Some Notes on Device-to-Device Communications Using the Uplink Channel

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Résumé – Nous présentons des méthodes afin d'analyser l'efficacité spectrale des liaisons *« device-to-device » (D2D)* partageant les ressources du canal montant d'un système cellulaire. Nous adressons particulièrement les influences des différents niveaux d'interférences et les méthodes permettant de les mitiger dans le récepteur du terminal D2D. Nous considérons davantage deux hypothèses importants sur le niveau de connaissances des interférences dans le récepteur de la station de base. Premièrement, nous traitons le scenario ou le transmetteur D2D possède une mémoire locale qui peut être exploiter par le réseau et que l'ordonnanceur de la station de base connait parfaitement l'information à véhiculer par le transmetteur D2D. Dans ce cas, l'interférence vu par la station de base peut être enlever parfaitement et résulte en aucune perte d'efficacité spectrale au niveau du canal montant. Le deuxième scenario considère le cas où la station de base ne connait pas les informations transmises par le terminal D2D. Nous montrons dans les deux cas que les méthodes sophistiquées au sein du récepteur du terminal D2D sont requises afin d'atteindre le plus haut niveau de performance. En même temps, l'utilisation de ces méthodes simplifie la tâche de l'ordonnanceur en ce qui concerne la recherche d'utilisateurs sur le canal montant compatibles avec les communications D2D.

Abstract – We provide an overview of the analysis of spectral efficiency for so-called *device-to-device (D2D)* links sharing the uplink resource of a cellular system. Specifically, we address the regimes of interference and the methods to mitigate them at the terminal receiver of the D2D communication. In addition, we consider two important assumptions regarding the knowledge of the interference at the basestation. Firstly, we address the scenario where the D2D transmitter is a local cache of information on behalf of the network and the basestation scheduler is aware of the content that is being offloaded. In this case, the interference seen by basestation can be completely removed and thus does not impair the spectral-efficiency of the uplink channel. The second scenario is where the basestation is not aware of the content and thus cannot remove it. We describe the regimes of operation which are simply characterized as weak, medium and strong interference. We show that in both scenarios, the use of the sophisticated interference cancelling methods at the D2D receiver can provide significant benefits and can reduce the burden on the basestation scheduler in finding compatible users to schedule in conjunction with D2D transmissions.

1 Introduction

Consider the communication scenario in Figure 1. Here the bottom-rightmost terminal is communicating directly with the top-rightmost terminal (terminal 1) on the same channel as the uplink communications to the basestation (terminal 2). This is the envisaged mode of operation in the current 3GPP cellular communication standard for the so-called *Sidelink channel* [1]. The main application scenario considered by 3GPP D2D communication links Although not considered as an application scenario in today, another potentially important scenario for operators is one where terminals are exploited by the infrastructure as distributed caches.

In this paper we consider use of D2D links firstly to aid in the distribution of content by coverage extension due to the proximity between devices. This can be seen as an instantiation of two-hop relaying strategies. The second usage of D2D links is to allow end-devices with cached content to exchange this content under the control of the local basestations either to aid in interference management of the overall network or due to the absence of the particular content in the local cache of the basestations. This communication would primarily be used to hide the content distribution in the background noise of the network and is made possible solely because of the combination of the proximity of the nodes and their capacity to store content with the macroscopic vision of basestations with respect to the nodes in their cells.

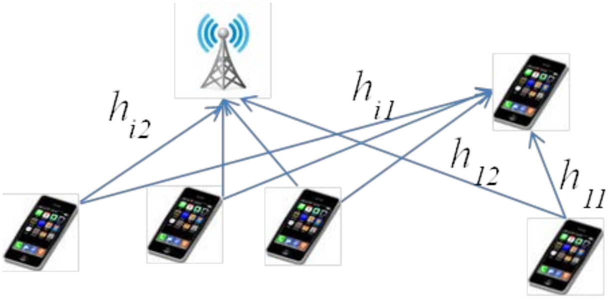

Figure 1 : General D2D Scenario with Reuse of Uplink Frequency

1.1 Channel Model

For the scenario shown in Figure 1 which corresponds to reuse of the uplink channel for a single D2D link among L transmitting nodes. Here the basestation schedules the transmission of $L-1$ uplink users which interfere with one D2D link. The combined interference channel is given by

$$y_{in} = \sum_{j=1}^{L} \sqrt{P_{ij}} h_{ijn} x_{jn} + z_{in}, i = 1,2, n = 1 \dots N$$

where P_{ij} and h_{ijn} are the average received power and instantaneous complex channel amplitude from node j to node i, and y_{in} and x_{jn} are the received signal at node at node i and transmitted signal from node j. The signals are assumed to comprise N signaling dimensions, which can appropriately model OFDM or SC-FDMA transmission. All channels are assumed to be known perfectly by both receivers. The transmitted signals are assumed to satisfy the average power constraint

$$\sum_{n=1}^{N} E\left|x_{jn}\right|^2 \leq 1$$

and the noise is assumed to be circularly-symmetric Gaussian noise with variance σ^2.

