An Efficient Spectrum Sharing and Interference Reduction for Cellular Network

S.Tamilselvan, S. Savitha, D. Prabakar

Abstract — To utilize spectrum resource more efficiently in a cellular network is very difficult. So to improve the resources, adhoc device to device communication was introduced. Interference management is a major component in designing these spectrum sharing schemes and it is critical that the licensed users maintain their QoS. A distributed dynamic spectrum protocol is proposed in which device to device users can communicate directly with each other and access the spectrum more efficiently. Network information is distributed by route discovery packet in a random access manner to establish the single hop or multihop link between D2D users. The discovery packet which contains network information will decrease the failure rate of the route discovery and also reduces the number of transmissions to find the route. The Performance metrics such as the route discovery failure probability and the number of transmission necessary to discover a route to the destination are to be analyzed. Finally using the found route, the simulation result shows that two D2D users can communicate with a low probability of outage and also reduces harmful interference to the macro users. The proposed protocol can be significantly achieved power saving using D2D route rather than connecting to the cellular base station. So spectrum resources are shared more efficiently between the macro user and device to device user.

Index Terms — Device-to-device, spectrum sharing, power control, interference management, route discovery.

I. INTRODUCTION

The number of wireless users is increasing at a rate faster than service provider can obtain new spectrum resources. New technologies like International Mobile Telecommunication (IMT) advanced and Third Generation Partnership Project (3GPP) Long Term Evolution (LTE) will help to satisfy the increasing demand. Since the spectrum has already been fully allocated, it seems impractical to fulfill the rising demands on bandwidth with the rising number of users in mobile communication system in future. Dynamic spectrum access techniques are becoming increasingly popular as another method to meet the high for service. Methods for different service providers cooperate together to improve the overall performance of their own customers is considered in [1]-[2].

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S.TAMILSELVAN received his BE in Electronics and communication Engineering from Madras University in 1999 and M.Tech in Electronics and Communication Engineering from the Pondicherry Engineering College in 2001

S. SAVITHA received the B.Tech degreeShe is currently pursuing M.Tech in the Department of Electronics and communication Engineering from Pondicherry Engineering College affiliated to Pondicherry University, Pondicherry, INDIA.

D. PRABAKAR received the B.Tech degree (2007) in the Department of Electronics and Communication Engineering from Arunai Engineering College affiliated to Anna University and M.Tech degree (2009)

A similar approach is taken in [3] to redistribute excess users to frequency bands with excess capacity. Another work is done in [4] where fixed relay stations are placed in the cell to form femtocell hotspots. A protocol is developed in [5] where base stations take advantage of the user topology and assign resources to cellular users so that they can communicate directly with each other without the need of the base station. A different approach is to dynamically share licensed spectrum with unlicensed users [6]–[10]. Methods to allocate a set of frequency resources to maximize the total number of simultaneous transmissions while minimizing interference are developed in [11]. Similarly, a pricing scheme is developed where users choose frequency channels and transmit powers to maximize their own gains while trying to reduce overall interference [12]. Spatial reuse techniques are used in [13] to define physical regions in a cellular network where unlicensed users could access the licensed spectrum while only causing minimal interference to the licensed users. Different areas in literature refer to these unlicensed users as low priority, cognitive, or device-to-device users.

Device-to-Device (D2D) users can simultaneously operate in the same frequency spectrum as a licensed cellular radio network [14]–[16]. In a distributed fashion, D2D users can control their power themselves and opportunistically access spectrum to discover routes among each other and to transmit data. The biggest challenge in such a scheme is the interference management, specifically how to keep the level of interference the licensed macro cell users receive within the allowed interference temperature while still achieving a level of performance for the unlicensed D2D users. Much of the existing literature approaches this problem with numerous assumptions to reduce the complexity. Interference is often managed by allocating the unlicensed users with frequency resources that are disjoint to those of the licensed network, either through a completely different frequency band or a subset of the same band that is currently not in use [17].

In our proposed method, we develop a distributed dynamic spectrum protocol to enable device-to-device communication. D2D users were intended to utilize statistical estimates of the channel gains to set a transmit power level that will be within the allowed interference temperature of the cellular network.

Using the calculated transmit power, two D2D users will attempt to discover either a single-hop or multi-hop route connecting each other. Network information of the discovery packet is utilized to improve both the success and efficiency of the route discovery. Random access techniques are used to ensure that only one D2D user accesses the spectrum at a given time.

