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Cellular Networks with an Overlaid Device to Device Network

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***Abstract*—Spectrum sharing is a novel opportunistic strategy to improve spectral efficiency of wireless networks. Much of the research to quantify such a gain is done under the premise that the spectrum is being used inefficiently by the primary network. Our main result is that even in a spectrally efficient network, device to device users can exploit the network topology to render gains in additional throughput. The focus will be on providing ad-hoc multihop access to a network for device to device users, that are transparent to the primary wireless cellular network, while sharing the primary network's resources.**

I. Introduction

This paper considers spectrum sharing strategies between cellular radio networks and infrastructure-less wireless networks [1]. In particular, we study a scenario where an ad-hoc device to device network can operate in the same spectrum, completely transparent to the licensed primary cellular radio network [2]. As an example, we will consider a WiMAX standard that employs OFDMA, such that communication channels among cellular users are orthogonal to each other [3]. Device to device users will use the signal power received in the downlink frame to determine their pathloss to the base station of the cellular network. Device to device users will then scale their transmit power based on the pathloss, such that they can communicate with each other directly during the uplink frame while causing only minimal interference to the base station. Modified route discovery protocols, such as the Dynamic Source Routing [4], can be used to find a multi-hop route connecting two device to device users. Results show that despite the stringent SINR requirements, communication among these device to device users can occur simultaneously with the cellular network, with high probability of success.

II. Network Architecture

In the following sections, we will describe the different components of our network.

A. Infrastructure Model

We define a generic cellular network, however, we note that adjustments for specific standards are straightforward to make. The network will consist of a circular cell of radius R, where each cell has at its center an access point or a base station (BS) equipped with omni-directional antennas. We further consider the available frequency resources of the system to be allocated to users in such a way that adjacent channel interference is negligible and need not be considered. This can be easily achieved by making the user's respective portions of the bandwidth orthogonal to each other in time or frequency, as in TDMA and FDMA systems, or separate them through other means such as coding, as in CDMA systems.

B. User Model

We consider two classes of users. A cellular user (CU) communicates solely through the BS. Standard scheduling methods and control signals allocate specific channels to CUs during the uplink and downlink frames of the system. A minimum SINR at the BS, β_{BS}, must be satisfied for a cellular link to exist between the BS and a CU. We assume that there exists a margin, κ, in the SINR at the BS to compensate for noise and interference events in the network. Such a margin is a common design feature of wireless systems.

Device to Device (D2D) users are those who do not communicate via the BS, but rather communicate directly with each other over one or more hops. We consider a single D2D transmitter (Tx) who has information to send to a single D2D receiver (Rx), and assume that both users are located in the same cell. We will allow D2D users to use the same frequency resources as the CUs as long as such use does not cause the SINR of the cellular link to fall below the required minimum β_{BS}. To accomplish this, we assume that D2D users have knowledge of κ and thus the amount of interference they can add to the system. We intend for the D2D mode to be an option for CUs who may not be able to obtain resources from a fully loaded BS operating at its capacity. For a D2D link to exist, a required minimum SINR, β_{DD}, must be satisfied between the Tx and Rx. For the multihop scenario, we assume that there are idle users in the network willing to form a multihop D2D link.

We will consider two different models for the user topology. First, both classes of users will be distributed uniformly in the cells. Secondly, the topology will be modeled in a fashion similar to [5], where D2D users will be distributed uniformly in a randomly placed cluster, while the CUs are still distributed uniformly through the cell. Such a topology is more realistic in modeling urban environments where business or residential complexes can often contain a dense population of people with idle cellular devices.

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C. Channel Model

We assume a pathloss channel

$$y = xd^{-\alpha} + n, \tag{1}$$

where the pathloss is defined in terms of the pathloss exponent α, and d, the distance between the particular transmitter and receiver. In addition, the received signal will be corrupted by AWGN. We will be primarily interested in the power levels of each signal and as such define the transmitted power $E[x\,x^*] = P_T$ and the received power $E[y\,y^*] = P_R$. We will use the subscripts BS, CU, and DD to designate the respective power levels of the base station, cellular user, and D2D user.

