Uplink Enhancement of Vehicular Users by Using D2D Communications

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***Abstract*—In this paper, we discuss one application enabled by device-to-device (D2D) communication for vehicular users inside well isolated public transportation vehicles. We study the feasibility of using D2D communication to enhance the uplink communication for vehicular user equipment (VUE) devices. D2D communication allows fast data exchange among VUE devices, and therefore, a number of VUE devices can cooperate with each other and send data to the base station (BS) together. We employ a generalized co-phasing technique for the cooperation with per-terminal power constraint, and compare the energy efficiency of single user direct transmission, and cooperative transmission participated by various number of VUE devices. As the public transportation vehicle moves away from the BS and for large vehicular penetration loss, less energy is required to send the same amount of data of each active VUE in the cooperative transmission than the individual VUE-to-BS communications. Hence VUE devices in well isolated vehicles, especially those ones with limited battery lives, can save energy because of the enhanced uplink communications.**

I. Introduction

Nowadays, due to high penetration of smartphones, tablets and increasing portabilities of laptops, public transportation vehicles, e.g., buses, trams, or trains, become natural hotspots for wireless data traffic. As more computation burdens of terminals can be shifted to the server sides by the fast development of cloud computing, people are expecting to access remote services not only at home or in the office, but also at higher speeds, especially on their way to work or driving their cars [1]. Hence, a reliable communication between a user terminal and the server needs to be guaranteed for these vehicular user equipment (VUE) devices. In the view of the European Union project Mobile and wireless communications Enablers for the Twenty-twenty Information Society (METIS), up to 50 active VUE devices per bus and up to 300 active VUE devices per train are expected beyond the year of 2020 [1]. Thus, due to the signifiant number of VUE devices, it is very important to serve them cost-effectively in wireless systems.

A significant problem faced by VUE devices is the vehicular penetration loss (VPL), which substantially attenuates the radio signals traveling between the VUE devices inside vehicles and the base station (BS). Measurements show that VPL can be as high as 25 dB in a minivan at the frequency of 2.4 GHz [2], and more than 30 dB VPL is expected for well isolated high speed trains [3]. Higher VPLs are foreseeable if higher frequency bands are used [4], e.g., the 3.6 GHz band allocated to next generation mobile communication systems.

In this study, we present a scheme using device-to-device (D2D) communication to enhance the uplink communication of VUE devices. Offering uplink services for several closely located active VUEs in a mobile communication system is challenging, as they are competing for a limited amount of shared resources. But the newly introduced D2D communication technique brings in the opportunities for the active VUEs to cooperate with each other to enhance their uplink communications. D2D communication allows direct data exchange between user devices, either within the cellular spectrum offered by cellular infrastructures [5], or using the open industrial, scientific and medical (ISM) radio bands, e.g., WiFi direct [6]. Due to the great potential of improving the spectrum and energy efficiency, D2D communication has been investigated by the 3rd Generation Partnership Project (3GPP) for future releases of the Long Term Evolution (LTE) systems [5].

If we assume several VUE devices can exchange their uplink data by using D2D communications, they can collaborate with each other and steer the transmit signal towards the BS, when the channel state information (CSI) is available at those VUE devices. In this way, the received signal-to-noise ratio (SNR) at the BS can be significantly improved. This can be regarded as a multiple-input and multiple-output (MIMO) system with distributed antennas at the transmitter side. This scheme can be very relevant for other indoor scenarios as well, e.g., in an office or in a shopping mall; however, in a bus or a train carriage, as the VUEs' positions are relatively stable, the discovery overhead to find D2D partners to cooperative with in such a scenario is smaller. In addition, by cooperating with each other, the participated VUEs can use the same time and frequency resources to send their data to the BS, and thereby improving the spectrum efficiency of the system.

Contributions: we argue that by exchanging data with each other using D2D communications, the VUEs can significantly reduce the radio frequency (RF) transmit energy for their uplink communications. We consider a scenario where several VUEs need to communicate with the BS. They can either communicate with the BS individually, or cooperate with each other for the uplink communication via a D2D service offered by the network. To this end, we compare the required overall RF transmit energy, including the RF energy for D2D communications, of the considered uplink cooperating scheme with individually VUE-to-BS communications. We show that when a public transportation vehicle is far away from the BS, and the communication is affected by high VPL, by cooperating with each other, the expended RF energy for each VUEs is lower than the direct VUE to BS communications. This is very beneficial from an energy efficiency point of view, especially for the VUEs that operate with limited battery lives.