Once a route is found between the two users, the D2D link quality in terms of the probability of outage and power savings can be quantified. Our results show that the network information in the discovery packets decreases the probability of failure in finding a route while significantly reducing the number of transmissions necessary to discover a route. With the framework in place to find routes between D2D users, derive the probability of outage for a link between any two D2D users is derived. Perfect channel inversion in the power control is consider to calculate an analytical lower bound on the outage probability and to show that our distributed power control using statistical estimates performs well compared to the lower bound. Therefore, to fully utilize the scarce radio resources, D2D communication as an underlay to cellular network is considered. D2D communication is promising for increasing the power saving and to improve spectrum utilization.

The rest of this paper is organized as follows. Section II describes the network architecture of the cellular model. Section III describes in detail how the power control and route discovery in the protocol work and give simulation results showing the performance of the route discovery. In Section IV we present the analytical expressions for the probability of outage and give results that quantify the performance of our device-to-device scheme. Concluding remarks and future extensions appear in Section V.

II. NETWORK ARCHITECTURE

A. Infrastructure and User Model

The network considered consists of seven circular cells of radius R with a base station (BS) equipped with an antenna located at the center of each cell. The uplink frame of the system is considered and it is assume to be divided into N_C orthogonal channels. The same N_C channels are available for use in each cell. For a cellular link to be established with the base station, a minimum SINR of β_B *is* required. Let us assume that there exists a margin κ in the required SINR at each base station.

The first type of user is a macro user (MU) and communicates by establishing a link with the nearest base station and having their information relayed to their intended destination. Macro users access the base station using standard control signaling found in today's cellular systems. There is N_M active macro users uniformly distributed in each cell and we assume that there is only one active macro user per channel.

This gives the relation $N_M = N_C$ which is in place to that the entire N_C channels which are actively in use in each cell and there are no spare channels to be reallocated elsewhere. This assumption holds for all cells in the network, thus neighboring cells have no channels to lend each other for cell-edge users.

The second type of user, a D2D user, communicates directly with each other in a distributed ad-hoc fashion over one or more hops without any assistance by the base station. All D2D users are uniformly distributed within a single randomly located circular cluster of radius r where we assume $r << R$. This user cluster is distributed such that the entire area of the cluster is within the boundary of the macro cell. Furthermore, two D2Ds are chosen in the cluster at random, where one is a D2D source (S) with information intended for the other, a D2D destination (D). If a single-hop link between the source and destination is not available N_D with idle D2D users willing to serve as relays in a multi-hop route is assumed.

D2D users communicate with each other on the same frequency channels used by macro users; however their use of those channels cannot cause the SINR of an active cellular link to fall by more than the allowed κ. To meet this requirement, assume that D2D users know the value of κ. Base stations in current cellular systems periodically broadcast information to users and the value of κ could be included in that standard control signaling. D2Ds utilize CSMA/CA to randomly access the channels and will discover each other using a protocol described in Section III-B. Finally, for a D2D link to exist, a minimum SINR of β_D must be achieved between a transmitting D2D and a receiving D2D. The D2D users and macro users only differ in their modes of communicating with each other, either directly or through the base station. In fact both classes of users would be composed of the same type of wireless devices. D2D users are simply macro users who could not be served by the base station.

B. Channel Model

The channel model is presented in the context of the network above. Three arbitrary users: a transmitter i, a receiver j, and an interferer k were considered. A pathloss dominated channel is assumed with multiplicative fading and additive white Gaussian noise. The large-scale fading is determined by the Euclidian distance d_{ij} between two users i and j and the pathloss exponent α. A Rayleigh random variable f_{ij} determines the small-scale fading between the same two users. The power of user's signals and corresponding SINR of their links are mainly taken into consideration and thus define user j's SINR as

$$\Gamma_j = \frac{P_{Ti} d_{ij}^{-\alpha} h_{ij}}{\sum_k P_{Tk} d_{ij}^{-\alpha} h_{ij} + \sigma^2} \tag{1}$$

Where P_{Ti} is the power used by the transmitter, $d^{-a}{}_{ij}$ is the path loss for the link between the transmitter and receiver, and $h_{ij} = |f_{ij}|^2$ is the channel gain. Similarly, P_{Tk} is the power used by the k'th interferer and $d^{-a}{}_{kj}$ and $h_{kj} = |f_{kj}|^2$ are the pathless and channel gain for the link between the k'th interferer and the receiver. Assumption is made such that all users observe the same noise power of σ^2. To denote the different parameters for the macro user, source, and destination the subscripts M, S, and D were used. All users are assumed to know the path loss of their respective links with the base station.