III. Spectrum Reuse Protocol

We propose a scheme in which D2D users can communicate amongst each other using the same time and frequency resources as the CUs in a cellular network. They can do so as long as their use of the spectrum does not result in a level of interference that causes the cellular link to break. To best accomplish this, we only allow D2D users to communicate with each other during the uplink frame of the network. During the uplink, there will be only one receiver, the immobile BS, and as such, D2D users only need to be concerned with the interference of their signal on one other user. If communication occurred during the downlink, interference would be seen at every CU in the system.

Two main challenges exist in such a protocol. First, D2D users need to determine which channels are available for use and how much power they can send on those respective channels. Secondly, D2D users with information to send need to discover other D2D users around them and find a route to their respective destinations. In this section, we will outline the steps for each of these components.

A. Resource Discovery

We assume there are N_C orthogonal channels available in the system and D2D users need to determine with how much power they can transmit on each channel as to not cause too much interference at the BS. The κ margin in the SINR at the BS determines the power control for the cellular link in order to compensate for the interference from the D2D users. We can see the effects of the power control by looking at the SNR of the cellular link, where after rearranging terms, gives a bound on the transmit power of the CU as

$$\begin{aligned} \frac{P_{T_{CU}} C^{-\alpha}}{N} &\geq \kappa\beta_{BS} \\ P_{T_{CU}} &\geq \kappa C^{\alpha} N \beta_{BS} \end{aligned} \tag{2}$$

where C is the distance between the CU and the BS. Looking at the SINR of the cellular link, and taking $P_{T_{CU}}$ to be the minimum allowed in (2), after rearranging terms, we get a bound on the transmit power of the D2D Tx as

$$\begin{aligned} \frac{P_{T_{CU}} C^{-\alpha}}{P_{T_{DD}} D^{-\alpha} + N} &\geq \beta_{BS} \\ (\kappa - 1) N D^{\alpha} &\geq P_{T_{DD}} \end{aligned} \tag{3}$$

where D is the distance between the D2D Tx and the BS.

At the beginning of each downlink frame, the BS transmits control signals at a constant power level, $P_{T_{BS}}$, to all CUs. From our channel model, we can show that the total pathloss between the BS and the D2D Tx is

$$D^{\alpha} = \frac{P_{T_{BS}}}{P_{R_{DD}} - N}. \tag{4}$$

We assume that the D2D Tx knows $P_{T_{BS}}$, and as such can calculate the pathloss. By knowing the pathloss, D2D users can then determine a corresponding $P_{T_{DD}}$ based on (3) and (4) that will not cause the cellular link to fall below the required minimum β_{BS}.

B. Neighbor and Path Discovery

Both neighbor and route discovery are topics that are rich in literature and several protocols have been developed. Two such protocols, DSR and AODV, have proven to be very efficient and robust in ad-hoc networks such as the ones we propose. DSR in particular is very robust against a highly dynamic topology and is able to maintain or repair routes with ease [4]. This is ideal for our D2D network as resource availability, and thus link availability, will be completely determined by the cellular network, a network that is also quite dynamic as mobile users enter and leave the network.

DSR is a source initiated packet based discovery protocol. In order to implement our spectrum sharing protocol, the standard DSR packet structure, which typically only contains node addresses, must be modified. We will require each user to also append on their own transmit power and the amount of interference that they see. From the previous section, we know users can determine the pathloss in between themselves if they know the source's transmit power. By knowing the pathloss, destination nodes can now determine a priori if they will be able to communicate back to the source at their own respective transmit power. If this backward link is not available, then there is no need to continue forwarding the discovery packet. This novel design feature greatly reduces the amount of contributed interference to the primary cellular network.

