Transmission Policies for Interference Management in Full-Duplex D2D Communication

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Abstract—Full-Duplex (FD) wireless and Device-to-Device (D2D) communication are two promising technologies that aspire to enhance the spectrum and energy efficiency of wireless networks, thus fulfilling key requirements of the 5th generation (5G) of mobile networks. Both technologies, however, generate excessive interference, which, if not managed effectively, threatens to compromise system performance. To this direction, we propose two transmission policies that enhance the communication of two interfering FD-enabled D2D pairs, derived from game theory and optimization theory. The game-theoretic policy allows the pairs to choose their transmission modes independently and the optimal policy to maximize their throughput, achieving significant gains when the pairs interfere strongly with each other.

Index Terms—full-duplex, device-to-device communication, 5G, game theory, optimization.

I. INTRODUCTION

The bandwidth demands of the mobile users are always increasing, since they want to enjoy the latest applications of the smartphone community, share multimedia content and be online on a daily basis. In turn, operators want to satisfy their customers, by evolving their infrastructure towards the hyped 5th generation (5G) of mobile networks, which will enhance the energy efficiency and address the spectrum shortage of current mobile communications [1]. Two promising technologies that aspire to achieve these goals are wireless full-duplex and device-to-device communication.

Full-Duplex (FD) allows a user to simultaneously transmit and receive in the same frequency band. Initially, this technology was deemed impractical for wireless transceivers, because of the huge self-interference leaking from the user’s transmitter directly to his receiver, but recent experimental works [2], [3] managed to sufficiently attenuate the self-interference signal to realize wireless FD communication. This achievement sparked new interest in FD technology, which promised to double the capacity of wireless networks. Although the throughput of a wireless link can be doubled with FD, if the self-interference is adequately suppressed, the performance of FD in a network is significantly reduced, since the interference imprint on the network is doubled, limiting spatial reuse [4].

Device-to-Device (D2D) communication allows users to communicate directly to offload traffic from the base station and reduce the energy consumption of the system [5]. In-band D2D has received particular attention, since it permits the D2D users to reuse the cellular spectrum, and it is further categorized as underlay, when the base stations reserve a portion of the cellular bandwidth for D2D traffic, or as overlay, when the D2D users compete with the primary cellular users for resources. However, in-band D2D introduces additional interference, which must be carefully addressed to realize the potentials of D2D technology.

From the above descriptions, it is seen that interference limits the performance of both technologies and must be managed effectively to guarantee performance. In the literature, some initial MAC protocols have been proposed that apply to FD communications. [6], [7] extend traditional HD protocols such as CSMA to the FD paradigm, but this is clearly sub-optimal. [8] considers an ad-hoc ALOHA network and analyses its performance with the mathematical tool of stochastic geometry. Since the performance bottleneck of an FD network lies in the selfish behavior of the users, it is better suited to a game-theoretic model. Game theory has been considered in [9], using the spatially averaged throughput of an ad-hoc network as utility, but the analysis is applied only to an HD network.

Motivated by these observations, in this paper we propose two interference-aware transmission policies, that enable two interfering D2D pairs to enhance their throughput. The game theoretic policy is derived modeling the interactions of the pairs as a non-cooperative game and yields a distributed MAC protocol, where the pairs choose their transmission modes independently based on a simple threshold test. The optimal policy is achieved through cooperation between the pairs, which increases the implementation complexity but has significant throughput gains when the level of interference is high. Our analysis allows us to highlight the challenges and reflect important points on the application of FD technology.

Our paper is structured as follows. In Section [II] we present the system model and describe the physical layer and the network layer aspects that are pertinent to our analysis. In Section [III] we derive the throughput of the D2D pairs, which will be used in the analysis of the next section as a performance metric. In Section [IV] we introduce two transmission policies, based on a game-theoretic formulation and an optimization problem, and compare their performances. In Section [V] we summarize our results and suggest future lines of work.

II. SYSTEM MODEL

We consider two FD-enabled D2D pairs, as shown in Fig. [I]. The two pairs span distances $R_1$ and $R_2$, have arbitrary orien-
and are separated by distance $D$, defined as the distance of the midpoints of $R_1$ and $R_2$. They operate in the same frequency band, overlaying primary cellular transmissions, so that the D2D users interfere with each other, but not with the primary cellular users. The users of each pair want to exchange packets and use a slotted protocol to synchronize their transmissions. In each slot, a pair can operate in Idle, Half-Duplex (HD) or Full-Duplex (FD) mode when it transmit 0, 1 or 2 packets respectively, and we denote the transmission modes of the two pairs as $a_1$ and $a_2$.

