Reliability Improvement Using Power Control in Device-to-Device Networks

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Abstract—In this paper, a new power control scheme is proposed to improve the reliability of a Device-to-Device (D2D) communication. The proposed scheme is optimal in terms of the probability of successful transmission. All transmitters in the network form a homogeneous Poisson Point Process (PPP). The complementary cumulative distribution function (CCDF) of the transmit power is derived at D2D receiver by using a complex channel model. In order to obtain the optimal transmission power of D2D communication, an expected transmission scale function $Z$ is designed, based on the CCDF of transmit power which is obtained in the above procedure. The optimum transmit power is calculated through maximizing function $Z$ for different D2D communication distance and different noise variance. The numerical results show that the transmit power of D2D link is effectively controlled. Our scheme achieves better performance on success probability than the fixed power scheme in good channel condition and their performances maintain the same in poor channel condition.

Index Terms—Device-To-Device; Power Control; Probability of Successful Transmission; LTE-A Network

I. INTRODUCTION

Wireless local area communities have become increasingly popular in recent years [1]. There is a scene where a media server is put up at a music concert from which visitors can download promotional material using a Device-to-Device (D2D) connection. Now, only WLAN and Bluetooth operating in the unlicensed bands could be used to setup a direct connection to the media server in local area [2-4]. However, operating in the unlicensed bands has defects, because it could not guarantee a controlled interference environment. Therefore, users are willing to pay a small amount of money to gain access to the licensed spectrum. The cellular network supports such access to the licensed bands, it enables D2D communication under laying cellular network [5, 6]. D2D communication model provides some advantages, such as enhanced network capacity, high spectrum efficiency and delay reduction [7, 8]. However, the new network architecture brings new challenges to the existing techniques of radio resource allocation and interference management for network operator.

First, in the coexisting macro cell and D2D network, the spectrum allocation between the macro cell and D2D is the most processing issue. There are mainly two resource sharing modes, i.e., non-orthogonal sharing mode and orthogonal sharing mode [9-12]. In non-orthogonal sharing mode, macro users (MUEs) share the same resource with D2D pairs. The spectrum efficiency can be improved while causing serious interference to each other, especially when D2D pairs are applied in densely populated area [13]. In orthogonal sharing mode, MUEs and D2D pairs get part of resources dedicatedly. There is no interference between macro cell and D2D. Though the spectrum efficiency is less than non-orthogonal mode, the other advantages, such as transmission power reduction and channel quality improvement will be obtained. In addition, orthogonal mode is manageable for network operator.

In orthogonal mode [14, 15], system network can be partitioned into two networks, macro network and D2D network from the network operator’s perspective, and each network contains a number of MUEs and D2D pairs, respectively. Reasonable resource allocation for different networks will improve the performance of entire network. The resource will be allocated to macro cell firstly in order to satisfy their data rate requirement as it is critical that MUEs maintain their expected quality of service. In contrast, the D2D network employs the redundant resource greedily to maximize the capacity of D2D pairs while MUEs have been served satisfactorily.

Second, due to the assumption of macro network and D2D operate on orthogonal mode, there is no cross-tier interference between them. Nevertheless, for maximizing capacity of D2D pairs in a single macro cell coverage, D2D pairs need to fully reuse the limited spectrum resource. Therefore, D2D receiver may suffer from severe interference from neighbor D2D pairs when they operate on the same resource. In the process of D2D session setup, it requires the measurements between D2D UEs to check if D2D link can satisfy the channel quality, that outage probability is less than threshold. Therefore, the interference avoidance mechanisms (i.e. power control, frequency allocation, etc.) for D2D pairs should be investigated.

Power control is one of the key factors for interference avoidance. The transmit power of D2D transmitter can be controlled by eNB in order to limit the interference to neighbor D2D pairs. The greater the transmission power is, the higher probability of successful transmission can be. However, a larger transmission power will increase...
the interference of entire network and reduce the sum rate of network. Therefore, the choice of transmission power is a compromise between D2D connectivity and entire network interference.

