IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received June 22, 2017, accepted July 18, 2017, date of publication July 25, 2017, date of current version August 29, 2017.

Digital Object Identifier 10.1109/ACCESS.2017.2731777

Latency of Cellular-Based V2X: Perspectives on TTI-Proportional Latency and TTI-Independent Latency

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This work was supported in part by the National Research Foundation of Korea (NRF) grant funded by the Korea government (NRF-2015R1A2A1A01006162) and in part by Institute for Information & communications Technology Promotion (IITP) grant funded by the Korea government (MSIP) (No.B0717-16-0024, Development on the core technologies of transmission, modulation and coding with low-power and low-complexity for massive connectivity in the IoT environment).

ABSTRACT Vehicle-to-everything (V2X) is a form of wireless communication that is extremely sensitive to latency, because the latency is directly related to driving safety. The V2X systems developed so far have been based on the LTE system. However, the conventional LTE system is not able to support the latency requirements of latency-aware V2X. Fortunately, the state-of-the-art cellular technology standard includes the development of latency reduction schemes, such as shortened transmission time intervals (TTI) and self-contained subframes. This paper verifies and analyzes the latency of cellular-based V2X with shortened TTI, which is one of the most efficient latency reduction schemes. To verify the feasibility of V2X service, we divide the V2X latency into two types of latency, TTI-independent latency and TTI-proportional latency. Moreover, using system-level simulations considering additional overhead from shortened TTI, we evaluate the latency of cellular-based V2X systems. Based on this feasibility verification, we then propose cellular-based V2X system design principles in terms of shortened TTI with only one OFDM symbol and while sustaining radio resource control connection.

INDEX TERMS Cellular networks, vehicular and wireless technologies, system analysis and design, latency, shortened TTI.

I. INTRODUCTION

Vehicle-to-Everything (V2X) communications are being investigated to support autonomous driving, road safety, and efficient traffic services, all of which are key emerging transformations in the future automobile industry [1]–[5]. V2X communications support these services by enabling the exchange of information between vehicles, infrastructure, and pedestrians, which can prevent car accidents and provide more efficient driving routes. Cellular systems are currently close to adopting V2X - they are reliable and support QoS control of a wireless link, which are some of the features that V2X services require to enable safe and efficient driving. More specifically, V2X has been standardized in the 3rd generation partnership project (3GPP) long term evolution (LTE) standard.

Cellular-based V2X systems consider latency to be the most important performance metric, while conventional cellular systems consider system throughput to be the most important performance metric [1], [5]. The reasons for this are as follows: First, the level of safety decreases as the delay in receiving safety information increases in V2X systems. While a delay in multimedia information may cause a movie to pause temporarily, delayed information in V2X communications could result in serious automobile accidents and injuries. Secondly, the volume of data transmission in V2X communications is much smaller than that in general cellular systems. Sensing information or safety notifications transmitted via a V2X link can be carried in a small packet. Hence, high-speed data transmissions are less important in V2X systems.

In this paper, we categorize the latency of V2X systems into one of two types depending on whether or not the latency is proportional to the transmission time interval (TTI), which is the minimum transmission time unit in cellular systems. Each data transmission, i.e., control signaling, scheduling configuration, retransmission process, and so on, consumes at least one TTI [6], [7]. In this paper, these elements of latency are referred to as *TTI-proportional latency (PL)*. On the other hand, other latency elements, such as backhaul transmissions, core network processing time, and the time for wireless link configuration processes are not related to the TTI duration. Consequently, these other latency elements are not proportional to the TTI. Hence, these elements of latency will be referred to as *TTI-independent latency (IL)*. Our analysis of the latency of cellular-based V2X services is based on these two latency factors *PL* and *IL*.

This paper provides analyses of the latency of cellular-based V2X systems and verifies the feasibility of V2X services with cellular-based systems. We first present the latency requirements of V2X services and the operating modes of cellular-based V2X. Then, an analysis of the latency of cellular-based V2X is performed from the PL and IL perspectives. The latency analysis will show that the current version of the cellular-based V2X system with a 1ms TTI duration is not able to satisfy the latency requirements of V2X services [5]. In the upcoming cellular system, the TTI duration will be much shorter due to the existence of multiple numerologies and shortened TTI units, such as slot and mini-slot [6]–[10]. Using *PL*, the effect of the shortened TTI on latency is analyzed in consideration of the V2X operation modes and latency requirements. Through practical system level simulations that consider the traffic loads and addition overhead, we also show that the latency increases faster as the traffic load increases for shorter TTI. Finally, cellular-based V2X system design principles are proposed in terms of shortened TTI.

II. LATENCY REQUIREMENTS AND OPERATING MODES

This section presents the latency requirements for V2X services. The latency requirements are given as a time threshold value (100ms, 50ms, 20ms, and 10ms for each application). V2X operation modes are then introduced. Communication procedures differ depending on the operation mode, resulting in differences in latency. We then provide a detailed latency analysis in Section III in consideration of the latency requirements and V2X operation modes.

A. LATENCY REQUIREMENT FOR VEHICLE-RELATED SERVICES

The V2X services can be categorized into three groups: 1) safety-related services, 2) non-safety-related services, and 3) automated driving-related services [1], [4].

1) Safety-related services are concerned with real-time safety messages, such as warning messages (e.g., abrupt brake warning message) to reduce the risk of car accidents. In these types of services, timeliness and reliability are considered to be key requirements. On the other hand, 2) non-safety-related services are intended to optimize the traffic flow on the road so that travel time is reduced. Thus, these services enable a more efficient and comfortable driving experience with no stringent requirements in terms of latency and reliability.

