Efficient Interference Control Technology for Vehicular Moving Networks

Sung-Min Oh, Changhee Lee, Jeong-Hwan Lee, Ae-Soon Park, and Jae Sheung Shin

This paper proposes an efficient interference control scheme for vehicular moving networks. The features of the proposed scheme are as follows: radio resources are separated into two resource groups to avoid interference between the cellular and vehicle-to-vehicle (V2V) links; V2V links are able to share the same radio resources for an improvement in the resource efficiency; and vehicles can adaptively adjust their transmission power according to the interference among the V2V links (based on the distributed power control (DPC) scheme derived using the network utility maximization method). The DPC scheme, which is the main feature of the proposed scheme, can improve both the reliability and data rate of a V2V link. Simulation results show that the DPC scheme improves the average signal-to-interference-plus-noise ratio of V2V links by more than 4 dB, and the sum data rate of the V2V links by 15% and 137% compared with conventional schemes.

Keywords: Vehicular moving network, vehicle-to-vehicle communication, interference control, resource allocation, distributed power control.

I. Introduction

Owing to the popularity of social networking applications (for example, Facebook and Twitter), demand for content sharing among mobile users has been gradually growing. With this trend, the number of mobile users using wireless broadband services in vehicles has also been increasing owing to the rapid growth of mobile devices (for example, smartphones and tablets). For these reasons, global research groups have begun to show interest in vehicular moving networks (VMNs), which can efficiently support content sharing among mobile users in vehicles by providing a vehicle-to-infrastructure (V2I) link and vehicle-to-vehicle (V2V) link [1]–[3]. In particular, for the mobile and wireless communications enablers of the twenty-twenty information society (METIS) project, which is one of the most well-known global projects for 5G wireless mobile communications, VMNs are being handled as one of the key research topics for 5G wireless mobile communications [1].

With the advent of the VMN, it is expected that the following merits can be obtained:

- *Fast and efficient information exchange among proximity vehicles*. A V2V link is able to reduce the transmission delay and improve the data rate compared with centralized communication using a base station (BS). This is because both the number of hops and the transmission distance can be decreased through V2V communication. In particular, for a proximity communication, the probability that the communication channel is within the line of sight can be high; thus, the data rate can be improved.
- *Reduction of penetration loss*. A mobile user in a vehicle suffers from penetration loss, because vehicles are generally surrounded by iron. By installing outer and inner antennas on

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a vehicle, penetration loss can be reduced by about 25 dB [4]–[5]. Here, an outer antenna is used for V2I and V2V links and an inner antenna is for drivers and passengers in a vehicle.

- *Enhanced signal quality by means of massive antennas*. For a VMN, it is possible to place a large number of outer antennas on a vehicle. This means that a VMN can achieve gains of high-order multiple-input and multiple-output (MIMO). This merit may have an effect on both V2V and V2I links.

In fact, the concept of a VMN has been already addressed. A representative system is a wireless access in vehicular environment (WAVE) based on IEEE 802.11p, which is an approved amendment to the IEEE 802.11 standard. However, a WAVE has critical weak points because it has a scalability problem in a high-density vehicle environment and requires the establishment of a new roadside infrastructure [6]–[8].

For this reason, several global companies have recently started to submit study items related to a VMN at a 3rd Generation Partnership Project (3GPP) meeting [8]–[11]. However, in cellular networks, there are also several research topics such as interference control for VMNs, group mobility, and a robustness improvement of the V2I link, and so on.

In this paper, we focus on the issue of interference control, which includes the resource allocation and power control for the V2I and V2V links in cellular networks. To support these communication links in cellular networks, the radio resources for mobile users have to be used. For this reason, it is necessary to study an efficient resource allocation scheme for cellular, V2I, and V2V links. Here, a BS can handle a V2I link as a cellular link if a vehicle is regarded as a mobile terminal. However, since the type of a V2V link differs from that of a cellular link, it is necessary to address the resource allocation scheme for a V2V link.

Unfortunately, there can be a trade-off between the resource efficiency and the signal quality according to the resource allocation schemes for V2V links. In the case of an orthogonal resource allocation scheme, the signal quality can be improved by avoiding the interference, whereas the resource efficiency can be reduced. On the other hand, a resource sharing scheme can lead to a deterioration of the signal quality by the interference. Therefore, this paper conducts a study on a novel power control scheme with an efficient resource allocation scheme for the VMN to improve the data rate and signal quality of a V2V link.

