Maximum-Throughput Sidelink Resource Allocation for NR-V2X Networks With the Energy-Efficient CSI Transmission

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ABSTRACT New radio vehicle-to-everything (NR-V2X) is an emerging technology based on the 5G cellular mobile communication networks. In this paper, the sidelink (SL) resource allocation for NR-V2X in Mode 1 is considered, where 5G base station (gNB) schedules SL resources to be used by V2X users (VUs) based on the periodically reported channel state information (CSI). To reduce the overhead, an energy efficient power allocation scheme of CSI transmission is proposed using hybrid spectrum access technology. With the knowledge of CSI, SL resource allocation is modeled as a mixed binary integer nonlinear programming (MBINP). It is designed to maximize the sum throughput of NR-V2X networks among different subcarriers subject to the total available power and the minimal transmission rate. To achieve that, the original MBINP is decomposed into two sub-problems, namely, subcarrier assignment and power allocation. Firstly, the appropriate subcarriers are quickly obtained by averaging the power allocation. Secondly, an alternative optimization mechanism is proposed to the power allocation. Simulation results show that the proposed power allocation scheme of CSI transmission can obviously save the energy consumption, and the proposed suboptimal SL resource allocation algorithm achieves better performance than the compared methods with relatively low complexity.

INDEX TERMS New radio vehicle-to-everything (NR-V2X), channel state information (CSI), subcarrier assignment, power allocation.

I. INTRODUCTION Vehicle-to-everything (V2X) [1], a typical application of Internet of things (IoT) in the field of intelligent transportation systems (ITS) [2], refers to ubiquitously intelligent vehicular networks based on the connectivity of the Intranet, the Internet, and the mobile Internet of vehicles, which share and exchange data according to the agreed communication protocol and data interaction standard. It realizes intelligent traffic managements and services, such as improved road safety, enhanced situation awareness and less traffic congestion, through real-time sensing and cooperating among pedestrians, roadside units, vehicles, networks and cloud [3].

Nowadays, there are two globally accepted approaches for V2X communications, namely, dedicated short range communications (DSRC) [4] based on WiFi technology and cellular vehicle to everything (C-V2X) [5] based on cellular technology. The beginning of C-V2X can only be traced back to 2015, more than 10 years later than DSRC. However, it develops rapidly with broad application prospects due to its large coverage, high capacity, superior quality of services (QoS). In particular, the latest version new radio V2X (NR-V2X) [6] based on the Fifth-generation (5G) cellular mobile communication is much superior to DSRC in supporting higher data rates and longer transmission ranges with higher reliability and lower latency.

To deal with the wireless channel impairments, sidelink (SL) [7] resource allocation, which is a primary concern...
in the design and operation of NR-V2X, presents unique challenges. One of these challenges results from the fact that the traffic volume and transmission rate of communication increases greatly [8]. Another challenge is imposed by reliability and latency requirements, which are rigorous for the safety-related V2X scenarios, e.g. automated driving [9].

The resource allocation of V2X has been attracting significant research interests and the optimization objectives are various [10], such as throughput maximization, energy efficiency maximization, interference minimization, etc. A novel Vehicle-to-vehicle (V2V)-enabled resource allocation scheme [11] based on C-V2X technology is proposed for vehicular ad hoc networks (VANETs). The objective of optimization is to minimize the total waiting time by the weighted sum of delay reduction. It can improve the latency performance with a moderate increase in vehicle’s speed, but it leads to a higher delay with high-speed vehicles. In [12], P. Wang et al. propose a dynamic vehicle resource matching algorithm to maximize the number of active C-V2X users, thus reducing the conflicts between C-V2X users and VANET users in the unlicensed spectrum. A novel approach of joint power control and resource allocation mode selection [13] is proposed to maximize the overall information value of V2X communication on the premise of considering both Proximity-Based Services (ProSe) Per-Packet Priority and communication link quality of V2X messages. A resource allocation strategy is proposed in [14] to guarantee fair coexistence among users. The optimization goal is to maximize the total throughput of cellular users (CUs) and non-safety V2X users (VUs). However, this scheme does not consider competing for users with different access technologies. In [15], C. Han et al propose a novel segmentation MAC (SMAC) scheme that the segmentation of the network and channel allocations are dynamically adjusted according to the density of vehicles. It can support dynamic allocation of wireless channels and ensure connectivity between network segments. An energy-efficient relay assisted transmission scheme based on V2X communications [16] is proposed to obtain the corresponding optimal power allocation, but this scheme cannot be applied to delay-sensitive applications.