III. DEVICE-TO-DEVICE COMMUNICATION

A dynamic spectrum access protocol is proposed in which D2D users can communicate directly with each other using the same frequency resources as an active uplink between a macro user and the base station. This protocol is opportunistic as a link between two D2D users can only be utilized if their use of the spectrum stays within the interference temperature of the network and does not cause the SINR of the cellular link to decrease by more than the allowed margin. To accomplish this, only D2D users are allowed to communicate with each other during the uplink frame of the network [15]. During the uplink transmission phase, only the stationary base station will receive interference from the D2Ds. Macro users will not receive any interference from the D2Ds as they will be uplinked to the base station. If D2D users communicated during the downlink, interference would be seen at every macro user in the system. It is impractical to assume that the macro user locations and channel conditions are known by each D2D user making it extremely difficult for D2D users to control the interference they cause. The same practical reasons prevent D2Ds from accurately controlling their power to adjust for interference from active macro users. Thus, macro user interference will not affect the power control but will be considered in D2D link quality when the SINR thresholds are evaluated.

There are two main steps in our protocol. First, the power control of D2D users. Because D2D's use of the macro user's bandwidth is constrained by how much interference they cause, the power control will be the main determining factor in the protocol's performance. Once an allowed transmit power has been calculated, the second step will be for a D2D user to discover either a single-hop or multi-hop route to their intended destination.

A. Power Control for Device-to-Device Users

A minimum SINR of β_B is required for a macro user link to exist with the base station so that there can be at most a κ change in the base station's SINR due to interference from a transmitting D2D user.

If D2D users control their interference perfectly, a macro user with perfect power control will achieve the required SINR of β_B. This result is obtained by the macro user scaling its own transmit power by κ.

Thus in the absence of the D2D interference, a macro user link will achieve an SNR or SINR with zero interference, of $\kappa\beta_B$. The effects of κ in the macro user link can be seen by looking at the SNR at the base station. After rearranging terms, a bound on the transmit power of macro users is given as

$$\frac{P_{TM}\, d_{MB}^{-\alpha} h_{MB}}{\sigma^2} \geq k\beta_B$$

$$P_{TM} \geq k\beta_B d_{MB}^{\alpha} h_{MB}^{-1} \triangleq P_{TM}^{min}, \qquad (2)$$

Where d^{-a}_{MB} and h_{MB} are the path loss and channel gain between a macro user and the base station. Assuming prefect knowledge of the channel gain, the bound in (2) gives a transmit power for macro users such that the probability of outage will be zero. The performance of the D2D users is mainly focused and the macro user power is controlled by the base station with an error free estimate of the channel gain. In practice, the estimate may contain some error causing the macro user to go into outage. This outage is independent of the D2D's use of the channel. The SINR of a macro user link that is interfered by a single random D2D user is evaluated. Without loss of generality, D2D as the source S is referred. Consider P_{TM} to be the allowed minimum (2), after rearranging terms, the bound on the transmit power of a D2D user can be given as

$$\frac{P_{TM}\, d_{MB}^{-\alpha} h_{MB}}{P_{TS}\, d_{SB}^{-\alpha} h_{SB} + \sigma^2} \geq \beta_B$$

$$P_{TS}^{max} \triangleq (k-1) d_{SB}^{\alpha} \sigma^2 h_{SB}^{-1} \geq P_{TS}, \qquad (3)$$

Where d^{-a}_{SB} and h_{SB} are the path loss and channel gain between the source and the base station. Assuming a D2D has perfect knowledge of κ and h_{SB}, the bound in (3) gives a transmit power that a D2D can use and not cause a macro user to go into outage. We assume that there is no coordination between D2Ds and the base station, so h_{SB} will be unknown and must be estimated. A statistical estimate is used and h_{SB} is assumed to be estimated by the mean of the fading, and define $\widehat{h_{SB}} \triangleq \mathrm{E}[h_{SB}]$. Using that estimate, a D2D can calculate a usable maximum transmit power which is given as $P_{Ts}^{max*} = (\kappa - 1) d^{a}_{SB}\sigma^2 (\widehat{h_{SB}})^{-1}$. The accuracy of $\widehat{h_{SB}}$ in estimating h_{SB} will determine how much interference the base station receives from a transmitting D2D user.

When $\widehat{h_{SB}} < h_{SB}$, the calculated maximum P_{Ts}^{max*} will exceed the true maximum P_{Ts}^{max} *and* the macro user will go into outage. Conversely, when $\widehat{h_{SB}} > h_{SB}$, P_{Ts}^{max*} will be lower than the true maximum.

This in turn means that a D2D could potentially use $P_{Ts}^{max} - P_{Ts}^{max*}$ additional transmit power and still not cause a macro user to go into outage. This can be exploited to allow for additional scaling of the D2D link power to improve D2D link quality at no cost to the macro user link quality.

Thus far, P_{Ts}^{max*} has been controlled to minimize the interference they cause to the base station. Ideally, the power control for a D2D user should also consider the link used to reach the intended destination D, specifically the fading h_{SD}. We know that for the source transmitting with power P_{Ts}^{max*}, a correctly received packet at the destination will have power $P_{RD} = P_{Ts}^{max*}\, d^{-a}_{SD}\, h_{SD}$. The additional power control mentioned just above could be realized in the form of an estimate of the fading, denoted as $\widehat{h_{SD}}$.