For the safety-related services, if we consider the frequency of periodic messages (e.g., from 1 to 10 messages/s) and the reaction time of most drivers (e.g., from 0.6 s to 1.4 s), then the maximum allowable end-to-end latency must not exceed 100ms [1]. In fact, depending on the service type, the latency requirement may even be less than 100ms, (e.g., 20ms for a pre-crash sensing warning).

In addition to these kinds of services, 3) automated driving-related services are now being developed as key transformations begin to occur in the automotive industry. These automated driving-related services require more rigorous latency, data rate, and positioning accuracy requirements. Therefore, the latency requirements for automated driving-related services are more stringent than those required for safety-related services. For example, automated overtaking or high density platooning services have a 10ms requirement.

Since the scope of this paper is the latency issue in V2X communications, we will be focusing on the 1) safety-related and 3) automated driving-related services. Table 1 lists the V2X service use cases and the corresponding latency requirements [3], [4].

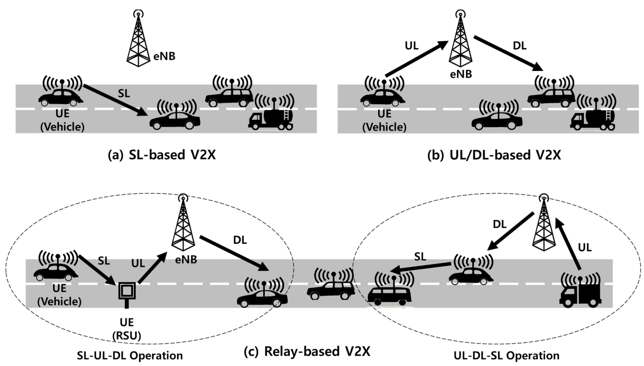


FIGURE 1. Modes of operation of V2X communications. (a) is the operating mode over SL. (b) is the operating mode over UL/DL. (c) is the convergence operating modes (a) and (b) and utilizes relay transmissions.

B. OPERATING MODES OF CELLULAR-BASED V2X COMMUNICATIONS

In Fig. 1, the cellular-based V2X communication system operating modes depicted are: (a) sidelink (SL)-based V2X, (b) uplink (UL)/downlink (DL)-based V2X and (c) relay-based V2X [3], [5].

The SL-based V2X in Fig. 1(a) is referred to as PC5-based V2X in 3GPP. In SL-based V2X, vehicles directly exchange their information by one-hop transmission. In this mode, the transmitter sends information about location, traffic, status, etc. to one or more receivers directly. Since this mode

TABLE 1. V2X service use cases and latency requirements.

Service Type	Use Cases	Description	Latency Requirement
Safety-related services	Forward collision warning (FCW)	The FCW application is intended to warn the driver of the host vehicle (HV) in case of an impending rear-end collision with a remote vehicle (RV) ahead in traffic in the same lane andwith the same direction of travel.	100 ms
	Control loss warning (CLW)	The CLW application enables an HV to broadcast a self-generated loss of control event to surrounding RVs.	100 ms
	Emergency warning	The emergency vehicle warning service enables each vehicle to acquire the location, speed and directional information of a nearby emergency vehicle.	100 ms
	Emergency stop	This use case describes how V2V communications are to be used in the case of an emergency stop in order to trigger safer behavior in other cars that are in close proximity to the stationary vehicle.	100 ms
	Queue warning	Using the V2I Service, relevant queuing information can be made available to other drivers beforehand. This minimizes the likelihood of crashes and allows drivers to take mitigation steps.	100 ms
	Road safety services	V2X messages are delivered from one UE that supports V2I Services to other UEs that also support V2I Services via a Road Side Unit (RSU), which may be installed at the road side.	100 ms
	Pre-crash sensing warning	The pre-crash sensing warning application provides warnings to vehicles in the event of an imminent and unavoidable collision by exchanging the attributes of the vehicle when a non-avoidable crash is anticipated.	20 ms
Automated driving-related services	Automated overtake	Executing safe overtaking maneuvers requires cooperation among vehicles travelling in multiple lanes in order to create the necessary gap to allow the overtaking vehicle to quickly merge into the lane corresponding to its direction of travel in time to avoid a collision with an oncoming vehicle.	10 ms
	Cooperative collision avoidance	Collisions between two or more vehicles are prevented by controlling the longitudinal velocity and displacement of each vehicle along their path without creating hazardous driving conditions for other vehicles that are not directly involved. All involved vehicles should undertake computing optimal collision avoidance actions and apply them in a cooperative manner.	100 ms
	High density platooning	High Density Platooning, i.e., the creation of closely spaced multiple-vehicle chains on a highway, has multiple benefits, such as fuel saving, accident prevention, etc.	10 ms
	See-through	For the safety of pedestrians who are crossing the road in front of an HV, the camera in the HV detects the situation and shares information regarding the pedestrian with RVs to the rear of the HV.	50 ms

operates in a broadcast manner, the same data can be transmitted efficiently to multiple nodes in a common resource. In this mode, the latency mainly occurs while establishing the uplink connection and resource allocation.

Fig. 1(b) shows the UL/DL-based V2X mode, also referred to as Uu-based V2X in 3GPP. In this V2X mode, two transmission hops must be made when exchanging information between vehicles. In this case, the information is first received at evolved node B (eNB) in an UL, then forwarded to destination receivers in a DL. For transmitting the information in the DL, appropriate DL protocols can be selected from among unicast, the multimedia broadcast multicast service (MBMS), or single cell point-to-multipoint (SC-PTM).