In this paper, we study the resource allocation for NR-V2X. Two SL resource allocation modes [17] are defined in NR-V2X. In Mode 1, 5G base station (gNB) schedules SL resources to be used by VUs; while in Mode 2, VUs determine SL transmission resources within SL resources. We concentrate on the SL resource allocation case in Mode 1. A SL resource allocation is formulated as a mixed integer nonlinear programming (MINLP), which maximizes the sum capacity subject to the total available power and the minimal transmission rate constraints. The original SL resource allocation problem is decomposed into two sub-problems, i.e., subcarrier assignment and power allocation. By averaging the power of each subcarrier, the appropriate subcarrier assignment is quickly acquired. Then, an alternative optimization mechanism is utilized to allocate the power.

Our optimization objective is to maximize the overall NR-V2X network throughput with the minimal rate constraints. Furthermore, we expect the transmission of the channel state information (CSI) is energy efficient to reduce the overhead. The main contributions of this paper are highlighted as follows.

(1) The knowledge of CSI in gNB is a prerequisite for resource allocation. To reduce the energy consumption in transmitting CSI from VUs to gNB, an energy efficient power allocation scheme is proposed. Different from the underlay or overlay spectrum sharing model, a hybrid spectrum access model is utilized, wherein multiple VUs and CUs co-exist, and the VUs use different transmission power according to the spectrum sense results. The dual decomposition technique is utilized to obtain their optimal solutions.

(2) A SL resource allocation is formulated as a mixed binary integer nonlinear programming (MBINP), which maximizes the sum capacity subject to the total available power and the minimal transmission rate constraints. The original SL resource allocation problem is decomposed into two sub-problems, i.e., subcarrier assignment and power allocation. By averaging the power of each subcarrier, the appropriate subcarrier assignment is quickly acquired. Then, an alternative optimization mechanism is utilized to allocate the power.

The rest of the paper is organized as follows. The system model of hybrid spectrum access is described in Section II. In Section III, we formulate the CSI transmission and SL resource allocation problem. Section IV deduces the proposed the energy-efficient power allocation scheme first and then the SL resource allocation scheme is decomposed into two sub-problems, namely, subcarrier assignment and power allocation. In section V, dual decomposition technique is utilized and a suboptimal scheme is proposed. Finally, performance evaluation and conclusion are provided in Section V and Section VI respectively.

II. SYSTEM MODEL

In this section, we present the model of an OFDM-based NR-V2X network where multiple VUs and CUs co-exist in the same geographical region. The hybrid NR-V2X spectrum access model is also presented because VUs share the same spectrum with CUs for CSI transmission.

A. NR-V2X SYSTEM MODEL

As illustrated in Fig. 1, the VUs co-exist with the CUs in the same geographical region. Two VUs directly communicate with each other through SL by exploiting the resource partition sliced to the V2X service in 5G network. Besides, when VUs report their CSI through uplink to gNB, they share the cellular uplink radio resources allocated to CUs, which introduces interference to the CUs. In order to handle this kind of the interference, VUs need to perform spectrum sensing before transmitting CSI to gNB and use the proper power according to the sensing results.

Furthermore, we assume that there are M VUs and each VU has only one antenna. Each sub-carrier resource is
The system model is assumed to be occupied by at most one pair of VUs link. The total sliced system bandwidth $B$ of NR-V2X service is divided into $N$ sub-carriers, and the bandwidth of each sub-carrier is $B_0 = B/N$. We define the sub-carriers’ index sets as $N = \{1, 2, \ldots, N\}$ and the VUs’ index sets as $M = \{1, 2, \ldots, M\}$.

