Performance Evaluation of NOMA for Sidelink Cellular-V2X Mode 4 in Driver Assistance System With Crash Warning

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ABSTRACT This article presents the performance characteristics of a potential extension of sidelink cellular-vehicle-to-everything mode 4 (simply called mode 4) with uplink non-orthogonal multiple access (UL-NOMA), named SPS-NOMA, in driver assistance systems with a crash warning. In SPS-NOMA, multiple nodes (e.g., cars or pedestrians with communication equipment) simultaneously broadcast their data frames at a time-frequency resource selected by sensing-based semi-persistent scheduling (sensing-based SPS), the distributed random access protocol of mode 4. The transmitted signals are superposed at the receiver sides, and successive interference canceller (SIC) supports decoding the superposed signal. In SPS-NOMA, sensing-based SPS is expected to enhance the signal-to-interference-plus-noise ratio at each SIC iteration. The effect boosts the performance gains of the SIC in broadcast cases and mitigates the channel congestion. Our computer simulations highlighted that SPS-NOMA improved the performance of the ordinary mode 4 by 38% in the fundamental node distribution model. In conclusion, SPS-NOMA is expected to be the next generation sidelink C-V2X as the extended mode 4.

INDEX TERMS Sidelink cellular-vehicle-to-everything mode 4, sensing-based semi-persistent scheduling, non-orthogonal multiple access, successive interference canceller, crash warning.

I. INTRODUCTION

In intelligent transportation systems (ITS) for smart cities [1], vehicle-to-everything (V2X) technologies have advanced driver assistance systems. In particular, a crash warning system (CWS) using V2X [2] improves safe driving because of wireless technologies cover sensors’ blind spots with radar and cameras. In the CWS, each node (e.g., a car, a pedestrian, or a drone with communication equipment) periodically broadcasts its data frame, which contains state data such as its location, speed, and direction. The system has the quality of service (QoS) requirements [3]–[5] to detect future traffic accidents, called potential crashes; specifically, nodes must receive sufficient numbers of frames periodically to predict potential crashes.

As a new V2X standard, sidelink cellular-V2X (C-V2X) mode 4 (called mode 4) [6]–[9] has emerged. Mode 4 provides device-to-device (D2D) communications through PC5 interfaces without any help of base stations (BSs). Mode 4 has a new slotted random access with a carrier-sensing history of past slots, called sensing-based semi-persistent scheduling (sensing-based SPS). In this protocol, nodes estimate the interference of slots from their history and select a transmission slot with estimated low interference. Nodes also continue to use the selected slot several times, i.e., in a semi-persistent manner. Such a manner provides slot reservations and generates interference patterns. The behaviors support the selection of a better broadcasting slot in many cases. Note that this article focuses on mode 4 in the CWS.

Mode 4 may undergo channel congestion in crowded environments, although mode 4 provides a better slot for
TABLE 1. Summary of Related Works of UL-NOMA.

| UL-NOMA communication modes and wireless technologies | Related works |
|------------------------------------------------------|---------------|
| **Unicast** | Cellular uplink networks [12]–[16] |
| **Broadcast** | **IEEE802.11p-based V2X or D2D-based C-V2X (except for mode 4)** [17]–[20] |
| | **Sidelink C-V2X mode 4 (sensing-based SPS)** | **Only our works** |

transmissions in many cases. For example, in crowded intersections, many nodes share the channel of mode 4. In such environments, several nodes simultaneously use a slot, generating frame collisions. At these events, nodes can typically decode the sufficiently strongest signal by capture effects [10] but fail to receive weaker signals; that is, nodes cannot obtain multiple frames in a slot. As a result, as long as the number of nodes exceeds a specific value, mode 4 may fail to satisfy the QoS requirements of the CWS. We have defined the maximum number of nodes as the node accommodation capacity (NAC) [11]. We need to increase the NAC as much as possible to use the CWS in crowded intersections.

One of the potential extensions of mode 4 is **uplink power-domain non-orthogonal multiple access** (called **UL-NOMA**) [12]–[20]. This article defines the NOMA involving multiple transmitters even in sidelink as the UL-NOMA because of the same technology essentially. In UL-NOMA, multiple nodes use a time-frequency domain simultaneously, and the transmitted signals are superposed at the receivers. At the receiver sides, successive interference canceller (SIC) enables the decoding of several signals, including weaker signals; at each iteration, the signal-to-interference-plus-noise ratio (SINR) must be large enough for decoding frames. Under these conditions, UL-NOMA is expected to access spectrum resources more efficiently than orthogonal multiple access (OMA). Note that this article does not focus on downlink NOMA [21]–[23].

II. RELATED WORKS

This section highlights the differences between this article and related works [12]–[20], [24], and [25]. The related works are divided into two groups. The first group is unicast-based UL-NOMA [12]–[20]. The second group is broadcast-based UL-NOMA [17]–[20], [24], and [25]. Table 1 summarizes the related works. This table emphasizes that the related works except for our works [24], [25] have not focused on UL-NOMA in mode 4. In our previous works, we proposed the concept of UL-NOMA in mode 4 in our conference papers. This article significantly extends the concept. In the following paragraphs, we briefly explain the related works and the differences between this article and the related works.