IV. Single-Hop Analysis

In this section, we will derive the analytical expressions for the probabilities of a single-hop D2D link existing simultaneously with a cellular link for the two different user topologies stated earlier.

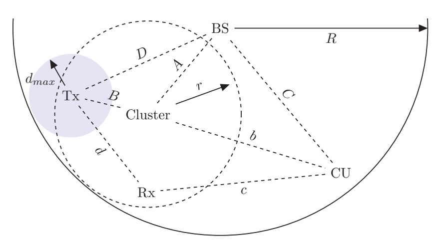

Fig. 1. System model for the various distances in the two user topologies. Note that the cluster is not present in the cell-wide D2D model.

A. Cell-Wide D2D User Distribution

We take a geometrical approach based on the various random distances that are present in our system. For a D2D link to exist, we know the SINR at the Rx must be above the required threshold β_{DD}. If we look at that SINR constraint for the D2D link, and use the transmit power bounds in (2) and (3), after rearranging terms, we get

$$\begin{aligned} \frac{P_{T_{DD}} d^{-\alpha}}{P_{T_{CU}} c^{-\alpha} + N} &\geq \beta_{DD} \\ \left(\frac{c^{\alpha}(K-1)}{\beta_D (K\beta_{BS} C^{\alpha} + c^{\alpha})} \right)^{\frac{1}{\alpha}} D &\geq d \end{aligned} \tag{5}$$

where c and d are the distances as shown in Fig. 1. We define this upper bound on d as d_{max}, where this is a bound on the maximum distance that can exist between a D2D Tx and Rx for a successful link as a function of the three random distances c, C, and D.

We are interested in the event of a D2D link existing between the Tx and Rx, an event we define as LE, and the probability of this event. We can formulate the probability as $Pr[\text{LE}] = Pr[d \leq d_{max}]$. The distance d_{max} defines a circle around the Tx in which the Rx must be located in order for a link to exist. Thus, the probability of the link existing is the ratio of all the Rx locations that result in a successful link, the Tx's coverage area, to all possible Rx locations, the area of the entire cell.

Because the location of the Tx is random, the case may occur in which the Tx is located close to the cell edge and part of the coverage area defined by d_{max} may fall outside the cell. We are only interested in the part of the Tx coverage area that overlaps with the cell. From [6], we can use a result for the intersection area, A_{INT}, for two circles. That formula is defined in terms of the three random distances c, C, and D. Thus taking the ratio of A_{INT} and the area of the cell, πR^2, and averaging over all realizations of c, C, and D, we have an expression for $Pr[\text{LE}]$ given in (7). The exact expressions for A_{INT} as well as the distributions for c, C, and D, can all be found in [6], [7], and [8].

B. Clustered D2D User Distribution

For the clustered user model, we consider a randomly located cluster, of radius r, inside the cell. We denote the distances A, B, and b, as shown in Fig. 1, which are the distances from the BS, D2D Tx, and the CU, respectively, to the center of the cluster. We keep the same definitions for c, C, and D made above, with the modification that D and c are now dependent on the other distances due to the introduction of the cluster. We define the event LEC to occur when a D2D link exists within the cluster. We can formulate the probability of this event in the same way as above with $Pr[\text{LEC}] = Pr[d \leq d_{max}]$. The value of d_{max} derived from (5) remains the same. As before, we can say the probability of the link existing is the ratio of all the Rx locations that result in a successful link, the Tx's coverage area, to all possible Rx locations, the area of the cluster. We use the same formula as above to find the intersection area of the Tx coverage area and the cluster area, where A_{INT} is now defined in terms of the six random distances that are present in the cluster model. Thus taking the ratio of A_{INT} and the area of the cluster, πr^2, and averaging over all realizations of all the distances, we have an expression for $Pr[\text{LEC}]$ given in (8). As before, the exact expressions for A_{INT} as well as the distributions for the various distances, can all be found in [6], [7], and [8].

