Journal of Network and Computer Applications 46 (2014) 305–314

Contents lists available at ScienceDirect

Journal of Network and Computer Applications

journal homepage: www.elsevier.com/locate/jnca

Performance analysis and enhancement for a cooperative wireless diversity network with spatially random mobile helpers

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ARTICLE INFO

Article history:
Received 14 January 2014
Received in revised form
5 May 2014
Accepted 12 July 2014
Available online 23 July 2014

Keywords:
Cooperative communications
Wireless diversity
Multiple helpers
Relay selection
Stochastic geometry
Mobility

ABSTRACT

In many studies on wireless cooperative diversity, it is often assumed that the number of helpers and their locations are deterministic or known *a priori*. In this paper, we relax such assumptions and investigate a wireless diversity system with distributed cooperation and spatially random helpers subject to random direction (RD) mobility. To enable opportunistic relaying with multiple helpers, we consider an ALOHA-like medium access control (MAC) scheme and a timer-based random backoff scheme for multi-helper coordination. Particularly, we analyze the upper bound of combined signal-to-noise ratio (SNR) and unconditional success probability with multi-helper cooperation. We also provide numerical approximations for the delay of the two MAC schemes. To characterize the tradeoff between the success probability and delay, we further define a success/delay ratio, which can be maximized by adapting the intensity of selected helpers. The numerical and simulation results validated the analysis accuracy and demonstrated insightful observations.

1. Introduction

Due to the unique features such as path loss and fading, wireless links support a much less bandwidth than wired links. Although the multiple-input and multiple-output (MIMO) technology can exploit spatial diversity to improve wireless channel capacity, it is not feasible to integrate multiple antennas in palm-sized mobile terminals due to the constraints on size, weight and battery. In recent years, there was extensive research on cooperative communications (Sendonaris et al., 2003a,b), which enable cooperation among mobile terminals to form virtual antennas and achieve spatial diversity via cooperation. Specifically, the cooperating helper nodes can relay the overheard signal from the source by various schemes, such as amplify-and-forward (AF) and decode-and-forward (DF). A variety of cooperative communication techniques were studied for wireless sensor networks (Tarng et al., 2009), wireless local area networks (Kumar and Nagarajan, 2013), and wireless ad hoc networks (Al-Sultan et al., 2014).

Generally speaking, the cooperation among wireless nodes, which brings spatial diversity gain, can be performed in a centralized or distributed manner. In centralized cooperation, the source gathers the knowledge about the helpers and selects the best helper(s) for cooperation. The analysis of the diversity gain often needs certain *a priori* deterministic knowledge of the network, such as the number of helpers, and their locations and characteristics of received signal strength (Avestimehr and Tse, 2007; Beaulieu and Hu, 2006; Nechiporenko et al., 2009). The collection of such knowledge is reasonable when the network topology is static. It becomes challenging, however, with a varying topology, e.g., when the nodes are moving and their locations are changing. In such circumstances, the received signal strength of helpers (e.g., the expectation of the received signal-to-noise ratio) presents dynamic variations which are related to the locations of helpers. Hence, the collected network knowledge can be out-of-date quickly with fast movements (Ju et al., 2013). As a result, the selected relay may not be the best due to lack of accurate network information, which undermines the achievable cooperation gain at the physical layer and/or the media access control (MAC) layer. On the other hand, a distributed approach requires minimum *a priori* knowledge of the helpers and thus is robust to network variations. Nonetheless, it is more complex to analyze the diversity gain of a distributed approach, especially in the case of multiple helpers where the spatial diversity gain of cooperation can be potentially high. From the physical-layer point of view, the more helpers, the higher the diversity gain. Meanwhile, more coordination delay may also be involved at the MAC layer. Hence, it is important to balance the tradeoff between the physical-layer diversity gain and MAC-layer delay.

Based on the above observations, this paper aims to address the following key questions:

- When the helpers are moving, the fading characteristics of the received signal strength are not static but varying with the

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http://dx.doi.org/10.1016/j.jnca.2014.07.012
1084-8045/

node locations. In such a case, how can we analyze the diversity gain?

- Considering node mobility, the spatial distribution of potential helpers is random depending on the overheard signal quality. In particular, the number of potential helpers becomes a random variable. How can the spatially random distribution of helpers impact on the diversity gain?
- Intuitively, there is a tradeoff between the physical-layer diversity gain and MAC-layer delay when multiple helpers are available. Nonetheless, the exact scaling relationship depends on the spatial distribution of helpers. How can we mathematically quantify the tradeoff and obtain an optimal balance point in this tradeoff relationship?

