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Outage protection for cellular-mode users in device-to-device communications through stochastic optimization

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ABSTRACT

In device-to-device (D2D) communications, the stochastic nature of the wireless channel causes the coexistence problem between cellular-mode and D2D-mode users a nontrivial task, especially when protection of cellular-mode users is strictly required. While related work has investigated the interference management problem in different scenarios, most approaches have considered only the long-term channel gain without explicitly addressing the randomness of the channel. In this paper, we aim to investigate the problem of D2D-mode users sharing the same radio resource blocks with the cellular-mode user under Rayleigh channel fading through stochastic optimization. Our objective is to determine the transmission powers of all D2D-mode users for optimizing their sum data rates while ensuring the outage probability of data sent by the cellular-mode user to stay below the desired protection threshold. We first introduce a new technique to transform both the objective and constraint functions involving random variables into equivalent yet deterministic forms. Since the formulated problem is non-linear and non-convex, we further tighten the upper bound of the transmission power constraint to reduce the complexity and uncertainty of searching for the optimal solution. To solve the formulated problem, we propose two different algorithms: the first algorithm reformulates and solves the problem as a linear programming (LP) problem while the second algorithm directly solves the non-linear problem based on the meta-heuristic of differential evolution (DE). Simulation results demonstrate that using the proposed algorithms the outage probability of the cellular-mode user can be maintained below the desired threshold despite the uncertainty of channel conditions, while the sum rate of D2D-mode users outperforms baseline methods under the same constraint.

1. Introduction

The tremendous increasing of mobile application data has severely exacerbated the scarcity of the wireless spectrum in addition to the huge number of users. In fact, the problem has been foreseen a decade ago when opportunistic communication drew lot of attention. A typical approach is the cognitive radio network (CRN) when an opportunistic or secondary user occupies a vacant spectrum hole which belongs to a licensed or primary user. Towards the next-generation wireless network (5G), device-to-device (D2D) communication has been proposed in LTE-advanced as an underlay to the cellular network that allows two LTE-capable devices in close proximity to communicate directly without going through the base station. Similar to CRN, D2D communication utilizes the spectrum resource allocated to the cellular-mode user. This direct communication enables the reuse of spectrum efficiently with higher throughput and lower latency [1,2]. With the increasing of proximity-based services [3] and social network applications [4], D2D communication has a great potential for providing reliable proximity-based services.

Although D2D communication has many advantages such as the spectrum efficiency or better network coverage, it also raises technical issues including the protection of cellular user who has higher priority to transmit. Indeed, operating on the same licensed spectrum band of the cellular network, users operating in the D2D mode (D2D users) could potentially cause intolerable interference to the cellular-mode user (CU) [5,6]. To resolve such a problem, the eNodeB can play a role as an allocator to assign resource blocks (RBs) to both CU and D2D users such that all RBs are used efficiently with minimum collision [7]. The optimization problem on the sharing of the precious spectrum can be further formulated as seen in [8–10]. Another approach relying on the regulation

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of transmission power to limit the potential interference caused by D2D signal to the cellular communication also exists in the literature [11,12]. Nevertheless, the protection problem has more challenges if we take the stochastic nature of channel which causes the received signal uncertainty into consideration. In the LTE-A, the CU feedbacks the channel state information (CSI) to the eNodeB as a manner to estimate the channel condition. Many works assume that the eNodeB has the full instantaneous CSI when scheduling resource blocks and power transmission [13–16]. In fact, full instantaneous CSI may become an intolerable overhead to D2D communication and the overall network. Even if the full CSI is supplied, such information may be imperfect due to the channel estimation error [17]. Additionally, the fast changing of channel may cause CSI to be outdated [18], resulting in difficulty to obtain the accurate solution. The target of this paper, therefore, is to solve the interference management problem in D2D communication when taking the Rayleigh fading into consideration. We are interested in taking into account the channel knowledge uncertainty while protecting the signal transmitted from a CU to the eNodeB. We realize that the stochastic nature of wireless transmissions and random noise further complicates the problem of interference management. To overcome such challenge, we apply the stochastic programming technique, in particular chance constraint programming, to ensure that the outage probability of signal-to-noise-and-interference (SINR) ratio at the eNodeB is guaranteed to stay below the predefined tolerance while still maximizing the transmission rate of D2D users.