The previous two results are based on a system where there is only a single channel available. We now consider that there are N_C orthogonal channels available where each channel has an active cellular link between a CU and the BS. We are interested in the probability that a D2D link can exist on any of the N_C channels. We will denote the probability of this event as $Pr[\text{Link on MC}]$. We recognize that since the channels are orthogonal, the link existence probability on a channel is independent of the other channels and will be the same for each channel. The independence of the identical probabilities allow us to multiply N_C identical single channel probabilities together. Because a link will either exist or not exist, we can use probability laws to write a link's existence in terms of the probability that a link does not exist. After using this rule twice, and from the orthogonality of the channels, we get

$$Pr[\text{Link on MC}] = 1 - \Big(1 - Pr[\text{Link on SC}]\Big)^{N_C} \tag{6}$$

where $Pr[\text{Link on SC}]$ is the probability that a D2D link exists on a single channel. Thus either the result obtained in (7) or (8) can be used for the single channel probability depending on which user topology is being considered.

V. Simulation Results

In this section, we will provide numerical verification for the single-hop analytical expressions derived above. In addition, we will also show the numerical results for the scenario where DSR is used to obtain a multihop D2D link in the clustered D2D model. We will limit the discussion of these results to one particular standard, that of the emerging WiMAX 802.16e. The network parameters used for numerical simulations are shown in Table I, and these values are representative of actual values defined in the WiMAX standard. We note that the single-hop analytical expressions in (7) and (8) will be approximated

$$Pr[\text{LE}] = \int_c \int_C \int_D \frac{A_{INT}}{\pi R^2}\, p_D(D)\, p_C(C)\, p_c(c)\, \mathrm{d}D\, \mathrm{d}C\, \mathrm{d}c \tag{7}$$

$$Pr[\text{LEC}] = \int_C \int_b \int_c \int_A \int_B \int_D \frac{A_{INT}}{\pi r^2}\, p_{D|B,A}(D|B,A)\, p_B(B)\, p_A(A)\, p_{c|b}(c|b)\, p_b(b)\, p_C(C)\, \mathrm{d}D\, \mathrm{d}B\, \mathrm{d}A\, \mathrm{d}c\, \mathrm{d}b\, \mathrm{d}C \tag{8}$$

through numerical integration in Mathematica. Those results will then be compared to a Matlab simulation of the same model.

TABLE I
WIMAX SIMULATION PARAMETERS

Parameter	Value
Minimum BS SINR (β_{BS})	10 dB
Minimum D2D SINR (β_{DD})	5 dB
Noise (N)	-104 dBm
SINR Margin at BS (κ)	3 dB
Cell Radius (R)	2 km

A. Cell-Wide D2D User Distribution

In Fig. 2, we plot the probability of a D2D link existing on any of N_C channels, the expression given in (6) evaluated with (7) for the single channel probability, for the scenario where both D2D users and cellular users are distributed cell-wide.

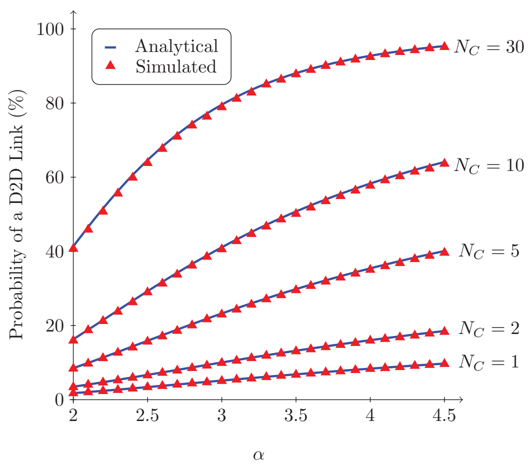

Fig. 2. Analytical and simulated results for the probability of a link existing on any of N_C channels, each with a single interfering cellular user, between a single D2D Tx and Rx.