Using that estimate, channel inversion can be used in the power control of the D2D link. The calculated maximum power of P_{Ts}^{max*} can be scaled to set a new usable transmit power for D2D users as $P^{*}_{TS} = P^{max*}_{TS}\, (\widehat{h_{SD}})^{-1}$. Numerous in current literature show that channel estimation is feasible but the distributed nature of the D2D communication may prohibit any additional overhead for channel estimation. As such, we use a constant estimate and assume $\widehat{h_{SD}} \triangleq \mathrm{E}[h_{SD}]$. This is a practical choice for the estimate and is equivalent to just power controlling over the pathloss and ignoring the fast effects. Perfect channel inversion is considered, $\widehat{h_{SD}} = h_{SD}$, which analyzes the system as if there were no interference constraints or limits on transmit power levels.

After the power control has been completed, the source is able to set it's transmit power to

$$P_{TS}^{*} = (k-1) d_{SB}^{\alpha} \sigma^2 (\widehat{h_{SB}})^{-1} (\widehat{h_{SD}})^{-1} \qquad (4)$$

The power in (4) assumes a single-hop link between the D2D source and destination. When a multi-hop route is formed, the same power is used by changing the subscripts $S = i$ and $D = j$ to denote a link between the i'th and j'th D2D users. Using the mean of the fading as the two estimates gives practical methods for D2Ds to set their own transmit power with minimal overhead. The second step of the protocol is D2Ds use a practical discovery method to establish routes using the transmit power just derived.

B. Distributed Route Discovery for Two-way Device-to Device Communication

The D2D routing protocol inspired by the DSR protocol is developed. DSR is a source initiated packet based discovery protocol.

The standard DSR protocol floods the network with discovery packets and in doing so, exchanges the address of the nodes in the network, so the destination will have a virtual map of how to reach the source.

A modified packet structure that also includes the channel number and transmits power used for transmission as well as the interference power seen by the transmitting node is used.

Previous research work shows that the flooding rules in D2DR help to keep the routing overhead small. Specifically, discovery packets are only allowed to traverse small areas of the network and will never traverse the same link twice, preventing loop problems. Furthermore, D2Ds employ CSMA/CA to ensure that only one D2D accesses the channel at a given time. By enforcing these rules, the number of discovery transmissions decreases, therefore reducing both the overhead and the interference effects of D2DR. In our implementation of the D2DR protocol, forwarding relays are intended to add their transmission power and measured interference power to the discovery packet in addition to their address. To begin, the D2D source broadcasts a packet intended for the destination and includes in the packet its transmission power P^*_{Ts} as calculated from (4), and its own measured interference power, I_S. Without loss of generality, assume the packet is received by the j'th D2D, denoted as node j. To see the effects of including those two powers in the discovery packet, we look at

$$\Gamma_j = \frac{P_{R_j}}{I_j + \sigma^2}, \tag{5}$$

Where Γ_j and P_{Rj} are the measured SINR and received powerat node j. I_j represents the measured sum interference power which accounts for both in-cell and out-of-cell interferers at node j. Using (5) and the fact that $P_{Rj} = P^*_{Ts}\, d^{-\alpha}_{Sj}\, h_{Sj}$ can be written as

$$d_{Sj}^{-\alpha}\, h_{Sj} = \frac{I_j\,(I_j + \sigma^2)}{P^*_{TS}}, \tag{6}$$

which solves for the combined path loss and channel gain. Node j knows P^*_{Ts} from the discovery packet, and Γ_j, I_j, and σ^2 are measured values, so node j can calculate the combined and channel gain. In a similar fashion, the required SINR constraint of β_D for node j, with transmit power P^*_{Tj} to communicate back to the source, can be rewritten to show

$$\frac{P^*_{Tj}\, d_{jS}^{-\alpha}\, h_{jS}}{I_S + \sigma^2} \geq \beta_D$$

$$P^*_{Tj} \;\geq\; d_{jS}^{\alpha}\, h_{jS}^{-1}(I_S + \sigma^2)\,\beta_D \triangleq P^{min}_{Tj}, \tag{7}$$

Which gives the minimum transmit power that node j must use to communicate with the source.

Symmetric channels were asumed such that $d^{-\alpha}_{Sj}\, h_{Sj} = d^{-\alpha}_{jS}\, h_{jS}$ and the discovery packet contains the interference power seen by the source, thus node j can calculate P^{min}_{Tj}. If $P^*_{Tj} \geq P^{min}_{Tj}$ is satisfied, node j knows that its packet will be received by the source even before it is transmitted. In certain topologies and channel conditions, there will be no value for P^*_{Tj} in which a two-way D2D link can be sustained and the link would be considered in outage. If node j is the D2D destination, then a single-hop route exists with the D2D source.