The first group is unicast-based UL-NOMA. The main topic of the group has been unicast cellular networks [12]–[15]. In the group, each of the unicast networks has a destination node, such as a BS or a D2D user. The authors [12] [13] proposed typical UL-NOMA systems in cellular uplink networks and evaluated the fundamental performance. The researchers [14]–[16] improved the SINR at each SIC iteration to boost the performance of UL-NOMA in the networks. The authors [14] proposed a layered user-pairing scheme. The scheme creates layers based on the distances between BSs and users. Selecting users in different
layers provides the differences in BS–user distances, and thus, the scheme upgrades the SINR at each SIC iteration. The authors [15] used multiple antennas to improve the SINR. Providing space diversity by multiple antennas improved the SINR. The authors [16] proposed an effective algorithm for paring D2D users with cellular users to improve the spectrum utilization efficiency. Unlike these existing works, this article focuses on broadcast systems, which have multiple receivers in a wide area. Superposing many signals is challenging to provide high SINRs for such multiple receivers, and thus, the performance gains of UL-NOMA may be limited.

The other group is broadcast-based UL-NOMA. The main topic of this group has been V2X networks [17]–[20]. The authors [17] proposed NOMA schemes for D2D-based V2X under the control of BSs. Other authors also investigated the schemes to boost the SINR at SIC iterations to improve the performance gains in broadcast networks as follows. The researchers [18] focused on IEEE802.11p with CSMA/CA and proposed using multiple antennas. The authors [19] proposed a distributed multiple access based on the distances between target receivers and target transmitters. The authors [20] focused on full-duplex NOMA (FD-NOMA) to enhance V2X performance, but the works did not focus on the slot selection mechanisms of mode 4. These works are strongly related to this article but have not focused on mode 4. Sensing-based SPS in mode 4 is expected to boost the SINR at SIC iterations.

Finally, we describe the novelty from our previous works [24], [25]. In the previous works, we proposed a basic concept of SPS-NOMA [24] and investigated the fundamental performance gains of SPS-NOMA in uniform node distribution model [24] and realistic node distribution models [25]. However, we have not focused on the key factors to improve the SINR at each SIC iteration, i.e., the slot selection mechanisms of sensing-based SPS, MCS, and RT. Based on the extensions of the SPS-NOMA concept, we propose a detailed design of SPS-NOMA in this article. Additionally, we evaluate the performance characteristics for the key factors and reveal the performance gains of SPS-NOMA in various node distribution models to highlight the effectiveness of mitigating the channel congestion.

III. SENSING-BASED SPS WITH UL-NOMA (SPS-NOMA)

In this section, we describe the system design of SPS-NOMA in the first subsection and then discuss the performance in the next subsection.

A. SYSTEM DESIGN OF SPS-NOMA

The proposed system aims to support SIC effects by sensing-based SPS. This system complies with the standard sensing-based SPS to select slots and transmit frames. The system also uses SIC decoders to decode frames in addition to sensing-based SPS procedures.

1) STEP 1: SENSING-BASED SPS-AIDED SLOT SELECTION

First, we explain the slot structure of SPS-NOMA. The main structure is the same as the standard of mode 4. Each slot contains a piece of sidelink control information (SCI) and a transport block (TB) occupied by several resource block pairs (RBPs). Every SCI includes the MCS index and the slot utilization counter; each TB conveys a CWS frame.

An RBP has four symbols in a time domain for reference signals. Initially, the reference signals are used for nodes to select slots and estimate channel gains for decoding frames. In addition to the roles at sensing-based SPS, the signals play roles in detecting simultaneous transmitters and estimating the channel gains for SIC decoding. For the new roles, the reference signals need to be orthogonal sequences between simultaneous transmitters. Methods, such as References [15], [26], can create such sequences. As an example, we can assume to use Zadoff-Chu sequences for reference signals based on [15]. The sequences are used in cellular networks. We can deploy the sequences in time and/or frequency domains, reusing the existing symbols used for reference signals of mode 4. The proposed method requires to prepare them enough to avoid collisions of them, at which multiple nodes share a reference signal. The collisions increase channel estimation errors and thus degrade SIC performance. Note that how to deploy orthogonal sequences in detail is out of scope.

Next, we briefly describe the slot selection mechanisms. The mechanisms use a history of past slots based on sensing-based SPS. The history is stored sensing information during the past 1000 milliseconds. At the beginning of the mechanisms, each node initializes the set of candidate slots to all the slots within the selection window (called SW), e.g., 100 milliseconds for 10 Hz. Subsequently, the node executes the following two mechanisms to exclude slots with estimated high interference from the candidate slots.