The system model is considered as a centralized resource planning and scheduling architecture, where gNB schedules SL resources to be used by VUs. The CSI of the VU-to-gNB link can be measured by gNB, while the CSI of the VU-to-VU link should be reported to gNB. We denote $h_{vb}$, $h_{cb}$, $h_{vv}$ as the channel coefficient of VU-to-gNB, CU-to-gNB and VU-to-VU links, respectively. $h_{vc}$ denotes the interference channel coefficient from the VU-to-CU. To simplify the expression, we define $i = vb, cb, vv$, so we have $|h_i|^2 = |g_i|^2 PL(d_m)$, where $g_i$ is the small-scale fading gain whose distribution is log-normal and $PL(d_m)$ is the pathloss with the distance $d_m$. Then, the achievable rate $r_{m,n}$ of the VU $m$ on the sub-carrier $n$ can be calculated as:

$$r_{m,n} = B_0 \log_2(1 + P_{m,n}g_{m,n})$$  \hspace{1cm} (1)

where $P_{m,n}$ is the power allocated to VE $m$ on the sub-carrier $n$ and $g_{m,n} = |h_i|^2/((\Gamma \cdot n_0 \cdot B_0)$ where $n_0$ is the power spectral density of additive white Gaussian noise. Generally, $\Gamma$ is the SNR gap that is related to a given bit-error-rate (BER) $P_b$ for a specific modulation/demodulation scheme. For example, $\Gamma = -\ln(5P_b)/1.5$ for an uncoded multilevel quadrature amplitude modulation (MQAM) system [19]. The sum rate of VE $m$ can be denoted as:

$$R_m = \sum_{n \in N} \rho_{m,n} r_{m,n}$$  \hspace{1cm} (2)

where $\rho_{m,n} \in \{0, 1\}$. $\rho_{m,n} = 1$ represents that sub-carrier $n$ is occupied by VU $m$, while $\rho_{m,n} = 0$ represents that sub-carrier $n$ is not occupied by VE $m$.

**B. HYBRID NR-V2X SPECTRUM ACCESS MODEL**

Each VU performs an energy-detection spectrum sensing on the shared uplink channel with the system model described in Fig.1 before it requests for resource allocation. The frame structure of VUs during this process is shown in Fig. 2, where $T_s$ and $T_d$ denote the time spent on spectrum sensing and the CSI data transmitting, respectively. In general, we model the sensing process as a binary hypothesis testing model, and the signal sensed by VUs can be expressed as:

$$y(k) = \begin{cases} n(k), & H_0 \\ h \cdot s(k) + n(k), & H_1 \end{cases}$$  \hspace{1cm} (3)

where $H_0$ denotes that a channel is idle, while $H_1$ denotes that a channel is actually occupied by a licensed CU. $n(k)$, $s(k)$ and $h$ represent the additive white noise signal, CU’s transmitting signal and channel gain, respectively. $k$ is a sample index.

The decision metric for the energy detector can be written as:

$$Y = \sum_{k=1}^{K} |y(k)|^2$$  \hspace{1cm} (4)

where $K$ is the size of the observation vector. The decision on the occupancy of a band can be obtained by comparing the decision metric $Y$ against a fixed threshold $\lambda$. Considering the detection probability $P_d$ and false alarm probability $P_f$ in spectrum sensing, they can be represented as [20]:

$$P_d = \Pr(Y > \lambda | H_1)$$

$$P_f = \Pr(Y > \lambda | H_0)$$  \hspace{1cm} (5)

By denoting $\overline{H_0}$ as the detected channel state is idle and $\overline{H_1}$ is busy, we have:

$$P(\overline{H_0}) = P(H_0)(1 - P_d) + P(H_1)(1 - P_d)$$  \hspace{1cm} (6)

$$P(\overline{H_1}) = P(H_0)P_f + P(H_1)P_d$$  \hspace{1cm} (7)

$$P(H_1/\overline{H_0}) = \frac{P(H_1)(1 - P_d)}{P(H_0)(1 - P_d) + P(H_1)(1 - P_d)}$$  \hspace{1cm} (8)

$$P(H_1/\overline{H_1}) = \frac{P(H_1)P_d}{P(H_0)P_f + P(H_1)P_d}$$  \hspace{1cm} (9)

where $P(\cdot)$ represents the probability. According to [21], the achievable rate expression $R_o(P_0, P_1)$ can be formulated as:

$$R_o(P_0, P_1) \approx R_f$$

$$= \frac{T_s}{T_d} \left( P(\overline{H_0})E[\log_2 \left( 1 + \frac{|h_{vb}|^2 P_0}{P(H_1/\overline{H_0}) \sigma_{c}^2 + \sigma_n^2} \right)] + P(\overline{H_1})E[\log_2 \left( 1 + \frac{|h_{vb}|^2 P_1}{P(H_1/\overline{H_1}) \sigma_{c}^2 + \sigma_n^2} \right)] \right)$$  \hspace{1cm} (10)