Solutions to deal with above problem have been discussed in different applications [16-19]. The transmit power of D2D transmitter is reduced by a back off value from the transmit power determined by the cellular power control when the D2D transmitter reuses cellular UL resources [16]. The eNB can use interference-aware scheduling to reduce the interference [17]. In addition, [18] [19] propose a novel resource allocation method that allows a D2D link reuses the resources of more than one cellular UEs, which can meet the high bandwidth requirement of D2D communication. However, the aforementioned mechanisms are evaluated only by the sum rate of D2D and cellular connections. In the scenario of D2D network, UE reuses the resources of more than one cellular UEs. In this scenario, the interference is heavier than the interference caused by reusing one cellular UE. For this reason, the probability of success has a more influence than the throughput on network performance. In [2], the new approach envisions a cellular controlled short-range communication network among cooperating mobile and wireless devices, the cellular resource are reused by D2D in an orthogonal manner. A strategy of resource allocation which limited to the spectrum efficiency has been proposed [20]. A power control algorithm has been proposed in [21], and all D2D links try to maximize the probability that they exceed the target SINR. This paper obtains a result that a Nash Equilibrium exists and the corresponding policy is for all links to transmit at constant power. In [22], CDF of the transmit power and SINR are derived for D2D network through seeking the transmit power allocation on each link that achieves the SINR target with minimum transmit power.

However, the aforementioned researches have the same defects in managing interference among D2D pairs. They don’t guarantee the reliability of D2D communication due to the dense deployment in limited area. In comparison with the existing literature, this paper has the following major contributions:

The closed-form expression of outage probability for a D2D receiver is derived considering co-channel interference. The channel propagation model is represented as a combination of Rayleigh fading and log-normal shadowing.

A heuristic power control scheme on the basis of contribution 1) is proposed in D2D network. In order to further reduce the outage probability, we propose an effective power control scheme based on the expected transmission scale function $Z$. Therefore, a power control problem of D2D transmission power would be mapped to maximizing function $Z$. Our approach obtains improvement of success probability in most cases.

The remainder of this article is organized as follows: In Section II we present the system model and basic assumption. In section III we compute the probability of successful transmission of D2D link, and then optimize transmission power. Section IV presents and discusses the simulation results. Finally, we draw conclusions and point at future works.

II. SYSTEM AND CHANNEL MODEL

A. Scenario Description

We study a single macro cell with coverage radius $R$, which consists of eNB and D2D pairs. The $i$-th D2D pair consists of D2D transmitter (D_Tx) and D2D receiver (D_Rx). The position of D_Tx is restricted to be $D_i$ from D_TX. The scenario is described in Fig. 1. We model the location of D2D pair in $\Omega$ follows a homogeneous PPP with constant intensity $\lambda$. The number of D2D pairs $N$ in $\Omega_g$ is Poisson with mean $\lambda*\Omega_R$

$$P\{N = n\} = e^{-\lambda*\Omega_R} \frac{(\lambda*\Omega_R)^n}{n!} \quad (1)$$

To simplify the optimization problem, there are hypothesizes.

Each D2D pair assigns equal transmission power $P_D$ on each sub-channel.

The co-channel interference from neighboring macrocells is ignored.

The chosen target SINR $\gamma$ at D_Rx is assumed to be fixed for all links in the network.

MUEs are assumed to be uniformly distributed inside macrocell. The D2D pairs are randomly distributed as a Poisson Point Process (PPP) with intensity $\lambda$ in a macrocell of radius $R$ [23].

B. Channel Model

Both theoretical and measurement-based propagation models indicate that average received signal power decreases logarithmically with distance. The average large-scale path loss for an arbitrary T–R separation is expressed as a function of distance by using a path loss exponent $\eta$

$$PL(dB) = 10log_10 \frac{r^{-\eta}}{\gamma} \quad (2)$$

Figure 1. System model of D2D communications with in a macro cell area
In this paper, channel propagation model is represented as a combination of Rayleigh fading and log-normal shadowing. When the $k$-th and $i$-th D2D pairs are allocated to the same sub-channel, the received power is exponentially distributed, due to Rayleigh fading, with pdf

$$f_i(a_i) = \frac{1}{p_i} e^{-\frac{a_i}{p_i}}$$  \hspace{1cm} (3)$$

where $p_i = P_{ir}$, $p_i$ is the transmission power of D2D and $l_i$ is the link attenuation.