- RSRP mechanism: This mechanism excludes slots that satisfy both the following two conditions. (a) The decoded SCI of any past slot within SW reserves the slots. Here, $\mathcal{M}$ shows the set of reserved slots. (b) The average RSRP over RBPs of any slot in $\mathcal{M}$ is higher than the threshold $P_{th}$. The behavior is shown as:

$$\exists P_{\text{RSRP}}^m > P_{th}, \quad m \in \mathcal{M}.$$  \hspace{1cm} (1)

The mechanism has been repeated until the number of non-excluded slots becomes 20% of the SW or more to guarantee the number of candidate slots. At every next iteration, the threshold increases by 3 dB. This mechanism passes the non-excluded slots to the following mechanism.

- Received signal strength indicator (RSSI) mechanism: This mechanism filters slots with high average RSSI over the corresponding past slots. The corresponding past slots are traced back from a candidate slot at a unit of the transmission period, e.g., 100 milliseconds.
The average RSSI $\tilde{P}_{\text{RSSI}}$ is written as:

$$\tilde{P}_{\text{RSSI}} = \frac{1}{|K|} \sum_{k \in K} p_{\text{RSSI}}^k,$$

where $K$ shows the set of the corresponding past slots. The RSSI in a past slot $k$ is represented by $p_{\text{RSSI}}^k$. Based on the average RSSI of candidate slots, this mechanism sorts the candidate slots in ascending order. Finally, it selects a slot from the top 20% of the sorted slots at random.

In addition to selecting the slot, the node selects a reference signal to transmit with data. The history helps to avoid collisions of the reference signals. The node uses the history and selects a sequence unused by other simultaneous transmitters.

2) STEP 2: SENSING-BASED SPS-AIDED TRANSMISSION

Every node uses the selected slot in a semi-persistent manner. The slot utilization counter was selected at random from a range of 5–15 [6] for 10 Hz as a standard. The value decreases by one after every transmission. After continuing to use the slot in the selected times, the node reselects a new slot by Step 1.

In SPS-NOMA, nodes can optionally use RT, a potential extension of the retransmission mechanism of mode 4. The RT is inspired by Reference [27] and the retransmissions. In the reference, nodes alternately used two slots at 10 Hz. Our system uses two independent slots at 20 Hz. In other words, a node has two SPS process of 10 Hz. Unlike the retransmissions, both slots are selected by the SPS mechanism. Fig. 1 shows the behavior of the RT. In Fig. 1, node-A uses the two reserved slots. The node alternately uses the first reserved slot and the second reserved slot every 100 milliseconds. The RT provides nodes with selection diversity to improve the SINR by retransmissions based on the SPS mechanism, and nodes send their up-to-date location data more frequently. Unfortunately, the congestion level also increases. The characteristics are shown in detail in Section III-B-3).

3) STEP 3: SIC-AIDED RECEPTION

Transmitted signals are superposed at each receiver. The mixed signal $y_j^{(1)}$ at receiver $j$ is expressed as:

$$y_j^{(1)} = \sum_{i \in \mathcal{I}^{(1)}} \sqrt{P_i} g_{ij} s_i + n,$$

where $P_i$ is the transmission power, which is the same power in all the nodes because of advertising. $\mathcal{I}^{(1)}$ is the set of simultaneous transmitters at the first SIC iteration. Each of the transmitters $i$ in $\mathcal{I}^{(1)}$ transmits the signal $s_i$, $g_{ij}$ is the channel gain between $i$ and $j$, $n$ is the additive white Gaussian noise at $j$ with the spectral power density of $N_0$.

Receivers use SIC and try to decode several signals in the superposed signal. The SIC decoder iterates the signal reception and interference cancellation. An example of the SIC decoding is as below. First, receiver $j$ tries to decode the strongest signal in the superposed signal by the capture effect, in which the signal is correctly decoded under the SINR is sufficiently strong for decoding; here, the receiver $j$ successfully decodes the signal from a transmitter $x$. Subsequently, the receiver estimates the channel gain from the reference signals. The estimated gain is denoted as $\tilde{g}_{ij}$. By re-modulating the decoded signal with the estimated gain, the receiver creates the replica signal. Then, the receiver subtracts the replica signal from the mixed signal. The subtracted signal is written as:

$$y_j^{(2)} = y_j^{(1)} - \sqrt{P_i} \tilde{g}_{ij} s_i \approx \sum_{i \in \mathcal{I}^{(1)} \setminus \{x\}} \sqrt{P_i} g_{ij} s_i + n.$$

Repeatedly, the receiver tries to decode the strongest signal in $y_j^{(2)}$ by the capture effect. With these procedures, receivers obtain multiple signals, including weaker signals than the strongest signal. Note that we may observe channel estimation errors practically, for example, due to collisions of reference signals. In such cases, channel estimation errors cause every SIC iteration to accumulate residual interference in Equation (4). As a result, the SIC performance degrades. Thus, the proposed method requires the number of available reference signals enough to avoid the collisions of reference signals, although the SPS mechanism supports to avoid the collisions.
B. PERFORMANCE ANALYSIS OF SPS-NOMA

In this section, we analyze the performance of SPS-NOMA compared with the current mode 4. To the end, we discuss the number of successful SIC iterations per transmission, denoted as \( L \); in other words, \( L \) is the number of received signals at each slot. The performance of SPS-NOMA becomes \( L \)-times as large as that of the current mode 4.

