwarding area called *WAVE-Area* to forward frames to WBSS users despite fast handoff. Data frames destined for a WBSS user joining the WBSS are cached in an WBSS provider and forwarded proactively or reactively to all the other WBSS providers in the WAVE-Area to quickly transmit data frames to the WBSS user which hands off between adjacent WBSSs. Then, the WBSS user receives the cached data from the new WBSS provider via a WAVE-poll frame after joining the new WBSS.

[4]Diverse policies for the transmission of WAVE-poll frames are out of scope in this paper.

In proactive mode, upto a predetermined number[5] of data frames destined for a WBSS user are in advance forwarded to the corresponding WAVE-Area. A WBSS provider has to update the cached data in the buffers of adjacent WBSS providers whenever the WBSS provider successfully transmits a data frame. The adjacent WBSS providers drop the data frame that the serving WBSS provider transmitted successfully, and keep caching the following data frames. It is reasonable to lay a burden on a powerful entity, a WBSS provider, and lift a burden from a quickly moving entity, a WBSS user.

In a reactive mode, if a WBSS user hears any other WBSS announcement differently from the WBSS which it currently joins, it may send a forwarding request to the current WBSS provider. The WBSS provider then forwards data destined for the WBSS users in its buffer to the adjacent WBSS provider whose WAVE announcement is received by the WBSS user. For a forwarding request, WBSS providers in the same WAVE-Area should share the same frequency channel. This reactive mode reduces the buffer overhead by eliminating unnecessary forwarding and caching but the collisions of frames from adjacent WBSSs may frequently occur.

V. Saturated WBSS Throughput Analysis

We reuse some equations in [8] to analyze the performance of W-UIM. The collision probability P_c and the average number of slots for the transmission of a single frame N_{sl} are given;

$$P_c = \frac{((1-\tau)^{-n}-1)(1-\tau)}{n\tau} - 1, \quad (1)$$

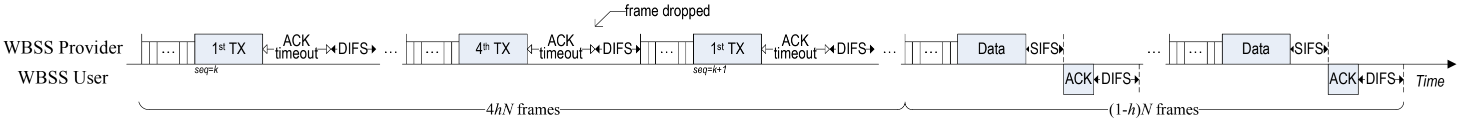
$$N_{sl} = \frac{1-\tau}{n\tau}, \quad (2)$$

where n is the number of contending WBSS users, and τ is the transmission probability of a WBSS user in a randomly chosen slot time.

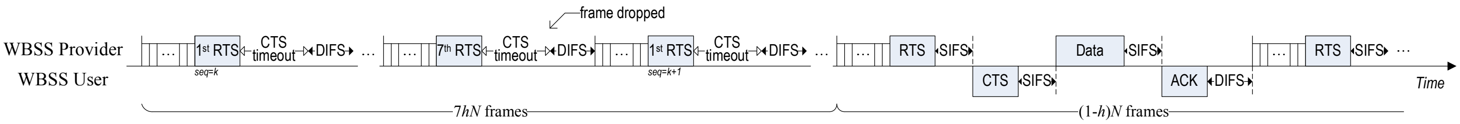
In legacy IEEE 802.11, a data frame which is not acknowledged is retransmitted for the predefined times. According to the IEEE 802.11 standard, an AP trying to transmit an orphan data frame[6] by using the basic channel access mechanism will finally drop the frame after *LongRetryLimit* retries, while in IEEE 802.11 with RTS/CTS the frame will drop after *ShortRetryLimit* retries. When a WBSS provider tries to transmit a data frame to a moving-away WBSS user, the wasted time W

[5]This is called a *cache threshold*, which is configurable depending on WBSS providers' buffering requirements.

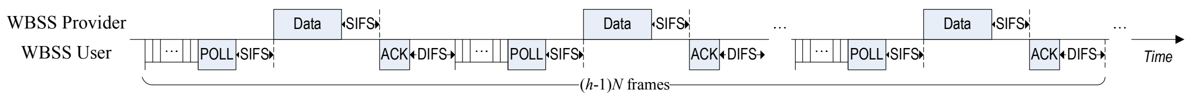
[6]We call a frame destined for a moving-away WBSS user an *orphan frame*.



(a) Legacy IEEE 802.11 without RTS/CTS, in which hN of N frames at a WBSS provider are lost.



(b) Legacy IEEE 802.11 with RTS/CTS, in which hN of N frames at a WBSS provider are lost.



(c) W-UIM, in which only $(1-h)N$ frames at a WBSS provider are transmitted.