If a single-hop route does not exist, then node j can continue the discovery process and serve as a relay. However, it will only continue the discovery if it knows that a two-way link exists with the D2D source.

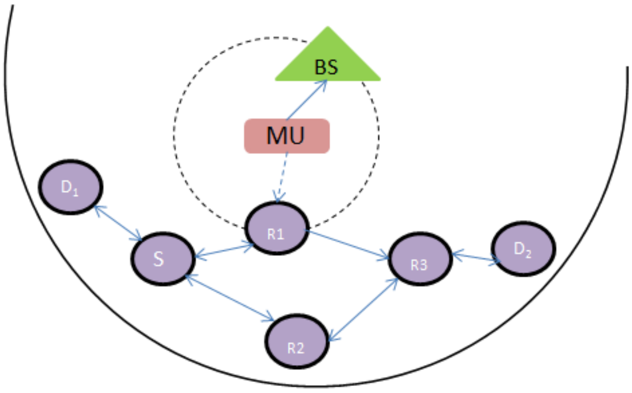

Figure 1. An example realization of what a cellular network with an under laid D2D network may look like.

The source (S) communicates over a single hop if possible, as to D1, or uses idle D2D users Ri as relays over a multi hop route, as to D2. The interference from the macro user (MU) causes too much interference for a two-way route to be used with relay R1 the discovery packet adding its own transmission power and interference power. Any node receiving it can repeat the steps in (5), (6), and (7) to determine if a two-way link exists. Once the D2D destination receives the packet, it will have a list of relay nodes that form a multi-hop route with the D2D source.

A multi-hop route connecting two random D2Ds can be discovered is shown in figure1. Assume that the source S wants to communicate with the destination D1 by using the same channel as the active macro user MU. The source transmits a discovery packet intended for D1 at a power level of P_{TS}. D1 is sufficiently far away from the interfering macro user to receive the packet and uses the values of P_{TS} and I_S contained in the packet to determine that a two-way single-hop link exists with S.

Now assume that S wants to communicate with D2. Each relay Ri would forward the discovery packet intended for D2 after adding their own transmit and interference power to the packet. A two-way route between R1 and R3 could not be used due to strong interference from the macro user. Using the powers in the discovery packet from R1, R3 would be able to determine that a two-way link does not exist with R1 and would not forward the discovery packet. This reduces the number of transmissions necessary for discovery and increases the chances of discovery packets along two way routes reaching the destination. A two-way route could be established using R2 instead. In both the single-hop and multi-hop routes discussed above, the destinations need to be able to reply back to the source with the correct routing. By doing so, the source knows a route exists to its intended destination and its message should be successfully delivered.

By including the transmission and interference powers in the discovery packet, D2D users get important network information about links with their neighbors. The network information will improve the likelihood that a two-way route is discovered and lower the number of transmissions necessary to do so.

TABLE 1.NETWORK PARAMETERS

System Parameters	Value
Cell Radius(R)	2000m
Cluster Radius(r)	500m
Number of Channels (N_C)	30
Number of MUs (N_M)	30
Noise(σ^2)	-96 dbm
Minimum BS SINR (β_B)	10db
Minimum D2D SINR(β_D)	5db
Interference Margin at BS(k)	3db
Mean of Rayleigh Fading(E[h_{ij}])	1

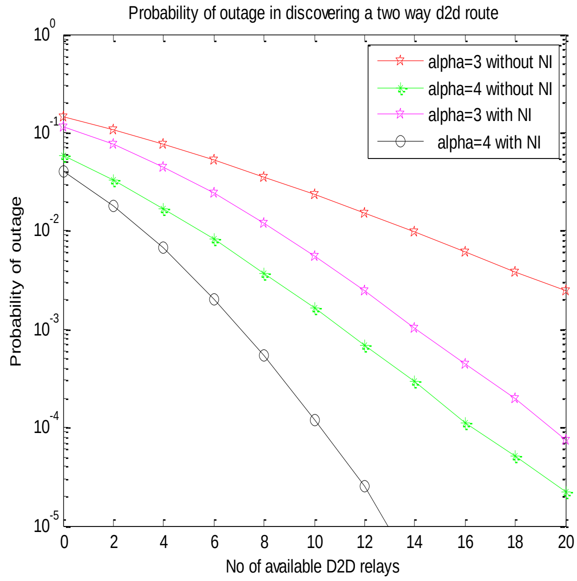

Figure 2. The probability of outage in discovering a two-way D2D route.