II. Related Works

Essentially, this research topic is similar to the subject of interference control for a device-to-device (D2D) link in cellular networks. However, there are different features between a V2V link and a D2D link, as follows:

- *Dynamic and fast topology change of V2V links*. Owing to the high vehicle speed, the duration of a V2V link is much shorter than that of a D2D link. For example, let the speed of a vehicle and a mobile user be equal to 60 km/h and 3 km/h, respectively. Then, if the communication range is assumed to be 200 m, the duration of a V2V link is about 12 s, whereas that of a D2D link is 4 min.
- *High reliability of a V2V link*. The current goal of D2D communication in 3GPP release 12 is to provide voice services for group communications [12]. Unlike D2D communication, the safety information for drivers and passengers (for example, car accident, traffic jam, and road hazard) is able to be delivered through a V2V link [6]–[7]. For this reason, reliability is a significant requirement of V2V communication.
- *High data rate transmission through a V2V link*. With the safety information, high data rate services can also be provided through a V2V link. In [5], the authors mentioned that it is necessary to restore the contents in a vehicle for vehicular social networks, which is expected to be a new trend in wireless networking. This means that it may be necessary to share multimedia services among drivers and passengers in different vehicles.

In this section, we would like to investigate previous studies related to interference control for D2D links based on the three features of V2V links mentioned above.

Numerous researches considering network performance improvement and interference mitigation of D2D links have been carried out [13]–[16]. Most of them have focused on the optimal power and resource allocation in D2D underlaid cellular networks (that is, resource sharing scheme between a D2D link and cellular link). In [13]–[16], the authors have solved the optimization problem to maximize the overall throughput under several constraints (for example, the signal-to-interference-plus-noise ratio (SINR), maximum transmission power, and resource allocation index). A common feature of these schemes is a centralized scheme.

To allocate the optimal power and resources in a centralized scheme, all devices have to measure the channel gain from all the other devices and transmit the measured information to a BS for every transmission time interval (TTI). In fact, it is very difficult to implement this operation. This is because all devices have to know the identifiers (IDs) of all the other devices and decode all reference signals transmitted by all other devices for every TTI. Although this operation is possible, the signaling overhead may be serious.

The 3GPP has specified an orthogonal resource allocation scheme and a path-loss-based power control scheme for D2D links [12]. To avoid the interference between the D2D link and cellular link, the radio resources are separated into a cellular resource group and D2D resource group. With this strategy, a BS orthogonally allocates the radio resources to D2D links within the D2D resource group. Therefore, this scheme can solve the interference without the problems of a centralized scheme. Unfortunately, the network performance of the system is not optimal. In particular, the data rate of the D2D link can be limited owing to the size of a D2D resource group. This means that it may be impossible to provide high data rate services through a D2D link when the resource allocation scheme specified by the 3GPP is applied to the system.

At this time, a resource-sharing scheme among D2D links in the D2D resource group can be considered to improve the resource efficiency. In this case, the interference among D2D links may occur. To mitigate the interference, it is necessary to consider a power control scheme for a D2D link. As mentioned above, an optimal power allocation scheme based on a centralized scheme has practical problems. Therefore, we would like to investigate several path-loss-based power control schemes that enable sending D2D devices to determine the transmission power based on the path-loss.

The power control scheme for a D2D link specified by 3GPP is operated based on the path-loss between a transmitting D2D device and a BS [12]. In this paper, this scheme is called as a 3GPP D2D power control (3GDPC) scheme. In the 3GDPC scheme, the receiving D2D devices can suffer from serious interference when the distance between D2D devices is much longer than that between a transmitting D2D device and a BS.

With the 3GDPC scheme, a power control scheme based on the path-loss between the communicating D2D devices has been generally considered. This paper calls this scheme as a general power control (GPC) scheme. However, it is difficult for this scheme to improve the network performance because the transmission power is limited by the path-loss between D2D devices and the strength of the target received power given by the networks.

From the point of view of V2V communication, the main problems of conventional schemes for the D2D link can be summarized as follows:

- The optimal power and resource allocation scheme has practical problems in that all devices have to measure the channel gain from all other devices and transmit the measured information to a BS for every TTI. Although it is implementable, this scheme may incur a serious signaling overhead in a V2V link owing to the dynamic and fast topology change of V2V links.
- Under a resource-sharing scheme, the 3GDPC scheme cannot guarantee the reliability of a V2V link owing to an incorrect path-loss, and the GPC scheme cannot provide high data rate services through a V2V link because of the limitation of the path-loss between vehicles and the strength of the target-received power.

Consequently, this paper proposes an efficient interference control scheme for V2V links. To enhance both the reliability and data rate of a V2V link whose topology can be dynamically changed, the proposed scheme uses a distributed power control (DPC) scheme with a radio resource partitioning scheme between the cellular and V2V links.

To present the proposed interference control scheme, this paper is organized as follows. In Section III, a system model is described. We derive the suboptimal transmission power for a V2V link in Section IV. Section V presents both the signal procedure and the parameter update algorithm of the proposed scheme in detail. Simulation results are discussed in Section VI, and this paper is concluded in Section VII.

