NO-V2X: Non-Orthogonal Multiple Access with Side Information for V2X Communications

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Abstract. We study a vehicle-to-everything (V2X) communication scenario where multiple vehicles coming from different road segments converge at a road junction and exchange their information via a road side unit. The high-mobility of vehicles determines that the communication is time-critical. If conventional orthogonal multiple access (OMA) is applied, not only the orthogonal resource allocation but also the scheduling overheads will incur significant delay. In addition, orthogonal domain may not be identified within short contact time among vehicles and the road-side unit. In contrast, non-orthogonal multiple access (NOMA) can provide low-delay and reliable communication by exploiting the overlapped or collided signals. In this paper, we investigate the application of NOMA with side information in V2X communications as the Non-orthogonal V2X (NO-V2X) scheme. NO-V2X takes the advantage of side information and physical-layer network coding (PNC) to increase the decoding success rate in the uplink phase and to reduce the required transmission power in the downlink phase. Our simulation results show that NO-V2X outperforms OMA and the conventional NOMA with successive interference cancellation (SIC).

Key words: non-orthogonal multiple access, V2X communication, side information, physical-layer network coding, network-coded multiple access

1 Introduction

The third generation partnership project (3GPP) group standardized the initial Cellular Vehicular-to-Everything (C-V2X) communication in Release 14 [1]. The document justifies that the world-wild research on connected vehicles (e.g. CCSA in China) shows the market requirement on Long Term Evolution (LTE) based V2X communication [2]. To respond to such situation, the standard proposes LTE-based V2X communication and offers three types of communications: vehicle-to-vehicle (V2V), vehicle-to-infrastructure/network (V2I/N) and vehicle-to-pedestrian (V2P) communications. Soon after, the 5G Automotive Association (5GAA) employed C-V2X for safety and cooperative driving in its white paper [3]. V2X is expected to provide real-time/low-latency, high-reliable communications in a dense moving environment due to the characteristic of vehicles.

Fig. 1 illustrates a common V2X communication scenario. Vehicles from different directions converge at a road junction, and they have different destination road segments. In such a short duration, each vehicle needs to transmit its self-information (e.g. traffic information of the road segment that it has traveled) to another vehicle (e.g. traffic information of the destination road segment). We consider the following transmission pattern: $1 \rightarrow 2 \rightarrow 3 \rightarrow 4 \rightarrow 1$, as illustrated in Fig. 1. The arrows represent the direction of information flow. Since the radio channels between

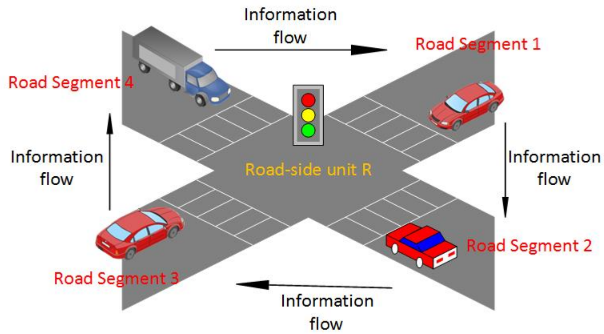

Fig. 1. V2X communication at a crossroad.

any two vehicles are obstructed by buildings or other obstacles, all vehicles need the road-side unit, R, to relay the self-information.

Based on orthogonal multiple access (OMA), the current LTE allocates spectrum resources to users in an orthogonal manner. For the case in Fig. 1, vehicles transmit data in either different time or frequency to the relay in the uplink phase, then the relay forwards the data in the same manner in the downlink phase. It is uncertain if OMA can meet the requirement of V2X communication. Considering a dense vehicular network in urban area, OMA needs to perform orthogonal resource allocation and requires overheads to schedule multiple users, which leads to increasing delay as the number of users increases. In addition, orthogonal domain may not be identified within short contact time among vehicles and the road-side unit. For the case in Fig. 1, OMA with 4-user access generates at least four times latency compared with single-user access. By exploiting the overlapped or collided signals, non-orthogonal multiple access (NOMA) [4] is considered as a promising candidate to achieve low-latency and high-reliability in V2X communication.