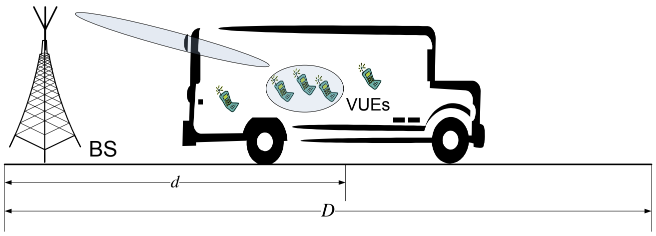

Figure 1. An illustration of cooperative uplink communication of VUEs

Notation. Throughout this paper, we shall use the notations as follows. Bold capital letters are used to represent matrices, whereas bold lower case letters denote vectors. The superscript ^{T} is the matrix transpose, while the superscript * is the conjugate transpose. The expectation is denoted as $E[\cdot]$, and $\log_2(\cdot)$ is the logarithmic function with base 2. The real part of a complex number c is denoted as $\mathcal{R}\{c\}$, and $\| \mathbf{x} \|$ is the Euclidean norm of the vector $\mathbf{x}$.

II. System model

The considered setup is depicted in Fig. 1, where n VUEs are inside a public transportation vehicle. We consider a noise limited system with frequency flat fading, where a BS has a fixed coverage of D meters. This assumption may be extended to wideband systems with frequency-selective fading through orthogonal frequency-division multiple access (OFDMA). In an OFDMA based system, this can be seen as a subchannel or a subchannel group whose bandwidth is much smaller than the coherence bandwidth [7, Ch. 12]. We assume m out of n VUEs are active and need to send data to the BS. In this study, we assume each active VUE has a reasonable large amount of data to send to the BS[1], e.g., sending emails with big attachments. The communication takes place in two steps: 1) each VUE exchange its data with all other VUEs by using D2D communication; 2) VUEs cooperate together to send the data to the BS.

When we consider frequency flat fading over the bandwidth of interest, if there are r antennas at the BS, the received signal at the BS can be written as

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{z}, \tag{1}$$

where $\mathbf{y} = [y_1 \cdots y_r]^T$ is the $r \times 1$ receive signal vector, $\mathbf{x} = [x_1 \cdots x_m]^T$ is the $m \times 1$ transmit signal vector, $\mathbf{z} = [z_1 \cdots z_r]^T$ is the $r \times 1$ noise vector with variance σ_z^2, and $\mathbf{H}$ is the $r \times m$ channel matrix, where each element $h_{a,\,b}$ in $\mathbf{H}$ is the channel between the ath receiving antenna and the bth VUE. We assume the CSI is available at the transmitter side, i.e., all the VUEs in a cooperation know $\mathbf{H}$. In practice, obtaining CSI at transmitter (CSIT) can be very challenging, especially for high-speed user devices. Nevertheless, by employing a semi-persistent scheduler[2] and using overlapping pilots, joint multi-user channel predictions can be performed at the BS. At a moderate vehicular speed[3], the uplink channel of each of the VUEs can be predicted with acceptable accuracy at the BS [8]. Then, either the BS can signal the channel information to each of the VUEs in the downlink, or to a particular VUE which can share the channel information to other participants over the D2D links. In Section III, we will show that the BS only needs to signal the transmit phase to individual VUEs, and therefore, the downlink signaling overhead is not substantial in order to enable the cooperation between VUEs.

The objective is to maximize the received SNR at the BS, so that the total data rate can be increased. Hence, it takes less time for the active VUEs to send the same amount of data. With CSIT and in the absence of a per-terminal transmit power constraint, the received SNR can be maximized by employing the maximum ratio transmission (MRT) scheme [9], where a single data stream is transmitted by all the VUEs that participate in the communication. However, MRT tends to allocate most of the power to a few VUEs with better channel conditions, which may violate the power constraints for some of the VUEs [10]. By just regulating the transmit power given by the MRT solution according to the maximum transmit power constraint results in significant performance degradation, since the received SNR is no longer maximized.