III. System Model

Figure 1 shows the reference network architecture for a VMN in cellular networks. In this paper, it is assumed that vehicles can directly communicate with each other through the cellular uplink spectrum, and a V2I link is handled as a cellular link. In addition, the resource partitioning scheme between the V2V link and cellular or V2I link is applied to the system. In

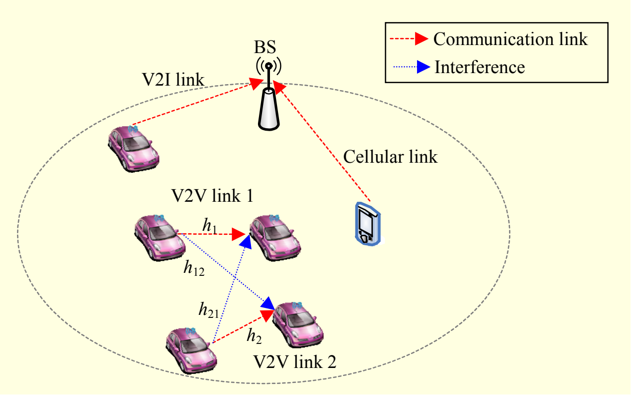

Fig. 1. Reference network architecture for VMN in cellular networks.

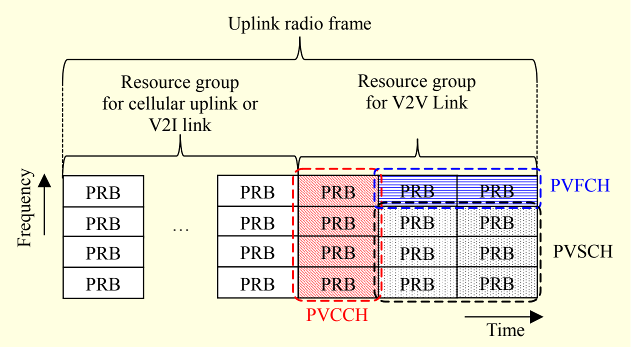

Fig. 2. Example of resource allocation for cellular, V2I, and V2V links.

other words, a BS can allocate a resource group that consists of several physical resource blocks (PRBs) only for V2V links, as shown in Fig. 2.

This paper assumes that the resource group for V2V links includes the physical V2V shared channel (PVSCH), the physical V2V feedback channel (PVFCH), and the physical V2V control channel (PVCCH). From hereinafter, PVSCH is exploited for data transmission between vehicles, and PVFCH is used for feedback transmission. In addition, PVCCH is used for transmitting the resource allocation information for PVSCH and PVFCH between vehicles. This indicates that the BS can simultaneously allocate resources for the feedback as well as the data transmission.

The BS also allows the V2V links to share the same PRBs within the allocated resource group for V2V links. In this paper, a random selection method used to choose V2V links that share the same PRBs is applied to the system. For this reason, the interference among V2V links within a single cell coverage can occur in the system. As a result, this paper focuses on a power control scheme for V2V links to solve the interference problem.

IV. Suboptimal Transmission Power for V2V Links

This section presents the derivation process for the suboptimal transmission power. We formulate a network utility maximization problem by considering the system model presented in Section III. To solve the suboptimal transmission power, we exploit a dual decomposition method [17].

1. Problem Formulation

Let N denote the number of V2V links that share the same PRBs in the system. For simplicity, it is assumed that the V2V links continuously use the same PRBs. Thus, a matrix of all transmission powers for V2V links in the system can be written as $\mathbf{P} = \{p_1, p_2, \ldots, p_N\}^{\mathrm{T}}$. For this reason, the SINR (γ_i) for V2V link i can be defined as

$$\gamma_i(\mathbf{P}) = p_i \cdot h_i \Big/ \left(\sum_{j \neq i} (p_j \cdot h_{ji}) + n_i \right), \tag{1}$$

where p_i, h_i, n_i, and h_{ji} indicate the transmission power of V2V link i; the channel gain of V2V link i; the receiver thermal noise power of V2V link i; and the channel gain between a sending vehicle of V2V link j and a receiving vehicle of V2V link i, respectively.

Let the utility function of V2V link i be denoted by $U(\gamma_i(\mathbf{P}))$, where this is a monotonic increasing function in terms of the SINR of V2V link i. Thus, the network utility maximization problem can be defined as

$$\begin{aligned} &\max \textstyle\sum U(\gamma_i(\mathbf{P})) \quad \text{for all } i \\ &\text{s.t.} \quad 0 \le \mathbf{P} \le \mathbf{P}_{\max}, \end{aligned} \tag{2}$$

where $\mathbf{P}_{\max}$ represents the matrix of the maximum transmission powers for V2V links. The goal of this problem is to determine the optimal transmission power of V2V links to maximize the network utility.