The concept of NOMA has been proposed and studied for a long time [5, 6], but the research on the practical application is relatively new and shoot up in recent years. NOMA allows multiple users to be served by one transceiver simultaneously at either the uplink and downlink phase. By sharing the spectrum resources at the same time, NOMA can boost the throughput and reduce the latency significantly, especially when the number of access users is large [7]. For the same case in Fig. 1, vehicles from different directions transmit data at the same time and frequency to the relay, the relay decodes the individual information and forwards it to all end nodes simultaneously. Thus, the delay of NOMA with 4-user access is the same as that of single-user access theoretically. To cope with the co-channel inference caused by spectrum sharing, various multi-user detection (MUD) techniques such as successive interference cancellation (SIC) [8] have been proposed. In this paper, we investigate the feasibility of applying NOMA in V2X communications. If the application is feasible, we would like to see if the performance can be further improved with respect to the characteristic of V2X communications.

Generally, a SIC-based NOMA receiver decides the decoding order according to the received power level. The user with the strongest power is decoded first and the signals from other users are regarded as noise. After one user is decoded, the corresponding signal is removed and the next strongest user is decoded. It turns out that the power difference among multi users is essential for SIC receivers. For 2-users access, when the power levels of two users are close, the decoding signal-to-noise ratio (SNR) for the strongest user is lower than 0 dB. Under such situation, the SIC receiver may fail to decode the strongest user due to the low SNR, and the other user cannot be decoded as well since the interference from the strongest user cannot be removed. Power control is simple in the downlink phase but difficult in the uplink phase, a common way to guarantee the power difference in the uplink phase is user grouping. This method requires the channel state information (CSI) to pair the strong user and the weak user [9].

Recently, several works on NOMA in V2X communications have been published [10–12], the three schemes are based on SIC. Specifically, [10] and [11] focus on scheduling design and resource allocation algorithm to maximize the decoding success rate and throughput, and [12] investigated the use of side information, which is used for interference cancellation for the strong user, to enhance the transmission of the weak user. Similar idea that exploits side information has been studied in previous works [13], the difference is that [12] studied the performance under multiple-input multiple-output spatial modulation (MIMO-SM) and V2V networks.

Different from static networks, the high-mobility of vehicles makes power control and user grouping in the uplink phase challenging, and this may destroy the time-critical transmission in Fig. 1. In this work, we investigate the possibility of removing power control and user grouping in the uplink phase. Specifically, all end nodes with random CSIs are allowed to transmit data at the same power level simultaneously, thus the overhead and delay can be reduced. In the downlink phase, we exploit the side information used for SIC to further improve the data exchange shown in Fig. 1. Different from the previous use of side information which simply re-transmit the side information to the weak user, we exploits the side information according to the pattern of V2X communications. Overall, this paper proposes a novel NO-V2X architecture that exploits the side information (e.g. self-information in the uplink phase and information used for SIC in the downlink phase) to achieve low-latency and reliable communication, the salient features of NO-V2X are as follows:

1. In the uplink phase, NO-V2X applies Network-Coded Multiple Access (NCMA) [14] and side information to increase the decoding success rate. The proposed NO-V2X outperforms SIC-based NOMA and OMA under independent Rayleigh fading channels.
2. In the downlink phase, benefit from the side information, NO-V2X applies Physical-layer Network Coding (PNC) to encode the transmitted data and the amount of data can be reduced by $\frac{1}{\#\text{ users}}$. In other word, the required transmission power can be reduced for achieving the same throughput and delay as conventional NOMA.

The remainder of this paper is organized as follows. Section II introduces the system models. After that, the proposed NO-V2X is discussed in Section III. NO-V2X can be divided into the uplink and downlink phases, and they are described in detail and evaluated with simulation results. Finally, IV concludes the paper.