We assume all the VUEs have the same maximum transmit power P_{u} for the uplink communication, i.e.,

$$E[| \, x_t \, |^2] \leq P_{\mathrm{u}}, \; t = 1, 2, \cdots, m. \tag{2}$$

Since all the VUEs are transmitting the same data at each time slot, the transmit signal can be written as

$$\mathbf{x} = [e^{\theta_1} \cdots e^{\theta_m}]^T u, \tag{3}$$

where $[e^{\theta_1} \cdots e^{\theta_m}]$ is a steering vector, and u is a data symbol with $E[| \, u \, |^2] = P_{\mathrm{u}}$. This clearly satisfies the per-terminal transmit power constraint, and now the problem of interest becomes to find the optimum phase of each VUEs so that the received SNR is maximized at the BS. We assume that the BS has perfect CSI, and performs maximum ratio combining (MRC) for data detection. Then, this problem is regarded as a generalized co-phasing scheme introduced in [11]. More details of the generalized co-phasing technique are discussed in Section III.

Recall that the cooperative communication is done in two steps, i.e., the D2D communications between VUEs, and the cooperative uplink transmissions. In the first step, if the time for the ith VUE to broadcast its message to all the other VUEs is T_{1i}, the total energy consumed in this step is

$$E_1 = \sum_{i=1}^{m} P_{\mathrm{D}_i} T_{1i}, \tag{4}$$

[1] We do not consider bursty data traffic in this study, e.g., control signaling for online gaming, since the time to transmit such small a data packet can be fairly short.

[2] A semi-persistent scheduler is necessary in this case, as certain number of continuos observations of the same frequency resource are required for the channel predictor to work.

[3] As the number of VUEs and their speed increases, the accuracy of the joint multi-user channel prediction degrades. But the studies in [8] show that, up to a velocity of 70 km/h, enough accuracy can be obtained by using overlapping pilots for 2 to 8 users in the uplink. As overlapping pilots are used, the pilots overhead does not increase noticeably compared to the single VUE case.

where P_{D_i} is transmit power of the ith VUE used for its D2D communication. For simplicity, in this study P_{D_i} is assumed to be the same for all VUEs.

In the second step, since we assume all the m VUEs are cooperating with each other, and sending the same data symbol concurrently, the time T_2 for the uplink communication is the same for all those VUEs. When all the m VUEs transmit at their maximum power P_{u}, the energy spent in this stage is

$$E_2 = m\, P_{\mathrm{u}}\, T_2. \tag{5}$$

For simplicity, we assume each active VUE have the same amount of N bits to transmit[4]. Thus, for the cooperative scheme, the energy spent on per information bit is

$$\bar{E}_{\mathrm{c}} = \frac{E_1 + E_2}{m\, N}. \tag{6}$$

Regarding individual VUE-to-BS communications, if the time needed for the communication is T_3, the energy spent on per information bit is

$$\bar{E}_{\mathrm{i}} = \frac{P_{\mathrm{u}}\, T_3}{N}. \tag{7}$$

Equation (6) and (7) will be used to evaluate the performance of the considered schemes, and the results are presented in Section IV.

The amount of data N needed to be transmitted is assumed to be known in this work. Thus, the transmission time T_{1i}, T_2, and T_3 can be determined if the data rate is known. For simplicity, in our work, the data rated is determined by the throughput based on mutual information [12], given as

$$R = B\, \log_2\left(1 + \gamma\right), \tag{8}$$

where γ is the received SNR and B is the bandwidth used for the communication.

For a single antenna point-to-point communication in a flat fading noise limited system, if the average transmit power is P_{t}, the received SNR can be expressed as

$$\gamma_1 = \frac{P_{\mathrm{t}} |h|^2\, L\, \varepsilon}{N_0}, \tag{9}$$

where h represents the channel coefficient and L models the pathloss between a receiver and a transmitter. For VUE-to-BS uplink communications, we use the 3GPP spatial channel model (SCM) for urban macrocell environment [13]. However, for D2D communications, there is no universal acceptable channel models yet. Thus, we align our pathloss assumption with the one used in [14, Table 2], and add an extra 20 dB fading margin to include the power loss caused by fading. A non-line-of-sight (NLOS) environment is assumed for VUE-to-BS communication, and a line-of-sight (LOS) environment is assumed for D2D communication, as the VUEs are usually located near to each other. The received SNR for D2D communication and individual VUE-to-BS communication can be determined by (9), and thereby T_{1i} and T_3 can be calculated accordingly. However, in order to determine T_2, the received SNR at the BS need to be obtained for the generalized co-phasing technique, and this problem will be discussed in detail in Section III.