2. Suboptimal Transmission Power

This paper solves (2) based on the dual decomposition [17]. The Lagrangian of (2) can be given as

$$\begin{aligned} F(\mathbf{P}, \mathbf{\Lambda}) &= \textstyle\sum U(\gamma_i(\mathbf{P})) + \sum \lambda_i \cdot (p_{\max} - p_i) \\ &= \textstyle\sum F_i(p_i, \lambda_i) + \sum \lambda_i \cdot p_{\max} \quad \text{for all } i, \end{aligned} \tag{3}$$

where $\lambda_i \ge 0$ indicates a Lagrangian multiplier for V2V link i, $\mathbf{\Lambda}$ is a matrix for all Lagrangian multipliers, and $F_i(p_i, \lambda_i) = U(\gamma_i(\mathbf{P})) - \lambda_i \cdot p_i$ [17]. The dual function of (3) is then given by

$$\begin{aligned} G(\mathbf{\Lambda}) &= \max F(\mathbf{P}, \mathbf{\Lambda}) \\ &= \textstyle\sum \max F_i(p_i, \lambda_i) + \sum \lambda_i \cdot p_{\max} \quad \text{for all } i. \end{aligned} \tag{4}$$

The first term of (4) means that the problem can be decomposed into subproblems to derive an optimal transmission power ($p_i^*(\lambda_i)$) for each V2V link i under the given λ_i as follows:

$$p_i^*(\lambda_i) = \max\,[U(\gamma_i(\mathbf{P})) - \lambda_i \cdot p_i] \quad \text{for all } i. \tag{5}$$

As a result, the master dual problem in terms of $\mathbf{\Lambda}$ can be written as

$$\begin{aligned} &\min\ G(\mathbf{\Lambda}) \quad \text{for all } i \\ &\text{s.t.} \quad 0 \le \mathbf{\Lambda}. \end{aligned} \tag{6}$$

Since the dual function $G(\mathbf{\Lambda})$ is continuously differentiable, a gradient projection method can be used to solve (6). Here, (4) can be written as $G(\mathbf{\Lambda}) = \sum F_i(p_i^*(\lambda_i), \lambda_i) + \sum \lambda_i \cdot p_{\max}$ for all i; thus, $\partial G(\mathbf{\Lambda})/\partial \lambda_i = p_{\max} - p_i^*(\lambda_i)$ for all i. Therefore,

$$\lambda_i(t+1) = \left(\lambda_i(t) - \beta \cdot \{p_{\max} - p_i^*[\lambda_i(t)]\}\right)^+ \quad \text{for all } i, \tag{7}$$

where $\beta > 0$ is a sufficiently small positive step size, $[k]^+ = \max\{k, 0\}$, and t is the iteration index. Consequently, the optimal dual variable ($\lambda_i^*(t)$) and optimal primal variable ($p_i^*[\lambda_i^*(t)]$) can be obtained by exchanging multiple feedbacks between a sending vehicle and a receiving vehicle in a V2V link. By using this feature, we propose the parameter update algorithm for the DPC scheme. The details of the algorithm will be presented in Section V.

At this time, it is necessary to verify the convergence of the dual variable $\mathbf{\Lambda}(t)$ and primal variable $\mathbf{P}[\mathbf{\Lambda}(t)]$, because the objective function in (2) can be a non-convex function if the utility function $U(x)$ is defined as $\log_2(1 + x)$. Fortunately, in [18], the authors have already proved that both the dual value and the primal value can converge if the gradient of $G(\lambda)$ is a Lipschitz function and the main parameters meet certain conditions, such as $0 < \beta < 2/Q$, $0 \le \mathbf{P}(0) \le \mathbf{P}_{\max}$, and $0 \le \mathbf{\Lambda}(0)$. Here, Q indicates a Lipschitz constant. However, because the objective function in (2) is a non-convex function, the duality cap may still exist. For this reason, this paper presents a performance comparison of the 3GDPC, GPC, and DPC schemes with respect to the sum data rate of V2V links in Section VI.

V. Proposed Interference Control Scheme

In this section, we describe the proposed interference control scheme. The main features of the proposed scheme can be briefly summarized as follows:

- It applies a resource partitioning scheme to avoid interference between a cellular link and a V2V link.
- It adopts the resource sharing scheme among V2V links to improve the resource efficiency.
- It enables individual vehicles to control the transmission power for their V2V link according to the interference caused by adjacent V2V links. This is the main feature of the proposed scheme because this feature can enhance both the reliability and data rate of V2V links.

Actually, the resource partitioning scheme and the resource sharing scheme were explained in Section III. In addition, the derivation process of the suboptimal transmission power for V2V links was also presented in Section IV. For this reason, this section focuses on the details of the signal procedure and the parameter update algorithm for the proposed scheme.

1. Signaling Procedure

Figure 3 shows the signaling procedure for the proposed scheme. It is assumed that a BS can periodically broadcast the main configuration parameters for the V2V resource group (for example, the size and position of the V2V resource group and the common information of PVCCH, PVSCH, and PVFCH) to all vehicles using the system information block (SIB) message specified in 3GPP LTE systems. In addition, the SIB message can also include the configuration parameters for the DPC scheme; for example, the DPC activity indicator, step size (β), initial Lagrangian multiplier ($\lambda_i(0)$), initial transmission power ($p_i(0)$), and iteration decision parameter (e). Here, the DPC activity indicator is a parameter used to inform vehicles of the activity status of the parameter update algorithm for the DPC scheme. Whenever vehicles receive this parameter, the vehicles trigger the DPC scheme with initial Lagrangian multiplier. This means that the new value of the optimal transmission power is periodically calculated.