Damping of cellular UL interferes, distributed as log-normal variables whose pdf is given by

$$f_i(l) = \frac{1}{\sqrt{2\pi\sigma_l l}} \exp\left[-\frac{(\ln l - \ln(\sigma_l^{-1}))^2}{2\sigma_l^2}\right], \ x_i = \ln l_i - \ln(\sigma_i^{-1})$$  \hspace{1cm} (4)$$

$r_i$ is the distance between $D_{Rx_0}$ and $D_{Tx_0}$, the pdf of $r_i$ is shown as

$$f_{r_i}(r) = \begin{cases} \frac{2r}{R^2}, & r \leq R \\ 0, & r > R \end{cases}$$  \hspace{1cm} (5)$$

The same happens for the pdf of received power by $D_{Rx_0}$ from $D_{Tx_0}$ and link damping from D2D transmitter $D_{Tx_0}$ are shown, respectively

$$f_0(a) = \frac{1}{p_0} e^{-\frac{a}{p_0}}$$  \hspace{1cm} (6)$$

$$f_{r_i}(l) = \frac{1}{\sqrt{2\pi\sigma_l l}} \exp\left[-\frac{(\ln l - \ln(\sigma_l^{-1}))^2}{2\sigma_l^2}\right], \ x_0 = \ln l_0 - \ln(D_0^{-1})$$  \hspace{1cm} (7)$$

where $p_0 = P_{Ir_0}$, $D_0$ is the distance between $D_{Rx_0}$ and $D_{Tx_0}$.

III. OPTIMUM TRANSMISSION POWER

The choice of transmission power is a compromise between network connectivity and network interference. The D2D session setup requires the measurements between network connectivity and network interference. The number of D2D pair is distributed as a passion variable, we obtain the statistics of the received interference power at D2D transmitter $D_{Tx_0}$ and $D_{Rx_0}$ shown as

$$p_i(r) = E_{\rho}[p_i] \hspace{1cm} (8)$$

According to equation (3), the pdf of interference power is exponentially distributed due to Rayleigh fading, , the expectations of $p_i$ can be evaluated as

$$p_i(r) = E_{\rho}[p_i] = \int_0^\infty da \int_0^\infty da \exp\left[-\frac{1}{p_i}[\gamma (\sum_{i=1}^{n} a_i + N_0)]\right] \prod_{i=1}^{n} f_i(a_i) = \exp(-\gamma) \prod_{i=1}^{n} 1 + \gamma p_i p_0$$  \hspace{1cm} (9)$$

where $\eta_0 = P_0/\eta_0$ is SNR of background noise only at the D2D receiver. Considering link damping $l_0$, $l_0$ and the distance $r_0$, i.e.(4),(7), we obtain the expectation of (10) as

$$p_i(r) = E_{\rho}[p_i] = \int_0^\infty f_i(l) dl \exp\left(-\frac{\gamma N_0}{P_{Ir_0}} \right) \prod_{i=1}^{n} 1 + \gamma \frac{p_i}{P_{Ir_0}}$$  \hspace{1cm} (11)$$

The number of D2D pair is distributed as a passion variable, we obtain the expectation of (11) as

$$p_i(R) = E_{\rho}[p_i(R)] = \int_0^\infty dx \frac{1}{\sigma} \phi\left(\frac{x_0}{\sigma}\right) \exp(-\xi D^* \exp(-(x_0)) \prod_{i=1}^{n} 1 \exp(-\xi D^* \exp(-(x_0)) \phi\left(\frac{x_0}{\sigma}\right) \exp(-\xi D^* \exp(-(x_0)) + 1.5 \pi R^2 I(x_0) - 1)$$  \hspace{1cm} (14)$$

where

$$I(x_0) = \int_0^\infty dx_0 \frac{1}{\sigma} \phi\left(\frac{x_0}{\sigma}\right) \exp(-\xi D^* \exp(-(x_0)) \prod_{i=1}^{n} 1 \exp(-\xi D^* \exp(-(x_0)) \phi\left(\frac{x_0}{\sigma}\right) \exp(-\xi D^* \exp(-(x_0)) + 1.5 \pi R^2 I(x_0) - 1)$$  \hspace{1cm} (13)$$

The number of D2D pair is distributed as a passion variable, we obtain the expectation of (11) as

$$p_i(R) = E_{\rho}[p_i(R)] = \int_0^\infty dx_0 \frac{1}{\sigma} \phi\left(\frac{x_0}{\sigma}\right) \exp(-\xi D^* \exp(-(x_0)) + 1.5 \pi R^2 I(x_0) - 1)$$  \hspace{1cm} (14)$$

A. Probability of Successful Transmission

A desirable model of working within LTE is the threshold model where we assume that the transmission is successful if the signal to interference power ratio is greater than some threshold.