[4]This is a valid assumption, if each of the VUE has a very larger amount of data to send to the BS.

III. Introduction to the Generalized Co-phasing Technique

In this section, we briefly present the idea of the generalized co-phasing technique introduced in [11]. The generalized co-phasing is a closed-loop MIMO scheme that exploit the CSIT when considering a per-antenna constraint. The same data symbol is sent at all the antennas but with different phases determined based on CSIT. Compared with MRT which only put a constraint on the total transmit power, the co-phasing scheme is more realistic, as almost all practical systems have per-antenna power constraints. In our study, each VUE is considered to be equipped with a single antenna, and thereby the per-antenna power constraint translates to a per-terminal power constraint.

We can rewrite the channel matrix $\mathbf{H}$ as

$$\mathbf{H} = [\mathbf{h}_1 \cdots \mathbf{h}_m], \tag{10}$$

where $\mathbf{h}_k,\ k = 1, \cdots\ m$ is the $k-$th column of $\mathbf{H}$. Then the received signal (1) at the BS can be written as

$$\mathbf{y} = \left(\sum_{k=1}^{m} e^{j\,\theta_k} \mathbf{h}_k\right) u + \mathbf{z}. \tag{11}$$

Let $\mathbf{h}_e = \sum_{k=1}^{m} e^{j\,\theta_k} \mathbf{h}_k$, then with an MRC detector at the BS with perfect CSI, the received SNR at the BS is

$$\gamma_2 = \frac{\parallel \mathbf{h}_e \parallel^2\ P_{\mathrm{u}}}{\sigma_z^2}. \tag{12}$$

In this study, we assume all the VUEs are transmitting at the same maximum power P_{u} for their uplink communication. Hence, to maximize the received SNR γ_2 at the BS is equivalent to maximize the Euclidean norm $\parallel \mathbf{h}_e \parallel^2$. From (11), we have

$$\parallel \mathbf{h}_e \parallel^2 = \sum_{k=1}^{m} \parallel \mathbf{h}_k \parallel^2 + 2 \sum_{k=1}^{m} \sum_{l=k+1}^{m} \mathcal{R}\left\{ e^{-j\,(\theta_k - \theta_l)}\, (\mathbf{h}_k^* \mathbf{h}_l) \right\}. \tag{13}$$

As we can observe in (13), $\parallel \mathbf{h}_e \parallel^2$ is maximized if

$$g\left(\theta_1,\, \theta_2 \cdots \theta_m\right) \triangleq 2 \sum_{k=1}^{m} \sum_{l=k+1}^{m} \mathcal{R}\left\{ e^{-j\,(\theta_k - \theta_l)}\, (\mathbf{h}_k^* \mathbf{h}_l) \right\} \tag{14}$$

is maximized. Thus, the optimization problem is formulated as follows.

$$\begin{aligned} &\text{Maximize} && g\left(\theta_1,\, \theta_2 \cdots \theta_m\right) \\ &\text{subject to} && 0 \le \theta_k < 2\,\pi \text{ for } k = 1,\, 2,\, \cdots,\, m. \end{aligned} \tag{15}$$

Problem (15) implies that not the absolute but only the relative phase between different terminals matters in order to maximize the received SNR at the BS. However, problem (15) is not convex. Thus, several heuristic and iterative based algorithms are suggested in [11] to solve this problem.

