D2D-Based Cooperative Uplink Transmission for Vehicular Users

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Abstract. In this paper, we study a wireless communication network in which multiple mobile users located within a public transportation vehicle intend to send data to the serving base station. Due to the vehicle penetration loss (VPL), conventional direct uplink transmission may demand an unnecessarily high power level to reach a satisfactory communication performance. To address this issue we consider establishing cooperation among the vehicular users through the multiplexing-mode device-to-device (D2D) communication technique before their scheduled uplink transmissions. By these means the users can adopt simple space-time coding to jointly deliver their data, when the transmitter-side channel state information is not available. Via analytical and simulation results, we show that the proposed scheme can enhance the achievable energy efficiency over the conventional uplink transmission approach.

Keywords: VPL · D2D · Energy efficiency · Space-time coding

1 Introduction

Wireless communication technologies have progressed rapidly in recent years. Nowadays mobile Internet connections can be found almost everywhere in modern human societies. This results in significant enhancements in mobile data traffic and also leads to great commercial profits for mobile Internet service providers. The quality of human life and effectiveness of work have been dramatically improved, when people can freely browse Internet, chat with friends, watch video, and download documents no matter whether they are staying at home/office or travelling in cars/trains. It is widely believed that the demand for higher data rate and better service quality will never end. The industry has predicted a 1000-fold increase in mobile data traffic within the next decade [1]. In addition, according to the vision of the EU METIS project, 50 billion devices will be connected to each other in the year 2020 [2]. Hence, efficiently using limited resources to establish reliable and cost-effective wireless communications to satisfy the ever-increasing service demands becomes more and more important.

Due to the facts that mobile Internet applications have penetrated into various aspects of human life and many people need to spend a huge amount of time

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in road traffic every day, it is commonly envisioned that, a typical challenging issue in the future 5G era is to deliver data services to end users located in moving vehicles, for example in public transportation buses. Apart from the mobility of vehicles, the difficulty in providing satisfactory data transmissions to these users comes mainly from an extra *vehicle penetration loss* (VPL) induced by the vehicle metal hull, compared with normal outdoor end users. Measurements have shown that the VPL can be as high as several tens dB [2]. Consequently a relative large transmission power level is usually desired, which would be hard for mobile devices with limited power budget. Therefore, it is not easy to guarantee the data communication quality for uplink transmissions.

To tackle this problem, reference [2] proposes to utilize the direct device-to-device (D2D) communication concept (which will be an inherent part in 5G systems [3]) to establish collaborations between vehicular user equipments (VUEs) within the same vehicle. In other words, the VUEs first share their messages through D2D technology before sending them to the serving base station (BS). By this means, the VUEs can form a virtual antenna array and thus can jointly beamform their messages to the BS. It is shown that this strategy can significantly reduce energy consumption for the VUEs without sacrificing performance.

However, to realize the above benefits, the VUEs are demanded to have a certain level of channel state information (CSI) regarding the uplink channels. Although some practical solutions with limited signalling overhead can be adopted to attain the transmitter-side CSI, they may not be always applicable in all realistic systems, especially when the vehicle velocity is relatively high. In addition, to demonstrate the potential of VUE cooperation, it is assumed that the D2D message sharing is also conducted with transmitter-side CSI and hence can be managed without potential decoding errors. Clearly, since the signal propagation environment inside a vehicle can be very complicated, decoding errors at the VUEs may occur with non-negligible probability and thus would affect the final communication performance.

In this paper, these practical issues are taken into consideration. Specifically, we study the situation that multiple VUEs intend to send their messages to the BS. To compensate the negative effect of the VPL, we allow two VUEs inside the same vehicle to form a cooperation pair, by sharing their messages through D2D communications, before the uplink transmissions start. It is known that operating D2D communications in the multiplex mode can further improve system spectral efficiency. Hence we allow potentially multiple VUE pairs (in different vehicles) to reuse the uplink channel of a normal cellular user. No transmitter-side CSI is available. If the message sharing of a cooperation pair is successful, the two VUEs adopt the Alamouti space-time coding to jointly send their messages. Our analytical and simulation results demonstrate that such a D2D-based cooperative uplink transmission scheme can significantly improve the energy efficiency compared with the conventional direct source-destination transmissions.