At this point we can already highlight two cases. Firstly, we have the case where receiver 2, the basestation, is scheduling a codeword coming from known content in node 1, the D2D transmitter. Here, the signal x_{1n} is known and thus $\sqrt{P_{i1}} h_{i1n} x_{1n}$may be stripped out from the received signal at receiver 2. This will be termed the Z-channel case. Secondly we the general case that receiver 2 is scheduling a codeword that is unknown. The first case would correspond to using the the D2D transmitter as a local cache of content that was previously sent to it for opportunistic offloading, whereas the second would correspond to content that is originating in the D2D transmitter.

In the following subsections we will provide bounds on the spectral efficiency that can be achieved in both cases. Specifically we are interested in evaluating the so-called sum-capacity in both cases. The information rate for node j in bits per dimension is denoted R_j and the sum-capacity is $\sum_{j=1}^{L} R_j$.

2 Using known results for the case $L = 2$

For the case $L = 2$ we can generalize the results from [2] (Z-Channel) to provide the sum-capacity exactly, albeit conditioned on a particular channel realization. This is given by Equation 1 (at the end of this document).

The first condition corresponds to the case where the interference from the uplink user is strong enough to be decoded at the D2D link prior to decoding the desired signal. In the literature, this is known as the strong interference condition. Under this condition, the D2D receiver (1) can completely decode the interfering signal, re-encode the waveform corresponding to the uplink transmission and subtract it from the total received signal. This is known as successive interference cancellation and is commonly used in commercial terminals when receiving multi-layer coded streams in MIMO or in basestations when multiple Terminals are scheduled on common resources (multiuser detection). In order to benefit under this condition, specific signal processing is therefore required at the D2D receiver. Moreover, if the channel estimation is lossy, the residual error from interference cancellation can be significant if the interference level is high, reducing the benefit when exploiting this regime.

The second condition says that the interfering signal is very weak. Under this condition, the D2D receiver treats the interference from the uplink signal as additive noise. Such receivers are commonly understood and their performance can be readily assessed using standard techniques.

The third condition, finally, corresponds to a moderate interference level. This is the most difficult regime to exploit efficiently because the signaling techniqterminals to achieve the spectral efficiencies predicted by this analysis would require that the basestation limit the code rate of the uplink user so that its signal component can be decoded by the D2D receiver (1) and stripped out prior to decoding the D2D signal. To see this, note that to be decoded by the D2D receiver, the rate of the first layer must satisfy

$$R_2 < \frac{1}{N} \sum_{n=1}^{N} \log_2 \left(1 + \frac{P_{21}|h_{21}|^2}{\sigma^2 + P_{11}|h_{11}|^2}\right)$$

and the rate of the D2D user is

$$R_1 < \frac{1}{N} \sum_{n=1}^{N} \log_2 \left(1 + \frac{P_{11}|h_{11}|^2}{\sigma^2}\right)$$

yielding the total rate sum rate

$$R_1 + R_2 < \frac{1}{N} \sum_{n=1}^{N} \log_2 \left(1 + \frac{P_{11}|h_{11}|^2}{\sigma^2} + \frac{P_{21}|h_{21}|^2}{\sigma^2}\right)$$

So, in this regime the uplink user pays the penalty to increase the rate of the D2D user which complicates the scheduling policy of the basestation. Moreover, in the other two regimes there is no such constraint on the uplink spectral efficiency as a function of the D2D link.

If now we turn to the case where interference is also experienced at the basestation we must resort to bounding the capacity by generalizing the results of [3]. This yields the following upper-bound to the sum-capacity

$$
\begin{aligned}
R_1 + R_2 \leq \min\Bigg(& \frac{1}{N}\sum_{n=1}^{N} \log_2\left(1 + \frac{P_{21}|h_{21}|^2}{\sigma^2} + \frac{P_{11}|h_{11}|^2}{\sigma^2 + P_{12}|h_{12}|^2}\right) \\
& + \frac{1}{N}\sum_{n=1}^{N} \log_2\left(1 + \frac{P_{12}|h_{12}|^2}{\sigma^2} + + \frac{P_{22}|h_{22}|^2}{\sigma^2 + P_{21}|h_{21}|^2}\right), \frac{1}{N}\sum_{n=1}^{N} \log_2\left(1 + \frac{P_{11}|h_{11}|^2}{\sigma^2}\right) \\
& + \frac{1}{N}\sum_{n=1}^{N} \log_2\left(1 + \frac{P_{22}|h_{22}|^2}{\sigma^2}\right), \Bigg)
\end{aligned}
$$

We can see two regimes of operations. In the case of very strong interference or very weak interference at both ends we are governed by the point-to-point channels (second term in the minimization). The very strong interference regime corresponds to where both receivers decode the interference and remove it prior to decoding the desired signals (similar to the case of known content). It is, in fact, the capacity of this interference channel. In a medium-interference scenario we see a similar behavior to the known content case, however this is only a bound to the channel capacity.