2 System models

Before introducing the proposed architecture, this section provides the details with respect to the system models. In this paper, we consider the V2X communication scenario as shown in Fig. 1.

2.1 NOMA uplink

In the uplink phase, K vehicles from different directions upload the self-information to the relay R. The received signal at R is

$$y(t) = \sum_{k=1}^{K} h_k(t)x_k(t) + n(t) \tag{1}$$

where t is the time index, $h_k(t)$ is the channel gain, $x_k(t)$ denotes the transmitted data, and $n(t)$ is the complex white Gaussian noise (WGN) with zero mean and variances N_o. The transmitted data undergo independent radio channel and the corresponding channel gain can be written as the product of slow fading and fast fading:

$$h_k(t) = h_k^{slow}(t)h_k^{fast}(t) \tag{2}$$

The slow fading is simplified as one and the fast fading is modeled as independent Rayleigh fading with expectation:

$$E(|h_k^{fast}(t)|^2) = 1 \tag{3}$$

2.2 NOMA downlink

In the downlink phase, SIC-based NOMA assigns different power levels to users according to the CSI. The transmitted signal from R is expressed as:

$$x(t) = \sum_{k=1}^{K} \alpha_k x_k(t) \tag{4}$$

The users with the worst channel (e.g. user $k = \arg\min_k |h_k(t)|^2$) is assigned with the maximum power, other users need to decode the data of user $k = \arg\min_k |h_k(t)|^2$ and remove it with SIC before decoding the target data. To guarantee the fairness among all users, we assign the power coefficients α_k to ensure that all users share the same capacity:

$$\begin{aligned} &C_k = log(1 + \frac{|\alpha_k h_k|^2}{N_o + (\sum_{\{j||h_j|>|h_k|\}} |\alpha_j|^2)|h_k|^2}) \\ &C_k = C_j, \forall k \neq j \\ &\sum_{k=1}^{K} \alpha_k^2 = 1 \end{aligned} \tag{5}$$

2.3 Physical-layer Network Coding (PNC) and Network-Coded Multiple Access (NCMA)

PNC is widely studied to boost the performance of two-way relay channel (TWRC) [15]. Consider a similar network in Fig. 1 with two users only. In this case, PNC decodes the XOR-ed output of two users $x_R = x_1 \oplus x_2$ instead of the individual information and broadcasts it in the downlink phase. One significant feature is that PNC works well under the power-balanced situation. Thus, PNC is regarded as NOMA and a new MUD architecture named Network-Coded Multiple Access (NCMA) was proposed in [14]. Consider a 2-user access case with $|h_1| > |h_2|$, NCMA decodes not only the individual information but also the XOR-ed output. SIC-based NOMA detects the strongest user while regarding the signals from other users as noise. The SIC decoder calculates the likelihood function of the data $x_1(t)$, namely the probability of $x_1(t)$ given the received signal $y(t)$, as

$$p(x_1(t)|y(t)) \propto \exp\{-|y(t) - h_1(t)x_1(t)|^2/(N_o + |h_2(t)|^2)\} \tag{6}$$

where the expected power of transmitted data $E(|x_2|^2)$ is normalized as one. In PNC, the detection is different. Specifically, the PNC decoder first calculates the likelihood function of the data pair $(x_1(t), x_2(t))$ as

$$p(x_1(t), x_2(t)|y(t)) \propto \exp\{-|y(t) - h_1(t)x_1(t) - h_2(t)x_2(t)|^2/N_o\} \tag{7}$$

And the likelihood function of individual information is calculated as:

$$p(x_1(t)|y(t)) = \sum_{x_2(t)} p(x_1(t), x_2(t)) \tag{8}$$

Similarly, the likelihood function of XOR-ed data is equivalent to:

$$p(x_1(t) \oplus x_2(t)|y(t)) = \sum_{x_1(t)\oplus x_2(t)} p(x_1(t), x_2(t)) \tag{9}$$