2 System Model and Transmission Process

We consider a wireless communication scenario in which several public transportation vehicles are running on a road section within the coverage of a serving BS, as illustrated in Fig. 1. Inside each vehicle, multiple VUEs intend to send their data to the BS. In conventional uplink transmissions, the VUEs individually communicate with the BS, using two orthogonal channels (e.g. TDMA time slots). However, it is known that when a signal travels through the vehicle hull, a notable reduction in signal strength will be induced. Due to such a VPL problem, the message delivery process would demand a large power level to avoid encountering poor performance. This would result in a low efficiency of resource utilization.

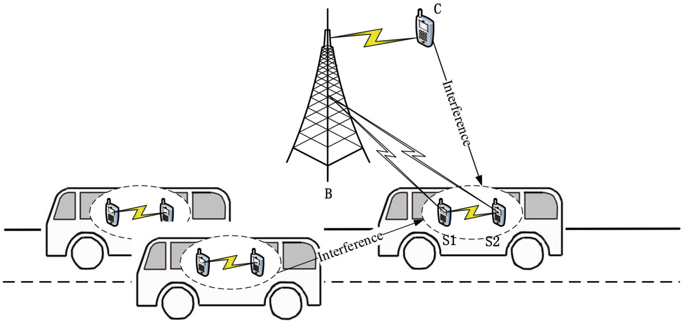


Fig. 1. System model.

To address this issue, in this paper we follow the idea proposed in reference [2] and consider establishing cooperation among the VUEs. Specifically, we require every two VUEs inside each vehicle to form a cooperation pair. Before being activated in their scheduled uplink transmission time, the VUEs in each cooperation pair share their messages via D2D communications. (The activities of the D2D message exchange process, such as channel and power assignment, can be monitored/controlled either directly by the serving macro BS or through the assistance of a micro BS/moving relay attached on the vehicle.) In other words, an extra channel is allocated to each cooperation pair. This channel can be divided into two unit time or frequency slots. In each slot, one VUE sends its data to the other. Albeit that such a D2D transmission channel can be reserved dedicatedly for these two VUEs, observing that the VPL would dramatically reduce signal power leakage outside the vehicle, to further exploit the D2D multiplexing gain and improve overall spectral efficiency, we consider the situation that the message exchange of one cooperation pair in each vehicle can reuse the uplink channel of a regular cellular user C, as displayed in Fig. 1.

Without loss of generality, we focus on one cooperation pair and denote the messages of the two VUEs by s_1 and s_2 respectively. Use P_d to denote the transmit power of the VUEs to exchange data and use R to denote the data rate of s_1 and s_2. For analytical simplicity, we consider a block Rayleigh fading environment. (The proposed transmission scheme is applicable in other fading environments.) Channel fading coefficients are modeled by random variables generated from complex Gaussian distribution $CN(0, \lambda)$, where λ reflects the effect of large-scale path loss (including the VPL if the signal goes through the vehicle hull). Due to the mobility of vehicles, the channel conditions may change rapidly. To avoid a large amount of signalling overhead, the fading coefficients are hence estimated and known at only the corresponding receivers.

In addition, we use x_c and P_c to represent the transmit signal and power of the cellular user C. x_{d_i} denotes the signal from other cooperation pairs that also reuse the uplink channel of C (assume there are a total of N such pairs and hence $i \in \{1, \cdots, N\}$). h'_{jc} (resp. h''_{jd_i}) is used to denote the channel coefficient between C (resp. the ith interfering cooperation pair) and the jth VUE in the considered cooperation pair. The number of superscript $'$ denotes how many times VPL would affect the signal propagation. Now for the D2D message exchange process, denoting the received signals of the two considered VUEs by y_1 and y_2 respectively, we can have

$$y_j = \sqrt{P_d} h_{jk} s_k + \sqrt{P_c} h'_{jc} x_c + \sum_{i=1}^{N} \sqrt{P_d} h''_{jd_i} x_{d_i} + n_j, \tag{1}$$

where $j, k \in \{1, 2\}$ $(j \neq k)$, h_{jk} denotes the channel fading coefficient between the transmitter k and receiver j, and n_j denotes the unit-power additive white Gaussian noise (AWGN). Clearly, the second and third terms on the right hand side (RHS) of (1) are the interference signals from C and other cooperation pairs.