Table I
EVALUATION PARAMETERS

Parameter	Value
Carrier frequency	2.6 GHz
Cell radius	866 meters
Number of antennas at the BS	2
VUE to BS pathloss model	$L_{\rm dB} = 39.1 + 35.1 \log_{10}(d)$
D2D pathloss model	$L_{\rm dB} = 41.1 + 16.9 \log_{10}(d_{\rm UE})$
D2D fading margin	20 dB
VUE to BS transmit power	23 dBm
D2D transmit power	10 dBm
Receiver noise figure at the BS	5 dB
Receiver noise figure at the VUE	9 dB
PRB size	180 kHz
Traffic model	Full buffer

In this evaluation, we use the iterative co-phasing algorithm proposed in [11], which can achieve a near optimal solution in most cases. This approach iteratively aline the phase of each terminal with all other terminals until the phases of all terminals converge, or alternatively, the algorithm terminates after a certain number of iterations. In order to understand how this method works, we can rewrite $g(\theta_1, \theta_2 \cdots \theta_m)$ with respect to the first terminal as

$$\begin{aligned} g(\theta_1, \theta_2 \cdots \theta_m) &= \mathcal{R}\left\{ e^{-j\,\theta_1} \sum_{l=2}^{m} e^{j\,\theta_l} \mathbf{h}_1^* \mathbf{h}_k \right\} \\ &+ \sum_{k=2}^{m} \mathcal{R}\left\{ e^{-j\,\theta_k} \sum_{l=k+1}^{m} e^{j\,\theta_k} \mathbf{h}_k^* \mathbf{h}_l \right\}. \end{aligned} \tag{16}$$

Observe that the second term does not depend on θ_1, the phase of the first terminal. In the same way, for each terminal k, similar expression as (16) can be obtained. Thus, for each terminal k, its phase can be chosen as a function of all other terminals, i.e.,

$$\theta_k = \measuredangle \left(\sum_{l=1,\, l \neq k}^{m} e^{j\,\theta_l} \mathbf{h}_k^* \mathbf{h}_l \right). \tag{17}$$

Simply we can arbitrarily initialize the phase of each terminal, or set the phases of all terminals to a common value, and determine the phase of each terminal in orders by using (17) in each iteration. The detailed performance evaluation is presented in Section IV.

IV. PERFORMANCE EVALUATION

In this section, we evaluate the energy efficiency performance of the considered schemes by using system level evaluations. The employed evaluation parameters are based on [13], [14], and are summarized in Table I[5]. VUEs are located inside a public transportation vehicle, and several of the VUEs need to send data to the BS. Only VUEs which require uplink communications are assumed to participate in the cooperation. This is a realistic assumption, as it is difficult to motivate that idle VUEs with no uplink traffic should participate in the cooperation. Each of the VUEs could communicate with the BS directly (baseline case), or different number of VUEs can cooperate with each other by using D2D communications. In a cooperation, based on the size of an average city bus, we assume a maximum distance of 5 meters is assumed between two furthest VUEs participants. One physical resource block (PRB), which is the smallest scheduling grant, is used for VUE-to-BS communications, and 10 PRBs are allocated for D2D communications. This is motivated by the fact that user devices are usually limited by their transmit power, and in practical systems, e.g, the LTE system, user devices can concentrate their power in a small bandwidth to maximize the coverage [15, Ch. 18]. However, compared to VUE-to-BS communication, for D2D communication, as VUEs are located near to each other, the communication is unlikely to be limited by power. Thus, wider bandwidth and lower transmit power is assumed in this study for D2D communications.