Fig. 1(c) is the relay-based V2X mode. This mode is not specifically named in 3GPP. In this mode, vehicles send their information over more than two hops. With multi-hop transmission, the information signal goes through road side units (RSU) and cellular networks. A transmitter can send V2X data to other user equipment (UE) or RSUs through the SL. The UEs that receive the data forward it to the eNB through the UL. The eNB then transmits the data to other UEs in the DL. This takes at least three hops, as depicted in Fig. 1(c). As shown on the right side of Fig. 1(c), the data transmission path can also be UL-DL-SL, depending on the location of the RSU and eNB. The relay-based V2X mode cannot help consuming the longest time for data transmission, resulting in the worst latency while the multi-hop transmission lengthens the communication distance.

III. LATENCY OF CELLULAR-BASED V2X COMMUNICATION

In this paper, the latency that occurs in V2X communications is separated into two latency factors: *PL* and *IL*.

PL is a latency factor linearly proportional to a TTI duration. The TTI is the most important design parameter in standardizing wireless communication systems. The TTI value is determined by taking waveforms, RF transmission characteristics, scheduling periods, link setup procedures, data decoding time, and so on into consideration. On the other hand, ***IL*** is a latency factor which cannot be changed even if the TTI duration varies. IL normally reflects core network backhaul latency, parts of MAC and upper layer latency (collectively referred to as upper layer latency), and so on.

In the following subsections, latency elements composing a whole latency are provided in detail. Almost all of them consist of both *IL* and *PL* factors. In order to distinguish one from the other, the *PL* is measured using TTI as the units while *IL* is measured using milliseconds (*ms*) as the units.

A. LATENCY OF EACH V2X ELEMENT

The latency elements in V2X are the configuration, message transmission, and processing latencies [5], [11], [12]. The configuration latency is the time required to set up a wireless connection after the disconnect event. The message transmission latency is the time duration required to transmit a message between network entities. The processing latency is the time required for network entities to process signals. These results are extracted and analyzed from [5] and [11].

- **Configuration latency**
  The configuration latency includes the radio resource control (RRC) connection, SL configuration, and paging latencies. The configuration latency does not always affect the latency of each transmission since it only occurs when the connection between two nodes has not yet been established.
  - **RRC connection latency**: The RRC connection latency is the time duration required to change the RRC state of the UE from idle to connected.
    1) The UE requests an RRC connection to the eNB to establish the connection (10.5 TTI).
    2) After the request, the eNB sets up the RRC connection (18 TTI).
    3) The eNB transmits the RRC security mode command, reconfigures the connection, and the UE completes the setup process (21.5 TTI).
  - **SL configuration latency**: The SL configuration latency is the time duration required to establish an SL connection between two UEs after the RRC connection has been established. Before the SL transmission, the source UE needs to make an SL connection to the destination UE through the eNB.
    1) The source UE transmits the SL UE information to the eNB (19.3 TTI + SR[1]/2).
    2) The eNB transmits the RRC reconfiguration message to the source UE and the destination UE through a unicast channel (4.8 TTI).
  - **Paging latency**: The paging latency is the time duration required to wait for the next paging cycle and the paging message decoding time (from 164 TTI to 324 TTI). This latency only occurs for unicast DL transmissions.
- **Message transmission latency**
  The message transmission latency includes the SL transmission, DL transmission, and UL transmission latencies. After the connection is configured, the UEs involved in the V2X communications transmit the message to the destination component.
  - **SL transmission latency**: The SL transmission latency is the time duration required for the source UE to send the V2X message to the destination UE through the SL. The SL transmission has two transmission modes, an autonomous scheduling mode (SL mode 2) and a non-autonomous scheduling mode (SL mode 1). Therefore, the SL scheduling time is not considered in SL mode 2. On the SL side, the latency components consist of the following:
    1) The UE waits for the SL scheduling period (16 + SR TTI).
    2) UE receives SL control information (SCI) transmission time (8 + SPS[2] TTI).
    3) Source UE transmits data over SL to destination UE (from 4 TTI to 22 TTI).
    4) The destination UE decodes received data (1.5 TTI).
    5) The upper layer of the destination UE processes decoded data (3*ms*).
  - **DL transmission latency:** The DL transmission latency is the time duration required for the eNB to send the V2X message to the destination UE through the DL. The latency of the DL transmission varies with the transmission protocols, such as unicast, MBMS, and SC-PTM, since the MBMS[3] and the SC-PTM[4] need to wait for a scheduling opportunity. On the DL side, the latency components generally consist of the following:
    1) The eNB encodes the data and waits for scheduling alignment (1.5 TTI).
    2) The eNB transmits the data to the other UE (1 TTI).
    3) The UE decodes the received data (1.5 TTI).
    4) If a transmission error occurs, the eNB retransmits the data (8 TTI × 10%).[5]
    5) The upper layer of the destination UE processes the decoded data (3*ms*).
  - **UL transmission latency:** The UL transmission latency is the time duration required for the source UE to send the V2X message to the eNB through the UL. The UL transmission is categorized as either pre-grant scheduling or dynamic scheduling (DS). With pre-grant scheduling, such as semi-persistent scheduling (SPS), the SR and SR grant process can be omitted. In SPS mode, the UEs just wait for the next SPS period before transmitting the V2X message to the eNB. The UL transmission with DS consists of the following:
    1) The UE waits for a SR period (1,10 TTI).