Upon receiving the exchanged data, each VUE tries to carry out decoding by treating all interference signals as noise. If the decoding processes at both VUEs are successful, during their scheduled uplink transmission time slots, the two VUEs utilize the Alamouti space-time coding to send their messages to the BS using two TDMA time slots. Denote the received signals at the BS by r_1 and r_2 respectively. We can have:

$$r_1 = \sqrt{P_a} g'_1 s_1 + \sqrt{P_a} g'_2 s_2 + \tilde{n}_1, \tag{2}$$

$$r_2 = -\sqrt{P_a} g'_1 s_2^* + \sqrt{P_a} g'_2 s_1^* + \tilde{n}_2, \tag{3}$$

where P_a is the transmission power of the VUEs, g'_j denotes the channel fading coefficient between the jth VUE and the BS, and $\tilde{n}_1$ and $\tilde{n}_2$ are the unit-power AWGN.

On the other hand, if any VUE cannot correctly decode the other VUE's message, the conventional direct uplink transmission is adopted. Each VUE uses power P_u, which can be different from P_a in (2) and (3), to transmit its data to the BS. The received signals are hence simply

$$r_k = \sqrt{P_u} g'_k s_k + \tilde{n}_k, \text{ for } k \in \{1, 2\}. \tag{4}$$

3 Energy Efficiency Analysis

To demonstrate that the proposed D2D-based uplink transmission scheme can potentially improve the wireless resource utilization efficiency, in this section we derive the expression of the system's achievable *energy efficiency*, ξ_{EE}. ξ_{EE} is defined as the average successful transmission data rate between each VUE and the BS, in bits per unit of bandwidth by using one joule energy. In what follows, we assume that the channel coding applied in the physical layer is sufficiently strong so that the outage probability dominates error probability at each receiver. Use $\mathcal{P}_{out}$ to denote the outage probability of each VUE, i.e., the probability that the BS cannot correctly decode the messages from that VUE. Then the achievable energy efficiency is calculated as:

$$\xi_{EE} = \frac{(1-\mathcal{P}_{out})R}{P_{total}}, \tag{5}$$

where P_{total} is the total power consumption of each VUE.

The value of $\mathcal{P}_{out}$ is dependent on whether the D2D message exchange process is successful. Denote the probability that a VUE cannot correctly decode the other VUE's message by $\mathcal{P}_c$. According to Eq. (1), $\mathcal{P}_c$ can be calculated by

$$\mathcal{P}_c = P_r\left\{\log\left(1+\frac{P_d|h_{jk}|^2}{P_c|h'_{jc}|^2+\sum_{i=1}^{N}P_d|h''_{jd_i}|^2+1}\right)<R\right\}. \tag{6}$$

In general, it is involved to attain a closed-form expression of $\mathcal{P}_c$ due to the unpredictable nature of the interference from other D2D pairs, i.e. the term $\sum_{i=1}^{N}P_d|h''_{jd_i}|^2$. However, as we mentioned earlier, the VPL can dramatically reduce signal power leakage. The power level P_d is also normally kept small, since the cooperative VUEs are located within the same vehicle. As a result, with high probability the interference signals from VUEs in other vehicles, which experience two times of VPL, would be much weaker compared with the interference from C plus noise. Hence in what follows, we will omit them to simplify the derivation of $\mathcal{P}_c$. In the next section, we will show via simulations that such a consideration does not induce much loss of accuracy because of these reasons.