To calculate the success probability of a packet transmission and, eventually, throughput, we need to introduce the signal model of our system. We assume that the users of pair 1 and pair 2 transmit with powers $P_1$ and $P_2$ respectively, and that their signals are degraded by power-law path-loss and Rayleigh fading. With these definitions, we express the Signal-to-Interference-Ratio (SIR) at the receiver of pair 1 as:

$$SIR_1 = \frac{S_1}{EI_2 + S_1}. \quad (1)$$

In the above equation
- $S_1$ represents the power of the useful signal, received from the other user of pair 1. It is equal to
  $$S_1 = P_1 h_1 R_1^{-\alpha}, \quad (2)$$
  where $h_1 \sim Exp(1)$ is the fading random variable, $P_1$ is the power transmitted from the other user of pair 1 and $\alpha$ is the path-loss coefficient.
- $EI_2$ represents the power of the external interference (EI), received from pair 2. It depends on the transmission mode of pair 2 and the cross-distances between the users of pair 1 and pair 2, which have been approximated with $D$. This assumption is reasonable for real networks, where $D$ is sufficiently longer than $R_1$ and $R_2$. It yields
  $$EI_2 = \begin{cases} 0 & \text{if } a_2 = \text{idle} \\
  P_2 h'' D^{-\alpha} & \text{if } a_2 = \text{HD} \\
  P_2 h' D^{-\alpha} + P_2 h'' D^{-\alpha} & \text{if } a_2 = \text{FD} \end{cases}, \quad (3)$$
  where $h', h'' \sim Exp(1)$ are the fading random variables of the interference paths, assumed independent to each other and to $h$.
- $S_1$ represents the power of the self-interference (SI), received by the user’s own transmission when he operates in FD mode. It actually refers to the remaining SI, after the receiver cancels a portion of the loop-back signal. It is equal to
  $$S_1 = \kappa P_1, \quad \kappa \sim Exp(\beta), \quad (4)$$
  where $\kappa$ is the SI cancellation coefficient, modeled as an exponential random variable with $E[\kappa] = 1/\beta$. The coefficient $\kappa$ is assumed random, because it incorporates thermal noise is neglected in our study, since interference has the most detrimental impact on communication.

\footnote{Please note that Fig. 1 depicts a specific network realization.}

\footnote{Thermal noise is neglected in our study, since interference has the most detrimental impact on communication.}

\footnote{All expressions will be derived from the point of view of pair 1, but can be applied to pair 2, by exchanging the indices of the variables.}

Based on this signal model, a transmission is considered successful when the SIR at the receiver stays above some threshold $\theta$ during the whole transmission. The threshold $\theta$ depends on the modulation and coding scheme of the physical layer, and it is related to the minimum Signal-to-Noise-Ratio ($SNR$) needed for perfectly reliable communication at rate $R$. It is given by the Shannon capacity formula

$$R = \log(1 + \theta) \Leftrightarrow \theta = 2^R - 1, \quad (5)$$

where $R$ is normalized over the transmission bandwidth. The capacity formula applies to the Additive White Gaussian Noise (AWGN) channel, but interference is commonly approximated as Gaussian, which allows substituting $SNR$ with $SIR$.

### III. Throughput Analysis

Based on the definitions of Section II in Section III-A we derive the success probabilities of transmission and in Section III-B the throughputs of the two pairs.

#### A. Derivation of the Success Probabilities

The success of a packet transmission, $P_s$, depends on the transmission modes of both pairs, $a_1$ and $a_2$. For the receiver of pair 1, it holds that

$$P_s = P(SIR_1 > \theta) = \mathbb{E} \left[ P(h > \frac{\theta R_1^2 (EI_2 + S_1)}{P_1}) \right] =$$

$$\mathbb{E} \left[ e^{-\frac{\theta R_1^2 (EI_2 + S_1)}{P_1}} \right] = M_{EI_2}(-\frac{\theta R_1^2}{P_1}) M_{S_1}(-\frac{\theta R_1^2}{P_1}), \quad (6)$$

where

$$M_{EI_2}(t) = \mathbb{E} \left[ e^{t EI_2} \right], \quad (7)$$

$$M_{S_1}(t) = \mathbb{E} \left[ e^{t S_1} \right] \quad (8)$$

denote the moment generating functions of random variables $EI_2$ and $S_1$.