where $R_f$ denotes the transmission rate of VU in one superframe; $\sigma_{c}^2$ and $\sigma_n^2$ denote the power of interference and noise, respectively. By using Hybrid Spectrum Access technology, VUs’ transmission power will be $P_0$, if the channel is detected.
as idle, and $P_1$ if the channel is detected as occupied. Meanwhile, the average power consumption in one superframe can be expressed as:

$$E_{av}(P_0, P_1) = P_1T_s + T_dE[P[H_0]P_0 + P[H_1]P_1] + P_1T_{sf}$$  (11)

where $P_s$ represents the power consumed in sensing process, and $E[P[H_0]P_0 + P[H_1]P_1]$ represents the average power consumed in CSI transmission. Circuit power $P_c$ includes the radio frequency circuits (excluding the radio-frequency amplifier) and baseband processing circuits [22].

### III. PROBLEM FORMULATION

In this section, we firstly analyze the energy efficiency of CSI transmission, and then formulate the resource allocation problem in SL.

#### A. ENERGY EFFICIENT POWER ALLOCATION FOR CSI TRANSMISSION

The energy efficiency is defined as the ratio of the average rate and the average power consumption in one slot, which can be expressed as:

$$\eta_{EE} = \frac{R_d(P_0, P_1)}{E_{av}(P_0, P_1)}$$  (12)

In order to improve the energy efficiency of spectrum sensing under the constraints of power limitation, minimum transmission rate and interference to the CU, the problem can be formulated as:

$$\max \eta_{EE} = \max_{P_0, P_1} \frac{R_d(P_0, P_1)}{E_{av}(P_0, P_1)}$$

s.t. $C1: T_dE[P[H_0]P_0 + P[H_1]P_1] \leq P_{ave}$

$C2: T_dE[(P[H_1](1-P_d)P_0 + P[H_1]P_dP_1) \cdot \lVert h_{vc} \rVert^2] \leq I^h$

$C3: R_d(P_0, P_1) \geq R_{min}$

$C4: P_0 \geq 0, P_1 \geq 0$  (13)

where $C1$ and $C4$ denote the constraint of power limitation, while $C2$ represents the interference constraint and $C3$ limits the minimum transmission rate of VU. $P_{ave}$, $I^h$ and $R_{min}$ denote the average transmission power limit of VUs, interference limit to CU caused by VUs and minimal transmission rate, respectively.

#### B. MAXIMUM-THROUGHPUT FOR NR-V2X COMMUNICATION

The throughput maximization SL resource allocation problem of NR-V2X networks with constraints of transmit power and VUs minimum transmission rate can be formulated as:

$$\max_{\rho_{m,n} \geq 0, n \in N} \sum_{m=1}^{M} \sum_{n=1}^{N} \rho_{m,n}P_{m,n}$$

s.t. $C5: P_{m,n} \geq 0, \forall m \in M, n \in N$

$C6: \sum_{n=1}^{N} \rho_{m,n}P_{m,n} \leq P_T, \forall m \in M$

$C7: R_m \geq R_{min}, \forall m \in M$

$C8: \rho_{m,n} = \{0, 1\}, \forall m \in M, n \in N$

$C9: \sum_{m=1}^{M} \rho_{m,n} = 1, \forall n \in N$  (14)

where $P_T$ represents the power limit and $R_{max, min}$ represents the minimum transmit rate of each VU. $C5$ and $C6$ denote the power constraint. Constraint $C7$ is used to ensure the minimum transmission rate requirement of each VU, and constraints $C8$ and $C9$ is employed to impose a restriction that each sub-carrier can only be allocated to at most one VU.

The optimization problem in (14) contains continuous variable $P_{m,n}$ and integer variable $\rho_{m,n}$ at the same time, so it’s a MBINP with inequality constraints, which is hard to solve directly.

### IV. THE PROPOSED CSI TRANSMISSION AND RESOURCE ALLOCATION ALGORITHM

We propose a two-stage scheme to address the resource allocation problem for V2X communication. The first stage is the power allocation of the CSI Transmission by VUs with low energy consumption. The second stage is the SL resource allocation by gNB.