Now $\mathcal{P}_c$ can be approximated as

$$\mathcal{P}_c \approx P_r\left\{\log\left(1+\frac{P_d|h_{jk}|^2}{P_c|h'_{jc}|^2+1}\right)<R\right\} = P_r\left\{\frac{P_d|h_{jk}|^2}{P_c|h'_{jc}|^2+1}<2^R-1\right\}. \tag{7}$$

Let $X = P_d|h_{jk}|^2$, $Y = P_c|h'_{jc}|^2+1$, and $Z=\frac{X}{Y}$. The probability density function (pdf) of X is $f_X(x)=\frac{1}{\lambda_d P_d}\exp(-\frac{x}{\lambda_d P_d})$, where λ_d denotes the variance of D2D channel coefficient h_{jk}. The pdf of Y is $f_Y(y)=\frac{1}{\lambda_c P_c}\exp(-\frac{y-1}{\lambda_c P_c})$, where λ_c is the variance of the channel from C to VUEs, i.e., h'_{jc}. Using the probability transformation rule [8] one can have the pdf of Z as $f_Z(z) = \frac{\lambda_c P_c+\lambda_c P_c\lambda_d P_d+\lambda_d P_d}{(\lambda_c P_c z+\lambda_d P_d)^2}\exp(-\frac{1}{\lambda_d P_d}z)$. Now the outage probability $\mathcal{P}_c$ is calculated as

$\mathcal{P}_c = P_r\{Z < 2^R - 1\} = F_Z(2^R - 1)$, where $F_Z(z)$ is the cumulative distribution function of Z. Hence $\mathcal{P}_c$ and can be derived as [9]

$$\mathcal{P}_c = 1 - \frac{\lambda_d P_d}{\lambda_c P_c(2^R - 1) + \lambda_d P_d} \exp(-\frac{2^R - 1}{\lambda_d P_d}). \tag{8}$$

Therefore, the system outage probability $\mathcal{P}_{out}$ can be expressed as

$$\mathcal{P}_{out} = (1 - \mathcal{P}_c)^2 \mathcal{P}_{co,out} + \left(1 - (1 - \mathcal{P}_c)^2\right) \mathcal{P}_{di,out}, \tag{9}$$

where $\mathcal{P}_{co,out}$ is the outage probability at the BS when the two VUEs cooperatively transmit their messages, and $\mathcal{P}_{di,out}$ represents the outage probability at the BS when the VUEs transmit their messages individually to the BS.

As we mentioned earlier, if the D2D message exchange process is successfully carried out, the two VUEs send their messages to the BS using the Alamouti space-time coding. The received signals at the BS can be expressed as (2) and (3). In order to decode s_1 and s_2 from the received signals r_1 and r_2, the BS can perform the following transform of the signals:

$$\tilde{s}_1 = \frac{g_1^{'*}}{\sqrt{|g_1'|^2 + |g_2'|^2}} r_1 + \frac{g_2'}{\sqrt{|g_1'|^2 + |g_2'|^2}} r_2^* = \sqrt{P_a}\sqrt{|g_1'|^2 + |g_2'|^2} s_1 + \hat{n}_1, \tag{10}$$

$$\tilde{s}_2 = \frac{g_2^{'*}}{\sqrt{|g_1'|^2 + |g_2'|^2}} r_1 - \frac{g_1'}{\sqrt{|g_1'|^2 + |g_2'|^2}} r_2^* = \sqrt{P_a}\sqrt{|g_1'|^2 + |g_2'|^2} s_2 + \hat{n}_2, \tag{11}$$

where $\hat{n}_1$ and $\hat{n}_2$ are complex Gaussian distributed random variables with unit power. It can be seen from the above equations that

$$\begin{aligned}\mathcal{P}_{co,out} &= P_r\left\{\log\left(1 + P_a|g_1'|^2 + P_a|g_2'|^2\right) < R\right\} \\ &= 1 - \exp(-\frac{2^R - 1}{P_a}) - \frac{2^R - 1}{P_a}\exp(-\frac{2^R - 1}{P_a}).\end{aligned} \tag{12}$$

In addition, if any VUE cannot correctly decode the other VUE's message, then they individually transmit their messages. From (4) it is easy to obtain:

$$\mathcal{P}_{di,out} = P_r\left\{\log\left(1 + P_u|g_1'|^2\right) < R\right\} = 1 - \exp(-\frac{2^R - 1}{P_u}). \tag{13}$$

As a result, the system outage probability can be calculated by substituting (7), (12), (13) into (9). Finally, the total power consumption is expressed as

$$P_{total} = P_d + (1 - \mathcal{P}_c)^2 P_a + \left(1 - (1 - \mathcal{P}_c)^2\right) P_u \tag{14}$$

Now, the system's achievable energy efficiency ξ_{EE} can be found by substituting the above equations to (5).