- To calculate $M_{EI_2}$, we need the moment generating function of the exponential fading variable
  $$M_h(t) = \mathbb{E} \left[ e^{t h} \right] = \frac{1}{1-t}, \quad t < 1. \quad (9)$$

Fig. 1. System model: a realization where pair 1 operates in FD mode and pair 2 in HD mode. Only the interference at pair 1 is depicted for clarity.
To simplify notation, we also define the helper variable
\[ \tau = \theta P_2 \left( \frac{R_1}{P_1} \right)^{\alpha}. \] (10)

Applying (3), (9) and (10) to (7), we find
\[ M_{EI} \left( -\frac{\theta R_1^2}{P_1} \right) = \begin{cases} 
1 & \text{if } a_2 = \text{Idle} \\
\frac{1}{1 + \theta R_1^2/\beta} & \text{if } a_2 = \text{HD}
\end{cases} \] if \( a_2 = \text{FD} \)

We can express the success probability of (6) compactly, introducing the parameters
\[ \lambda_1 \triangleq \frac{1}{1 + \frac{\theta}{\beta}} \] and
\[ \mu_1 \triangleq \frac{1}{1 + \frac{\theta P_2 (R_1^2)}{\beta}} \] (13)

and denoting the number of pair 2’s transmissions by \( n_2 \). Combining (11), (12) and (13) into (6) yields
\[ P_{s_1} = \begin{cases} 
0 & \text{if } a_1 = \text{Idle} \\
\mu_1^{n_2} & \text{if } a_1 = \text{HD} \\
\lambda_1^{n_2} & \text{if } a_1 = \text{FD}
\end{cases} \] (14)

Parameters \( \lambda \) and \( \mu \) are useful because they abstract the physical layer aspects of our system and distinguish the impact of EI and SI on transmission. Let us describe them in more detail at this point.

- \( \lambda \) encapsulates SI. It depends on the intra-pair distance, the SI attenuation factor, the STIR threshold and the pathloss, but not on the transmitted power. It ranges between 0, when SI is strong, and 1, when SI is fully canceled.

- \( \mu \) encapsulates EI. It coincides with the success probability of an HD transmission when one external user interferes, and becomes \( \mu^2 \) when two external users interfere. In this sense, an FD transmission doubles the interference imprint on the rest of the network. \( \mu \) tends to 0 when the pairs strongly interfere and to 1 when they do not interact.

\section*{B. Derivation of Throughput}

We define throughput as the number of successful transmissions that a pair accomplishes in one slot and denote it by \( \rho \).

For player 1
- if \( a_1 = \text{Idle} \)
  \[ \rho_1 = 0. \] (15)
- if \( a_1 = \text{HD} \)
  \[ \rho_1 = 1 \cdot P_{s_1} + 0 \cdot (1 - P_{s_1}) = P_{s_1}. \] (16)
- if \( a_1 = \text{FD} \)
  \[ \rho_1 = P_{s_1}^{(1)} + P_{s_1}^{(2)} = 2P_{s_1}. \] (17)

where \( P_{s_1}^{(1)} \) and \( P_{s_1}^{(2)} \) distinguish the success probabilities at the two receivers of pair 1. They are considered equal, based on our assumption that both receivers experience the same mean EI from pair 2.

To finish the derivation, we note that \( P_{s_1} \) must be substituted from (14), considering the transmission modes of both pairs.

\section*{IV. Transmission Policies in FD D2D}

Since the throughput of the D2D pairs depends on interference, in this section we propose two interference-aware transmission policies that shape the interference pattern of the network and enhance performance. In Section IV-A, we introduce a game-theoretic policy which forces the network to operate in a stable equilibrium, and in Section IV-C we derive an optimal policy which maximizes throughput. In Section IV-C we compare the performance of the two policies.

\subsection*{A. Game-Theoretic Transmission Policy}

The D2D pairs have an incentive to operate in FD mode to increase their transmission rate, but if all pairs adopt this policy, the excessive interference degrades throughput. This outcome is due to the selfish behavior of the D2D users, who want to transmit without considering the burden that they cause to their neighbors. We model this conflicting situation as a non-cooperative game, defined as a tuple \( G = (N, \mathcal{S}_i, \mathcal{U}_i), \quad i \in N \), where \( N \) is the set of players, \( \mathcal{S}_i \) is the set of the strategies of player \( i \) and \( \mathcal{U}_i \) is the utility of player \( i \). In our formulation
\[ G = (\{1, 2\}, \{\text{Idle, HD, FD}\}, \rho_i), \quad i \in \{1, 2\}, \] (18)

which is represented in the matrix form shown in Table I.

