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NA-SMT: A Network-Assisted Service Message Transmission Protocol for Reliable IoV Communications

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ABSTRACT Cellular V2X (C-V2X) is an emerging standard that will enable the employment of the 6G Internet of Vehicles (IoV). It is envisaged to provide seamless connectivity, long-range communications, higher data rate transmissions, and centralized and ad hoc modes of communications for vehicular applications. In particular, service applications that require data transmission between vehicles and infrastructure stations known as Road Side Units (RSUs) can greatly benefit from C-V2X. In this paper, we propose a Network-Assisted Service Message Transmission (NA-SMT) protocol that uses Uu and PC5 links of C-V2X to efficiently disseminate service messages from RSUs to the vehicles. In the first phase of the NA-SMT protocol, RSUs select downlink relay vehicles for each service message with the highest Channel Quality Indicator (CQI) within a defined reliable range of the destination vehicle. The second phase of the NA-SMT protocol schedules V2V transmission by cooperative sub-channel allocation by the RSUs to reliably disseminate service messages to the destination. Simulation results show that NA-SMT protocol improves packet reception ratio and end-to-end delay of service messages at different channel conditions and service message generation rates.

INDEX TERMS Internet of Things, vehicular networks, intelligent transportation systems.

I. INTRODUCTION

Vehicular communications will play a central role in future smart cities by disseminating city-wide information about various services, thus forming a robust Internet of Vehicles (IoV). The information shared by vehicles include traffic density situation at various roads, traffic management to maintain smooth traffic flow within the city, advertisements by shops and stores, multi-media content retrieval from the Internet and Electric Vehicle (EV) charge scheduling information [1], [2]. Vehicular communications will also improve safety of the passengers by making intelligent driving decisions based on periodic information received from the neighborhood traffic [3], [4]. In addition, timely and more precise information about emergency events will save travelers from inconvenience.

Third Generation Partnership Project (3GPP) made several modifications in their release 14 to support vehicular communications [5], [6]. The updated standard known as Cellular V2X (C-V2X) has the potential to provide higher data rates and better connectivity as compared to the IEEE 802.11p standard [7]. The key features of C-V2X are the support for cellular communications between infrastructure units and vehicles over Uu interface, direct communications between vehicles over PC5 interface and operation in the 5.9GHz band [8]–[11]. Recent studies have shown that C-V2X can reduce the latency of V2V safety message dissemination as compared to the IEEE 802.11p [12]. A future vehicular communication system could involve an integrated network utilizing both C-V2X and IEEE 802.11p to support safety and non-safety applications [5], [13]–[21]. With the advent of 6G communications, many novel vehicular applications will be supported by higher data rates [22]–[30].

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Service messages are of vital importance in vehicular communications particularly for applications such as EV charge scheduling and route guidance. As service messages enable many value added services, and hence generate plenty of business opportunities for the 5G operators. These messages in the form of advertisements and city traffic information could be sent by central data analytics center of a smart city or power grid to the vehicles through Road Side Units (RSUs) [31]–[34]. Service message could also be of the form query and response, where vehicles generate query messages (e.g., optimal EV charging station location) and transmit it to their nearest RSUs. These messages are forwarded to the data analytics center which processes the query and sends back the response/reply message to the RSUs. Finally, this service message is transmitted to the vehicle that generated the query.

To effectively disseminate service messages, vehicle mobility is a key issue since the vehicle that generates query changes its location by the time the response has arrived. As a result, a combination of Infrastructure to Vehicle (I2V) and Vehicle to Vehicle (V2V) communications will be required to transmit these service messages. Since I2V communication over Uu interface involves sharing of resources with the cellular users, service messages should be transmitted at a higher data rate so as to use less number of cellular resources. Moreover, for V2V communications over PC5 interface, either the RSUs (network) or the vehicles themselves need to allocate the resources to reliably transmit service messages to the destination [35]–[37].

In this paper, we propose a Network-Assisted Service Message Transmission (NA-SMT) protocol for service message sharing between vehicles and RSUs. Using C-V2X, RSUs in the form of network allocates resources for I2V and V2V links. NA-SMT works in two steps, where the first step efficiently selects relay vehicles for I2V link which have the highest Channel Quality Indicator (CQI) and within a defined reliable distance to the destination vehicle. In the second step, RSU uses relay vehicles and additional cooperative vehicles to reliably transmit service messages to the destination vehicle. Simulation results show that the NA-SMT protocol reduces the end-to-end delay and improves the packet reception ratio of service messages as compared to other cellular scheduling and transmission techniques.

II. RELATED WORKS

A. CELLULAR V2X STANDARD

Cellular V2X (C-V2x) is the latest standard to support vehicular communications using LTE. It is published in the Third Generation Partnership Project (3GPP) release 14. As compared to the IEEE 802.11p which was regarded as the de-facto standard for vehicular communications, C-V2X makes use of cellular communications for vehicular applications. Particularly, in release 14, two types of communications have been defined; between base station (BS) and vehicles using Uu interface and between vehicles using PC5 interface. Additionally, two new modes of V2V communications (besides mode 1 and mode 2 previously defined in release 12 for Device to Device (D2D) communications), mode 3 and mode 4 have been introduced. In mode 3, base station controls the resource allocation whereas mode 4 allows autonomous resource allocation by vehicles.