In this paper, we assume that vehicles are in a radio resource control (RRC)-connected state. Thus, as shown in Fig. 3, the sending vehicle can request the required PRBs to the BS by sending the buffer status report (BSR) for a V2V link. The BS receiving the BSR is able to transmit an uplink grant for a V2V link to the vehicle. The feature of the uplink grant designed in this paper is to include the resource allocation information for both the PVFCH and the PVSCH.

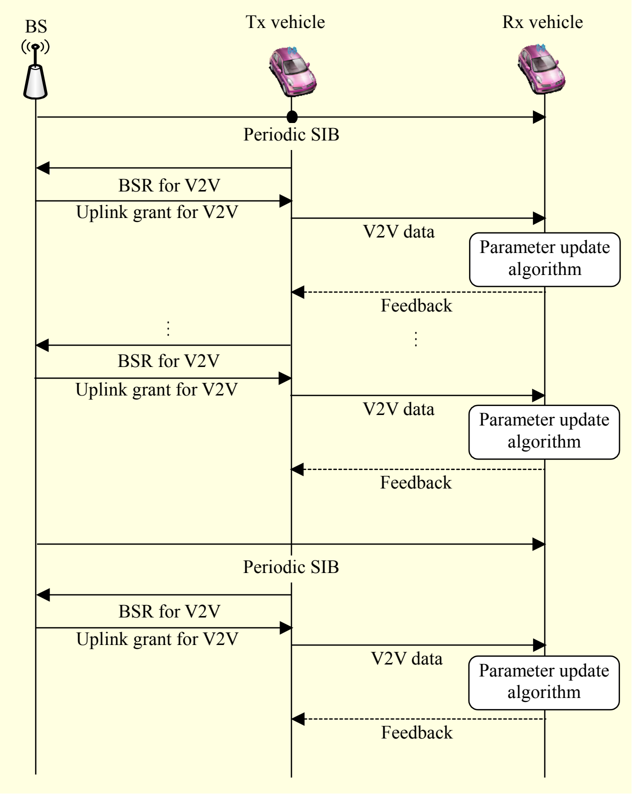

Fig. 3. Signaling procedure for proposed scheme.

The sending vehicle transmits V2V data to the receiving vehicle through the PVSCH resource assigned by the PVCCH. In addition, it also transmits the resource allocation information for the PVFCH through the PVCCH to the receiving vehicle. In this paper, it is assumed that the receiving vehicle can estimate its own channel gain ($h_i(0)$) by using a reference signal of the V2V link, such as the demodulation reference signal or the dedicated reference signal. With this property, since the receiving vehicle has already obtained the initial transmission power ($p_i(0)$) from the SIB message, it can derive the interference plus noise level ($\mathrm{IN}_i(0)$) by using

$$\mathrm{IN}_i(0) = \sum_{j \ne i} \left(p_j(0) \cdot h_{ji}(0) \right) + n_i = \mathrm{TRP}_i(0) - p_i(0) \cdot h_i(0), \quad (8)$$

where $\mathrm{TRP}_i(0)$ indicates the total received power strength for V2V link i at the initial transmission. Therefore, by means of this process, the receiving vehicle can calculate $p_i(t)$ and $\lambda_i(t)$ for all positive integers t, as shown in Fig. 4. The receiving vehicle transmits the calculated transmission power to the sending vehicle through the PVFCH resources. Note that the

```
Parameter update algorithm for DPC scheme at V2V link $i$
Receive the periodic SIB
**Initialization:** $\beta$, $p_i(0)$, $p_{\max}$, DPC activity indicator, $e$, and $\lambda_i(0)$
$t \leftarrow 0$
if DPC activity indicator is activate then
    $flag \leftarrow 1$
else
    $flag \leftarrow 0$
end if
while receive the V2V data do
        if $flag = 1$ then
            measure $H_i(t)$ and $\mathrm{IN}_i(t)$
            $H_i$ and $\mathrm{IN}_i \leftarrow$ average $H_i(t)$ and $\mathrm{IN}_i(t)$
            $p_i(t+1) \leftarrow \min\left\{\max_{P_i}\{U_i(\gamma_i(p_i(t),\mathrm{IN}_i,H_i)) - \lambda_i(t)\cdot p_i(t)\}, p_{\max}\right\}$
            $\lambda_i(t+1) \leftarrow [\lambda_i(t) + \beta\cdot(p_i(t+1) - p_{\max})]^+$
            if $|p_i(t+1) - p_i(t)| \leq e$ then
                tx power $\leftarrow p_i(t)$
                $flag \leftarrow 0$
            else
                tx power $\leftarrow p_i(t+1)$
            end if
        else
                tx power $\leftarrow$ previous tx power
        end if
        transmit tx power to the sending vehicle
        $t \leftarrow t+1$
end while
```

Fig. 4. Parameter update algorithm for DPC scheme at V2V link *i*.

vehicles can derive the suboptimal transmission power without the information of the transmission power ($p_j(t)$) for all $j \neq i$ and the channel gain ($h_{ji}(t)$) for all $j \neq i$, which is one of the most important features of the proposed scheme.