We see that the probability of a D2D link is increasing with α. For larger α, the greater the decay in the power levels of transmitted signals. Recall that the D2D Tx's signal is seen as interference by the BS. With increasing α, the interference power received at the BS decays faster. Because D2D mode is ideal for shorter distances, the normally harmful affects of pathloss actually help reduce the interference at the BS. The positive effects of the pathloss on the interference are more significant than the negative effects of the pathloss on the D2D's desired signal, and thus the reason why we see better results with increasing α. One other trend we notice is that with increasing N_C we see higher probabilities. This result should be intuitive in that with more resources for a given system, the chance that multiple links can exist simultaneously should also increase.

B. Clustered D2D User Distribution

In Fig. 3, we plot the probability of a D2D link existing on a single channel, the expression given in (8), for the scenario where D2D users are distributed in a cluster. In the non-clustered model, the cell radius R had no effect on the link's existence. However, we discovered that the ratio of the cluster radius to the cell radius does impact the link's existence for the clustered model. We can see that for the various radius ratios presented, that the single channel link probability for the cluster model is significantly higher than some of the multiple channel link probabilities for the non-clustered model.

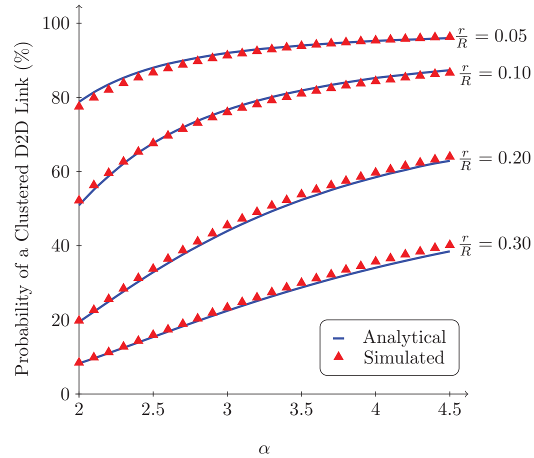

Fig. 3. Analytical and simulated results for the probability of a link existing between a single D2D Tx and Rx located inside a randomly placed cluster in the presence of interference from a cellular user for various radius ratios.

In Fig. 4, we plot the multiple channel probability, the expression given in (6) evaluated with (8) for the single channel probability, for a radius ratio of 0.25. We can immediately see that it takes much fewer channels than the cell-wide model to achieve the same high probabilities of a D2D link existence.

C. Clustered D2D User Distribution with Multihop

For the multihop scenario, we consider a cluster of radius 0.25 km, where the center of the cluster is located 1 km away from the BS. We further assume that there are 30 orthogonal channels available in the system. We keep the value of all the other network parameters to be the same as those in Table I. Because we are now considering multihop, we look at a link's existence as a function of the number of idle users who are willing to help form a D2D link. Idle users are distributed in the same manner as the D2D TX and Rx, and we vary the number of idle users from 0, the case where no relay user is necessary and a direct link exists between the Tx and Rx, to 20 users capable of acting as intermediate relay nodes.

We can see in Fig. 5 that a multihop D2D link can exist with high probability for a relatively small number of idle users. Looking at the two curves for $\alpha \leq 3$, we see that there is no single-hop link for the Tx and Rx since there is zero probability when there are zero idle users. Thus a multihop link is the only way to connect the Tx and Rx. Looking at the two curves for $\alpha \geq 3.5$, there is some nonzero probability for a single-hop link between the Tx and Rx. By considering multihop links, the chance that the Tx and Rx can establish a link only increases.