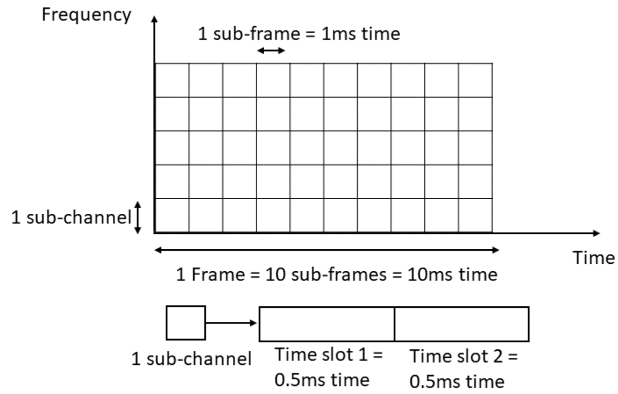

FIGURE 1. C-V2X frame structure.

C-V2X frame structure is same as in the LTE standard and is shown in Fig. 1. The radio resources are divided into frames. Each frame consists of 10 sub-frames of 1ms. The smallest resource unit which can be scheduled is 1 sub-channel, also known as scheduling block (SB). Each sub-frame has many sub-channels depending on the channel bandwidth. A sub-channel is further divided into two time slots of 0.5ms each. A vehicle is always allocated a sub-channel i.e., two time slots as per the standard.

The modulation and coding scheme (MCS) used for transmission in a sub-channel depends on the Channel Quality Indicator (CQI) which is a 4 bit value that vehicles periodically broadcast to the base station using Uu interface [38], [39]. CQI is calculated by the vehicles based on received signal strength of the pilot signals sent by the RSUs. A higher CQI indicates better channel conditions and hence, higher modulation and more efficient coding scheme. Vehicles periodically report their CQI values to the base station. Three different type of CQI feedback schemes exist in literature including wide-band CQI feedback, sub-band level CQI feedback and UE-selected sub-band CQI feedback. In wide-band CQI feedback, UE reports only one value of CQI averaged over the system bandwidth. In sub-band CQI feedback, UE reports CQI value for every sub-band whereas in UE-selected sub-band CQI feedback, UE reports average CQI of M sub-bands that have the highest CQI.

B. EXISTING TECHNIQUES IN THE LITERATURE

Several techniques have been proposed to disseminate safety and non-safety messages in vehicular networks. We can divide them into two categories, IEEE 802.11p based and cellular based.

IEEE 802.11p based techniques utilize IEEE 802.11p standard to disseminate vehicular messages. Reference [35] proposes link-layer cooperation technique where vehicles utilize their unused time slots to cooperate with other vehicles whose direct message transmission has failed. Multiple relay vehicles are selected that transmit cooperative messages over their unused time slots. Reference [40] proposed a probabilistic multi-hop message forwarding mechanism to reduce emergency notification delay. The proposed protocol uses node indexes to compute forwarding probability and a clustering mechanism to reduce number of potential relay nodes. Another technique in reference [41] uses a spectrum sharing protocol where cellular V2X users and IEEE 802.11p users co-exist. The first phase of the protocol utilizes energy sensing technique considering interference of both type of users. In the second phase, matching theory based transmission scheduling algorithm is used that transmits messages using an interference-based utility function.

In the cellular-based techniques, [42] proposes use of a short term sensing time slot at the beginning of each resource unit. The advantage of the enhanced sensing in the introduced time slot is that vehicles can detect simultaneous transmissions and reduce collisions. In [42], authors propose a novel reservation scheme for C-V2X transmissions. Vehicles with an intention to transmit messages reserve their resource unit by explicit announcement to the neighborhood. This reduces the chances of collisions among C-V2X messages. The work in [43] uses channel sensing mechanism to adaptively select the transmission power and packet inter-arrival time. As a result, the interference between vehicles is reduced and resource block reuse factor is increased.

Authors in [44] proposes a resource allocation algorithm for V2V communications where the base station computes optimal links that reduce message latency. The proposed algorithm uses greedy approach for link selection and considers factors such as interference and SINR. In [45], a QoS aware and collision free sub-channel allocation scheme proposed. The proposed technique divides road segment in to clusters and develops a mathematical model to avoid inter-cluster and intra-cluster collisions. Lastly, performance of C-V2X safety message transmission in mode 4 is evaluated in [46]. Results for performance metrics such as packet error rate and packet inter-arrival rate are provided at different resource parameters and modulation coding indexes.

C. CONTRIBUTIONS OF THE PAPER

As compared to the existing work in literature, the proposed NA-SMT technique finds reliable relay vehicles in the coverage range of RSUs to disseminate service messages. For this, we propose a reliable distance threshold metric and also use *CQI* metric to efficiently select cooperative relay vehicles. Moreover, we also propose a scheduling algorithm to assign priority sub-channels to the relay vehicle transmissions. The major advantage of the proposed technique is that it reduces the number of transmissions needed for I2V communications due to selection of reliable vehicles. Moreover, the priority scheduling improves the end-to-end delay of the service messages.