#### A. POWER ALLOCATION ALGORITHM FOR CSI TRANSMISSION

The objective function in (13) is a ratio of two functions with respect to $P_0$, $P_1$ and $R_{ave}(P_0, P_1)$ is concave while $E_{ave}(P_0, P_1)$ is affine [23]. The quasi-concave problems can be converted to convex functions by fractional programming, and the new objective function can be formulated as:

$$g(P_0, P_1, \alpha) = R_d(P_0, P_1) - \alpha E_{av}(P_0, P_1)$$  (15)

where $\alpha$ is positive. Then the problem in (13) can be expressed as:

$$\max g(P_0, P_1, \alpha) = \max_{P_0, P_1} \{R_d(P_0, P_1) - \alpha E_{av}(P_0, P_1)\}$$

s.t. $C1 - C4$  (16)

The lemme Dinkelbach in [24] points out the relationship between (13) and (16).

**Lemma 1:** We have $\alpha^* = \max \{g(P_0, P_1, \alpha) | P_0, P_1 | S\} = \eta_{EE}(P_0^*, P_1^*)$ when and only when

$$F(\alpha^*) = F(\alpha^*, P_0^*, P_1^*) = 0$$

$$g(\alpha^*) = (P_0^*, P_1^*)$$  (17)

It is obvious that (13) and (16) share the same optimal solution when (17) is satisfied. The Lagrangian problem in (16) is given by

$$L(P_0, P_1, \alpha, \tau, \nu, \varepsilon)$$

$$= R_d(P_0, P_1) - \alpha E_{av}(P_0, P_1)$$

$$- \tau \{T_dE[P[H_0]P_0 + P[H_1]P_1] - P_{ave}\}$$

$$- \nu \{T_dE[(P[H_1](1-P_d)P_0 + P[H_1]P_dP_1) \cdot \lVert h_{vc} \rVert^2] - I^h\}$$

$$+ \varepsilon \{R_d(P_0, P_1) - R_{min}\}$$  (18)

where $\tau$, $\varepsilon$, $\nu$ are positive Lagrange multiplier of $C1$, $C2$ and $C3$ respectively. According to the KKT condition [25], $P_0^*$
Algorithm 1 Energy-Efficient CSI Transmission

1: Initialization: \( \alpha^{(0)} = \alpha_0, \tau^{(0)} = \tau_0, \nu^{(0)} = \nu_0, \epsilon^{(0)} = \epsilon_0 \), iteration step size \( \delta > 0 \), error threshold \( \overline{\theta}_{1,2} > 0 \), \( F(\alpha) = \infty \), the maximum number of iterations \( L_{\text{max}} \).
2: while \( |F(\alpha)| \geq \overline{\theta}_1 \) and \( i < L_{\text{max}} \) do
3: calculate \( P_0^i \) and \( P_1^i \)
4: update lagrange multiplier \( \tau, \nu, \epsilon \)
5: \( \alpha^{i+1} = \frac{P_0^i P_1^i}{F_\text{ave}(P_0^i P_1^i)} \)
6: if \( \left| \nu^i \left[ P_\text{ave} - T_d E[P(H) P_0 + P(H) P_1] \right] \right| \leq \theta_2 \)
7: update \( i = i + 1 \)
8: end if
9: end while
10: return \( \alpha, P_0^\ast, P_1^\ast \)

and \( P_0^\ast \) can be written as:

\[
P_0^\ast = \left[ \frac{P(H_0)(1 + \epsilon)}{T_d^\ast \left( \langle \alpha + \tau \rangle P(H_0) + \nu P(H_1)(1 - P_d) \right) + P(H) P_1} \right] \left( \frac{\sigma_{\text{a}}^2 + \sigma_{\text{h}}^2}{\langle \text{h}_{\text{b}} \rangle^2} \right) \]

\[
P_1^\ast = \left[ \frac{P(H_1)(1 + \epsilon)}{T_d^\ast \left( \langle \alpha + \tau \rangle P(H_1) + \nu T_d P(H_1) P_d \right) + P(H) P_1} \right] \left( \frac{\sigma_{\text{a}}^2 + \sigma_{\text{h}}^2}{\langle \text{h}_{\text{b}} \rangle^2} \right)
\]

where \( [x]^+ = \max(x, 0) \).

