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Coverage and capacity analysis of relay-based device-to-device communications underlaid cellular networks

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ABSTRACT

Coverage and capacity are the key parameters of 4G and beyond wireless networks. These parameters of Long Term Evolution Advanced (LTE-A) networks can be greatly enhanced by enabling device-to-device (D2D) communication. In this paper, full duplex amplify and forward (FDAF) relay nodes (RNs) have been introduced to assisting cellular and D2D communications. The coverage probability (CP) and transmission capacity (TC) for both the cellular and D2D communications have been analyzed with FDAF relay based network. The D2D users can communicate directly or via relaying with FDAF RNs. Cellular users, D2D users and RNs in the network have been modeled using homogeneous spatial poisson point process (SPPP). The closed-form expressions of CP and TC for cellular as well as D2D communications have been derived by using stochastic geometry. The pairing of D2D users is decided by the shortest distance reduced path loss and formed pair either directly or via RN assistance. The approximate complementary cumulative distribution function (CCDF) of the signal to interference plus noise ratio (SINR) for both the cellular users and the D2D users have been derived. The closed form expressions of CP and TC show that coverage and capacity of both the cellular and D2D communications are influenced by various parameters such as D2D user density, relay node density and the distance of D2D pair. Results show the improvement of CP and TC for cellular and D2D communications with the help of RNs.

1. Introduction

Communication through wireless networks becomes essential in our daily lives. The coverage and transmission capacity of existing and next-generation cellular networks should be enhanced on a priority basis. The concept of D2D communication is to allow the user equipment (UE) to communicate directly without transferring the data through a base station (BS) or infrastructure [1]. D2D communication plays a crucial role to enhance the coverage and transmission capacity of cellular and D2D communications [2–7]. In D2D enabled cellular networks, the cellular, and D2D users can share the spectrum resources in two ways: *inband* where D2D communication utilizes cellular (i.e. licensed) spectrum and *outband* where D2D communication utilizes unlicensed spectrum [8]. Inband D2D can be further categorized into two categories: *underlay* where D2D users share the same frequency resources used by cellular users and *overlay* where both cellular and D2D communications use orthogonal spectrum resources. In both underlay and overlay schemes, D2D users enjoy much higher data rate than regular cellular users [9], however, underlay is more popular than overlay scheme due to the frequency of cellular users reused by the D2D users that improve the spectral efficiency of the cellular network [10]. The number of cellular users has risen exponentially in recent days. One of the big challenges is to accommodate all users within the limited available spectrum. Another challenge is the requirement of huge bandwidth for their excessive data rate applications such as online gaming, video sharing etc. [11].

The coverage of the wireless network is a key parameter and has been studied widely [12,8]. The coverage probability of cellular users and their gain with retention probability are analyzed by using homogeneous marked poisson point process (MPPP) [4,13]. The coverage performance for cellular networks with highly dense underlay D2D communication has been dealt [6]. The distribution of D2D users is modeled as a homogeneous spatial poisson point process (SPPP) and evaluated coverage probabilities analytically and numerically for both D2D user and cellular user. The performance analysis of D2D communication underlaying cellular networks has been discussed in [12]. The authors in [14], have analyzed the coverage probability for full duplex relay based D2D communication network. The performance of D2D communication in the cellular network has been studied by varying load [15].

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The transmission capacity is another key parameter of the wireless network and studied widely [16–20]. In [21], the D2D transmission capacity has been studied where D2D multiplexing of orthogonal and non-orthogonal resource sharing modes are used and also studied D2D system interference in LTE cellular networks. By enabling direct path links (DPLs) between UEs for local communication has significantly enhanced the capacity of the cellular network [2]. The system throughput result by Monte Carlo simulation technique enables DPLs. The authors in [22], have proposed a new topology that is a less expensive which employs mobile UE node as a virtual infrastructure that works as a relay to enhance cellular capacity and also improve network coverage.

Stochastic geometry is used to study the random phenomena on the 2D-plane. The system has been modeled using stochastic geometry [23] that concerns random collections of points, referred to as point processes. According to the previous studies done by researchers, either coverage or capacity was analyzed for D2D enabled cellular communication. In this paper, the cellular users, D2D users, and relay nodes are modeled as a homogeneous spatial poisson point process (SPPP) [24] and derived the closed-form expressions of the coverage probability and transmission capacity both for cellular and D2D communications.