III. SYSTEM MODEL

We consider a cellular V2X communication scenario as shown in Fig. 2 where vehicles on the road and RSUs are equipped with C-V2X transceivers. As discussed in section II-A, vehicles communicate with each other over the PC5 interface (V2V link). On the other hand, communication between RSUs and vehicles takes place over the Uu interface (I2V link). We assume that vehicles share periodic CAMs with each other using V2V link. Since service messages are also shared over the V2V link, we assume that vehicles use time multiplexing where half of the time is allocated for transmission of CAMs and the other half is reserved for service messages. This is similar to the time multiplexing between control channel (CCH) and service channel (SCH) using IEEE 802.11p protocol [47], [48].

In this paper, we focus on transmission of downlink service messages i.e., from RSUs to the vehicles. These service messages could be the route guidance data, nearest gas station information, notification of an emergency event, special sales offer from the city super store, multi-media download from the Internet etc. We assume that RSUs are connected to the vehicles as well as the data analytics center (back bone network which has city-wide information from all RSUs). Initially, vehicles send service request messages to their connected RSUs which forwards this request to the data analytics center. Once the service request message is processed by the data analytics center, it passes it back to the RSU which in turn transmits this downlink service message back to the requesting vehicle.

We assume that vehicles periodically send their sub-band CQI values to the corresponding RSUs. A sub-band CQI provides feedback of p adjacent sub-channels where p can be any value between 2 and 8. Here, we also introduce the concept of reliable distance threshold and maximum distance threshold that will be later used in the proposed work. These thresholds are computed by each vehicle based on received CAMs. A vehicle's reliable distance threshold $d^{reliable}$ is defined as the distance up to which it receives packets with 90% reliability. As vehicles receive a CAM from the neighboring vehicles at least 10 times per second, $d^{reliable}$ of a vehicle is the distance from the furthest neighboring vehicle from which it received 9 or more CAMs in the last 1 second. A vehicle's maximum distance threshold d^{max} is defined as the distance up to which it receives packets with 50% reliability. d^{max} is also computed by each vehicle from CAMs received within last 1 second. Note that both $d^{reliable}$ and d^{max} vary with time. We assume that vehicles periodically send their $d^{reliable}$ and d^{max} values to their connected RSUs along with the sub-band CQI values.

IV. WORKING OF PROPOSED NA-SMT PROTOCOL

In this section, we explain the working of the proposed Network-Assisted Service Message Transmission (NA-SMT) protocol as shown in Algo. 1. The goal of the NA-SMT protocol is to effectively disseminate service messages from the RSUs to the vehicles that initiated the service request

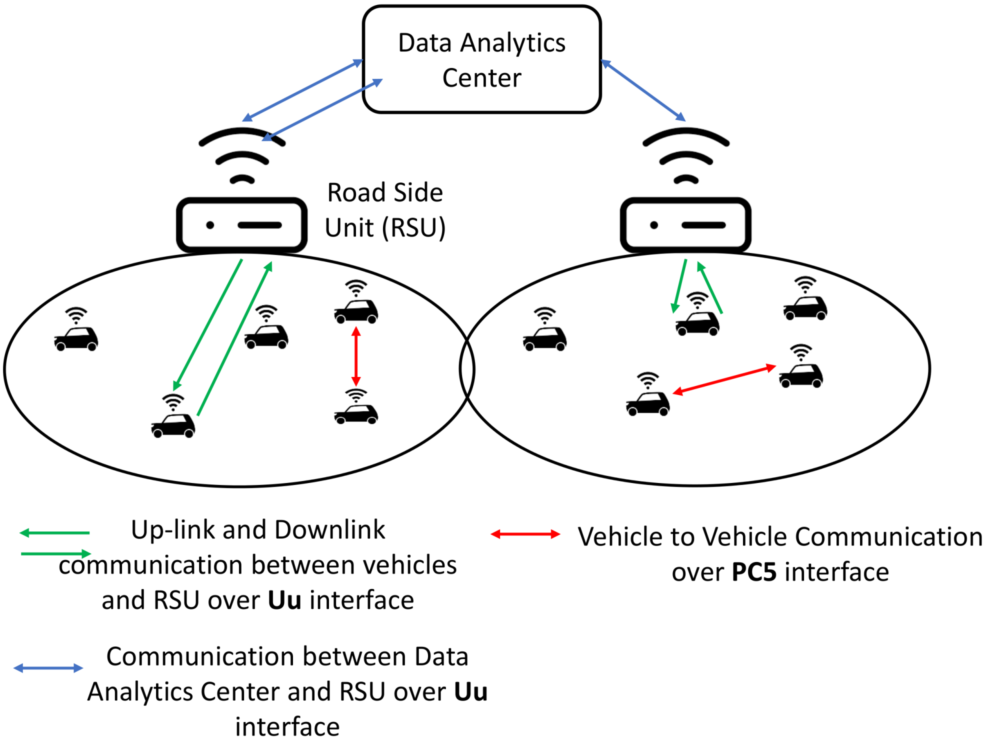

FIGURE 2. Service message transmission using V2V and V2I communications in C-V2X.