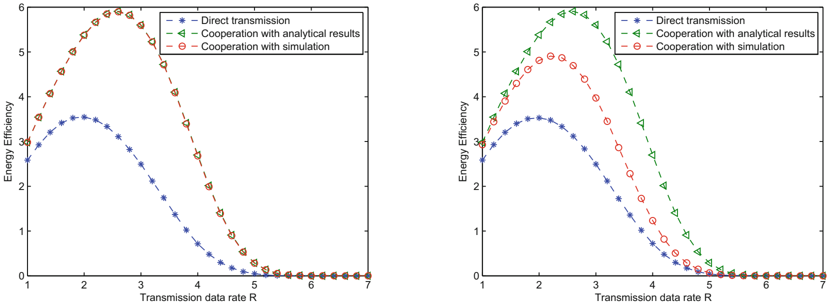
4 Numerical Evaluations

In this section we use simulation results to compare the proposed scheme with the conventional direct uplink transmission. In what follows, we assume the cell radius to be 800 m, and the distance between the road section and the BS is 200 m. The target cooperation VUE pair is assumed to locate in the center of the road section. For presentation simplicity, we choose C to be close to the BS. Hence the distances from the target VUE pair to the BS and C are both 200 m. The road section is one directional. The distance between adjacent vehicles follows an exponential distribution, whose pdf is governed by $f(x) = \theta e^{-\theta x}$ for $x > 0$ (the value of θ can represent the traffic density). In addition, we consider an extreme situation in which every vehicle on the road contains one pair of cooperation VUEs that reuse the uplink channel of C, in order to maximize the overall usage efficiency of system resource and also study the impact of inter-vehicle interference.

The main simulation parameters follow [10]: The bandwidth is 10 kHz and the noise density is 174 dBm/Hz. The transmit power of C is set to be $P_c = 25$ dBm. The path loss between the target VUEs is set to follow the indoor model $PL_d = 38.46 + 20 \log_{10} d_d$ dB, where the distance d_d is set to be 5 m. The path loss between C (and also other co-channel cooperation pairs) and the target VUEs follows the outdoor model: $PL_o = 15.3 + 37.6 \log_{10} d_o$ dB. Further, the VPL is set to be 20 dB.

In each of the following figures, we plot three performance curves. The first is termed "direct transmission" and represents the energy efficiency of conventional direct uplink transmission. The other two represent the performance of the proposed transmission strategy. In other words, before the scheduled uplink transmission, the two target VUEs share their messages through D2D communication, being potentially interfered by C and other VUEs reusing the same channel. In Sect. 3, we omitted the interference from other VUEs and obtained the approach to derive the closed-form of the achievable energy efficiency. The performance curve plotted following this derivation is termed "cooperation with analytical results." We also carried out simulations that take the interference from other VUEs into consideration, in order to see how such interference actually affects system performance. The associated curve is termed "cooperation with simulation." The second is termed "cooperation with analytical results." This curve is plotted according to the analytical derivations provided in Sect. 3.

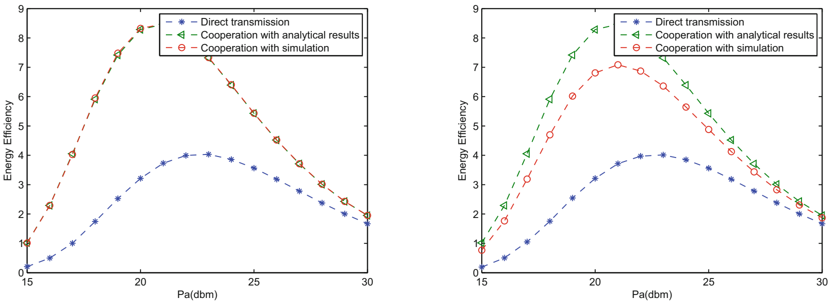
Figure 2 plots the achievable energy efficiency versus transmission data rate, when we fix $P_d = 10$ dBm and $P_a = 25$ dBm. First consider the case with light traffic, $\theta = 0.01$ (i.e., the average distance between two adjacent vehicles is 100 m), shown in Fig. 2(a). It can be seen that the simulation results nicely match the analytical results. In other words, the analysis provided in Sect. 3 can be adopted to correctly predict the performance of the considered system. Further, within a large range of transmission rate, the proposed scheme leads to a significant energy efficiency improvement over the conventional uplink transmission. Note that this performance gain is achieved without extra bandwidth consumption, since the D2D transmissions reuse the uplink channel of C.