After the individual and XOR-ed data detection, the receiver may decode partial data as illustrated in Table. 1. The black ticks shown in the table denote the successfully received packets (e.g., with CRC checking). As can be seen, three out of six packets of x_1 are received while only two packets of x_2 are correct. In the meanwhile, $x_1 \oplus x_2$ is also decoded and two packets pass the checking. In NCMA, bridging on PHY and MAC layers is performed:

PHY-layer Bridging: In time slot three and five, both x_1 and $x_1 \oplus x_2$ are decoded, in this case, x_2 can also be decoded with $x_2 = x_1 \oplus x_1 \oplus x_2$. Thus, $x_1 \oplus x_2$ can be used to recover x_1 or x_2 via PHY-layer bridging, and the data recovered by PHY-layer bridging are denoted with blue circles.

MAC-layer Bridging: Applying an erasure channel code (e.g., the Reed-Solomon (RS) code), one frame is partitioned into multiple packets. We assume the use of a (6, 3) RS code, and thus one frame can be recovered once three packets are received. In Table 1, the packets of x_1 at time slots one, four and six can be recovered with RS code, and we denotes them with red triangles. Then, we can decoded the lone $x_1 \oplus x_2$ packets at time slot one and four accordingly.

Through performing the PHY-layer and MAC-layer bridging, the PNC decoder can be used to enhance the MUD decoder, and NCMA has been theoretically and practically verified to be a feasible receiver for power-balanced NOMA [16]. However, the goal of NCMA is to decode the individual information of all users under the access point (AP) mode, which may be an overkill for the V2X scenario considered as the vehicles are supposed to have side information.

3 NO-V2X

In the introduction section, a question regarding the feasibility of NOMA in V2X communications is raised. We give the positive response to the question by exploiting the usage of side information in this section. Our study is divided into the uplink and the downlink phases, and we will show how NOMA based V2X communication benefits from side information in the two phases. To begin with, we study the feasibility of allowing all users with random CSIs to transmit data in the same power level.

Table 1. NCMA decoding

Time Slot	x_1	x_2	$x_1 \oplus x_2$
1	△	√	
2	√		
3	√	○	√
4	△	√	
5	√	○	√
6	△		

3.1 NO-V2X uplink

As discussed above, the key bottleneck to apply NOMA in V2X communications is the delay caused by complicated scheduling and resource allocation. Unlike the previous NOMA architectures that employ either power control or user grouping, the proposed NO-V2X allows all users with diverse CSIs to transmit data in the same power level simultaneously in the uplink phase, thus the requirement of low-latency can be achieved. PNC is verified to provide good performance under the power-balanced situation [14, 16], thus is exploited in NCMA to boost the MUD throughput.

In this work, we further investigate the direct usage of the XOR-ed output of two packets (e.g., $x_1 \oplus x_2$). For the V2X communication shown in Fig. 1, user 1 requires the information from direction 4 (i.e., x_4). Inspired from PNC, relay R can either transmit x_4 or $x_1 \oplus x_4$ to user 1 in the downlink phase since the user can recover $x_4 = x_1 \oplus x_4 \oplus x_1$ with the side information x_1. Similarly, the decoded XOR-ed output of other packets can be used in the downlink phase since the end node can recover the target data with side information. Previous work [16] has proved the high success rate of PNC decoders under power-balanced situation. We further evaluate the proposed NO-V2X under random power levels. Specifically, independent Rayleigh fading is utilized to model the channels for all users.

Fig. 2 and 3 show the throughput and delay of the V2X network illustrated in Fig. 1. Three types of decoders are simulated: OMA, SIC-based NOMA and NO-V2X. As can be seen, the two

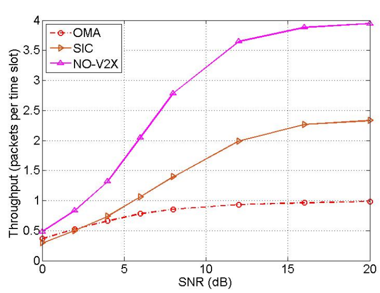

Fig. 2. Throughput of 4-user uplink.