(we use the term *reply vehicle* for it in this paper). The key idea of NA-SMT protocol is to find a relay vehicle for the service message with the best possible CQI so that RSUs can transmit the service message at the highest data rate, thus requiring less number of sub-channels. This is achieved using $I2Vscheduling$ algorithm.

Another important criterion for relay vehicle selection is that it should be near to the reply vehicle, preferably within $d^{reliable}$ of the reply vehicle. In case, the relay vehicle is more than $d^{reliable}$ distance away from the reply vehicle, another relay vehicle (we call it as *cooperative vehicle* in this paper) is selected to transmit reply message to the reply vehicle. This is achieved by using $V2Vscheduling$ algorithm.

RSUs continuously receive processed requests (reply messages) from the data analytics center and place them in a reply messages queue Q_{reply}. As discussed in Section III, RSUs also periodically receives CQI, $d^{reliable}$ and d^{max} from each vehicle. This information is kept in separate lists L_c, $L_d^{reliable}$ and L_d^{max} respectively (each list stores the values against the vehicle ID's). As mentioned earlier, NA-SMT protocol uses two algorithms $I2Vscheduling$ and $V2Vscheduling$ for service message transmission which are explained in the following sub-sections.

A. I2V SCHEDULING ALGORITHM

RSUs run $I2Vscheduling$ algorithm shown in Algo. 1 at the start of each downlink sub-frame to schedule the downlink reply message transmissions for all sub-channels within the sub-frame. Let each sub-frame on the Uu interface consists of $K_{subframe}$ sub-channels. The goal of the algorithm is to select a relay vehicle for a reply message that has the highest CQI. The relay vehicle is selected using $DownlinkRelaySelection()$ procedure.

At first, the vehicle's CQI list L_c is divided in to h sub-lists, where sub-list L_c^i consists of vehicles that reported a CQI of i. The algorithm starts with the highest CQI list L_c^h and looks for a potential relay vehicle in that list. It then picks the first message from the reply messages queue (i.e., $q = 1$) and stores its vehicle ID in V_{reply}. The reliable distance threshold and maximum distance threshold of the reply vehicle is placed in $d_{reply}^{reliable}$ and d_{reply}^{max} respectively. If V_{reply} exists in L_c^h, it implies that the link between the reply vehicle and the RSU has a CQI of h, and the RSU can directly transmit this message to the reply vehicle. In this case, the relay vehicle is same as the reply vehicle. RSU also maintains a cooperation flag F_{coop} to identify if the relay vehicle requires a cooperative vehicle to transmit reply message to the reply vehicle. F_{coop} is set to FALSE here (meaning no cooperative vehicle is needed). Finally, V_{reply} is removed from the Q_{reply}.

In case, the reply vehicle does not exist in L_c^h, the algorithm sorts L_c^h in decreasing order of distances between the reply vehicle and vehicles in L_c^h (i.e., for j^{th} vehicle in L_c^h, $d = d_{reply-j}$). The algorithm then finds the first vehicle in L_c^h that lies within the maximum distance threshold of the reply vehicle, d_{reply}^{max}. If such a vehicle is found, it is selected as the relay vehicle and reply message for vehicle V_{reply} is removed from Q_{reply}. The cooperation flag is set to FALSE if distance between the reply vehicle and the relay vehicle ($d_{reply-relay}$)

is less than $d_{reply}^{reliable}$ and vice versa. This is done to mark the requirement of a cooperative vehicle for the reply message transmission if the relay vehicle lies beyond $d_{reply}^{reliable}$. In case, no relay vehicle for the reply message could be selected from L_c^h, the algorithm proceeds to L_c^{h-1} and so on.

RSUs maintain a service message table *SMT* to record the relay vehicles and the cooperation flag for a given reply message. This is to be used during $V2Vscheduling$ algorithm. Therefore, V_{reply}, V_{relay} and F_{coop} are inserted in the first row of *SMT*. The algorithm finally schedules transmission of V_{reply} to the relay vehicle V_{relay} in the next non-scheduled downlink-subchannel over Uu interface.

Algorithm 1 Network-Assisted Service Message Transmission (NA-SMT) Protocol

Receive processed requests i.e., reply messages from the data analytics center and insert them in the reply messages queue Q_{reply}
Periodically receive channel quality indicator *CQI* value from each vehicle and insert it in the vehicle's CQI list L_c
Periodically receive reliable distance threshold $d^{reliable}$ value from each vehicle and insert it in the vehicle's reliable distance threshold list $L_d^{reliable}$
Periodically receive maximum distance threshold d^{max} value from each vehicle and insert it in the vehicle's maximum distance threshold list L_d^{max}
$K_{subframe}$ = number of sub-channels in a sub-frame
for *start time of each downlink sub-frame* **do**
    for *sub-channels* $1 : K_{subframe}$ **do**
        run algorithm $I2Vscheduling$
    end
end
for *every transmission window* T_w **do**
    run algorithm $V2Vscheduling()$
end

B. V2V SCHEDULING ALGORITHM

$V2Vscheduling$ algorithm is run by the RSUs to broadcast scheduling information for the PC5 interface to all vehicles. This information is transmitted every T_w seconds containing scheduling information of the next T_w seconds. We call T_w as the transmission window in this paper. Let K_{tw} be the number of sub-channels in the transmission window and $K_{allocated}$ be the number of sub-channels that have been allocated in current T_w. Let S_{map} be the scheduling map that contains information regarding vehicle IDs that have been allocated each sub-channel. The algorithm starts by picking the first row of *SMT* which contains three values of V_{reply}, V_{relay} and F_{coop}. If F_{coop} is FALSE, then the next free sub-channel K_{free} in the S_{map} is assigned to V_{relay}. A sub-channel cooperative flag $subchannel_{coop}$ is maintained to identify if a given sub-channel is for cooperative transmission or not.