To answer the above questions, we focus on a wireless diversity system with multiple helpers based on a distributed cooperation strategy. Each node independently decides to cooperate as a helper or not based on its local estimates of signal-to-noise ratio (SNR) between the source, the destination, and itself. As such, each node does not need to acquire a global knowledge of other helper candidates and their channel characteristics. Moreover, the potential helpers are assumed subject to random direction (RD) mobility (Nain et al., 2005). As a result, the spatial distribution of helpers becomes random. Hence, we apply stochastic geometry (Stoyan et al., 1995; Haenggi et al., 2009) to model the random locations of potential helper nodes and analyze the aggregate cooperative performance with multiple helpers. The key contributions of this paper are several-fold:

- Assume that all the nodes, except the source and the destination, are distributed as a Poisson point process (PPP). Considering the spatial random locations, we analyze the helper set with $p(x)$-*thinning* (Stoyan et al., 1995) and derive the exact form and approximation forms of the probability distribution of the upper bound of the total combined SNR.
- Based on the SNR upper bound, we further obtain the unconditional success probability of the multi-helper cooperation strategy. This is the probability that the received SNR is above a given threshold and it is also the complement of the outage probability. The success probability is proved to be approximately linear with the number of helpers and the helper intensity under certain conditions.
- To evaluate the tradeoff between the success probability and delay, we consider two medium access control (MAC) schemes to coordinate multiple helpers, i.e., an ALOHA-like scheme and a timer-based random backoff scheme. It is shown that the delay of the ALOHA scheme increases exponentially with the number of helpers, whereas the delay of the timer-based scheme increases more slowly. To characterize the tradeoff, we further define a success/delay ratio, which can be maximized by adapting the intensity measure of selected helpers.

The remainder of this paper is organized as follows. In Section 2, we introduce the related work. The system model under study is defined in Section 3. In Section 4, we present our analysis for the unconditional success probability, delay, outage-delay tradeoff and success/delay ratio. The numerical and simulation results in Section 5 validate the analysis accuracy and demonstrate the performance tradeoff. In Section 6, we conclude the paper and highlight some future research directions to extend this work.

2. Related work

Cooperative wireless networks at the physical layer have been widely studied in the literature. The basic AF and DF relaying schemes were proposed and analyzed in Laneman et al. (2004), where maximum ratio combining (MRC) was considered at the destination node to obtain the total SNR. As the proposed form for the total SNR is very complicated, it is more tractable and feasible to apply an upper bound and lower bound in practice. A lower bound for the total SNR was proposed in Anghel and Kaveh (2004), while an upper bound can be found in Anghel and Kaveh (2004) and Ikki and Ahmed (2007). Based on the total SNR expression, the conditional outage performance can be analyzed accordingly. In Avestimehr and Tse (2007), the outage performance of cooperative relaying was evaluated for a Rayleigh fading and half-duplex channel in the low SNR regime. In Beaulieu and Hu (2006) and Suraweera et al. (2006), a closed-form conditional outage probability of DF was derived for a Rayleigh fading and Nakagami-m fading channel, respectively. In Nechiporenko et al. (2009), the probability density function (PDF) of the total SNR upper bound was proposed under both an *i.i.d* and non-*i.i.d* condition. The outage probability for each case was also derived correspondingly. However, the outage analysis in Nechiporenko et al. (2009) is still conditional and further improved in Ikki and Ahmed (2009) and Amarasuriya et al. (2010). The work in Ikki and Ahmed (2009) considered that N strongest helpers are selected out of M candidates, although how to select them was not discussed. In Amarasuriya et al. (2010), a dynamic scheme of selecting multiple helpers was proposed.

Cooperation at the MAC layer needs to address two important questions: (1) when to cooperate and (2) whom to cooperate with Zhuang and Ismail (2012) and Zhuang and Zhou (2013). If a single entity (e.g., the source) answers both questions, it is centralized cooperative MAC, such as Yang et al. (2012). Yang et al. (2012) propose a relay assignment scheme at the source and also consider helper incentive. A global optimal policy is designed to associate each source with a best relay so that the overall system capacity is maximized. On the other hand, a distributed cooperative MAC solution usually has the helper entities answer both questions in a decentralized fashion, e.g., Shan et al. (2011). The timer-based selection scheme proposed in Shan et al. (2011) is based on the assumption that a helper with a shorter channel access time is preferable. Thus, the first responding helper is supposed to be the optimal helper. As such, no information broadcast is necessary for the helpers to obtain knowledge of other competitors, which alleviates the network from broadcast traffic. Even though Yang et al. (2012) and Shan et al. (2011) are good cooperative MAC solutions, both focus on a static topology and single best helper assumption.

In the meantime, there has been little work in the literature that considers the tradeoff between the physical layer and the MAC layer for cooperative communications. The cross-layer solution in Shan et al. (2011) did not address this tradeoff but only exploit the physical-layer parameters as criteria for helper selection at the MAC layer. The general tradeoff between power consumption at the physical layer and delay at the MAC layer is explored in Zhang and Tang (2013) and Choi (2013), but they are not for the cooperative communication scenario. In this paper, we aim to analytically quantify the tradeoff between the physical-layer outage probability and the MAC-layer delay with cooperation among spatially random moving helpers.

Many existing studies on the cooperative diversity performance did not explicitly address the effect of the spatial distribution of helpers. The theory of stochastic geometry (Stoyan et al., 1995) provides a powerful approach to model the locations of spatially random helpers. It has been increasingly widely used for wireless network analysis. In Haenggi et al. (2009), the methodologies of stochastic geometry were extensively reviewed in the context of wireless networks. In Gong and Haenggi (2014), different mobility models, such as the random waypoint model, were defined in