To achieve the optimal solution of Lagrange multiplier, we use subgradient algorithm, and the Lagrange multiplier variable of \( (i + 1) \)th iteration can be expressed as:

\[
\begin{align*}
\tau^{i+1} &= \left[ \tau^i - \delta \nu^i \left[ P_\text{ave} - T_d E[P(H_0) P_0 + P(H_1) P_1] \right] \right]^+ \\
\nu^{i+1} &= \left[ \nu^i - \delta \left[ \nu^i \left( \nu^i - \overline{\theta}_1 T_d E[(P(H_1)(1 - P_d) P_0 + P(H_1) P_d P_1)] \right) + P(H_1) P_d P_1 \cdot \langle \text{h}_{\text{c}} \rangle^2 \right] \right]^+ \\
\epsilon^{i+1} &= \left[ \epsilon^i - \delta \epsilon^i \left( \epsilon^i - \overline{\theta}_1 (R_d(P_0, P_1) - R_{\text{min}}) \right) \right]^+
\end{align*}
\]

where \( i \) and \( \delta \) denote the iteration index and the step size, respectively. The optimal solution of power allocation can be obtained until the algorithm converges. The algorithm of CSI Transmission is described in detail.

Furthermore, we propose a suboptimal SL resource allocation scheme for NR-V2X, where the CSI has already been acquired by gNB in the first stage. In the second stage, a two-step scheme is proposed. The first step is to allocate \( N \) sub-carriers to \( M \) VUs according to their transmission rates, and the second step is to allocate transmission power to VUs.

B. SUB-CARRIER ALLOCATION FOR NR-V2X COMMUNICATION

In OFDM system, \( N \) sub-carriers are allocated to \( M \) VUs and the transmission rate of VU \( m \) with the average transmission power \( P_{\text{avg}} = \frac{P_d \cdot M}{N} \) can be expressed as:

\[
R_{m,n} = B_0 \log_2(1 + P_{\text{avg}} \gamma_{m,n})
\]

The proposed sub-carrier allocation algorithm considers the fairness among VUs. In the first round of allocation, the sub-carriers that can obtain the maximum possible transmission rate are selected from \( N \) sub-carriers and allocated to VUs. The VU who obtains the worst possible transmission rate has the priority to select sub-carrier with the maximum possible transmission rate in the second round of sub-carrier allocation and the allocation finishes when available sub-carriers are empty.

C. POWER ALLOCATION FOR NR-V2X COMMUNICATION

We define the set of sub-carriers allocated to VU \( m \) as \( N_m \), after the sub-carrier allocation, the transmission rate of each VU can be expressed as:

\[
R_m = B_0 \sum_{n \in N_m} \log_2(1 + P_{m,n} \gamma_{m,n})
\]

and the optimization problem can be simplified as:

\[
\min_{m=1}^{M} \sum_{n \in N_m} \log_2(1 + P_{m,n} \gamma_{m,n})
\]

\[
s.t. \quad C10 : P_{m,n} \geq 0, \quad \forall m \in M, \quad n \in N_m
\]

\[
C11 : R_m - R_{m,\text{min}} \geq 0
\]

\[
C12 : P_T - \sum_{n \in N_m} P_{m,n} \geq 0
\]

where \( C10 \) and \( C12 \) denote the power constraint while \( C11 \) is used to ensure the minimum transmission rate requirement of each VU. It’s an optimization problem with inequality constraints, and the Lagrangian of which can be formulated as:

\[
L(p, \nu, \lambda, \mu) = \sum_{m=1}^{M} \sum_{n \in N_m} B_0 \log_2(1 + P_{m,n} \gamma_{m,n}) + \sum_{m=1}^{M} \sum_{n \in N_m} v_{m,n} P_{m,n} + \sum_{m=1}^{M} \lambda_m (\sum_{n \in N_m} r_{m,n} - R_{m,\text{min}}) - \sum_{m=1}^{M} \mu_m (P_{m,n} - P_T)
\]

where \( v_{m,n}, \lambda_m, \mu_m \) are Lagrange multipliers for the constraints \( C10, C11 \) and \( C12 \) of (26) respectively.
The necessary conditions for optimization are given by KKT conditions:

\[
\frac{1 + \lambda_m^*}{\ln 2} \frac{y_{m,n}B_0}{1 + P_{m,n}y_{m,n}} + v_{m,n}^* - \mu_m^* = 0 \tag{28}
\]

\[
\lambda_m^* \sum_{n \in N_m} B_0 \log_2(1 + P_{m,n}y_{m,n}) - R_{\min} = 0 \quad \lambda_m^* \geq 0 \tag{29}
\]