[1] The Scheduling Request (SR) period is the waiting time for the uplink control channel. (10 TTI for the normal SR period and 1 TTI for the short SR period)

[2] The Semi-Persistent Scheduling (SPS) period is configured as 10, 40, or 80 TTI.

[3] The Multicast channel Scheduling Period (MSP) is configured as 40 TTI.

[4] The SC-PTM scheduling period (SSP) is configured as 1 or 10 TTI.

[5] The block error rate is assumed as 10%.

2) The UE does the SR grant process with the eNB (4 TTI).
3) The UE transmits the data over the UL[6] (6.8 TTI).
4) With the buffer status report (BSR), the UL transmission needs the BSR time (8 TTI).

- **Processing latency** The processing latency is the time duration required for network and RSU processing and occurs in the backhaul system and the upper layer of the transmission system (e.g., application layer processing).
  - **Network processing latency:** The network processing latency is the time duration required from the time of the eNB reception of the V2X message in the UL to the time when the eNB is ready to transmit the V2V message over the DL. It includes the time duration required for backhaul transmission (20*ms*).
  - **RSU processing latency:** The RSU Processing Latency denotes the processing time required at the RSU side. It includes the upper layer processing time in the RSU (3*ms*).

Table 2(a) represents the summary and value of each latency element based on the *PL* and *IL*. These results make it possible to estimate the latency of V2X transmissions in each operating mode. Moreover, the effect of V2X with a shortened TTI can be evaluated based on these results.

B. LATENCY OF V2X OPERATING MODES

V2X communication basically uses three operating modes. Since each mode has its own communication procedures affecting the latency described in Fig. 1, latency must be evaluated separately mode by mode. For consistency with the previous latency evaluation, *PL* is denoted using TTIs as the units while TTI-independent-latency is denoted using *ms*.

- **SL-based V2X latency:** In SL-based V2X operation, the source UEs directly transmit the V2X message to the destination UEs. Therefore, this operation only considers the SL transmission latency.
- **UL/DL-based V2X latency:** In UL/DL-based V2X operation, the source UEs transmit the V2X message to the eNB over the UL. Then, the eNB transmits the V2X message to the destination UE over the DL. Therefore, this operation only considers 1) the UL transmission latency, 2) the network processing latency, and 3) the DL transmission latency. In Table 2(b), a UL transmission with a short SR and DS and without a separate BSR is considered to be the default.
- **Relay-based V2X latency** Relay-based V2X operation has two modes of operation: SL-UL-DL and UL-DL-SL. In SL-UL-DL operation, 1) the source UE transmits the V2X message to the near RSU or other UEs over the SL. 2) Then, the near RSU or other UEs transmit the V2X message to the eNB over the UL. 3) The eNB transmits the V2X message to the destination UE over the DL. In UL-DL-SL operation, the transmission process is the reverse of the SL-UL-DL operation.

[6]This is almost identical to the DL Data transmission, and includes items such as UL data encoding, UL data transmission, UL data decoding time, and retransmission time.

IV. LATENCY OF V2X SYSTEMS WITH SHORTENED TTI

A. LATENCY REDUCTION SCHEMES

Shortened TTI, semi-persistent scheduling, contention-based transmission, and self-contained subframes are examples of schemes designed to reduce cellular system latency [6]–[10]. They reduce the *IL* by reducing the minimum unit of transmission (Shortened TTI), the UL scheduling period (semi-persistent scheduling and contention-based transmission), and by changing the frame structure.

All of them except shortened TTI focus on reducing the UL latency, since UL transmission has additional processes and is more susceptible to delays than DL transmission. These schemes are not efficient in V2X systems because the latency of the V2X systems derives not only from the UL, but also from the DL and SL. On the other hand, shortened TTI reduces all *PL* in DL, SL, and UL transmission. Shortened TTI can thus be expected to reduce the overall latency of the V2X system. Therefore, we will focus on a V2X system using shortened TTI as a candidate for latency-aware V2X systems.

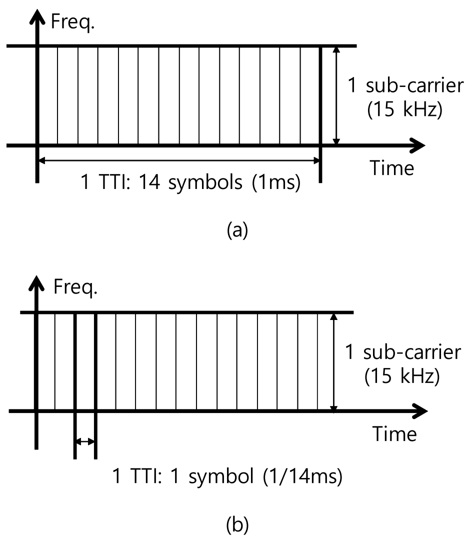


FIGURE 2. Shortened TTI frame structure for low latency systems. (a) is the sub-frame structure of the conventional cellular system. (b) is the sub-frame structure of the shortened TTI system with mini-slot.

Shortened TTI reduces *PL* by reconstructing the subframe structure as shown Fig. 2. A slot & mini-slot structure reduces the TTI by reducing the number of symbols in the TTI subframe. For instance, each TTI becomes 1/2ms and 1/14ms with 7 OFDM symbols or 1 OFDM symbol in each TTI, respectively.

However, shortened TTI has the disadvantage of increasing the overhead, which results from additional scheduling and reference signals and from retransmission. These overheads are expected to increase as the TTI is reduced, but no clear

TABLE 2. Latency evaluation of V2X communication systems.