C. Route Discovery Simulation Results

Our network model was simulated for 10^6 random topologies in MATLAB. The various network parameters used for the simulations are shown in Table I.

These simulation results show the performance of the center macro cell only but take into account the interference effects from the six other surrounding macro cells. Figure2 shows the probability of outage in discovering a two-way D2D route versus the number of available D2D relays (N_D) in the cluster. From the graph it can be noted that for a given value of N_D, not all relays participate in the route connecting the source and destination and also as N_D increases, the outage rate decreases.

Relays willing to forward information for the D2D source can help overcome high attenuation channels due to large distances and random fading. As α increases, probability of outage decreases. Even though each hop in the D2D route sees higher attenuation, interference from cellular users is lower, and D2Ds interfere with the BS less allowing them to transmit at a higher power. Finally, the figure 2 shows that using the network information in the discovery packet will significantly improve the probability of discovering a two-way route.

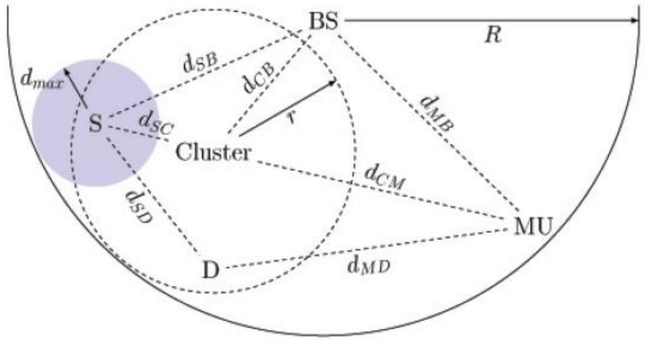

Figure 3. Network topology realization presenting the various random distances in the model.

IV. OUTAGE ANALYSIS OF DEVICE - TO - DEVICE COMMUNICATION

The D2D outage probability using both the distance and fading channel probability distributions is derived which allows us to consider all D2D locations in the macro cell and all possible channel conditions between users.

A. Single-hop Probability of Outage Derivation

An example network topology realization is shown in figure 3 as we derive the outage probability of a single-hop link between two randomly placed D2Ds. The probability is defined as $P^{out}{}_D$. As a first step, the outage probability is driven for all channels in terms of the outage probability for a single channel.

The available bandwidth is divided into N_C orthogonal channels and D2Ds are able to access any of them. The orthogonality of those channels results in a link's outage on channel C_i being independent of and identically distributed to a link's outage on channel C_j for $i \neq j$. Thus we can easily write

$$P_D^{out} = \left(P_{D|Ci}^{out} \right)^{Nc}, \qquad \textbf{(8)}$$

which gives the probability of outage for a single-hop D2Dlink on N_C orthogonal channels. Assuming a given channel C_i, the second step is to derive the probability of outage $P^{out}{}_{D|Ci}$. The geometry of the model to define the outage in terms of the random distance between the source and destination is used. Only a single D2D source-destination pair separated by a distance d_{SD} is considered.

We know for a D2D link to exist, the SINR at the destination must be above the required threshold β_D. If we look at the SINR equation for the D2D link and set the macro user and D2D user transmit powers as $P_{TM} = P^{min}{}_{TM}$ and $P_{TS} = P^*{}_{TS}$, as derived in Section III-A, after rearranging terms, we obtain

$$\beta_D \leq \frac{P_{TS}\, d_{SD}^{-\alpha}\, h_{SD}}{P_{TM}\, d_{MD}^{-\alpha}\, h_{MD} + \sigma^2}$$

$$d_{SD} \leq \left(\frac{d_{MD}^{\alpha}(k-1)\, d_{SB}^{\alpha}\, h_{SD}\, h_{MB}\,(\overline{h_{SB}})^{-1}}{\beta_D(\overline{h_{SD}})\,[k\, \beta_B\, d_{MB}^{\alpha}\, h_{MD} + d_{MD}^{\alpha}\, h_{MB}} \right)^{\frac{1}{\alpha}} \triangleq dmax \qquad \textbf{(9)}$$

which gives an upper bound on the allowed distance between the D2D source and destination as a function of the network parameters in the model. The distance d_{max} is the maximum transmission distance of the source and defines a region around the source, shown by the shaded area in figure 3, in which the destination must be located in order to satisfy the required SINR β_D. Thus, the probability of a link satisfying the SINR requirement and not being in outage, $Pr[d_{SD} \leq d_{max}]$, is the ratio of all the feasible locations of the destination that result in a successful link, which is the coverage region of the source, to all possible destination locations, the area of the entire cluster.

B .Bounds on the Single-hop Probability of Outage

The exact model as shown in figure 4 was simulated for10^6 random topologies. The probability of outage in (8) for a single D2D link sharing any of the N_C channels with an active macro user versus the path loss exponent α is plotted in figure 4.