[5]The distance for calculating the pathloss is in the unit of meters

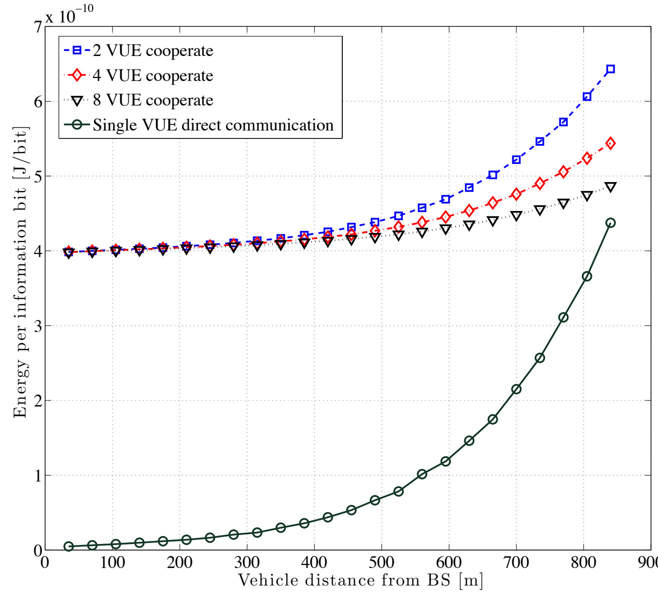

Figure 2. Energy per information bit when VPL = 20 dB

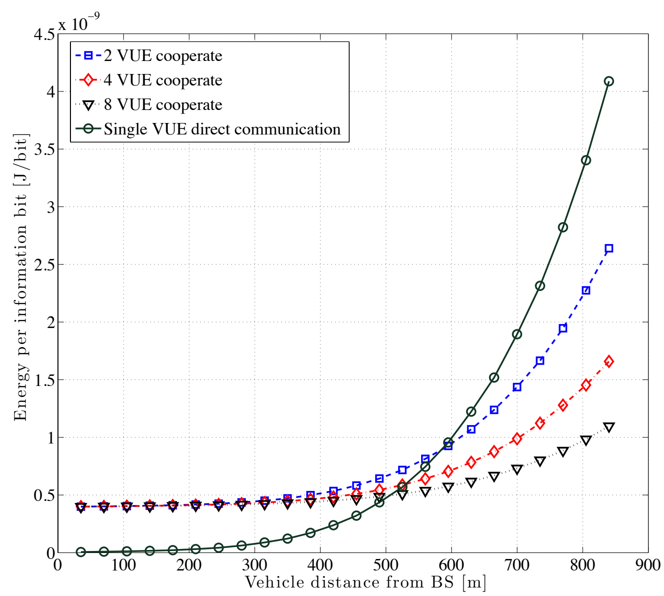

Figure 3. Energy per information bit when VPL = 30 dB

Figs. 2 and 3 plot the average expanded energy per information bit when different number of VUEs cooperate with each other in the cases of VPL equal to 20 dB, and 30 dB. As we can see from both figures, for the cooperative transmissions, the more VUEs participate in the cooperation, the lower the energy spent on the communication. However, when VPL is 20 dB, the individual direct communication of each VUE with the BS costs less energy than the cooperating transmission. This is because the energy saved by the VUE cooperation is less than the energy overhead introduced by the D2D communication.

Nevertheless, when the communication is affected by higher VPL, i.e, 30 dB, the energy saving of using VUE cooperation can be observed as the public transportation vehicle is moving away from the BS. This is due to the fact that VUEs are power limited for uplink communications. When the VPL is high, the communications are conducted in a power limited region, and therefore even if two VUEs cooperate, it results in significant increasing of data rate. Thus, all active VUEs can send their data faster, and spend less energy in total even when including the overhead caused by D2D communication.

V. Discussion and Conclusion

We presented an application based on D2D communications to enhance uplink communications of VUEs inside well isolated public transportation vehicles, as higher uplink traffic demand are expected in such vehicles due to the requirement of working or entreatment, e.g, file exchange by email, or high definition video communications. When the VPL is moderate, each VUE prefers individual uplink communication with the BS, as the overhead of D2D communications may be big. However, at high VPL, by cooperating with each other, all the VUEs participated in the cooperation can save energy. This is very beneficial, especially for the VUEs that have limited battery lives. In the cases of well-isolated high speed trains or long range coaches, a 30 dB or even higher VPL is fairly common [3]. Note that, in this study, we do not consider power control schemes for D2D communication. The communication overhead of D2D communications could be further reduced by employing proper power control schemes [16]. Hence, even more energy savings can be expected.

Moreover, due to the relative low transmit power of D2D communications and high VPL of the vehicle, the interference generated by D2D communications can be well isolated inside the vehicles. Thus, in such scenarios, the interference management overhead for the cellular system can be significantly lowered compared to other outdoor scenarios with D2D communications. In addition, the synchronization requirement of the D2D uplink cooperation can be easily satisfied, since in current cellular systems, for the uplink communication, there are already mechanisms to guarantee proper time and frequency synchronizations between different user devices [15, Ch. 15, 16, 18].

As the number of participated VUEs increase, the delays caused by D2D communication could potentially make this scheme not applicable for delay sensitive data traffic. Furthermore, whether D2D broadcast or multicast can be supported in future cellular systems is still uncertain. Nevertheless, as we showed in Section IV, even when two VUEs are cooperating, both parties can benefit from each other. Thus, D2D communication brings in new opportunities for VUEs that are affected by high VPL.

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