Fig. 4. N frame transmissions when hN WBSS users move away.

caused by the orphan data frame is given in Eq. (3), where W_{min}, $maxRetryLimit$ and m are the minimum contention window size, the maximum number of retransmissions, and the number of backoff stages, respectively. T is the transmission time of a single data frame.

$$W = \frac{2^{W_{\min}}(2^{\text{maxRetryLimit}}-1)-m}{2} + 4T, \quad (3)$$

$$T = T_{\text{Data}} + T_{\text{SIFS}} + T_{\text{ACK}} + T_{\text{DIFS}} \quad (4)$$

We can express the throughput S as the following ratio;

$$S = \frac{\text{average payload length in a frame}}{\text{average frame transmission time}} \quad (5)$$

Letting the orphan frame ratio, which is the number of orphan frames to the total number of frames in the buffer of the AP, be h, the above throughput S is given by:

$$S = \frac{(1-h)\,\text{payloadLength}}{(1-h)\,(T_s + P_c T_c + N_{sl} T_{sl}) + hW} \quad (6)$$

Here, T_{sl}, T_s and T_c, mean a time slot, the successful transmission time and the wasted time caused by a collision, respectively. As shown in Fig. 4(a) and (b), both T_s and T_c in legacy IEEE 802.11 without RTS/CTS are just T, while the two values in legacy IEEE 802.11 with RTS/CTS are as follows:

$$T_s = T_{\text{RTS}} + T_{\text{SIFS}} + T_{\text{CTS}} + T_{\text{SIFS}} + T, \quad (7)$$

$$T_c = T_{\text{RTS}} + T_{\text{SIFS}} + T_{\text{CTS}} + T_{\text{DIFS}} \quad (8)$$

We now analyze W-UIM in the same way. Since we use a polling-based approach, the wasted time is removed, i.e., W becomes zero, as shown in Fig. 4(c). However, T_s and T_c should be modified due to the overhead of WAVE-poll frames;

$$T_s = T_{\text{Poll}} + T_{\text{SIFS}} + T, \quad (9)$$

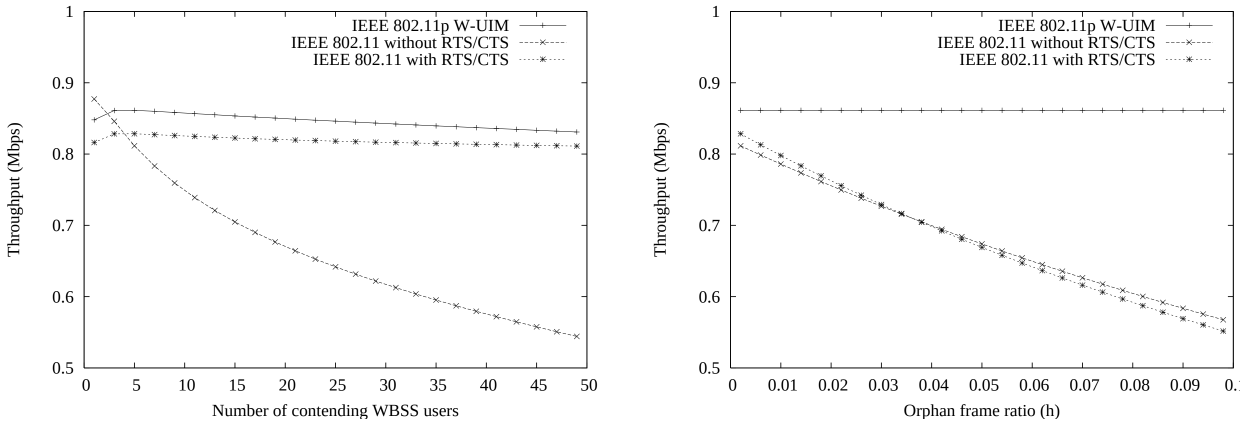
$$T_c = T_{\text{Poll}} + T_{\text{ACKtimeout}} \quad (10)$$

For analysis, we used the parameters defined in IEEE 802.11b, and 1000 bytes for the payload length. The PHY bit-rate for WAVE-poll, RTS, CTS and ACK frames is 1Mbps, and 1Mbps or 11Mbps for data frames.

In Fig. 5(a), we plotted the WBSS throughput as the number of contending WBSS users varies, where the data rate is 1Mbps and the orphan frame ratio h is fixed to 0.001. The throughput of legacy IEEE 802.11 without RTS/CTS is severely degraded as more WBSS users contend, while legacy IEEE 802.11 with RTS/CTS and W-UIM show stable throughput. It is because the RTS/CTS mechanism and the W-UIM have a little collision overhead due to the small size of RTS/CTS and WAVE-poll frames, respectively.