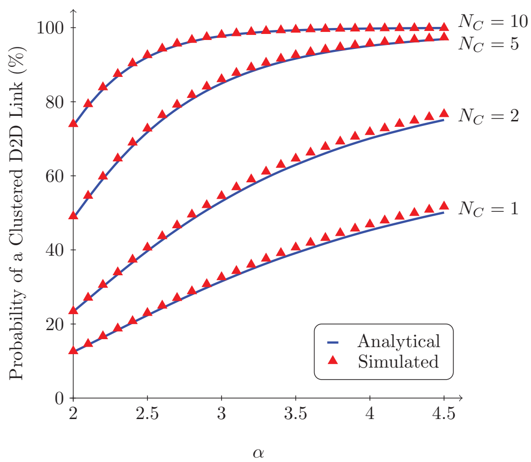

Fig. 4. Analytical and simulated results for the probability of a link existing on any of N_C channels, each with a single interfering cellular user, between a single D2D Tx and Rx located inside a randomly placed cluster, for a fixed radius ratio of 0.25.

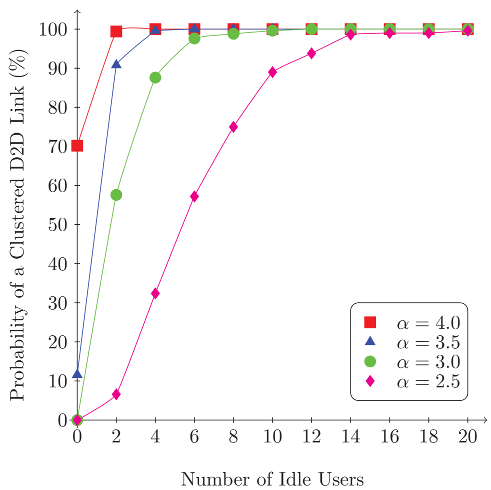

Fig. 5. The probability of a multihop D2D link existing on any of 30 orthogonal channels, each with a single interfering cellular user, between a single D2D Tx and Rx located inside a randomly placed cluster of radius 0.25 km.

Link existence as a metric by itself can be misleading when considering multihop links. It is well known that the total number of hops in a link is one of the key factors in both throughput and delay. Thus we examine the lengths of the routes in Fig. 6 that were found for the previous plot. We see that the average route length is less than 3 hops, and more often closer to 2 hops. This result is very beneficial to an ad-hoc network as it keeps the end-to-end delay of the system down, while communicating information at a reasonable throughput. We note that these results show that while the previous plot was a function of the number of idle users, only one or two idle users were used on average to form the multihop D2D link.

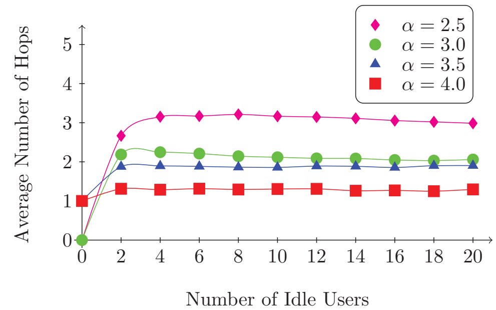

Fig. 6. The average number of hops for a multihop D2D link existing on any of 30 orthogonal channels, each with a single interfering cellular user, between a single D2D Tx and Rx located inside a randomly placed cluster of radius 0.25 km

VI. Conclusion

We have presented a spectrum sharing protocol in which an ad-hoc device to device (D2D) network can use the same frequency resources that are actively being used by a cellular network, but without causing the cellular link to fall below the required minimum SINR. For this protocol, we proposed two realistic user models for the D2D users and derived analytical expressions for the probability of the existence of a single-hop D2D link that does not cause the cellular link to break. The cell-wide D2D user model shows that such a D2D link can exist with significant probability, but the clustered D2D model shows that a D2D link can exist with very high probability in certain user topologies.

We provided simulation results verifying the analytical expressions obtained. In addition, we gave numerical simulations for the clustered D2D model where the DSR protocol was used to obtain a multihop link when a direct link was not available. By considering multihop, the probability that a D2D link can exist further increases. As a result of this protocol, the overall user capacity and spectral efficiency of the network can be improved.

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