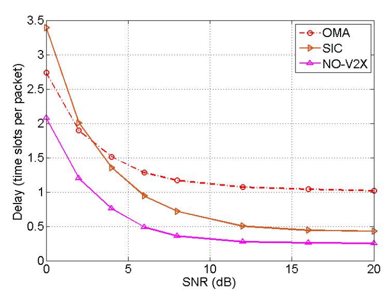

Fig. 3. Delay of 4-user uplink.

NOMA methods outperform the OMA method, the gap reaches the highest in the high SNR regime. Notice that the maximum throughput is 4 packets per time slot and the minimum delay is 0.25 time slot per packet when there is no error. But the SIC decoder can only achieve the throughput of less than 2.5 packets per time slot. The reason is that the success of SIC decoding strongly depends on the power difference among users. When there is no power control, SIC decoder cannot guarantee reliable communication, thus is not suitable for such V2X communication scenario in Fig.

1. By contrast, the NO-V2X decoder shows high throughput and low delay under random power levels. Furthermore, NO-V2X reaches the maximum throughput and minimum delay at 20 dB. Actually, in the low SNR regime (e.g., 4 dB), NO-V2X already provides more than 60% throughput improvement compared to the other two methods. Therefore, NO-V2X appears to be the solution to satisfy the requirement of random power levels in NOMA, and enables robust time-critical V2X communications.

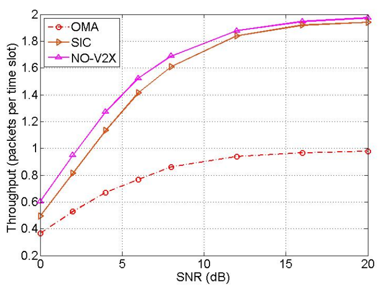

Fig. 4. Throughput of 2-user uplink.

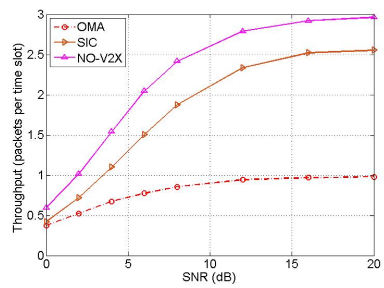

Fig. 5. Throughput of 3-user uplink.

In addition, the 2-user and 3-user uplink cases are shown in Fig. 4 and 5 to compare the performance of the three methods under different number of access users. The 2-user case is equivalent to the TWRC network and the 3-user network is performing data exchange at a T junction. The two simulations draw the same conclusions: 1) NO-V2X provides the best performance, followed by SIC, and the two NOMA methods outperforms the OMA method; and 2) NO-V2X can reach the maximum throughput at around 20 dB SNR. The key difference among Fig. 2, 4 and 5 is that the gaps between any two algorithms become larger as the number of access users increases. Therefore, NO-V2X is especially suitable for practical dense V2X communications where the number of connected vehicles is large.

3.2 NO-V2X downlink

The previous subsection studies the feasibility of NOMA in V2X communications. The study shows that NO-V2X offers the positive response via using NCMA and side information in the uplink phase. In this subsection, we investigate the downlink phase. For simplification, data from all users are assumed to be successfully decoded in the uplink phase. Different from the uplink phase, power control is simple in the downlink phase and is widely studied and utilized in NOMA systems. Inspired from the use of side information in coordinated direct and relay transmission, this work exploits the information for interference cancellation in the downlink phase. Instead of broadcasting the individual data, NO-V2X transmits the XOR-ed data in the downlink phase. The algorithm of the NO-V2X downlink is illustrated in Algorithm 1.