Algorithm 2 I2V Scheduling Algorithm

run procedure *DownlinkRelaySelection*()
Schedule transmission of V_{reply} to the relay vehicle V_{relay} in the next non-scheduled downlink sub-channel over Uu interface
procedure `DownlinkRelaySelection()`
    Input: Reply messages queue Q_{reply}, vehicle's CQI list L_c, vehicle's reliable distance threshold list $L_d^{reliable}$, vehicle's maximum distance threshold list L_d^{max}
    $L_c^1 - L_c^h \leftarrow$ sub-lists of vehicles with CQI value of 1 to the highest h
    for $q = 1 : Q$ **do**
        for $m = h : 1$ **do**
            $V_{reply} \leftarrow$ vehicle *ID* of q^{th} reply message in Q_{reply}
            $d_{reply}^{reliable} \leftarrow$ distance threshold of vehicle V_{reply} in $L_d^{reliable}$
            $d_{reply}^{max} \leftarrow$ distance threshold of vehicle V_{reply} in L_d^{max}
            if $V_{reply} \exists L_c^m$ **then**
                $V_{relay} = V_{reply}$
                $F_{coop} = false$
                remove V_{reply} from Q_{reply}
                BREAK
            end
            else
                Sort L_c^m in decreasing order of $d = d_{reply-j}$
                for *all vehicles j in* L_c^m **do**
                    if $d < d_{reply}^{max}$ **then**
                        $d_{relay} = d$
                        $V_{relay} = j$
                        Remove V_{reply} from Q_{reply}
                        if $d_{reply-relay} < d_{reply}^{reliable}$ **then**
                            F_{coop} = FALSE
                        end
                        else
                            F_{coop} = TRUE
                        end
                        BREAK
                    end
                end
            end
        end
    end
    Insert V_{reply}, V_{relay} and F_{coop} in the first row of service messages table *SMT*
    return V_{reply} and V_{relay}
end

Here $subchannel_{coop}$ is set to FALSE (meaning that the current sub-channel is not used for cooperative transmission). $K_{allocated}$ is increased by 1 in this case.

Algorithm 3 V2V Scheduling Algorithm

Input: Destination vehicle V_{reply}, Relay vehicle V_{relay}
K_{tw} = number of sub-channels in the transmission window
$K_{allocated} = 0$
while $K_{allocated} < K_{tw}$ **do**
  $(V_{reply}, V_{relay}, F_{coop}) \leftarrow$ first row of *SMT*
  if $F_{coop} == FALSE$ **then**
    $K_{allocated} = K_{allocated} + 1$
    Assign next free sub-channel K_{free} in the S_{map} to V_{relay} and mark sub-channel cooperation flag $subchannel_{coop}$ as FALSE
  end
  else
    $V_{coop} = CooperativeVehicleSelection()$
    $K_{allocated} = K_{allocated} + 2$
    Assign next free sub-channel K_{free} in the S_{map} to V_{relay} and mark $subchannel_{coop}$ as FALSE
    Assign sub-channel $K_{free} + K_{subframe}$ in the S_{map} to V_{coop} and mark $subchannel_{coop}$ as TRUE
  end
  delete first row of *SMT*
end
Broadcast S_{map} to all vehicles in the cell
procedure `CooperativeVehicleSelection()`
  Input: vehicle's reliable distance threshold list $L_d^{reliable}$, vehicle's maximum distance threshold list L_d^{max}
  for *all vehicles v located in between* V_{reply} *and* V_{relay} **do**
    Condition 1 $\rightarrow d_{v-relay} < d_v^{reliable}$
    Condition 2 $\rightarrow d_{v-reply} < d_{reply}^{reliable}$
    $\rightarrow$Pick all vehicles that satisfy conditions 1 and 2 and select V_{coop} as the vehicle closest to V_{reply}
    $\rightarrow$In case none of the vehicles satisfy both conditions 1 and 2, pick all vehicles that satisfy only condition 1 and select V_{coop} as the vehicle closest to V_{reply}
    $\rightarrow$In case none of the vehicles satisfy condition 1, pick all vehicles that satisfy only condition 2 and select V_{coop} as the vehicle closest to V_{relay}
    $\rightarrow$In case none of the vehicles satisfy any of the conditions 1 and 2, pick a random vehicle and select it as V_{coop}
  end
  return V_{coop}
end

In case, F_{coop} is TRUE, it means that the relay vehicle is outside $d^{reliable}$ of the reply vehicle. For such a case, the relay vehicle at first transmits the reply message which may or may not be received by the reply vehicle. An additional cooperative vehicle is selected which receives the original reply message (from the relay vehicle) and again transmits it to the reply vehicle so that probability of outage is reduced. The cooperative vehicle selection is done using *CooperativeVehicleSelection*() procedure. It works by checking all vehicles v located between V_{reply} and V_{relay} for the following two conditions given in equations 1 and 2:

Algorithm 4 V2V Transmission Algorithm

Input: Scheduling Map S_{map}
for *1*:K_{tw} **do**
  if $F_{coop} == FALSE$ **then**
    Transmit next reply message from the transmission queue
  end
  else
    Transmit reply message received in the same sub-channel of the last sub-frame
  end
end

$$d_{v-relay} < d_v^{reliable} \tag{1}$$
$$d_{v-reply} < d_{reply}^{reliable} \tag{2}$$

Here, $d_{v-relay}$ is the distance between the vehicle v and the relay vehicle, and $d_{v-reply}$ is the distance between the vehicle v and the reply vehicle. All vehicles that satisfy the above two conditions are good candidates for the cooperative vehicle. This is because the relay vehicle is within their $d^{reliable}$ (resulting in higher probability of packet reception), and they are located within $d^{reliable}$ of the reply vehicle. In such a case, vehicle that is closest to V_{reply} is selected as cooperative vehicle V_{coop}.

If both conditions 1 and 2 are not satisfied, the algorithm selects potential cooperative vehicles that satisfies only condition 1 so that cooperative vehicle lies within $d^{reliable}$ of the relay vehicle. This increases the probability of reception of reply message at the selected relay vehicle. The selected cooperative vehicle in this case is the one which lies closest to V_{reply}. Similarly, if condition 1 is not satisfied by any vehicle, the algorithm checks for condition 2. In case, none of the vehicles satisfy any of the two conditions, a random vehicle is selected as a cooperative vehicle.

Once the cooperative vehicle is selected, the next free sub-channel K_{free} in the S_{map} is assigned to V_{relay} and the sub-channel cooperative flag $subchannel_{coop}$ is set to FALSE. This sub-channel is used for transmission of the reply message by the relay vehicle. Also, the sub-channel $K_{free} + K_{subframe}$ (same sub-channel in the next sub-frame) is assigned for cooperative transmission (from cooperative vehicle to the reply vehicle) and $subchannel_{coop}$ is set to TRUE. Cooperative vehicle thus forwards the reply message received in the same sub-channel of the last sub-frame. At this point, the first row of *SMT* is deleted and the sub-channel allocation procedure is continued unless $K_{allocated}$ reaches K_{tw}. Afterwards, the RSU broadcasts the scheduling map S_{map} to all vehicles.

C. V2V TRANSMISSION ALGORITHM

Vehicles use $V2Vtransmission$ algorithm to transmit service messages to each other. Vehicles receive S_{map} from the RSUs at start of every transmission window T_w. Each vehicle transmits the first reply message from its transmission queue in its allocated sub-channel in the S_{map} if sub-channel cooperation flag $subchannel_{coop}$ is marked as FALSE. All vehicles located in between the relay vehicle and the reply vehicle that receive the reply message store it for 1 sub-frame time i.e., 1ms. In case, the vehicle is allocated a sub-channel in the S_{map} and $subchannel_{coop}$ is marked as TRUE, it transmits the received reply message in the same sub-channel of the last sub-frame.

TABLE 1. Simulation parameters.

Parameter		Value
Traffic	Road area	1km×1km
	Vehicle density	1200 vehicles/km^2
	Number of lanes	6
	Vehicle speed	$15-30$ m/s
C-V2X	Number of RSUs	4
	Cell Radius	500m
	SNR Threshold	25 dB
	Transmit Power	23 dBm
	Noise Power	-114 dBm
	Bandwidth	10 MHz
Service Message	Packet size	200 bytes
	Packet generation rate	$5, 10, 20$ packets/s
Propagation model	Pathloss	Dual-slope $2, 4$
	Fading	Nakagami $m = 1, 3, 5$
Algorithm Parameters	$K_{subframe}$	25
	Transmission Window T_w	5s

V. PERFORMANCE EVALUATION

A. SIMULATION SCENARIO

In this section, we discuss the performance evaluation of proposed NA-SMT protocol. We implemented the proposed technique in NS-3 simulator. The simulation parameters are listed in Table 1. We simulate a 1km×1km of a realistic urban road network scenario using SUMO traffic simulator. The traffic density is taken as 1200 vehicles/km^2 and there are 6 lanes per road segment (3 per direction). This corresponds to a high traffic density scenario. Vehicles speed are uniformly distributed between 15 m/s and 30 m/s.

We place 4 RSUs in the road area and cell radius of each RSU is 500m. SNR threshold for correct packet detection is taken as 25dB. Transmit power and noise power is 23dBm and −114dBm respectively. The bandwidth of C-V2X is 10MHz.

For propagation model, we consider a dual slope channel model with path loss exponent of 2 till a transmitter-receiver distance of 200m and path loss exponent of 4 after 200m. Nakagami-m Fading is used to model multi-path fading. We simulate different channel conditions by using Nakagami-m values of 1, 3 and 5 (where $m = 5$ refers to the best channel conditions and $m = 1$ refers to the worst channel conditions). Number of sub-frames per sub-channel $K_{subframe}$ are taken as 25. Transmission window T_w is taken as 5s.