\( L \) depends on the SINR at each SIC iteration. The SINR at the \( l \)-th SIC iteration is represented as:

\[
\gamma^{(l)}_j = \frac{P_i |g_{ij}|^2}{\sum_{i \in \mathcal{I}^{(l)} \setminus \{k\}} P_i |g_{ij}|^2 + N_0},
\]  
(5)

where the received signal from transmitter \( x \) is the strongest power at receiver \( j \). In Equation (5), \( \mathcal{I}^{(l)} \) shows the set of simultaneous transmitters at the \( l \)-th SIC iteration. \( |\mathcal{I}^{(l)}| = |\mathcal{I}^{(1)}| -(l-1) \). Given the channel gain as:

\[
|g_{ij}|^2 = c_{ij} d_{ij}^{-\alpha},
\]  
(6)

From Equation (6), Equation (5) is transformed as:

\[
\gamma^{(l)}_j = \frac{P_i c_{ij} d_{ij}^{-\alpha}}{\sum_{i \in \mathcal{I}^{(l)} \setminus \{k\}} P_i c_{ij} d_{ij}^{-\alpha} + N_0}. 
\]  
(7)

\( d_{ij} \) is the distance between \( i \) and \( j \). \( c_{ij} \) is the coefficient between \( i \) and \( j \). \( \alpha \) is the path loss exponent. Given a frame reception model [10] with the SINR threshold \( \gamma_{th} \), \( L \) satisfies the following condition:

\[
\left( \bigwedge_{l=1}^{L} \gamma^{(l)}_j > \gamma_{th} \right) \land \left( \gamma^{(L+1)}_j < \gamma_{th} \right). 
\]  
(8)

Based on the above discussions, \( L \) depends on the following parameters: the channel gains of simultaneous transmitters to a receiver \( g_{ij} \), the number of simultaneous transmitters \( |\mathcal{I}^{(l)}| \), and the SINR threshold \( \gamma_{th} \). In SPS-NOMA, these parameters are mainly operated by the slot selection mechanisms, MCS, and RT. In the following subsections, we discuss the relationship between these parameters and the key factors in SPS-NOMA.

1) SENSING-BASED SPS-AIDED SLOT SELECTION

The first key factor is the slot selection mechanisms of sensing-based SPS. The mechanism operates \( g_{ij} \) and \( |\mathcal{I}^{(l)}| \). Based on Equation (7), we analyze the mechanisms and \( L \) below.

– RSRP mechanism

This mechanism assesses the power contribution of the strongest signal in the candidate slots. A node \( z \) senses the following average RSRP when the transmitter \( x \) in Equation (7) reserves a candidate slot in a past SCI under \( \gamma_z^{(1)} > \gamma_{th} \):

\[
P_{RSRP} = P_i \hat{c}_{xz} d_{xz}^{-\alpha},
\]  
(9)

where \( \hat{c}_{xz} \) is the average \( c_{xz} \) over reference signals in used RBPs. From Equation (1) and Equation (9), the filtering condition of this mechanism is written as:

\[
P_i \hat{c}_{xz} d_{xz}^{-\alpha} > P_{th} \iff d_{xz}^{-\alpha} > \frac{P_{th}}{P_i \hat{c}_{xz}} \iff d_{xz} < \sqrt{\frac{P_i \hat{c}_{xz}}{P_{th}}}. 
\]  
(10)

From Equation (10), this mechanism excludes slots that \( x \) near \( z \) uses. At such a slot, the channel difference between \( g_{ij} \) and \( g_{kj} \) is small at receiver \( j \), and thus, \( \gamma_j^{(l)} \) is also small. As \( P_{th} \) increases, this effect also increases. In contrast, a \( P_{th} \) that is too small limits \( |\mathcal{I}^{(l)}| \). \( L \) depends on the two impacts.

Unfortunately, this mechanism does not cover slots with the non-decoded SCI, even if the slots provide higher interference than the other slots. As collision errors increase, the contributions of the mechanism decrease.

– RSSI mechanism

This mechanism assesses the expected interference at the future slots, based on the RSSIs at the past slots. A node \( z \) senses the following RSSI at the corresponding past slot \( k \):

\[
P_{RSSI}^k = \sum_{i \in \mathcal{I}^{(l)}} P_i c_{iz} d_{iz}^{-\alpha} + N_0. 
\]  
(11)

By this mechanism, \( z \) uses a slot with a relatively lower RSSI than other slots. At such a slot, the number of simultaneous transmitters is likely to be smaller, and the number of transmitters near \( z \) is likely to be smaller than the other slots. As a result, \( \gamma_j^{(l)} \) is expected to decrease on average.