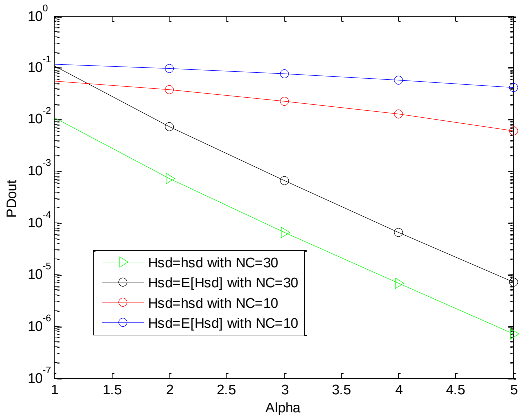

Figure 4. Probability of outage for D2D users

A fixed radius ratio of r/R = 0.25 is used and the number of channels in the network is varied. A perfect channel estimate of $\widetilde{h_{SD}}$ = h_{SD} is considered for the power control which gives a lower bound on the outage probability. Perfect knowledge of the channel is difficult to obtain in practice so, our protocol uses a statistical estimate of $\widetilde{h_{SD}}$ =E[h_{SD}] in the power control. It can be noted that as NC increases, P_{Dout} decreases as D2Ds lower interference from macro users. This in turn makes fading effects along the source-destination link, h_{SD}, more significant. With increasing α, D2Ds can transmit at a have more diversity in the resources that they can use. The increased diversity allows them to choose a channel with perfect channel gain estimates and statistical estimates in the D2D source's power control are considered. There is a higher power due to the reduction in their interference at the base station. The analytical probability of outage for a macro user, P_{Mout}, who is sharing its channel with a D2D link, is shown in figure 5.

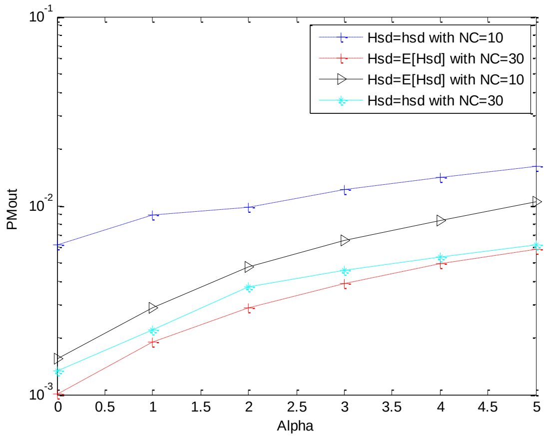

Figure 5. Probability of outage for macro users

The calculations to derive P_{Mout} are done in the same manner as that for a D2D link; however they are much easier due to the fixed location of the base station. It can be observed that as N_C varies; most values of P_{Mout} are less than 10^{-2} and start to level off for large α. In order for the D2D outage probability to decrease with α, it is expected for the macro user outage probability to increase. This is an analytical upper bound on the D2D outage where it shows the best performance of a D2D link while guaranteeing that the power control over the D2D source-destination link does not cause outage at the base station. In this scenario, the outage of the macro user link comes from the estimate of the channel gain between the D2D source and the base station. It can be also noted that as the different channel gain estimates cause the D2D outage to increase, there is a corresponding decrease in the macro user outage as there is always a tradeoff in performance as the two different classes of users try to share the spectrum.

C. Multi-hop Simulation Results

The performance of the network can be further quantified by looking at the power savings when D2D communication with perfect channel gain estimates and statistical estimates are considered. To quantify this, the cellular mode power is considered to be the sum of the powers for the D2D source to reach the base station, P_{TSB}, and for the base station to reach the D2D destination, $P_{TBD.}$

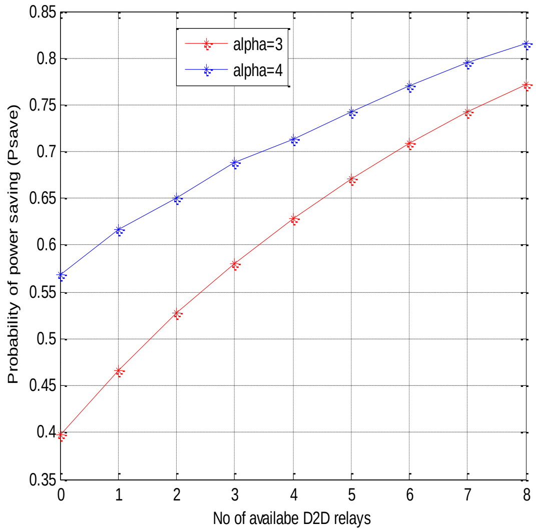

Figure 6. Power Saving in D2D Communication

The D2D mode power is calculated for a route of length N_{Hops} as the sum of the D2D's transmit power used in the route where the n'th D2D transmits with power P^*_{TDn}. Using these powers, the power savings is calculated as

$$P_{save} = \frac{P_{T_{SB}} + P_{T_{BD}} - \sum_{n=1}^{N_{Hops}} P^*_{T_{D_n}}}{P_{T_{SB}} + P_{T_{BD}}} \qquad \textbf{(10)}$$