B. RESULTS

We compare proposed NA-SMT protocol with the following three techniques:

- **Cellular transmission with First Come First Serve scheduling (Cellular-FCFS):** where RSUs transmit the downlink reply messages directly to the reply vehicle in a first come first serve manner from the reply queue Q_{reply} [49].
- **Cellular transmission with Maximum Throughput scheduling (Cellular-MT):** where RSUs transmit the downlink reply messages directly to the reply vehicle in order of vehicles with the highest CQI from the reply queue Q_{reply} [49].
- **Cellular Relaying plus V2V Communication (Cellular-Relay):** where RSUs transmit the downlink reply messages in a first come first serve manner to the relay vehicle that has the highest CQI. The relay vehicle could be any vehicle within the cell and need not be present in the reply queue Q_{reply}. The relay vehicles then transmit the reply messages using PC5 interface.

Fig.3 shows the Packet Reception Ratio (PRR) of service messages at different channel conditions.. The rate of service message generation is set to 10 packets per second and vehicle speeds are set to 25m/s. It can been seen that NA-SMT protocol has the highest packet reception ratio as compared to other scheduling techniques. Cellular-FCFS has the lowest PRR reaching as low as 0.65 as it does not consider CQI while transmitting reply messages. On the other hand Cellular-MT has $0.02-0.17$ lower PRR than NA-SMT. This is because although Cellular-MT protocol transmits downlink reply message to the vehicle with the highest CQI, it transmits message directly to the reply vehicle and does not use intermediate relays which are required if the reply vehicle is far away from the RSU. Finally Cellular-Relay protocol achieves a PRR of $0.83 - 0.98$ at different channel conditions performing better than Cellular-FCFS and Cellular-MT protocol. This is due to selection of relay vehicles with the highest CQI and then transmitting the reply message via relay vehicles using PC5 interface. However, Cellular-Relay has a 0.08 lower PRR than NA-SMT at $m = 1$ due to absence of cooperative vehicles on the PC5 interface.

We plot end-to-end delay of service messages at different service message generation rates in Fig. 4. Nakagami m is taken as 3 whereas vehicle speed is set to 25m/s. As the service message generation rate is increased, queuing time for reply messages in the reply queue at RSU increases, hence the end-to-end delay also gets increased. Cellular-MT protocol shows the highest change in end-to-end delay with the increase in service message generation rate. This is because

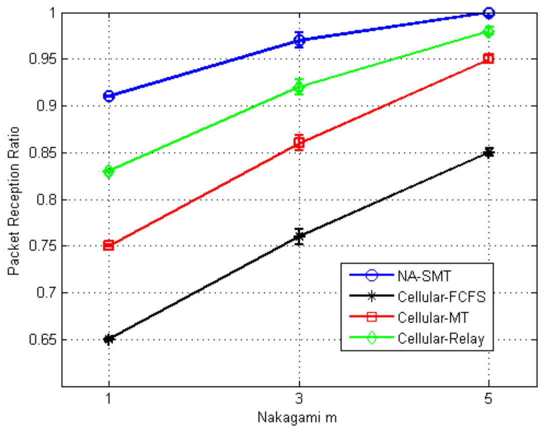

FIGURE 3. **Packet reception ratio at different channel conditions [Service message generation rate = 10 packets/s, vehicle speed = 25 m/s].**

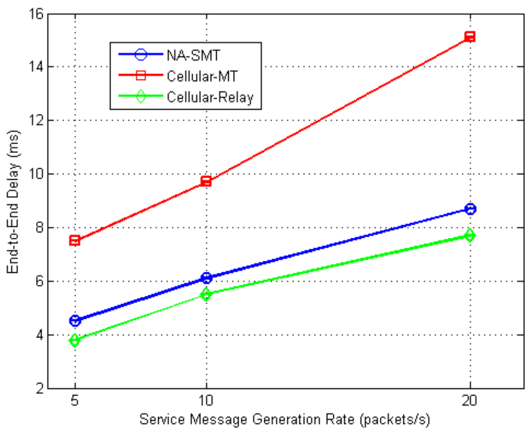

FIGURE 4. **End-to-end delay at different service message generation rate [Nakagami $m = 3$, vehicle speed = 25 m/s].**

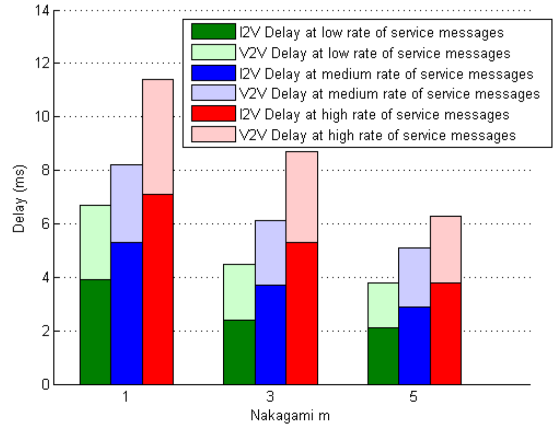

FIGURE 5. **I2V and V2V delays at different service message generation rate and channel conditions [Vehicle speed = 25 m/s].**