This game admits a single dominant solution. The reason is that for every player the Idle strategy is always strictly dominated, since it contributes zero to his utility, and between

\begin{table}[h]
\centering
\caption{Throughput game for two interfering D2D pairs}
\begin{tabular}{|c|c|c|c|}
\hline
 & P2 & P1 & P2
\hline
& Idle & HD & FD \\
\hline
Idle & 0, 0 & 0, 1 & 0, 2, \lambda_2 \\
\hline
HD & 1, 0 & \mu_1, \mu_2 & \mu_1^2, 2\lambda_2 \mu_2 \\
\hline
FD & 2\lambda_1, 0 & 2\lambda_1 \mu_1, \mu_2^2 & 2\lambda_1 \mu_1^2, 2\lambda_2 \mu_2^2 \\
\hline
\end{tabular}
\end{table}
HD and FD, there is a strictly dominant strategy, depending on the value of his SI parameter. For player 1, FD dominates HD when
\[ 2\lambda_1 > 1 \implies \beta > R_1^\alpha \] (19a)
and HD dominates FD when
\[ 2\lambda_1 < 1 \implies \beta < R_1^\alpha \] (19b)
Since \( \beta \) represents the mean SI attenuation, (19) instructs player 1 to play FD when his SI cancellation is adequate and HD otherwise. This criterion also applies to player 2, so it determines one strictly dominant solution, which constitutes the unique pure Nash Equilibrium (NE) of the game. The uniqueness of the dominant solution precludes the existence of a NE in mixed strategies. Fig. 2 visualizes the four possible combinations of strategies for the NE.

Since the players choose their strategies without considering the parameters of their opponents, the NE yields a distributed transmission policy, which causes the pairs to transmit in every time slot. We denote these pure strategies

- **pure HD**: pair operates continuously in HD mode
- **pure FD**: pair operates continuously in FD mode.

We now illustrate the effect of the game-theoretic transmission policy on the utility of player 1. Fig. 3 depicts the throughput of player 1 as a function of the EI parameter \( \mu_1 \) for every candidate NE. We assume \( \lambda_1 = 0.8 > 0.5 \) to focus on the FD technology. We observe that the performance drops when player 2 switches from pure HD to pure FD, which is justified by the doubling of EI. We also verify that, regardless of the strategy of player 2, player 1 responds with pure FD which leads to better throughput, as predicted by the NE. Another important observation is that the strategy combination (pure HD, pure HD) outperforms (pure FD, pure FD) when \( \mu_1 \) is low, even though the SI parameter \( \lambda_1 \) favors pure FD. The reason is that the good SI cancellation is overshadowed by the strong EI that the pairs generate, possibly due to proximity or high transmitter power. In this case, the optimal strategy combination (pure HD, pure HD) cannot be achieved when players operate independently and some form of cooperation is needed instead.

### B. Optimal Transmission Policy

In Section IV-A, we observed that the NE is not necessarily optimal when EI is strong and \( \mu_1 \) and \( \mu_2 \) are close to 0. In this case, the pairs can gain by mutually agreeing to mix their strategies with Idle to sporadically alleviate EI. We introduce a new transmission policy which permits the two pairs to operate in Idle, HD and FD mode with probabilities \( p_0 \), \( p_1 \) and \( p_2 \) respectively and optimize its performance. We consider the symmetric case, where

\[ \lambda_1 = \lambda_2 = \lambda \]
\[ \mu_1 = \mu_2 = \mu. \] (20)

and summarize the throughput in Table II, modifying Table I of Section IV-A. We then formulate the optimization problem

\[
\text{maximize } \rho = \sum_{i,j} p_i p_j U(a_i, a_j) = p_0 p_1 + \mu p_1^2 + \mu^2 p_1 p_2 + 2\lambda p_2 p_0 + 2\lambda \mu p_2 p_1 + 2\lambda \mu^2 p_2^2
\]
\[ \text{s.t. } p_0 + p_1 + p_2 = 1 \]
\[ 0 < p_0, p_1, p_2 < 1 \] (21)

To solve (21), we substitute \( p_2 = 1 - p_1 - p_0 \) and locate

| P1 | P2 |
|---|---|---|
| **Idle** | **HD** | **FD** |
| **HD** | \( \mu, \mu \) | \( \mu^2, 2\lambda \mu \) |
| **FD** | \( 2\lambda, 2\lambda \mu, \mu^2 \) | \( 2\lambda \mu^2, 2\lambda \mu^2 \) |
Continuing with the analysis