We can mimic the known channel case where we use either single-user decoding (interference as noise) or interference cancellation at the D2D receiver. This will result in the following achievable rate

$$
\begin{aligned}
R_1 + R_2 \geq \max\Bigg(& \frac{1}{N}\sum_{n=1}^{N} \log_2\left(1 + \frac{P_{11}|h_{11}|^2}{\sigma^2 + P_{12}|h_{12}|^2}\right) \\
& + \frac{1}{N}\sum_{n=1}^{N} \log_2\left(1 + \frac{P_{22}|h_{22}|^2}{\sigma^2 + P_{21}|h_{21}|^2}\right), \frac{1}{N}\sum_{n=1}^{N} \log_2\left(1 + \frac{P_{11}|h_{11}|^2}{\sigma^2}\right) \\
& + \min\left(\frac{1}{N}\sum_{n=1}^{N} \log_2\left(1 + \frac{P_{22}|h_{22}|^2}{\sigma^2}\right), \right) \frac{1}{N}\sum_{n=1}^{N} \log_2\left(1 + \frac{P_{21}|h_{21}|^2}{\sigma^2 + P_{11}|h_{11}|^2}\right)\Bigg)
\end{aligned}
$$

The first term in the maximization is the achievable rate with both receivers treating interference as noise. This will be a good strategy when both interference terms are very weak. The second term is where the D2D user first must decode the uplink signal, which puts a constraint on the spectral-efficiency of the uplink user and results the minimization term on the rate of the uplink user. We could add a third term where we impose decoding of the D2D user at the basestation, but this is neglected here as it would likely not be beneficial in most practical scenarios.

3 Numerical Results

At this point we can already say that the most favourable conditions are either very strong interference when the D2D receiver is capable of performing successive interference cancellation or very weak interference since they both provide virtually orthogonal channels. The intermediate case suffers from a loss in dimensionality of the signal-space. This is depicted in Figure 4 where we show the influence of the strength of the interference on spectral-efficiency for the special case of $\frac{\mathrm{P}_{11}}{\sigma^2} = 20\mathrm{dB}$, $\frac{\mathrm{P}_{22}}{\sigma^2} = 6\mathrm{dB}$ and variable interference levels. These correspond to the case where we choose transmit powers yielding a high signal-to-noise ratio on the D2D link and a moderate one on the uplink. This highlights the need for scheduling of compatible uplink users with a D2D link since the UL or D2D links can be severely impaired and would hurt the overall efficiency. The overall spectral-efficiency, $R_1 + R_2$, in the three regimes of operation are shown by the three solid curves. The effect on the D2D user (R_1)is shown by the dotted curve in all three regimes and the UL link $R_2$by the dash-dotted curve. We see that in the weak interference regime the D2D link starts to suffer progressively as the interference strength increases. At a certain point it is the UL user that radically loses capacity at the expense of giving full rate to the D2D user. The UL capacity progressively increases with the interference level until reaching its maximum.

In practice, if we can schedule the uplink user so that it is below the noise floor of the D2D link, we can achieve the total sum capacity to within 1 bit. Similarly, for very strong interference, in this case greater than 5 dB above the desired D2D signal, we can also achieve a very high spectral-efficiency. In practical situations, however, this may be difficult to exploit, firstly because of the dynamic range requirements of the D2D receiver which may be costly, and secondly because of timing asynchronism of the incoming uplink signal which will be advanced for the receiver of the basestation. A successive interference cancelling receiver is also required in both the medium and strong interference regimes.

4 Conclusions and Extenstions

In this work we provide an initial analysis of the regimes of operation for D2D communication sharing the uplink channel. We considered two cases, namely where content scheduled by a basestation is known and when it is autonomously chosen by the D2D transmitter and thus unknown to the basestation. The results show that sophisticated receivers at the D2D terminal receiver may be required to achieve fundamental limits. The work reported here was limited to the case where only one interfering uplink signal is considered. We will present a more general lower bound on the sum rate for an arbitrary number of interference uplink users.