2. Parameter Update Algorithm for DPC Scheme

Figure 4 indicates the parameter update algorithm for the DPC scheme. As shown in Fig. 4, this algorithm is initialized and reactivated whenever the vehicle receives an SIB message including the DPC parameters. This is for the synchronization of the DPC scheme among vehicles. After receiving the SIB message, the receiving vehicle measures $H_i(t)$ and $\mathrm{IN}_i(t)$ and obtains the respective averages H_i and IN_i. In addition, it calculates $p_i(t+1)$ and $\lambda_i(t+1)$ by using (5) and (7), respectively. When the difference between $p_i(t)$ and $p_i(t+1)$ is larger than the iteration decision parameter (e), the receiving vehicle sends $p_i(t+1)$ to the sending vehicle and performs the next iteration. In the opposite case, the receiving vehicle sends $p_i(t)$ to the sending vehicle and stops the iteration by setting the *flag* as 0. Since this indicates that the transmission power converges to a suboptimal value under a certain condition, the receiving vehicle continuously sends the stored suboptimal transmission power to the sending vehicle until it receives the SIB message.

VI. Simulation Results

To evaluate the performance of the DPC scheme, we have simulated the SINR of the V2V links, the sum data rate of the V2V links, and the number of iterations. This paper considers the 3GDPC and GPC schemes as the conventional schemes. In the simulation, only V2V links exist within a single macro cell whose radius is 167 m and the maximum number of V2V links is 12. In addition, it is assumed that all V2V links share all PRBs in a subframe. The maximum transmission range of a V2V link is 100 m and the speed of a vehicle is 60 km/h. In the simulation, we have considered the path-loss and shadowing model for the channel model of a V2V link.

Furthermore, it has been implemented that a sending vehicle randomly moves within a cell every 1 s. A receiving vehicle is uniformly positioned in the maximum transmission range of the sending vehicle whenever the sending vehicle moves. The simulation parameters are as shown in Table 1.

Table 1. Simulation parameters.

Simulation parameters		Value
Carrier frequency		2 GHz
System bandwidth		1.4 MHz
Path-loss model between vehicles		$\max(27.06 + 42.93\cdot\log_{10}(d), 38.47 + 20\cdot\log_{10}(d))$ dB [12]
Shadowing model between vehicles	Gaussian distribution	Zero mean and standard deviation 6.67 dB [19]
	Decorrelation distance	4.5 m [19]
Maximum V2V transmission power		30 dBm
Noise density		– 174 dBm/Hz
Power control	Target received power	– 88 dBm
	Parameter for fractional power control (α)	0.8
DPC	Transmission period of SIB	5 s
	Initial Lagrangian multiplier ($\lambda(0)$)	0.01
	Initial transmission power ($p(0)$)	24 dBm
	Step size (β)	10^{-5}
	Iteration decision parameter (e)	0.1

1. SINR of V2V Links

Figures 5(a) and 5(b) show the SINR cumulative distribution function (CDF) of V2V links when the number of V2V links is 2 and 12, respectively. As shown in Figs. 5(a) and 5(b), in the