\[
\mu_m^*(P_T - \sum_{n \in N_m} P_{m,n}) = 0 \quad \mu_m^* \geq 0 \tag{30}
\]

where \(P_{m,n}^*, \lambda_m^*, v_{m,n}^*, \) and \(\mu_m^*\) are the primal and dual optimal points with zero dual gap. According to (30), if \(P_{m,n}^* \neq 0\), we have \(v_{m,n} = 0\). So \(P_{m,n}\) can be worked out by substituting \(v_{m,n} = 0\) into (28). Otherwise, \(P_{m,n}^* = 0\). That is:

\[
P_{m,n}^* = \left( \frac{(1 + \lambda_m^*B_0)}{\mu_m^* \ln 2} - \frac{1}{y_{m,n}} \right)^{+} \tag{32}
\]

To achieve the optimal solution of Lagrange multiplier, we use subgradient algorithm, and the Lagrange multiplier variable of \((i+1)^{th}\) iteration can be expressed as:

\[
\lambda_m^{i+1} = \left[ \lambda_m^i + \delta \left( \sum_{n \in N_m} B_0 \log_2(1 + P_{m,n}y_{m,n}) - R_{\min} \right) \right]^{+} \tag{33}
\]

\[
\mu_m^{i+1} = \left[ \mu_m^i + \delta \left( P_T - \sum_{n \in N_m} P_{m,n} \right) \right]^{+} \tag{34}
\]

where \(i\) and \(\delta\) denote the iteration index and the step size, respectively. The suboptimal power allocation are shown as follows.

V. PERFORMANCE EVALUATION

In this section, we evaluate the performance of the proposed CSI transmission scheme and the suboptimal resource allocation algorithm for V2X communication. We model the system as a cellular cell centered by gNB and M VUs which are assumed in urban area are uniformly distributed in the cell. The amplitude of the multipath channel fading of VU-to-gNB uplink is independent Rayleigh distributed random variables, while that of the SL is independent Rician distribution ones. Two link states between VUs are considered, which are line-of-sight (LoS) and non-line-of-sight (NLOS), and each state of each link shares same parameter of pass loss (PL) and fading. According to [26], the probability of VU-to-VU link state LOS is \(P(LOS) = \min \left\{ 1, 1.05 \times e^{(-0.0114 \times d_{m})} \right\}\), and the probability of VU-to-VU link state NLOS is \(P(NLOS) = 1 - P(LOS)\). For comparison, we take the scheme in [27] and [28] as references. In [27], SUs(Secondary user) use traditional opportunistic spectrum access technology to take advantage of idle channels of PUs(Primary user). In [28], the genetic algorithm(GA) is used to allocate subcarriers and power. For a fair comparison, we adopt the simulation parameters in Table 1 for the transmission schemes.

### Algorithm 2 Suboptimal Power Allocation in NR-V2X

1. Initialization: \( \lambda_m^{(0)} = \lambda_0, \mu_m^{(0)} = \mu_0\), iteration step size \(\delta > 0\), error threshold \(\vartheta_1, 2 > 0\), the maximum number of iterations \(L_{\text{max}}\)

2. \textbf{while} \(|F(\alpha)| \geq \vartheta_1\) and \(i < L_{\text{max}}\) \textbf{do}

3. calculate \(P_{m,n}\)

4. update lagrange multiplier \(\lambda_m, \mu_m\)

5. \textbf{if}

\[ |\lambda_m| \sum_{n \in N_m} B_0 \log_2(1 + P_{m,n}y_{m,n}) - R_{\min}| \leq \vartheta_1 \]

and

\[ |\mu_m| P_T - \sum_{n \in N_m} P_{m,n} | \leq \vartheta_2 \]

\textbf{then}

6. break

7. \textbf{end if}

8. update \(i = i + 1\)

9. \textbf{end while}

10. return \(P_{m,n}\)