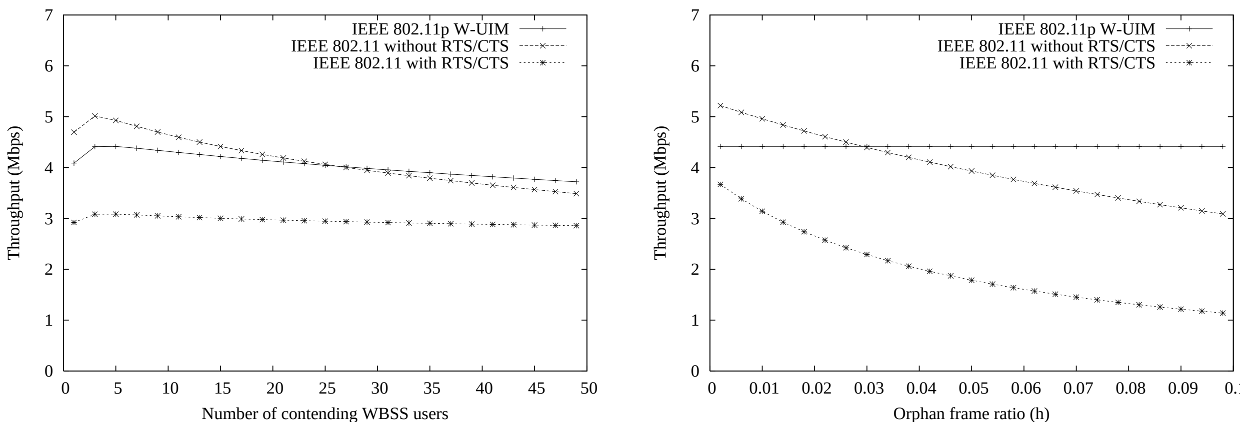
However, the RTS/CTS mechanism cannot deal with the situation that the WBSS user moves out of the WBSS provider's coverage. Fig. 5(b) shows the WBSS throughput depending on the orphan frame ratio of the WBSS provider when the data rate is 1Mbps.. In both legacy IEEE 802.11 without RTS/CTS and with RTS/CTS, the throughput is getting lower due to the longer wasted time caused by orphan frames destined for disappearing WBSS users. However, W-UIM keeps stable WBSS throughput irrespectively of the number of disappearing WBSS users. Note that the factor h does not affect the WBSS throughput because W is zero in a polling-based approach.

Fig. 6(a) shows the WBSS throughput as the number of



(a) $h = 0.1\%$ (b) Five contending WBSS users

Fig. 5. Saturated WBSS throughput when the data rate is 1Mbps.



(a) $h = 1\%$ (b) Five contending WBSS users

Fig. 6. Saturated WBSS throughput when the data rate is 11Mbps.

contending WBSS users varies, where the data rate is 11Mbps and the orphan frame ratio is fixed to 0.01. It is noted that the throughput of legacy IEEE 802.11 without RTS/CTS is higher than that of IEEE 802.11p W-UIM when the number of contending WBSS users is relatively small. This is because WAVE-poll frames transmitted at 1Mbps cause larger overhead than orphan frames transmitted at 11Mbps. However, their gap decreases as the number of contending WBSS users increases, and in the end it is reversed due to the increased number of orphan frames. If a rate adaptation [9] is coupled, it is expected that IEEE 802.11p W-UIM achieves the best WBSS throughput since the orphan frame will be transmitted at a low bit-rate. Legacy IEEE 802.11 with RTS/CTS has the worst WBSS throughput due to RTS/CTS, which are transmitted at 1Mbps, as well as orphan frames.

Fig. 6(b) shows the WBSS throughput depending on the orphan frame ratio of the WBSS provider when the data rate is 11Mbps. Since WAVE-poll frames transmitted at 1Mbps raise some overhead, legacy IEEE 802.11 without RTS/CTS achieves higher throughput than IEEE 802.11p W-UIM when the orphan frame ratio is quite small. As the ratio of orphan increases, however, the WBSS throughput of IEEE 802.11 without RTS/CTS decreases while IEEE 802.11p W-UIM has a stable WBSS throughput due to a polling-based approach. Legacy IEEE 802.11 with RTS/CTS still has the worst WBSS throughput due to RTS/CTS/orphan frames.

VI. Conclusion

In this paper, we first pointed out new challenges with which IEEE 802.11p Wireless Access in the Vehicular Environment (WAVE) is faced. Then, we proposed a new solicitation-based IEEE 802.11p operation mode called *WBSS User Initiation Mode* (W-UIM) to address those challenges. In W-UIM, a WBSS user solicits data frames destined for itself in an opportunistic manner, by requesting the transmissions of the frames from a WBSS provider by a *WAVE-poll* frame. Throughput analysis reveals that W-UIM achieves the stable saturated WBSS throughput higher than IEEE 802.11 irrespectively of the number of contending and moving-away WBSS users. As future work, we will investigate a rate adaptation technique for IEEE 802.11p W-UIM.

VII. Acknowledgment

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