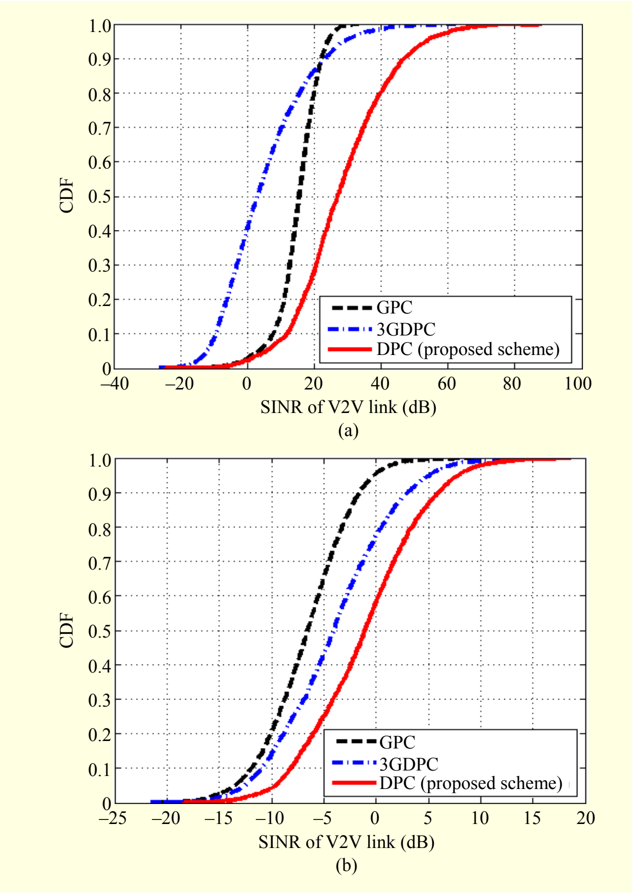

Fig. 5. SINR CDF of V2V links: (a) number of V2V links is 2 and (b) number of V2V links is 12.

case of the GPC scheme, the 10th percentile of the SINR CDF is decreased from about 10 dB to –13 dB as the number of V2V links increases from 2 to 12. The reason for this is as follows. In the case of the GPC scheme, because the sending vehicle calculates the transmission power based on the path-loss between adjacent vehicles, the strength of the interference among V2V links can be low when the number of V2V links is small. However, when the number of V2V links is large, the SINR of the GPC scheme is able to be dramatically decreased owing to the increase in interference among the V2V links.

In Fig. 5(a), in the case of the 3GDPC scheme, the 10th percentile of the SINR CDF is approximately –10 dB although the number of V2V links is equal to two. This is due to the following reason. In the case of the 3GDPC scheme, a sending vehicle calculates the transmission power based on the path-loss between the sending vehicle and a BS. Through this feature, the strength of the received signal can be lower than the desired signal strength when the distance between vehicles is longer than the distance between the sending vehicle and the BS. In this case, the SINR of the V2V link can be extremely deteriorated because the strength of the interference may be much stronger than that of the received signal when the receiving vehicle is near another sending vehicle. However, as shown in Fig. 5(b), the SINR of the 3GDPC scheme may be higher than that of the GPC scheme. This is because the strength of the received signal can be higher than the interference strength in the opposite case.

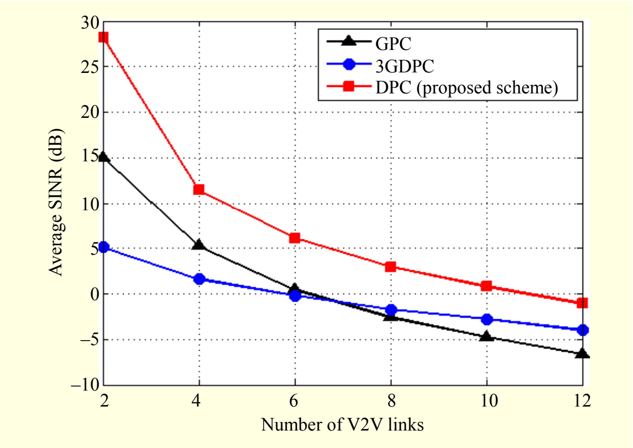

Fig. 6. Average SINR of V2V links according to number of V2V links.

In Figs. 5(a) and 5(b), the DPC scheme is superior to the GPC and 3GDPC schemes regardless of the number of V2V links, because the vehicles are able to adaptively control the transmission power according to the interference among V2V links. In particular, in the case of the DPC scheme, the 10th percentile of the SINR CDF is about –6 dB when the number of V2V links is 12, whereas that of the 3GDPC and GPC schemes is about –12 dB.

Figure 6 shows the average SINR of V2V links according to the number of V2V links. As shown in Fig. 6, the DPC scheme can improve the average SINR by more than 4 dB compared with the conventional schemes. In addition, the average SINR of the DPC scheme is consistently higher than that of the conventional schemes regardless of the number of V2V links. Consequently, it can be considered that the DPC scheme can improve the signal quality compared with the conventional schemes.

2. Sum Data Rate of V2V Links

Figure 7 shows the sum data rate of V2V links according to the number of V2V links. Here, the sum data rate of V2V links indicates the total summation of the data rates for all V2V links in the cell. In the case of the DPC and 3GDPC schemes, the sum data rate increases as the number of V2V links increases. This is because the rate of increase of the data rate owing to the increased number of V2V links is larger than the rate of decrease of the data rate owing to the increase in interference.

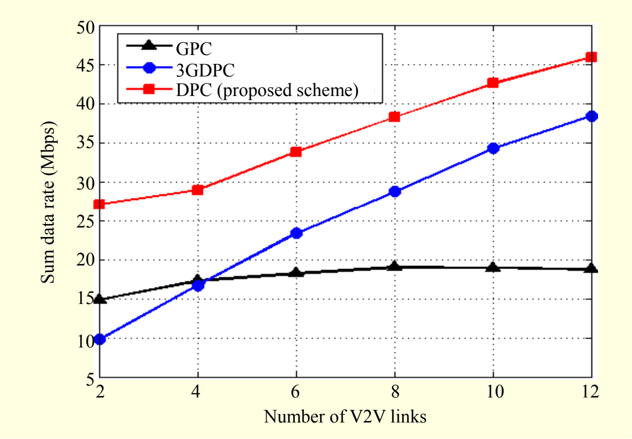

Fig. 7. Sum data rate of V2V links according to number of V2V links.