Unfortunately, this mechanism refers to no reservations. Positively, the behavior covers the assessments of the collided slots, which the RSRP mechanism does not support. Negatively, the average RSSI of this mechanism in Equation (2) may include RSSIs of past slots unrelated to future slots; in other words, \( \mathcal{K} \) may include nodes that do not reserve the candidate slot. For example, transmitters in a slot may not use the same slot after 1000 milliseconds. In such cases, this mechanism incorrectly predicts the interference, and thus, nodes may not select a better slot for SPS-NOMA. When the positive effect is more dominant than the negative impact of this behavior, the mechanism enhances \( L \).

2) MCS

The second key factor is MCS. It operates the trade-off between SINR threshold \( \gamma_{th} \) and the average interference level. At first, low-index MCSs allow nodes to decode signals more reliably than high-index MCSs. In a threshold-based model, the effect means that the SINR threshold \( \gamma_{th} \) decreases. Decreasing the SINR threshold is effective for every SIC iteration in Equation (8).

However, low-index MCSs convey fewer data bits per symbol than high-index MCSs. This characteristic decreases the number of slots, increasing the number of simultaneous transmitters \( |\mathcal{I}^{(l)}| \) per slot at each SIC iteration. Increasing \( |\mathcal{I}^{(l)}| \) means to amplify the interference in \( \gamma_j^{(l)} \). Based on these two impacts, low-index MCSs provide larger \( L \) than high-index MCSs when decreasing the SINR threshold is more dominant than amplifying the interference.

3) REDUNDANT TRANSMISSION

The third key factor is RT. The RT provides the trade-off between the SINR selection diversity and the average interference level. As the positive impact, using multiple slots boosts selection diversity for interference and fading in the time and...
frequency domains. This diversity provides to increase the SINR \( \gamma_j^{(l)} \). Fig. 1 illustrates the diversity effects. In Fig. 1, node-A uses the first slot with node-B and the second slot with node-C. In the first slot, node-A cannot obtain a sufficiently large SINR for the receiver due to transmitting frames with node-B. In the second reserved slot, node-A obtains enough SINR for the SIC decoding. In particular, high-index MCSs are more effective than low-index MCSs in terms of the number of available slots.

As the negative impact, RT becomes twice as many frames as nothing of RT. The increase involves increasing the number of simultaneous transmitters \( |T^{(l)}| \) at each slot on average, i.e., the interference is amplified on average. As the number of nodes is more, the negative impact of the redundancy is more dominant. Although the number of frames increases in proportion to the number of nodes originally, the redundancy doubles the increasing ratio. Thus, \( L \) increases when the selection diversity is more dominant than amplifying the interference.

IV. EVALUATION MODEL

We focused on CWS scenarios because the system has been one of the most important V2X applications. We implemented SPS-NOMA in our system-level simulator [25] and simulated the behaviors of SPS-NOMA in the CWS in crash scenarios. The simulator computed the system-level performance based on the simulated SINRs. In the first subsection, we describe the performance metrics and the CWS scenarios considering the QoS requirements, summarized in Table 2. In the second subsection, we explain the wireless parameters. Note that the QoS requirements in Table 2 are similar to the evaluations.

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### TABLE 2. QoS Requirements of the CWS.

| Requirements                  | Required values                      |
|-------------------------------|--------------------------------------|
| Frame update frequency        | 10 Hz or more [3]                    |
|                               | (Every 100 milliseconds)             |
| Reliability of frame reception| 90% or higher [3]                    |
| Warning period                | 2.5–3.5 seconds [4]                  |
| Maximum end-to-end latency    | 100 milliseconds [5]                 |

A. PERFORMANCE METRICS AND CRASH SCENARIOS (CWS MODEL)

We used the following two performance metrics and used another metric for the RT in addition to the two metrics. The first metric is the frame reception reliability per time window of 100 milliseconds during the warning period, defined as frame receivability (FR). In other words, this metric indicates the probability that a receiver correctly receives one or more frames from a transmitter during a time window. The time window reflects the first requirement in Table 2 because the target system essentially requires reliably periodic frame reception per time window. The warning period included ten windows, and thus, the FR \( p_{FR} \) was computed as:

\[
p_{FR} = \frac{n_{success}}{10},
\]

where \( n_{success} \) is the number of success windows per second and is divided by the total number of windows per second (i.e., ten windows). This metric provides system-required performance. This metric is based on the concept of the packet delivery ratio (PDR) used in many studies [7] [8]. Note that a packet is the same meaning as a frame in this article.

The second metric was NAC. Based on the FR, we refined it as the maximum number of surrounding nodes under \( p_{FR} \geq 0.9 \). This metric shows the performance under the required reliability of the CWS and the feasibility of methods for channel congestion. We mainly compared this metric of each method. Note that we did not measure a maximum end-to-end latency of transmitted frames because sensing-based SPS-NOMA suppresses the latency up to 100 milliseconds.