Figure 6 shows the power savings in D2D. N_D = 0 corresponds to a single-hop route between the source and destination. When $\alpha \geq 3$ significant amount of power saving can be achieved [7]. These power savings come from the fact that D2Ds can communicate over shorter distances more efficiently than longer links with the base station. When α is larger, D2Ds become more isolated from the base station making shorter distance hops more efficient.

D. Comparison between D2DR and DSR

Figure 7 shows comparison between D2DR and DSR. It can be observed as the number of available D2D relay increases, probability of outage will be reduced. The path loss $\alpha = 4$ for D2DR outperforms DSR. D2DR will never discover a 1-way route as done by DSR. With sufficient numbers of potential relays, D2DR increases in discovering a 2-way route.

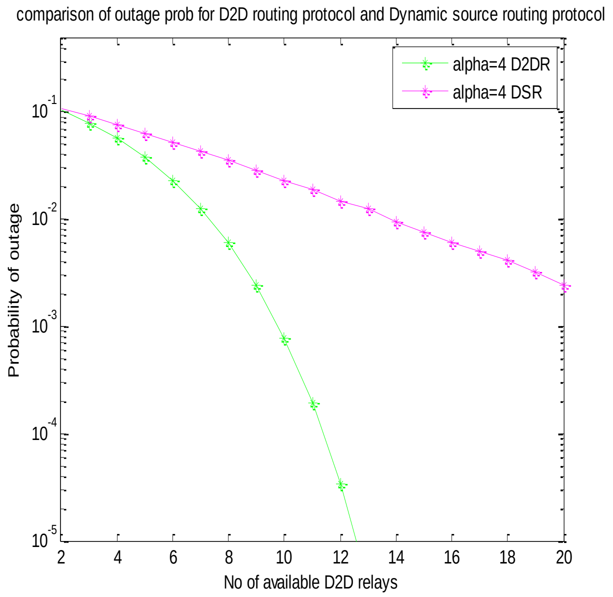

Figure 7. Comparison of outage probability for D2D routing protocol and Dynamic source routing protocol

V. CONCLUSIONS

In this paper we have presented an opportunistic communication scheme in which an ad-hoc Device-to-Device network can simultaneously communicate on the same set of frequency resources as a fully loaded cellular radio network. A practical protocol for D2Ds has been developed to use this scheme in a distributed manner and with no coordination from the base station. The first step of D2D users' is to control their powers to a level which causes minimal interference to the base station. Then using the calculated power, the second step is to employ a discovery protocol to establish a route connecting them to their intended destination. Results show that including network information in the discovery packet significantly lowers the route discovery's failure probability and reduces the number of transmissions necessary to discover a route to the destination. Using a practical statistical estimate in the power control, our protocol shows performance near to the lower bound. However, large improvements in the D2D performance come at a cost of only a small loss in macro user performance. Furthermore, simulation results show that significant power savings can be gained using D2D routes rather than connecting to the cellular base station.

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S.TAMILSELVAN received his BE in Electronics and communication Engineering from Madras University in 1999 and M.Tech in Electronics and Communication Engineering from the Pondicherry Engineering College in 2001. He received his PhD degree in the area of Wireless Communication from Pondicherry University during the year 2011. Currently, he is working as an Assistant Professor in the Department of ECE, Pondicherry Engineering College, India. His current research interests are in wireless communication systems, mobile and distributed computing.

S. SAVITHA received the B.Tech degree (2012) in the Department of Electronics and Communication Engineering from sri manakula vinayagar engineering college affiliated to Pondicherry University. She is currently pursuing M.Tech in the Department of Electronics and communication Engineering from Pondicherry Engineering College affiliated to Pondicherry University, Pondicherry, INDIA.

D. PRABAKAR received the B.Tech degree (2007) in the Department of Electronics and Communication Engineering from Arunai Engineering College affiliated to Anna University and M.Tech degree (2009) in the Department of Electronics and Communication Engineering from Pondicherry Engineering College affiliated to Pondicherry University, Pondicherry, INDIA. He is currently working as Assistant Professor in the Dept. of Electronics and Communication Engineering, PRIST University, Pondicherry, India. His research interests include Wireless Communication and Wireless Networks.