(a) $\theta = 0.01$ (b) $\theta = 0.1$

Fig. 2. ξ_{EE} versus R

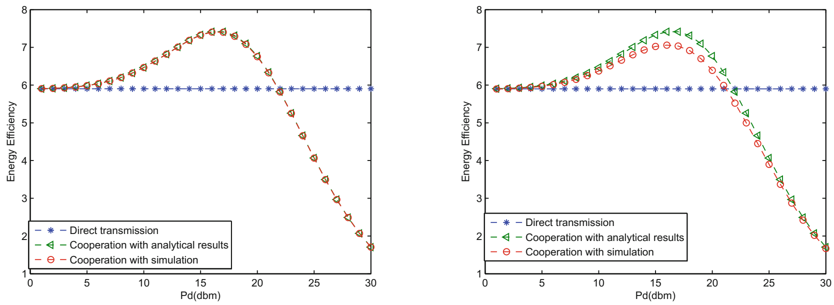
Moreover, when the transmission data rate is very large, the fixed power level is hard to support successfully transmission. Hence almost no message can be received. Both schemes attain very small energy efficiency. Figure 2(b) plots the case when the traffic density is high, $\theta = 0.1$ (i.e., the average distance between adjacent vehicles is 10 m). We can see that in this case the interference between VUE pairs will affect the system performance. But the proposed scheme still performs better than conventional direct transmission.



(a) $\theta = 0.01$ (b) $\theta = 0.1$

Fig. 3. ξ_{EE} versus P_a

Figure 3 plots the similar trend as that in Fig. 2. Specifically, when the traffic is low, ignoring the interference between VUE pairs does not lead to much analytical inaccuracy. For a wide range of P_a, the proposed scheme is more efficient than direct transmission. However, if P_a is too small, a large portion of the source messages would be lost, even with user cooperation. If P_a is too large, the outage probability at the BS approaches zero, even with direct transmission. Hence in both cases, the proposed scheme attains similar performance as direct transmission. But it is worth noting that the parameter settings in these extreme cases are not sufficiently good. When P_a is small, a smaller transmission rate should be chosen, to increase the probability of correct decoding, and when P_a is large, the transmission should also be large to maintain a good level of throughput. If we follow such choices, the proposed scheme would exhibits more significant performance advantages again. Finally, when the traffic is very heavy, the analytical result can be a little bit bias compared with the true performance.



(a) $\theta = 0.01$ (b) $\theta = 0.1$

Fig. 4. ξ_{EE} versus P_d

Figure 4 plots the achievable energy efficiency versus D2D transmission power. When the traffic density is low, which can be seen in Fig. 4(a), ignoring the interference will not cause inaccuracy in Sect. 3. When P_d is small and close to zero, it is hard to decode successfully. Thus the system is nearly equal to direct transmission. For a wide range of P_d, by using D2D technology the VUE pair can decode successfully and performance can obtain a better performance. When P_d becomes larger, the probability that VUEs decode successfully is equal to one and increasing P_d leads to waste of energy. So, the energy efficiency decreases. In Fig. 4(b), when traffic is high, ignoring inter-vehicle interference may become serious and hence affect the system performance.

5 Conclusion

We have proposed a D2D-based cooperative transmission scheme to improve the uplink transmission energy efficiency for mobile users locating inside public transportation vehicles. Specifically, before the scheduled uplink transmissions, two such VUEs are permitted to share their messages via D2D transmission. If the message sharing is successful, then they adopt the Alamouti space-time coding to carry out uplink transmissions. To improve system channel usage efficiency, we have considered the case that the D2D transmissions can reuse the uplink channel of a regular cellular user. We have provided the method to analyze the system achievable energy efficiency, and used numerical results to clearly exhibit the advantages of the proposed scheme over conventional direct uplink transmissions.

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