We measured the FR of a node (called a target receiver) from a node (called a target transmitter). Fig. 2 presents the behavior of the two nodes before 3 seconds prior to their potential crash. As shown in Fig. 2, the two nodes frontally approached each other. Such a head-on crash scenario provides the longest distance during the warning period in other crash scenarios. Thus, the link undergoes the worst performance. We distributed the other nodes within the range radius of 300 m from the center of the circle in Fig. 2. The surrounding nodes played a role in creating the channel congestion; specifically, they were competitors of the slot selections and interference for the target nodes. In Fig. 2, the target transmitter and the other two nodes used a slot at the same time.

The density of the nodes complied with the uniform model or Bologna models, building various crowded environments. The uniform model was one of the fundamental stochastic models and thus provided us with the average performance. Additionally, the model freely operated the number of nodes,
allowing us to evaluate NAC; we investigated the performance at the number of nodes from 60 nodes to 500 nodes. The Bologna models were based on Bologna data through the simulation of urban mobility (SUMO) simulator [28], [29]. The data are open location data in Bologna, Italy, available at http://sumo.dlr.de/wiki/Data/Scenarios. Many researchers have used these data to obtain realistic node distribution models [28], [29]. Thus, the model provided us with a realistic performance. From the Bologna data, we selected the intersection shown in Fig. 3 (a). Fig. 3 (b) shows that the number of nodes within 300 m varied with time. The horizontal axis is the time from the beginning time of the data in seconds. The curve shows that the number of nodes was the highest at 3250 s, and we can observe to distribute more nodes around the time than the other time.

All the nodes moved in their specified directions. The target nodes were assumed to move at 60 km/h in urban areas. The surrounding nodes moved as follows. In the uniform model, each of the speeds was either 3 km/h for pedestrians or 15 km/h, or 60 km/h for cars [30]. The directions were fixed at random. In the Bologna model, the speeds complied with the mobility of the nodes in the data. The locations were updated every 50 milliseconds, in contrast to Reference [30], which updated them every 100 milliseconds. The reason for using 50 milliseconds is that the smallest transmission period was 50 milliseconds in using the RT.

**FIGURE 2.** The abstract image of the node distribution and communication behaviors before 3 seconds prior to the potential crash.

**FIGURE 3.** The geographic and stochastic information of the Bologna model.

Each slot has several RBPs. The number of occupied RBP depends on the used MCS. We used two typical MCSs: MCS 4 as a low-index MCS and MCS 9 as a high-index MCS. The two MCSs present the relationship between the number of slots and the SINR threshold, as analyzed in Section III–B–2). Given the frame size of 190 bytes at the standard of CWS [7], each slot consumes 24 RBPs at MCS 4 and 12 RBPs at MCS 9 [31]. Thus, the system had two slots per millisecond at MCS 4 and four slots per millisecond at MCS 9. The number of slots was 2000 slots/s for MCS 4 and 4000 slots/s for MCS 9. In our simulations, all the nodes completely synchronized the timing of the slots by GNSS.

The channel model was as follows. The transmission power was set to 23 dBm [7]. We assumed that the power was divided into occupied RBPs [32]. The transmitted signals attenuated along to the WINNER+ B1 model [33], which METIS has recommended for mode 4 [34]. In particular, we used the LOS model to create the most severe interference conditions at the node densities. In the model, the antenna height was 1.5 m [34]. In our simulations, the propagation model included log-normal shadowing gains with a deviation of 3 dB [7]. The gains were independent and identically distributed (i.i.d.) values between nodes. In each node, the decorrelation distance was 10 m [8], [30]. The shadowing gains were updated with updating locations [30], i.e., every
TABLE 3. Summary of wireless parameters.

| Parameters for bandwidth | Values |
|--------------------------|--------|
| Carrier Frequency        | 5.9 GHz [6] |
| Bandwidth                | 10 MHz (50 RBs) |
| Frame size               | 190 bytes [7] |
| MCS index                | 4 or 9 (the default is 4) |
| The number of RBPs per slot | MCS 4: 24 pairs  
MCS 9: 12 pairs |
| The number of subchannels | MCS 4: 2  
MCS 9: 4 |

| Parameters for channel | Values |
|-----------------------|--------|
| Transmission power    | 23 dBm [7] |
| Propagation model     | WINNER+ [33] |
| Shadowing model       | Log-normal [7] |
| Shadowing deviation   | 3 dB [7] |
| Noise power per RB    | −110 dBm [35] [36] |
| SINR threshold        | MCS 4: 2.7 dB  
MCS 9: 9.6 dB |

| Parameters for SPS-NOMA | Values |
|-------------------------|--------|
| Number of transmissions | 10 Hz |
| Initial RSRP threshold  | −110 dBm [6] (Default) |
| Slot utilization counter | 5–15 [6] |

50 milliseconds. Also, the noise power per RB was set to −110 dBm [35], [36]. We assumed that frames were correctly received under the simulated SINR was above the SINR threshold. The threshold was 2.7 dB for MCS 4 or 9.6 dB for MCS 9 [31].