In this paper, we investigate the scenario where D2D users are allowed to reuse the spectrum resources assigned to the CU and we focus on the power control of D2D transmitters to protect the QoS of the CU transmission. Towards this goal, the stochastic nature of the wireless channel modeled by Rayleigh fading is taken into account such that random variables appear in both objective and constraint functions. Our objective thus is to maximize the expected sum data rates of D2D users while ensuring the outage probability of the cellular link to stay below the desired protection threshold. The problem appears in a highly intractable chance-constrained model and to solve it, we propose a technique to transform both the objective and constraint functions involving random variables into *equivalent yet deterministic forms*. Firstly, the transformation of the constraint function is based on the derivation of the probability density function (PDF) of a complex random variable representing aggregate interference measured at the cellular link. Secondly, the closed-form of the objective function is obtained when we successfully derive the PDF of a random variable which is a combination of two random variables denoting the Rayleigh channel gain. The proposed transformation technique hence paves the way towards solving the chance-constrained problem.

While the proposed transformation technique removes random variables in both objective and constraint functions, the problem, however, turns into non-linear and non-convex optimization. To resolve such challenge, we propose a two-step solution. In the first step, we tighten the upper bound of the transmission power based on the probabilistic constraint function. The search space therefore is limited to within a much smaller range, thus leading to a significant improvement in facilitating faster convergence speed and better convergence quality for solving the non-linear problem. In the second step, we introduce two algorithms to solve the transformed chance-constrained problem. The first algorithm is based on the linearization technique when we relax and separate the constraint function into simpler functions. The second algorithm is based on the meta-heuristic differential evolution (DE). Specially, we extend the original DE designed for unconstrained optimization to yield feasible solutions. To verify the proposed transformation technique and algorithms, we perform extensive simulation. In the performance section, we show that the proposed technique to tighten the search space does significantly help the convergence of both algorithms. Moreover, these two algorithms outperform baseline methods in terms of getting higher transmission rates for D2D users while keeping the outage probability of the CU-BS link below the desired threshold.

To the best of our knowledge, this research is the first one to investigate the impact of channel fading on both transmission rates of D2D users and outage probability of the CU-BS link. Our contribution comprises of explicitly addressing the impact of channel fading into the interference management between D2D and CU, and a set of techniques for effectively and systematically solving the proposed chance-constrained formulation. The problem involving random variables can also be applied to scenarios where it is difficult or taxing to obtain precise channel information among D2D users.

The rest of the paper is organized as follows. Section 2 presents related work in this field. Section 3 presents the target network scenario, where we also formulate the chance-constrained optimization problem with consideration of Rayleigh fading and its transformation. Section 4 shows how we tighten the upper bound and presents two algorithms based on linearization and DE. Evaluation results are shown in Section 5 before we conclude in Section 6.

2. Related work

The impact of fading phenomenon in wireless environment has been studied extensively in literature. A popular approach that has been brought to D2D communication is to replace the time-varying channel gain by its expected value. The authors in [19] introduce a dynamic power control algorithm to mitigate the mutual interference between D2D and cellular users by using the expected value of the received interference. To tackle the randomness of channel gain, research work in [14] considers the worst-case or bounds of the random variable. A more popular approach based on sampling technique like Monte Carlo [20] or recently the analytical Bernstein approximation [21] to address the problem of fading channels can also be found in literature. We discuss in the following advantages as well as drawbacks of these methods.

Early work that considers power control for time-varying signals often replaces the channel gain by its expected value. In a work by Kandukuri and Boyd [22], authors consider optimal power control for fading wireless channels. A metric of the certainty-equivalent margin (CEM) that is derived by ignoring all statistical variation of both signal and noise power by replacing these random variables with their expected values is proposed. Since the CEM can be used to derive the upper and lower bound of the outage probability, the authors investigate and solve the optimization problem to maximize the CEM. As a result, the method can avoid to directly minimizing the outage probability which contain random variables. Such approach is reasonable when channel variability is slower than adaptability of system control. As we present later in Section 5, the replacement of random variable by its expectation has drawback in terms of poor performance for the target environment.

Another solution addressing the time-varying signal problem uses the worst-case analysis which is quite useful if the extreme value of the random variable is relatively easy to obtain. The authors in [14] introduce an algorithm to control interference-limited area with the goal to enhance the overall capacity of cellular networks. They investigate the ergodic capacity of the D2D system through derivation of the lower bound of the received SINR that only result in the minimum achievable D2D capacity for the worst-case of the proposed control scheme. In [23], a