For the data x_i transmitted from user i to j, conventional NOMA systems broadcast it directly in the downlink phase. But it is possible to transmit $x_i \oplus x_j$ instead of x_i as user j can recover x_i with the side information x_j. Let us assume the CSIs in Fig. 1 as $|h_1| > |h_4| > |h_3| > |h_2|$, the relay encodes the data as shown in Fig. 6. The first step is to encode the data x_i transmitted from user i to j as $x_i \oplus x_j$, e.g., the data x_1 sent to user 2 is encoded as $x_1 \oplus x_2$. The next step is to remove the data sent to the strongest user since the strongest user can recover the target data from the side information sent to other users. For instance, user 1 undergoes the best channel in Fig. 6, thus the encoded data sent to user 1 $x_4 \oplus x_1$ are deleted. But user 1 can recover the target XOR-ed data as $x_4 \oplus x_1 = (x_1 \oplus x_2) \oplus (x_2 \oplus x_3) \oplus (x_3 \oplus x_4)$. The final step is to assign the power coefficients α_k

Algorithm 1 Pseudocode for NO-V2X downlink

Encode data transmitted from user i to j as $x_i \oplus x_j$
Eliminate the encoded data sent to the strongest user (i.e., the user with the best channel)
According to (5), assign the power coefficient α_k to other users
Broadcast the superimposed signal according to (4)
for All users j **do**
  Decode the XOR-ed data $x_i \oplus x_j$ with NOMA receiver, for the strongest user k, the target XOR-ed data is equivalent to the XOR-ed output of all XOR-ed data
  Recover the target data $x_i = x_i \oplus x_j \oplus x_j$ with side information x_j
end for

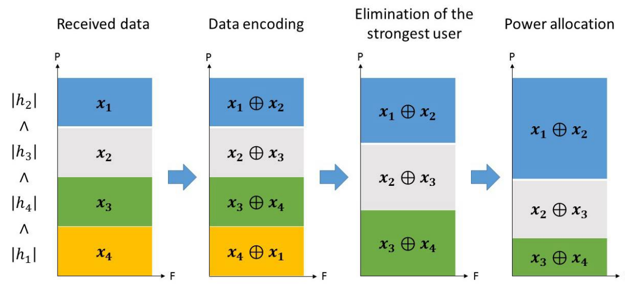

Fig. 6. An example of NO-V2X downlink.

to other users according to (5), the user with better channel is allocated with less power. It can be seen in Fig. 6 that user 2 with the worst channel is assigned with the largest power. After receiving the encoded data, each user recovers the target data with the side information. By exploiting the side information, NO-V2X can reduce the amount of transmitted data by one user in the downlink phase.

Fig. 7 and 8 show the throughput and delay for the V2X network illustrated in Fig. 1. In the low

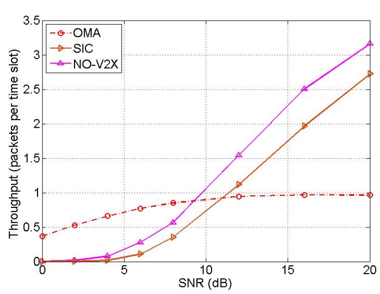

Fig. 7. Throughput of 4-user downlink.

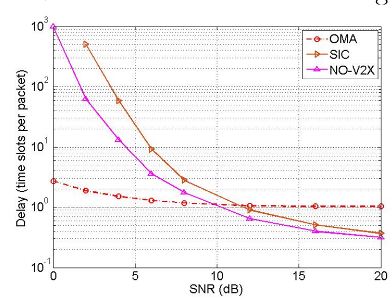

Fig. 8. Delay of 4-user downlink.

SNR regime, the OMA method shows better performance while the two NOMA methods provides low throughput and high delay. The reason is that the limited transmission power provided by one relay can hardly satisfy the throughput requirement of multiple users. In fact, the two NOMA algorithms can provide better overall throughput by applying other power allocation algorithms such as water-filling algorithm [17]. The goal of this work is to guarantee fairness, thus the power allocation algorithm in (5) assigns the same capacity to all access users. When the SNR is around

10 dB, the two NOMA methods reach similar throughput and delay as the OMA method. The advantage of NO-V2X comes from the side information, and thus the data of the strongest user can be removed. In the 4-user access case, NO-V2X reduces $\frac{1}{4} = 25\%$ data in the downlink phase. This results in around 0.5 throughput improvement compared with SIC-based NOMA. When the SNR is higher than 10 dB, NO-V2X provides more than 2 dB SNR gain compared with the other two methods.