Next, we describe SPS-NOMA parameters. At first, nodes transmitted frames at 10 Hz, except for 20 Hz for the RT. The initial RSRP threshold was set to −110 dBm [6] by default, which is the same value as noise power. Also, each slot utilization counter was 5–15 times for 10 Hz at the standard. We assumed the perfect channel estimation because of the following reasons. First, our main aim is to present the primary performance characteristics of the proposed method as the first step. The fundamental assumption supports the essential performance of SPS-NOMA; many related works [16]–[23] also assumed the perfect channel estimation to show the essential performance. Second, channel estimation techniques have advanced [37] and will improve the estimation accuracy in the future. The third reason is related to the collisions of reference signals, which cause channel estimation errors. Reference [26] assumed to use twelve orthogonal sequences for reference signals. Also, the ideal assumptions of related works [18]–[23] mean that their systems have prepared many reference signals enough to avoid collisions of reference signals. Based on the above works, our proposed method can also assume to be available to use similar numbers of the signals. Compared with the number of available reference signals, at most several nodes simultaneously share a slot because of at most 500 nodes per 100 slots at MCS 4 and the RT. In addition to the numbers of reference signals, the proposed method uses the sensing history to avoid the collisions of reference signals, as described in Section III-A-1). Finally, given the system has enough numbers of reference signals, the interference is expected to provide more dominant impacts to SIC performance degradation than collisions of reference signals.

Finally, we describe how to measure the FR and the PDR. We averaged 2000 outputs to guarantee the computational accuracy of these metrics; specifically, the sizes of the errors of the 95%-confidence interval were within ±0.02 in all the plotted data. As reference values of computational accuracy of data, we drew the error bar for each plotted data. Additionally, each simulation ran for 4.1 seconds to exclude the transition duration of the sensing-based SPS. Nodes generated the first frames within the first 100 milliseconds. During the next 3 seconds, nodes have executed their SPS procedures at least twice. After these durations, the FR during the last second was investigated.

V. PERFORMANCE EVALUATION OF SPS-NOMA

The first subsection presents the impacts of the key factors and performance gains of SPS-NOMA in the uniform model. The next subsection highlights the practical performance gains of SPS-NOMA in the Bologna model.

A. PERFORMANCE CHARACTERISTICS AND AVERAGE PERFORMANCE

1) SLOT SELECTION MECHANISMS OF SENSING-BASED SPS

This subsection focuses on the performance characteristics of SPS-NOMA for the sensing-based SPS mechanism. Fig. 4 presents the performance characteristics for the initial RSRP threshold at MCS 4 at 360 nodes. The horizontal axis is the initial RSRP threshold, and the vertical axis is the FR. Fig. 4 shows the performance trend of SPS-NOMA for the RSRP threshold discussed in Section III–B–1). The small thresholds, such as −110 dBm, were effective for
the performance improvements. In the simulations, avoiding selecting slots used by near transmitters was more effective than decreasing the number of superposed signals.

Fig. 5 depicts the FR characteristics of SPS-NOMA and UL-NOMA with either of the slot selection mechanisms for the number of nodes at MCS 4. In other words, this graph shows the contributions of each mechanism in SPS-NOMA. The horizontal axis is the number of nodes, and the vertical axis is the FR. The label of RSRP-only or RSSI-only means methods implementing either of the slot selections. Fig. 5 highlighted that the RSRP mechanism was more dominant in the performance of SPS-NOMA than the RSSI mechanism. In UL-NOMA, the RSRP mechanism achieved an NAC of 360 nodes, which is the performance close to SPS-NOMA; the RSSI mechanism reached an NAC of 260 nodes. Thus, the RSRP mechanism was 38% larger NAC than the RSSI mechanism.

Fig. 6 shows the FR trends of each mechanism of UL-NOMA and OMA. The graph highlighted the performance gains of UL-NOMA in each mechanism compared with OMA at MCS 4. The axes are the same as in Fig. 5. UL-NOMA boosted the NAC of the original RSRP mechanism by 29% and the NAC of the original RSSI mechanism by 30%. In summary, SPS mechanisms and UL-NOMA are significant synergies.

2) MCS
Fig. 7 highlights the FR trends of SPS-NOMA for every MCS index in comparison with the current mode 4. This graph emphasized the positive and negative impacts of the choice of MCS for SPS-NOMA. The axes are the same as Fig. 5.

At first, we can observe the trade-off of the choice of the MCS from Fig. 7. In MCS 4, the current mode 4 accommodated 260 nodes; SPS-NOMA accommodated 360 nodes. Thus, SPS-NOMA improved the performance of current mode 4 by 38%. In MCS 9, the current mode 4 achieved an NAC of 220 nodes, and SPS-NOMA achieved an NAC of 240 nodes. The performance gain was limited, and the improvement ratio was 9%. By comparing the performance gains for mode 4 at MCS 4 and 9, we highlight that decreasing the SINR threshold contributes to more effective SIC decoding than decreasing the number of slots. Notably, these results demonstrated that congestion environments needed the ability to cover collisions, which has low-index MCSs.