Under the assumptions of Section II, the probability of D2D link successful setup, $p_s$, is given by the probability that SINR is greater than a given threshold $\gamma$

$$p_s = Pr\left[\frac{P_t}{P_t + N_0} > \gamma\right] = Pr\left[P_0 > \gamma(P_t + N_0)\right]$$  \hspace{1cm} (8)$$

where $P_0$ is the received power from the D2D transmitter, $P_t$ is the interference power from other D2D pairs, and $N_0$ is the power of the background noise. Let CCDF of $P_0$ be $F_0^*(a) = e^{-a/P_0}$, $p_s$ is shown as

$$p_s = F_0^*(\gamma(P_t + N_0)) = \exp\left[-\frac{(\gamma(P_t + N_0))}{P_0}\right]\hspace{1cm} (9)$$

Using the assumptions of Section II, the probability of D2D link successful setup, $p_s$, is given by the probability that SINR is greater than a given threshold $\gamma$
Thus, we have \( \overline{p}_r = \lim_{R \to \infty} p_r(R) \). Using expectations, this may be evaluated as
\[
\overline{p}_r = \lim_{R \to \infty} p_r(R) = \int_{-\infty}^{\infty} dx_0 \int_{-\infty}^{\infty} \frac{1}{\sigma} \phi(x_0) \exp\left[-\frac{x_0^2}{2}\right] \times \exp\left[-\xi D^2 \exp(-x_0) + \lim_{a \to \infty} \lambda \pi R^2 \left[I(x_1) - 1\right] \right]
\]
\[
\lim_{a \to \infty} \lambda \pi R^2 \left[I(x_1) - 1\right]
\]
where \( \lambda \pi R^2 \left[I(x_1) - 1\right] \) is such a measure, because of the absolute convergence of integrals. By using (15) and the following relationship
\[
\int_{-\infty}^{\infty} 2\pi \sin \left(\frac{2\pi x}{\eta}\right) = \frac{4\pi}{\beta} \sin \left(\frac{2\pi}{\eta}\right)
\]
the success probability of D2D link is shown as
\[
p_r = \int_{-\infty}^{\infty} \frac{1}{\sigma} \phi(x_0) dx_0 \exp\left[-\xi D^2 \exp(-x_0) - S(x_0)\right]
\]
where \( S(x_0) = \lambda \pi D^2 \gamma \exp\left(\frac{2\gamma^2}{\eta^2} \frac{2x_0}{\eta^2} \frac{2\pi}{\eta}\right) \).

Notice that the success probability of D2D link is independent of the noise level \( N_0 \). We consider the constant standard deviation \( \sigma = 6dB \) and \( \gamma = 6.6dB \). Fig. 2 illustrates the parameter \( \xi \) expressed in (12) versus probability of successful transmission with different D2D distance \( D \). For different distance, the probability of successful transmission is increase with a decrease both in \( D \) and parameter \( \xi \). For example, there is a short D2D distance, i.e., \( D=10m \), the success probability will be larger than 0.8 when \( \xi \leq 80dB \). The success probability will decrease as D2D distance increase, when \( D \) increase to 100m, the success probability of D2D communication will not be tolerated.

B. Expected Transmission Scale Function \( Z \)

We are now ready to apply the above statistics of the D2D success probability to the determination of the optimum transmission power in cellular network.

In wireless network, the probability of successful transmission increases as the transmission power increases. However, in choosing a great transmission power, the mutual interference artificially increases in D2D networks. Therefore, a great power causes the probability of successful transmission and the sum rate of network decrease in turn. The expected transmission scale function \( Z \) is such a measure, \( Z \) is shown as
\[
Z = \frac{p_r}{\overline{p}_r}
\]

In order to present function \( Z \) as a dimensionless quantity, let \( p_r = \frac{\gamma N_0}{\xi} \), we present
\[
Z = \frac{\xi}{\gamma N_0} p_r
\]
where $p_\gamma$ depends on (17). We normalize the expected transmission scale $Z$, Fig. 3 shows $\xi$ versus normalized expected transmission scale $Z$. Normalized scale $Z$ increases to the maximum as $\xi$ increases. The location of maximum point increase as $D$ decrease, that is, along with D2D communication distance is increasing as the optimum transmission power increases. So an optimization problem of D2D transmission power can be formulated as

$$\max_{\xi} \frac{\xi}{\gamma N_0} p_\gamma$$  \hspace{1cm} (20)