### Table 1. Simulation parameters.

| Parameter | Value |
|-----------|-------|
| Number of VUs\(M\) | 4 |
| Power of interference\(\sigma^2_s\) | 1 |
| Power of noise\(\sigma^2_n\) | 0.2 |
| Circuit power\(P_c\) | 0.1W |
| Sensing power\(P_s\) | 0.02W |
| Probability of idle channel\(\langle P(H_0)\rangle\) | 0.7 |
| Interference limit to CU caused by VUs\(\langle f^{th}\rangle\) | -8dB |
| Cell radius\(r\) | 300m |
| Bandwidth\(B\) | 10MHz |
| Noise power\(N_0\) | 10^{-14}W |
| Bit error rate\(F_e\) | 10^{-6} |
| Center frequency\(f_c\) | 60GHz |
| Pathloss model for LOS | \(P_L = 38.77 + 16.7 \log_{10}(d_m) + 18.2 \log_{10}(f_c)\) |
| Pathloss model for NLOS | \(P_L = 36.85 + 30 \log_{10}(d_m) + 18.9 \log_{10}(f_c)\) |
| Shadowing standard deviation | 4dB |

A. ENERGY EFFICIENCY OF CSI TRANSMISSION

To simplify the description, we denote the energy efficiency maximization algorithm under traditional opportunistic spectrum access model used in [27] as “OSA” and our proposed model as “Hybrid”.

In Fig.3, we compare the energy efficiency \(\eta_{\text{EE}}\) performance between OSA and Hybrid. We can observe that the \(\eta_{\text{EE}}\) improves with \(P_{\text{ave}}\) increases, and when \(P_{\text{ave}} \geq -10dB\), the value of EE is basically unchanged and the superiority of Hybrid becomes more obvious, which is because the larger the transmission power threshold of the system. The larger the feasible range of the original optimization problem with respect to the variables, the higher the \(\eta_{\text{EE}}\) is.
FIGURE 3. $\eta_{EE}$ versus $P_{ave}$ with OSA/Hybrid schemes ($T_s = 8$ ms, $R_{min} = 0.05$ bits/Hz).

However, when the transmission power is increased to a certain value, the conditions for constraining $\eta_{EE}$ at this time mainly depend on interference.

In Fig. 4 the $\eta_{EE}$ of the considered different schemes versus the sensing time with different $R_{min}$ is illustrated. It can be observed that the proposed Hybrid scheme is better than the OSA scheme and the $\eta_{EE}$ has a slight increase until it reaches a peak at 8 ms and then decreases with the increase of sensing time, which is because the increase of sensing time will shorten the time for data transmission, and this will decrease the transmission rate. As we can also see from the Fig. 4, with the increase of $R_{min}$, $\eta_{EE}$ decrease, which is because VUs have to consume more power to satisfy the needs of $R_{min}$.

B. THROUGHPUT SIDELINK RESOURCE ALLOCATION

The comparison of system throughput versus the minimal rate requirements between the proposed scheme and the schemes in [28] is illustrated in Fig. 5. It is obvious that the system throughput decreases with the growth of minimal rate requirements, which is because many subchannels are allocated to the users with low channel gains to satisfy their rate requirements. It can be also observed that our scheme performs better than the scheme using GA for allocation under the constraint of minimal rate requirement.

We compare the system throughput between two schemes when the power limitations of VUs change in Fig. 6. It can be observed that the system throughput improves with the increase of power limitation, which is easy to understand. Obviously, our proposed algorithm shows better performance when the power limitation changes.

The system throughput versus the number of subcarriers is displayed in Fig. 7. It can be observed that the system throughput increases with the number of subcarriers which is because more subcarriers means that VUs are easier to be allocated with better subcarriers, then the system throughput will be larger. It can be also observed that our proposed algorithm has better performance.

In Fig. 8, we show how the distance between VUs affects the system throughput of two schemes. It can be observed that the system throughput decreases with the increase of the distance between VUs. The reason is that the fading increases with the distance between VUs. As the distance between
users range from 5 to 30 m, the system throughput decreases about 74.1%. It is obvious that the distance between the VUs has a great influence on the proposed algorithm. When VUs are close, our proposed algorithm has obvious advantage over GA.

VI. CONCLUSION

In this paper, we propose a novel SL resource allocation, which adopts resource partition for NR-V2X slice. A centralized architecture is considered, where gNB should acquire the CSI of the V2X links before the SL resource allocation. The proposed SL resource allocation is implemented in two stages. In the first stage, an energy efficient power allocation scheme using hybrid spectrum access technology is proposed to reduce the overhead of CSI transmission. In the second stage, gNB allocates the resource with the objective of maximizing the sum throughput is modeled as a MBINP. We utilize the dual decomposition technique to obtain the optimal solution. Furthermore, we present a low complexity suboptimal scheme. It is suitable for the NR-V2X networks with higher reliability and lower latency requirements.

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