Category	Name	Description	Mode	Minimum time	Average time	Maximum time
Configuration latency	L-RRC	Latency for RRC connection establishment and data bearer establishment	Any Mode	50 TTI	50 TTI	50 TTI
	L-SL$_{CONFIG}$	Latency for reception of SL configuration via dedicated signaling	Any Mode	{24.6, 29.1} TTI (SR = 1,10 TTI)	{24.6, 29.1} TTI (SR = 1,10 TTI)	{24.6, 29.1} TTI (SR = 1,10 TTI)
	L$_{PAGING}$	Latency for reception of paging message	Any Mode	164 TTI	164 TTI	324 TTI
Message transmission latency	L-SL	Latency for message transmission from UE to UE (RSU) via SL	SL Mode 1	{34 , 38.5} TTI + 3ms (SR = 1,10 TTI)	{34 , 38.5} TTI + 3ms (SR = 1,10 TTI)	{101.6, 110.6} TTI + 3ms (SR = 1,10 TTI)
			SL Mode 2	17.5 TTI + 3ms	51 TTI + 3ms	84.5 TTI + 3ms
	L-UL	Latency for message transmission from UE to eNB via UL	SPS	{8, 23, 43} TTI (SPS = 10,40,80 TTI)	{8, 23, 43} TTI (SPS = 10,40,80 TTI)	{13, 43, 83} TTI (SPS = 10,40,80 TTI)
			DS without a separate BSR	{11.8, 16.3} TTI (SR = 1,10 TTI)	{11.8, 16.3} TTI (SR = 1,10 TTI)	{12.3, 21.3} TTI (SR = 1,10 TTI)
			DS with a separate BSR	{19.8, 24.3} TTI (SR = 1,10 TTI)	{19.8, 24.3} TTI (SR = 1,10 TTI)	{20.3, 29.3} TTI (SR = 1,10 TTI)
	L-DL	Latency for message transmission from eNB to UE via DL	Unicast	4.8 TTI + 3ms	4.8 TTI + 3ms	4.8 TTI + 3ms
			MBMS	4.5 TTI + 3ms	26.5 TTI	43.5 TTI + 3ms
			SCPTM	4.5 TTI + 3ms	{4.5, 7.5} TTI + 3ms (SSP = 1,10 TTI)	{4.5, 13.5} TTI +3ms (SSP = 1,10 TTI)
Processing latency	L-NW	Latency for network processing of received message	Unicast	20ms	20ms	20ms
			MBMS	20ms	20ms	20ms
			SCPTM	20ms	20ms	20ms
	L-RSU	Latency for RSU processing	Any Mode	3ms	3ms	3ms

(a)

Operation scenario	Sub scenario		Latency	Minimum time	Maximum Time
SL-based V2X	SL Mode 1		L-SL = (L-RRC + L-SL$_{CONFIG}$) + L-SL	(74.6 TTI) + 34 TTI + 3ms	(74.6 TTI) + 101.6 TTI + 3ms
	SL Mode 2			(74.6 TTI) + 17.5 TTI + 3ms	(74.6 TTI) + 84.5 TTI + 3ms
UL/DL-based V2X	Unicast		L-UD$_{UC}$ = (2×L-RRC + L$_{PAGING}$) + L-UL + L-NW$_{UC}$ + L-DL$_{UC}$	(264 TTI) + 12.8 TTI + 23ms	(424 TTI) + 17.8 TTI + 23ms
	MBMS		L-UD$_{MBMS}$ = (L-RRC) + L-UL + L-NW$_{MBMS}$ + L-DL$_{MBMS}$	(50 TTI) + 12.5 TTI + 23ms	(50 TTI) + 56.5 TTI + 23ms
	SCPTM		L-UD$_{SCPTM}$ = (L-RRC) + L-UL + L-NW$_{SCPTM}$ + L-DL$_{SCPTM}$	(50 TTI) + 12.5 TTI + 23ms	(50 TTI) + 17.5 TTI + 23ms
Relay-based V2X	SL-UL-DL	Unicast	L-SL + L-RSU + L-UD$_{UC}$	(338.6 TTI) + 30.3 TTI + 29ms	(498.6 TTI) + 102.3 TTI + 29ms
		MBMS	L-SL + L-RSU + L-UD$_{MBMS}$	(124.6 TTI) + 30 TTI + 29ms	(124.6 TTI) + 141 TTI + 29ms
		SCPTM	L-SL + L-RSU + L-UD$_{SCPTM}$	(124.6 TTI) + 30 TTI + 29ms	(124.6 TTI) + 102 TTI + 29ms
	UL-DL-SL	Unicast	L-SL + L-RSU + L-UD$_{UC}$ – (L-RRC)	(288.6 TTI) + 30.3 TTI + 29ms	(448.6 TTI) + 102.3 TTI + 29ms
		MBMS	L-SL + L-RSU + L-UD$_{MBMS}$	(124.6 TTI) + 30 TTI + 29ms	(124.6 TTI) + 141 TTI + 29ms
		SCPTM	L-SL + L-RSU + L-UD$_{SCPTM}$	(124.6 TTI) + 30 TTI + 29ms	(124.6 TTI) + 102 TTI + 29ms

(b)

figures have yet been researched. In this paper, the additional overhead compared with conventional systems is assumed to be 10% and 30% for 1/2ms TTI and 1/14ms TTI in the SLS, respectively, based on [7].