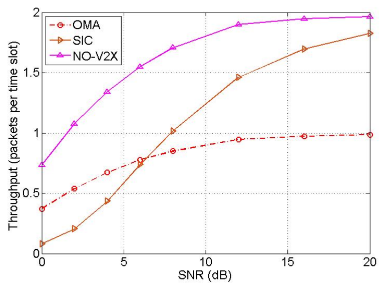

Fig. 9. Throughput of 2-user downlink.

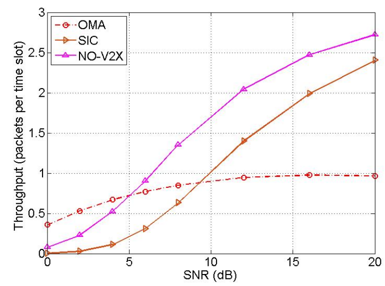

Fig. 10. Throughput of 3-user downlink.

Similar to the uplink phase, the 2-user and 3-user cases are also considered and simulated, the results are shown in Fig. 9 and 10. From the two simulations, we can observe that the OMA provides better performance compared with SIC in the low SNR regime. By exploiting the side information, NO-V2X reaches the same throughput as the SIC method but reduces the amount of transmitted data. The percentages of reduced data in the two cases are $\frac{1}{2} = 50\%$ and $\frac{1}{3} \approx 33\%$, respectively. In the 2-user access case, the relay transmits the XOR-ed output of the data received from the two users and no data overlap in the power domain. This case is equivalent to PNC in TWRC and the two users can recover the target data via the same XOR-ed data. Under such situation, NO-V2X outperforms OMA, even though in the low SNR regime. One interesting point is that NO-V2X shows larger throughput gap compared with SIC when the number of access user increases in the uplink phase, but this trend is inverse in the downlink phase. However, the utilization of other power allocation algorithms is possible to improve the performance in the downlink phase. NO-V2X improves the downlink phase by reducing the amount of transmitted data, and it is compatible to any power control algorithms.

4 Conclusion and future work

In this paper, we have investigated the feasibility of NOMA in V2X communications. By studying a time-critical V2X communication, we proposed a NO-V2X architecture that exploits the use of side information to boost the throughput and to reduce the delay in both the uplink and downlink phases. The paper has studied three problems: 1) the feasibility of allowing all users with random CSIs to transmit data in the same power level in the uplink phase is verified with the support of PNC. We show that the integration of MUD and PNC makes time-critical V2X communications possible; 2) Different from the conventional individual user detection, NO-V2X exploits the network-coded side information and further improve the decoding success rate in the uplink phase; and 3) the required transmission power in the downlink phase can be reduced since NO-V2X removes the data sent to the strongest user. Overall, our simulation results verify that NO-V2X outperforms OMA and SIC-based NOMA. Specifically, for the 4-user access case, NO-V2X provides more than 60% throughput enhancement when the SNR is higher than 4 dB in the uplink phase and more than 2 dB SNR gain when the SNR is higher than 10 dB in the downlink phase. However, there are still many extensions that can be done. For instance, besides the circular transmission pattern considered, other cases with a random data demand will be studied. In addition, we studied the uplink and downlink phases separately in this paper, joint consideration of both phases will be our next step.

Acknowledgment

The work of I. W.-H. Ho is partially supported by the Early Career Scheme (Project No. 25200714) established under the University Grant Committee (UGC) of the Hong Kong Special Administrative Region (HKSAR), China; and by The Hong Kong Polytechnic University (Projects G-YBK6, G-YBR2, G-YBXJ). The work of Z. Situ is partially supported by the National Natural Science Foundation of China (Project No. 61401384).

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