In this paper, FDAF relays have been used in D2D enabled cellular communication to enhance the coverage probability and the transmission capacity of the network. Relays can receive and retransmit the signals between source and destination and can be used to increase the coverage of cellular networks. A relay-based cooperative communication system is shown in Fig. 1. The FDAF relay provides less delay, amplifies signal power and increases the spectral efficiency. The performance parameters of the system are derived in a tractable manner as a function of SINR threshold, link distance, user density and the cell radius. The main contributions in this paper are summarized as follows:

- The FDAF relays assist the cellular communication and D2D communication both, therefore it improves the coverage probability and transmission capacity of the networks.
- The closed form expressions of CP and TC as a function of D2D user density λ_d and SIR threshold γ_{th} are derived and analyzed.
- The impact of D2D user density λ_d, RN density λ_{rn} and D2D link distance on CP and TC are also analyzed.

The remainder of this paper is organized as follows: following the introduction, the system model with relay based D2D enabled cellular network description has been presented in Section 2. Section 3 covers the analysis of relay based D2D communications key parameters such as coverage probability and transmission capacity for cellular and D2D communications. The effect of D2D density and relay node density on these parameters are also discussed. Numerical explanations and simulated results with description are presented in Section 4 followed by the conclusion of the overall paper in Section 5.

Notation: The following notations are used in this paper. The notations $f_X(\cdot), F_X(\cdot)$, and $\mathcal{L}_X(\cdot)$ are used to denote the probability density function (PDF), the cumulative distribution function (CDF), and the Laplace transform (LT), respectively for the random variable X. $\mathbb{P}(\cdot)$ denotes the probability. $\mathbb{E}(\cdot)$ denotes the expectation over all random variable in $(\cdot)$ and $\mathbb{E}_X(\cdot)$ denotes the expectation over random variable X.

2. System model and scenario description

In this section, the system model and scenario description are provided. A single cellular system assisted by FDAF relays enabled with D2D communication is considered as shown in Fig. 2. It comprised of a base station located at the center, two cellular users (CeU) communicate directly, one CeU assisted by FDAF relay, two direct D2D users (DUs) pair and two DUs pair with the assistance of FDAF relay. The uplink resource of cellular users is shared by potential D2D users. In this scenario, cellular users are communicating directly with a base station in cellular mode and D2D users communicate through a direct link or by the assistance of relays in D2D mode. The D2D users are distributed as spatial poisson point process (SPPP) with density λ_d in the finite two-dimensional plane $\Re^2$. The channel model includes path loss and Rayleigh fading distributed exponentially with unity mean. The networks operate in time division duplex (TDD) mode. LTE-A uses Orthogonal Frequency Division Multiplexing (OFDM) technique and whole cellular uplink resource is divided into K-frequency flat sub-channels. These all sub-channels are used by cellular users as well as D2D users in the networks. To analyze scenario analytically, following assumptions are made based on the theory of stochastic geometry for wireless networks.

Assumption 1. The cellular transmission power is denoted as P_c. The distribution of cellular users is as SPPP in the finite two-dimensional plane $\Re^2$ denoted as Φ_c with density λ_c.

Assumption 2. The D2D transmission power is denoted as P_d. Again the distribution of D2D users is as SPPP in the finite two-dimensional plane $\Re^2$ denoted as Φ_d with density λ_d.

Assumption 3. FDAF relay node transmission power is denoted as P_{rn}. If the distance between RN and either the D2D transmitter or receiver are shorter than cell radius (R) then D2D communication occurs via RN. In case of more than one RN available, the D2D pair randomly chooses anyone to forward the signals. The distribution of RNs is as SPPP in the finite two-dimensional plane $\Re^2$ denoted as Φ_{rn} with density λ_{rn}.

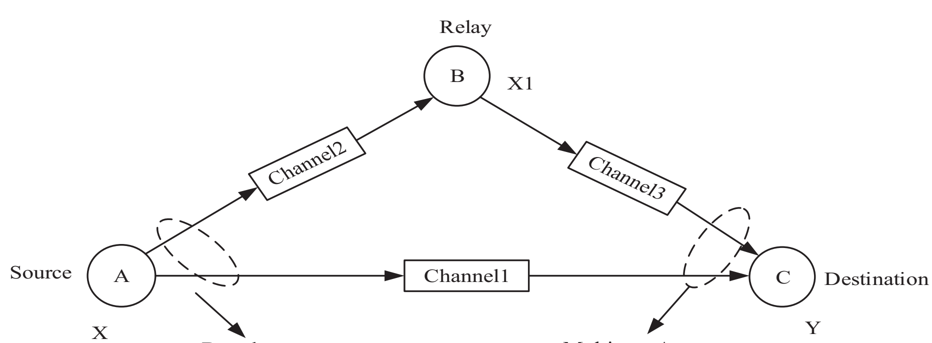

Fig. 1. Relay based cooperative communication system.

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