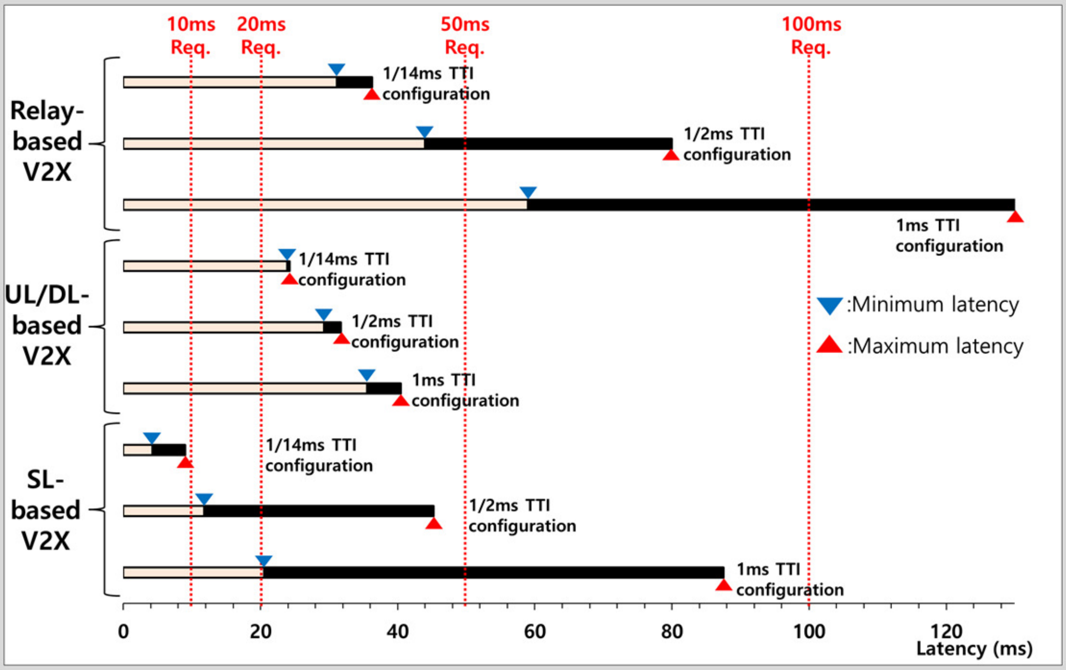
B. EVALUATION OF V2X LATENCY WITH SHORTENED TTI

In this section, we evaluate the latency performance enhancement to the V2X system achieved with shortened TTI.

			LTE-based V2X		V2X with shortened TTI			
Operation scenario	Sub scenario		1TTI = 1ms		1TTI = 1/2ms		1TTI = 1/14ms	
			Minimum time	Maximum time	Maximum time	Maximum time	Maximum time	Maximum time
SL-based V2X	SL Mode 1		(74.60) + 37ms	(74.60) + 104.60ms	(37.30) + 20ms	(37.30) + 53.80ms	(5.33) + 5.43ms	(5.33) + 10.26ms
	SL Mode 2		(74.60) + 20.50ms	(74.60) + 87.50ms	(37.30) + 11.75ms	(37.30) + 45.25ms	(5.33) + 4.25ms	(5.33) + 9.04ms
UL/DL-based V2X	Unicast		(264) + 35.80ms	(424) + 40.80ms	(132) + 29.40ms	(212) + 31.90ms	(18.86) + 23.91ms	(30.29) + 24.27ms
	MBMS		(50) + 35.50ms	(50) + 79.50ms	(25) + 29.25ms	(25) + 51.25ms	(3.57) + 23.89ms	(3.57) + 27.04ms
	SCPTM		(50) + 35.50ms	(50) + 40.50ms	(25) + 29.25ms	(25) + 31.75ms	(3.57) + 23.89ms	(3.57) + 24.25ms
Relay-based V2X	SL-UL-DL	Unicast	(338.60) + 59.30ms	(498.60) + 131.30ms	(169.30) + 44.15ms	(249.30) + 80.15ms	(24.19) + 31.16ms	(35.61) + 36.31ms
		MBMS	(124.60) + 59ms	(124.60) + 170ms	(62.30) + 44ms	(62.30) + 99.50ms	(8.90) + 31.14ms	(8.90) + 39.07ms
		SCPTM	(124.60) + 59ms	(124.60) + 131ms	(62.30) + 44ms	(62.30) + 80ms	(8.90) + 31.14ms	(8.90) + 36.29ms
	UL-DL-SL	Unicast	(288.60) + 59.30ms	(448.60) + 131.30ms	(144.30) + 44.15ms	(224.30) + 80.15ms	(20.61) + 31.16ms	(32.04) + 36.31ms
		MBMS	(124.60) + 59ms	(124.60) + 170ms	(62.30) + 44ms	(62.30) + 99.50ms	(8.90) + 31.14ms	(8.90) + 39.07ms
		SCPTM	(124.60) + 59ms	(124.60) + 131ms	(62.30) + 44ms	(62.30) + 80ms	(8.90) + 31.14ms	(8.90) + 36.29ms

:<10ms :<20ms :<50ms :<100ms :>100ms

(a) Evaluation for latency of V2X communication system with the shortened TTI.