[1] 3GPP, Evolved Universal Terrestrial Radio Access Network (EUTRAN) - Overall Description, Stage 2 (Release 13), 3GPP, 2016.

[2] I. Sason, "On Achievable Rate Regions for the Gaussian Interference Channel," IEEE Transactions on Information Theory, vol. 50, no. 6, pp. 1345-1356, 2004.

[3] R. Etkin and D. Tse, "Gaussian Interference Channel Capacity to Within One Bit," IEEE Transactions on Information Theory, vol. 54, no. 12, pp. 5534-5562, 2008.

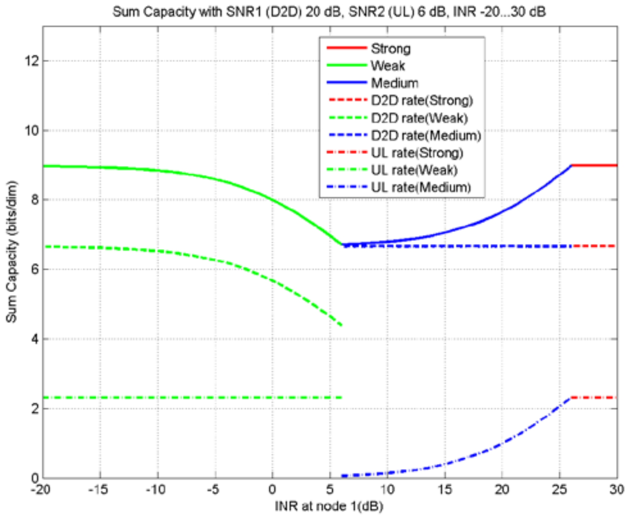

Figure 2: Sum-Capacity comparison known D2D content at the basestation.

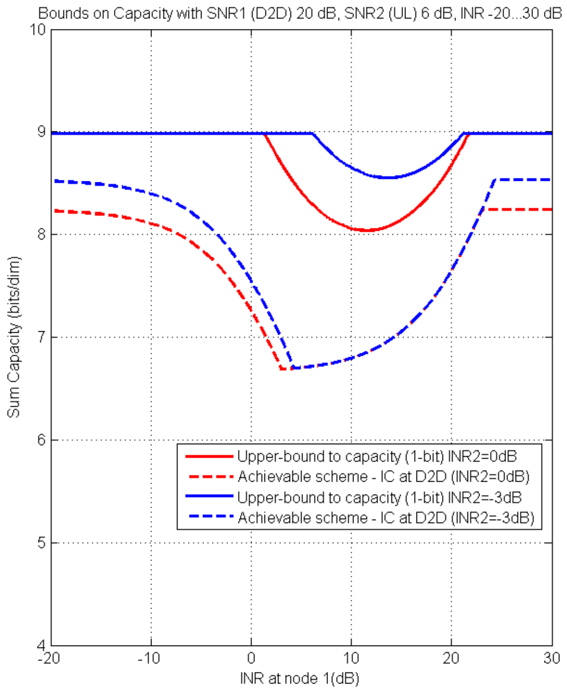

Figure 3:Sum-capacity bound and simple achievable scheme for unknown D2D content at the basestation

$$R_1 + R_2 = \begin{cases} \frac{1}{N}\sum_{n=1}^{N}\log_2\left(1+\frac{P_{22}|h_{22}|^2}{\sigma^2}\right)+\frac{1}{N}\sum_{n=1}^{N}\log_2\left(1+\frac{P_{11}|h_{11}|^2}{\sigma^2}\right), \text{if} \sum_{n=1}^{N}\log_2\left(1+\frac{P_{22}|h_{22}|^2}{\sigma^2}\right) < \sum_{n=1}^{N}\log_2\left(1+\frac{P_{21}|h_{21}|^2}{\sigma^2+P_{11}|h_{11}|^2}\right) \\ \frac{1}{N}\sum_{n=1}^{N}\log_2\left(1+\frac{P_{22}|h_{22}|^2}{\sigma^2}\right)+\frac{1}{N}\sum_{n=1}^{N}\log_2\left(1+\frac{P_{11}|h_{11}|^2}{\sigma^2+P_{21}|h_{21}|^2}\right), \text{ if } \sum_{n=1}^{N}\log_2\left(1+\frac{P_{21}|h_{21}|^2}{\sigma^2}\right) < \sum_{n=1}^{N}\log_2\left(1+\frac{P_{22}|h_{22}|^2}{\sigma^2}\right) \\ \frac{1}{N}\sum_{n=1}^{N}\log_2\left(1+\frac{P_{11}|h_{11}|^2}{\sigma^2}+\frac{P_{21}|h_{21}|^2}{\sigma^2}\right), \text{otherwise} \end{cases}$$

Equation 1