C. Transmission Power Optimization

In order to find the optimum value through maximizing scale function $Z$, we can optimize (19) over the parameter $\xi$. Setting the partial derivative with respect to $\xi$ to zero yields the following equation

$$\frac{\partial Z}{\partial \xi} = \frac{1}{\gamma N_0} \left( p_\gamma + \xi \frac{\partial p_\gamma}{\partial \xi} \right) = 0$$  \hspace{1cm} (21)

Recalling (17), (21) becomes

$$\int -\frac{1}{\sigma} \phi \left( \frac{x_0}{\sigma} \right) dx_0 \exp \left[ -\xi D^* \exp(-x_0) - S(x_0) \right] \times \left[ 1 - \xi D^* \exp(-x_0) \right] = 0$$  \hspace{1cm} (22)

A numerical solution of (22) allows us to get the optimum value $\xi_0$, and to determine $p_{\gamma 0}$ from (12) as

$$p_{\gamma 0} = \frac{\gamma N_0}{\xi_0}$$  \hspace{1cm} (23)

IV. NUMERICAL RESULTS

We consider a single cell where $k$ D2D pairs share the available resources. In this section, we propose the numerical simulations to evaluate the performance of the power control method presented in Section III.

We optimize the transmit power of D2D transmitter through maximizing the expected transmission scale $Z$. We use equation (17), (18) and (22) to calculate the probability of successful transmission and expected transmission scale $Z$ at D2D receiver. The important parameters are described as follows, the threshold of SINR at D2D receiver is $6.6\text{dB}$, $k$ cellular users are randomly distributed as a Poisson point process with parameter $\lambda=2$.

According to equation (22) and the above parameters, the optimal parameter $\xi_0$ can be calculated for different standard derivation $\sigma$ and different distances of D2D link $D$. Fig. 4 shows the optimal parameter $\xi_0$ versus $\sigma$ for different D2D communication distance $D$. With the increasing of $D$, the optimal parameter $\xi_0$ is increasing gradually. In other words, the transmission power decreases as D2D distance increases according to (23), because the transmission power is limited by the expected scale function $Z$. When D2D distance increases, the D2D receiver is close to another D2D transmitter according to the Poisson distributed of location of D2D pairs in the single cell, it means D2D receiver will obtain more interference from another D2D transmitter. In the same way, the optimal parameter $\xi_0$ increases with deterioration of channel conditions since $\sigma$ increasing.

The optimal probability of successful transmission can be obtained from the optimum parameter $\xi_0$ and other constant parameters. Standard deviation $\sigma$ versus optimal probability for different distance $D$ is illustrated.

From Fig. 5, the optimal value of $p_{\gamma 0}$ is decreasing as $\sigma$ increases, even though, for proximity in D2D communications, it shows a slightly increasing behavior in low standard deviation, far above the fixed power. The behavior of probability increases as $\sigma$ increases in low standard deviation, especially in short distance of D2D communication. We have two factors affecting the success probability. On one hand, since $\sigma$ in proportion to $\xi_0$, the larger $\sigma$ is, the lower success probability is for which present in Fig. 2. One the other hand, the larger $\sigma$ is, the weaker the interference at D2D receiver is for which analyzed in Fig. 4. As $\sigma$ increases, both two competing factors start to act simultaneously. The probability of successful transmission improved comparing with the fixed transmission power due to the optimal scheme is significant, especially for great channel conditions (i.e. small $\sigma$). As $\sigma$ increases, the received power decreases gradually, the power has been drowned in noise, resulting in closing to the fixed transmission power case. To sum up, our proposed scheme can obtain the greater probability of successful transmission than fixed power scheme when $\sigma \leq 10\text{dB}$ and it also obtains the same performance in poor channel condition.
V. Conclusion

In this paper, an optimization algorithm for D2D transmission power is proposed in the scenario where several D2D pairs reuse the same resources. This algorithm consists of three phases: 1) the statistics of the received interference power at D2D receiver is derived; 2) an expected transmission scale function $Z$ is proposed as a measure; 3) the optimum transmission power is calculated through maximizing function $Z$. Simulation results demonstrated that our strategy achieves better success probability performance as compared to the fixed transmit power strategy versus different D2D distance.

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