(b) Comparison of latency requirement and latency of each operation mode

FIGURE 3. **Evaluation and comparison of latency in a V2X communication system with shortened TTI: (a) represents the latency evaluations and (b) illustrates a comparison of the latency requirements and latency evaluations.**

We will refer to V2X with shortened TTI as V2X-s in this paper. Fig. 3 shows the latency comparison of the V2X and V2X-s systems for different TTI configurations. The 1*ms* TTI configuration denotes the conventional cellular-based V2X system. The 1/2*ms* and 1/14*ms* TTI configurations can be implemented in the V2X-s system. The 1/2*ms* TTI is just a half-length of the conventional LTE subframe. In this case, a slot has 7 OFDM symbols with 15kHz subcarrier spacing. The 1/14*ms* TTI has just one OFDM symbol with 15kHz subcarrier spacing in each TTI. In this figure, the values in parentheses denote the configuration latency which occurs when the connection has not yet been established. For this result, it is assumed that the SR, SPS, and SPP are set up at the minimum value that they can achieve.

Fig. 3(a) shows that cellular-based V2X can support only the limited number of V2X services presented Table I. In this case, 85.5*ms* is the minimum latency when SCPTM in UL/DL-based V2X is utilized. Based on this minimum time, only 3 transmission methodologies can support V2X services with the 100*ms* latency requirement. In Table I, the pre-crash sensing warning might not be able to be implemented in the LTE system, even though this is obviously one of the most important in terms of vehicle driving safety. Combinations of relay-based V2X and unicast cause latencies that are too large to be utilized for V2X due to the paging time.

Cellular-based V2X systems are not appropriate for latency-aware automated driving-related services, as shown in Fig. 3(a). This is because SL-based V2X with SL mode 1 and relay-based V2X are not able to support the 100*ms* latency requirement that is necessary for safety-related services, such as FCW, emergency warnings, etc. SL-based V2X with SL mode 2 and UL/DL-based V2X with MBMS are able to meet the 100*ms* requirement. Moreover, UL/DL-based V2X with unicast or SCPTM are also able to support the 50*ms* latency requirement for see-through service. This is because UL/DL-based V2X with unicast or SCPTM has an advantage in scheduling the waiting time for the transmission.

In the same figure, we can see that V2X-s meets the latency requirements of the V2X services defined in Table I. With a 1/2ms TTI configuration, all of the modes of operation available in V2X-s are able to meet the 100*ms* latency requirement. However, there are no acceptable modes for V2X services with latency requirements not to exceed 20*ms*. The 20*ms* latency requirement can finally be satisfied when the V2X-s system adopts the SL operation mode with the 1/14ms configuration. The *IL* portion of the whole latency in SL operation mode is relatively smaller in this case. The same system can even achieve latencies lower than 10*ms*. This result shows us that SL-based V2X should be implemented with shortened TTI if the goal is to include the automated overtake and high density platooning V2X services.

Fig. 3(b) illustrates the latency performance of various V2X operation modes versus the latency requirements of the V2X services. Only the SL-based V2X mode with 1/14ms TTI configuration is suitable for V2X services with 10*ms* latency requirements. If the relay-based V2X mode is not adopted, all of the V2X modes can support the V2X services with 50*ms* latency requirements. The relay-based V2X mode might be not suitable for latency-aware V2X services because of the large number of transmission procedures, which reduces the benefits from shortened TTI.

C. SLS RESULTS OF V2X SYSTEMS WITH SHORTENED TTI

Consistent with the previous results shown in this paper, we performed system level simulation (SLS) under variable traffic demands.

We considered only the SL-based V2X mode in SLS. The reason for selecting the SL-based V2X mode is that it achieves the minimum latency. Hence, we can evaluate the degradation of the best latency performance as the traffic demand increases. SLS mainly performs resource block allocation over plural TTIs. If the traffic demand increases, V2X data cannot be scheduled in a TTI. This phenomenon commonly occurs with the SL-based V2X mode as well as UL/DL-based and relay-based modes. Therefore, SLS results on the SL-based V2X mode can be easily extended and applied to other operation modes.

Fig. 4 shows the SL-based V2X (SL mode 2) latency as the traffic demand increases. Low traffic, mid traffic, and high traffic demands represent a 20% resource utilization (RU), 50% RU, and 80% RU, respectively. The simulation parameters are summarized in Fig. 3(a) based on [5] and [13]. The additional overhead of V2X-s compared with conventional systems is assumed to be 10% and 30% for 1/2ms TTI and 1/14ms, respectively.

Fig. 4(b) illustrates the effects of the shortened TTI with low traffic demand. The benefits of the V2X-s systems can be clearly seen. The 1/14 TTI configuration has only 24% latency and 13% latency compared with 1/2 TTI configuration and 1 TTI configuration, respectively. Fig. 4(c) represents the data transmission time in terms of the TTI. In the theoretical evaluations presented in Table 2 and Fig. 3, we have assumed that the data transmission completes within 1 TTI based on [7]. However, the shortened TTI can carry a smaller amount of data, which results in segmented packet transmissions and additional overhead with shortened TTI.

The negative effect of segmented packet transmissions on the latency worsens as the traffic load increases, as depicted in Fig. 4(d), because the number of allocated resource blocks decreases. The segmented packet problem is one of the most significant latency performance degeneration issues associated with shortened TTI. The SLS results are provided to represent the segmented packet problem, the since the segmented packet problem is difficult to evaluate using mathematical analysis.

D. DESIGN PRINCIPLES FOR LATENCY-AWARE V2X SERVICES

For V2X services with latency requirements under 20, such as the pre-crash sensing warning and services related to automated driving, our research on V2X-s has brought the following design principles to the forefront.