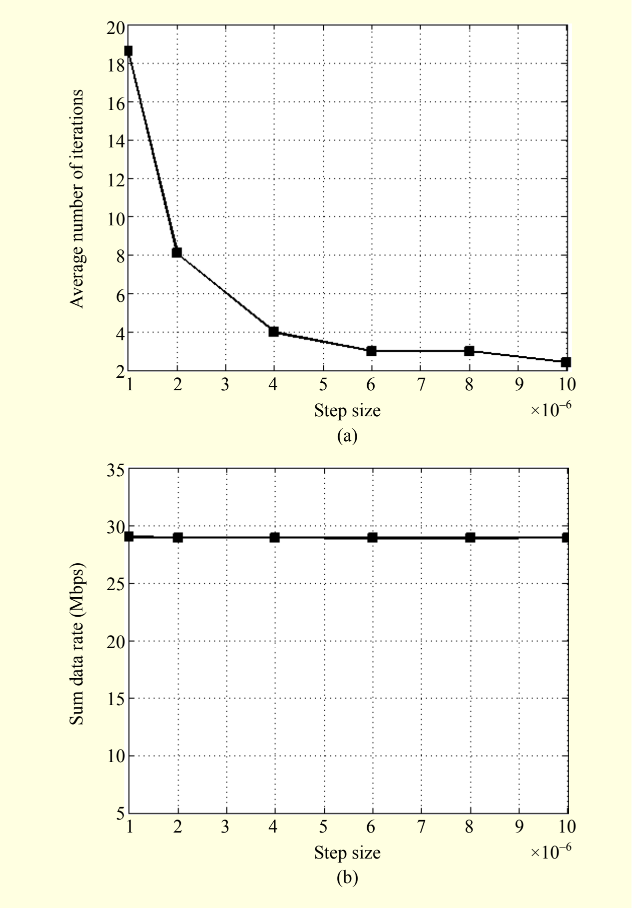

Fig. 8. Performance of DPC scheme according to step size when number of V2V links is four: (a) average number of iterations and (b) sum data rate of V2V links.

On the other hand, the sum data rate of the GPC scheme is not increased when the number of V2V links is larger than four. This is because of the limitation of the path-loss between vehicles and the target received power. As shown in Fig. 7, when the number of V2V links is 12, the sum data rate of the DPC scheme is improved by about 15% and 137% compared with the 3GDPC and GPC schemes, respectively. Therefore, it can be regarded that the DPC scheme can enhance the data rate of the V2V links compared with these conventional schemes.

3. Average Number of Iterations for DPC Scheme

In the case of the DPC scheme, several iterations are needed to derive the optimal transmission power. For this reason, this paper evaluates the average number of iterations required to converge to the optimal value according to the step size. As shown in Fig. 8(a), the average number of iterations is about three when the step size is larger than 6×10^{-6}. In addition, Fig. 8(b) shows that the sum data rate is approximately maintained regardless of the step size.

In the LTE system, the latency of the transmitting, decoding, and encoding processes of a message or data is generally 4 ms. If the number of iterations is three without a retransmission, then the time required to converge to the optimal value reaches about 48 ms when considering the resource request and allocation procedure presented in Fig. 3. Even if the number of iterations is 20, the time to converge to the optimal value is about 320 ms. This convergence time is less than the 12 s mentioned in Section II. As a result, it can be considered that the DPC scheme is adequate for V2V communication.

VII. Conclusion

By considering the features of a VMN, this paper has presented several problems of previous related works; that is, the practical problems of the optimal power and resource allocation scheme, the reliability of the 3GDPC scheme, and the data rate limitation of the GPC scheme. To solve these problems, this paper has proposed an efficient interference control scheme for a VMN. In addition, this paper has also presented a system model including the channel structure, signaling procedure, and parameter update algorithm for the proposed scheme. In particular, the DPC scheme, which is the main feature of the proposed scheme, can improve both the data rate and reliability of a V2V link. The simulation results have shown that the DPC scheme improves the average SINR by more than 4 dB and the sum data rate by 15% and 137% compared with conventional schemes.

In this paper, we have focused on a single-cell environment; thus, the study of an inter-cell coordination scheme is needed to make the proposed scheme run well in a multi-cell environment. For this reason, our future work is to design an interference control scheme for V2V links and evaluate the performance of the proposed scheme under a multi-cell environment.

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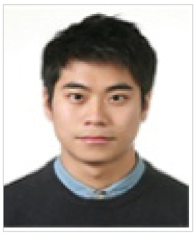

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