Next, we compare the performance of SPS-NOMA for the choice of MCS. Based on Fig. 7, using MCS 4 showed better performance than using MCS 9 for SPS-NOMA; the performance difference was 50%. Thus, SPS-NOMA recommended using MCS 4 to improve performance more.

3) REDUNDANT TRANSMISSION
Fig. 8 plots the FR characteristics of SPS-NOMA with/without RT. The axes are the same as in Fig. 5. In Fig. 8, we can observe the trend (the positive and negative impacts) of the RT, as discussed in Section III–B–3). In MCS 4, at small numbers of nodes, less than 320, the RT improves the FR above the method without the RT. However, at numbers of nodes more than 340, the negative impact of the RT was observed. As a result, the NAC decreased by 6% below the SPS-NOMA without the RT. At MCS 9, such a trend was also observed, as well as at MCS 4. The negative impact was represented at 360 nodes or more. In MCS 9, the method with the RT provided 8% more NAC than the method without the RT. Based on these results, amplifying the interference,
i.e., the negative impact, was more dominant than the impact of selection diversity, i.e., the positive impact, especially in MCS 4. In the uniform model, the effects of the RT were limited for increasing the maximum NAC.

In Fig. 9, we show the FR and PDR trends in the RT. As a reference, we plotted the PDR trend of the current mode 4 at MCS 9. The horizontal axis is the number of nodes. The vertical axis is the FR or PDR. This graph demonstrated that the RT at both MCSs showed much lower PDRs than mode 4 at MCS 9 overall. In other words, the negative impact of the redundancy reduced the reception reliability per frame, even in using SIC. In contrast, we can observe that the redundancy effects increased the reliability per time window by comparing the FR and PDR at the same MCSs.

B. REALISTIC PERFORMANCE OF SPS-NOMA

Fig. 10 plots the FR characteristics of SPS-NOMA and the current mode 4 in the Bologna model. This graph shows the practical performance of SPS-NOMA. The horizontal axis is time; the number of nodes varied with time, as shown in Fig. 3. The vertical axis is the FR. To emphasize the effects of SPS-NOMA, we plot the performance of SPS-NOMA at only MCS 4 and mode 4 at both MCSs.

First, we describe the overall trends. In this evaluation, the SPS-NOMA with the RT showed consistently better performance than the other methods. SPS-NOMA without the RT followed the above method. These methods outperformed the current mode 4. Next, we compare the number of situations that satisfied the QoS requirements. In mode 4, the number of satisfied situations was nine in MCS 4 and three in MCS 9. In contrast, SPS-NOMA without/with the RT satisfied the requirements in 20 or 22 situations, respectively. Particularly, SPS-NOMA with the RT addressed 144% more situations than the current mode 4 and satisfied the requirements in most situations in the Bologna models.

As examples, we show the largest FR gain and the smallest gain between SPS-NOMA with the RT and mode 4 at MCS 4 under satisfying the QoS requirements. First, the SPS-NOMA provided the smallest gain at 250 s. Then, the mode 4 and the SPS-NOMA provided the FRs of 0.95 and 0.99, respectively; the gain was 5%. Also, the SPS-NOMA provided the largest gain at 3750 s in other situations, compared with the mode 4.
At the time, the mode 4 and the SPS-NOMA achieved the FRs of 0.84 and 0.92, respectively; the gain was 10%, and the SPS-NOMA became to satisfy the QoS requirements.

Fig. 11 shows the FR and the PDR trends of the RT. The horizontal axis is time, and the vertical axis is the same as Fig. 9. As well as Fig. 9, we referred to the PDR characteristics of the current mode 4 at MCS 9. The RT showed smaller PDR than mode 4 at MCS 9 in most situations, even in the Bologna model because of redundancy. In other words, at the level of reception reliability per frame, SIC was not useful to cover the negative impact of the redundancy; however, at the reception reliability per time window, the RT significantly supported to improve SIC gains. In conclusion, SPS-NOMA also advanced the performance of the current mode 4 in the realistic node distribution model. In particular, the RT mechanism was effective in practical uses.

VI. CONCLUSION
This article highlighted the performance gains of SPS-NOMA in the CWS to explore the next generation sidelink C-V2X. SPS-NOMA uses UL-NOMA in mode 4. In SPS-NOMA, multiple nodes simultaneously broadcast frames, and receivers decode the superposed signal by SIC. SPS-NOMA enables nodes to access the V2X channel more efficiently than the current mode 4. Our simulation results highlighted that SPS-NOMA outperformed mode 4 in the uniform node distribution model and realistic models. In the uniform model, SPS-NOMA boosted the NAC of mode 4 by 38%. In realistic cases, the proposed method satisfied the QoS requirements of the CWS in 144% more situations than the current mode 4. These results demonstrated that SPS-NOMA showed an excellent option for the potential extension of sidelink C-V2X mode 4.

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