First, "one-OFDM-symbol" TTI (1/14 TTI) should be the method of choice in V2X systems. If this is not possible because of signaling overhead inefficiency, wider subcarrier

Parameter	Setup
Carrier frequency	6GHz
Carrier bandwidth	10 MHz (SL)
Antenna Configuration	2x2 MIMO
Transmit power	UE: 23dBm
UE receiver noise figure	9dB
Traffic load (resource utilization)	20, 50, 80%
Packet size	800 bytes
eNB deployment	Wrap around model option 2 (optional) for freeway case
Pathloss model	128.1 + 37.6log10(R), R in kilometers
Penetration loss	0 dB
Shadowing distribution	Log-normal
Shadowing standard deviation	8 dB
Fast fading	3GPP Spatial Channel Model (SCM) NLOS in with fixed large scale parameters during the simulation.

(a) System level simulation parameters

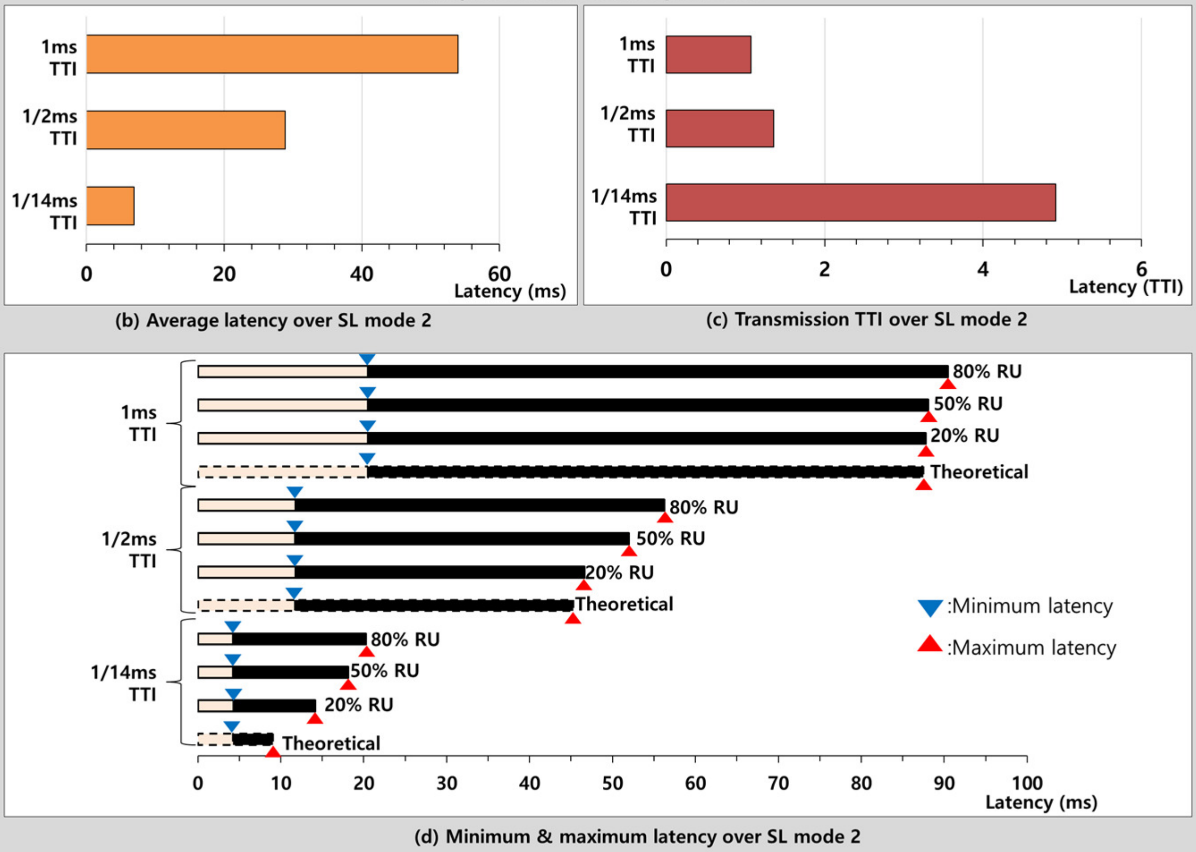


FIGURE 4. SLS results for latency of V2X communication system with shortened TTI.

spacings should be considered, since the duration of one OFDM symbol is inversely proportional to the subcarrier spacing. Based on our results, it should be possible to satisfy $TTI*(1/f_s+T_g) < 1/14ms$, where f_s is the subcarrier spacing and T_g is a guard interval, such as a cyclic prefix. Once the given formula is satisfied, a subcarrier spacing and number of OFDM symbols in a TTI can be selected that is suitable for the system's specific purposes.

Second, the RRC connection should be sustained while a V2X service continues if the goal is to implement V2X services with $10ms$ latency requirements. In Fig. 3(b), no results reflect the RRC connection time of 50 TTIs (values noted in parentheses). If RRC connection re-establishment time is needed for data transmission, no V2X modes will be able to support V2X services with $10ms$ latency requirements.

Third, the data traffic load should be kept below a certain level. As the traffic load increases, the segmented packet transmissions increase and the latency of transmission increases. Based on our SLS results, RU should be at least lower than 80% to support the 20*ms* latency requirement.

V. CONCLUSION

This paper presents a new analysis of the latency of V2X systems from the *PL* and *IL* perspectives. Based on these analyses, we were able to conclude that the conventional cellular-based V2X system is not able to satisfy the latency requirements of V2X services. Moreover, the feasibility of V2X service was verified based on the analyses in terms of the latency. The SLS results evaluate the degradation of the latency performance with the segmented packet as the traffic demand increases. Accordingly, we verified the feasibility of the V2X services and suggested design principles for V2X systems.

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