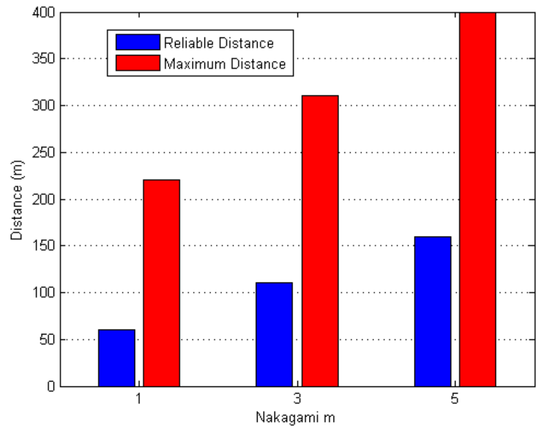

FIGURE 6. **Reliable distance and maximum distance at different channel conditions [Vehicle speed = 25 m/s].**

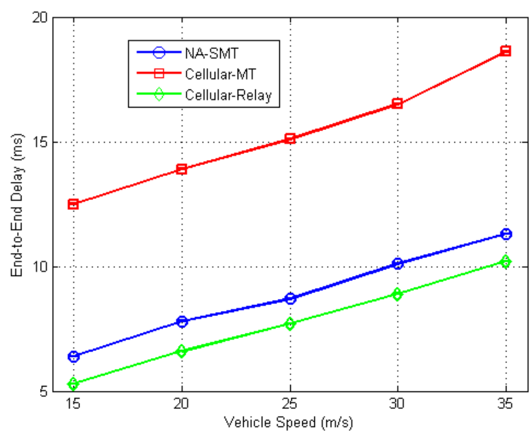

FIGURE 7. **End-to-End Delay at different vehicle speeds [[Service message generation rate = 20 packets/s, Nakagami $m = 3$].**

Cellular-MT transmits the reply messages in order of vehicles having highest CQI, as a result vehicles with lower CQI suffer higher queuing delays resulting in increased end-to-end delay. On the other hand, both NA-SMT and Cellular-Relay protocols have $4-9$ms lower end-to-end delay than the Cellular-MT protocol. This is because while Cellular-MT only uses the reply message queue to select a destination vehicle for next transmission, NA-SMT and Cellular-Relay searches all the vehicles within the cell for highest CQI link. As a result, there are more chances to find a vehicle operating at the highest CQI and thus higher data rate transmission. It should be noted that Cellular-Relay has a lower delay than the NA-SMT protocol as it does not use cooperative vehicles on the PC5 interface. While this results in $1-1.5$ms higher end-to-end delay, the packet reception ratio is increased up to 0.1 as shown in Fig. 3.

Fig. 5 shows I2V and V2V delays at different service message generation rate and channel conditions for the proposed NA-SMT protocol. End-to-end delay of service messages goes up to 11.4ms at the highest service message rate (20 packets/s) and worst channel conditions ($m = 1$). Moreover, service messages at the highest packet generation rate can be transmitted in 3.8 ms at a good channel condition of $m = 5$. It can be also be seen that as the rate of service messages is increased, the percentage of I2V delay in the end-to-end delay goes up by 2%. This is because of the queuing time faced by the service messages at the RSU.

We also plot reliable distance and maximum distance of vehicles at different channel conditions in Fig. 6. The reliable distance of vehicles increase from 50 to 150 when Nakagami

m is increased from 1 to 3. Similarly, maximum distance is 400m at $m = 5$ but reduces to 220m at $m = 1$.

Finally, we plot the impact of mobility on end-to-end delay in Fig. 7. It can be seen that the increase in vehicle speed has a negative effect on the end-to-end delay as the reply vehicle moves away quickly from the RSU, hence requiring transmission over a higher distance. Cellular-MT protocol gets a much higher impact on end-to-end delay since it directly transmits the messages to the reply vehicle. With increase in mobility, it is difficult to find vehicles with the higher CQI and hence causes an increased delay. At a vehicle speed of 35 m/s, NA-SMT, Cellular-MT and Cellular-Relay have an end-to-end delay of 11.3ms, 18.6ms and 10.2ms respectively.

VI. CONCLUSION

In this paper, we propose a novel technique known as NA-SMT to efficiently transmit service messages between vehicles and RSUs using C-V2X. NA-SMT protocol transmits service messages to the destination using I2V communications from RSUs to selected relay vehicles based on CQI and reliable distance threshold. In addition, service messages from the relay vehicles to the destination vehicles are reliably transmitted over the PC5 interface with the help of selected cooperative vehicles. Compared to the existing algorithms, the proposed technique uses reliable distance threshold and CQI metric to select relay vehicles, and utilizes priority scheduling for I2V communications. Simulation results highlight the advantages gained by NA-SMT protocol in terms of reduced end-to-end delay and improved packet reception ratio as compared to maximum throughput and relaying based techniques. In the future, we aim to further improve the reliability of data transmission using intelligent reflecting surfaces.

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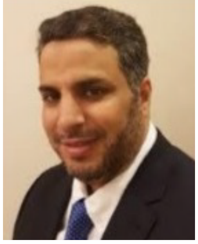

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