- if \( p_2 = 0 \) (mixed HD)
  \[
  \rho = p_0 p_1 + \mu p_1^2 = p_1 (1 - (1 - \mu) p_1).
  \]
  This is maximized at
  \[
  p_1 = \begin{cases}
    \frac{1}{2(1-\mu)} & : \mu < 1/2 \\
    1 & : \mu > 1/2
  \end{cases},
  \]
  yielding
  \[
  \rho_{\text{max}} = \begin{cases}
    \frac{1}{4(1-\mu)} & : \mu < 1/2 \\
    \mu & : \mu > 1/2
  \end{cases}.
  \]

- if \( p_1 = 0 \) (mixed FD)
  \[
  \rho = 2 \lambda p_2 p_0 + 2 \lambda \mu^2 p_2^2 = 2 \lambda p_2 (1 - (1 - \mu^2) p_2).
  \]
  This is maximized at
  \[
  p_2 = \begin{cases}
    \frac{1}{2(1-\mu^2)} & : \mu < 1/\sqrt{2} \\
    1 & : \mu > 1/\sqrt{2}
  \end{cases},
  \]
  yielding
  \[
  \rho_{\text{max}} = \begin{cases}
    \frac{\lambda}{2 \lambda^2} & : \mu < 1/\sqrt{2} \\
    \mu & : \mu > 1/\sqrt{2}
  \end{cases}.
  \]

- if \( p_0 = 0 \) (mixed hybrid)
  \[
  \rho = \mu p_1^2 + \mu^2 p_1 p_2 + 2 \lambda \mu p_2 p_1 + 2 \lambda \mu^2 p_2^2.
  \]
  This is maximized at
  \[
  p_1 = \begin{cases}
    1 & : \mu < 2(1 - \lambda) \\
    \frac{2 \lambda - 2 \lambda \mu - \lambda (1-\mu)}{2 \lambda - 2 \lambda \mu (1-\mu)} & : 2(1 - \lambda) < \mu < \frac{2 \lambda}{4 \lambda - 1}
  \end{cases},
  \]
  \[
  p_2 = \begin{cases}
    \frac{2 \lambda - 2 \lambda \mu - \lambda (1-\mu)}{2 \lambda - 2 \lambda \mu (1-\mu)} & : \mu < 2(1 - \lambda)
  \end{cases}.
  \]

where the limits of \( \mu \) are valid only when
\[
0 < 2(1 - \lambda) < \frac{2 \lambda}{4 \lambda - 1} < 1.
\]
the users to mutually choose their strategies, according to the common experienced EI parameter $\mu$. In the rest of the section we will not consider the mixed hybrid strategy of the optimal policy, as it had inferior performance compared to the other mixed strategies in all considered cases.

To compare the two policies, Fig. 7 depicts their throughput for a case with low SI ($\lambda > 0.5$) and a case with high SI ($\lambda < 0.5$). For the low SI case, we choose $\lambda = 1$, which implies perfect SI cancellation and favors FD regardless of EI, as shown in Fig. 5. For the high SI case, the choice of $\lambda$ is irrelevant, since the resulting strategy is always HD and its throughput is not affected by SI. These choices allow us to compare the FD to the HD mode, as well as the two transmission policies.

In Fig. 7 we observe that the optimal mixed strategies coincide with the pure strategies for $\mu > 1/2$ in the HD case and $\mu > 1/\sqrt{2}$ in the FD case, as shown in the throughput expressions (25) and (28). For smaller $\mu$, the gains of optimization become apparent, as the throughput of the game policy is driven to zero, while the optimal policy still permits some precious throughput. For $\mu = 0$ the gain of mixed FD is 0.5 and the gain of mixed HD is 0.25. We also observe that, when EI is strong, pure FD has inferior performance than both the pure HD and the mixed HD strategy, despite perfect cancellation of SI. FD is unconditionally superior to HD, only in the optimal mixed FD mode, which indicates that FD technology should be used carefully to realize its promised performance advantages.

V. CONCLUSION

We considered the communication of two FD-enabled D2D pairs, whose interference limits their throughput. We proposed two interference-aware transmission policies, derived by formulating their interactions as a non-cooperative game and as an optimization problem. The game-theoretic policy yields a distributed MAC protocol, which enables the pairs to independently choose their transmission modes based on a simple threshold test. The optimal strategy requires cooperation from the D2D pairs, but offers significant gains in throughput when the interference between the pairs is high. In future work, we plan to extend our game formulation to the N-pair case.

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