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Throughput analysis of cognitive wireless networks with Poisson distributed nodes based on location information ☆

Pedro H.J. Nardelli [a,*], Carlos H.M. de Lima [b], Hirley Alves [a], Paulo Cardieri [c], Matti Latva-aho [a]

[a] Center for Wireless Communications (CWC), University of Oulu, Finland
[b] São Paulo State University, Campus São João da Boa Vista, Brazil
[c] Wireless Technology Laboratory (WissTek), State University of Campinas, Brazil

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ABSTRACT

This paper provides a statistical characterization of the individual achievable rates in bits/s/Hz and the spatial throughput of bipolar Poisson wireless networks in bits/s/Hz/m^2. We assume that all cognitive transmitters know the distance to their receiver's closest interferers and use this side-information to autonomously tune their coding rates to avoid outage events for each spatial realization. Considering that the closest interferer approximates the aggregate interference of all transmitters treated as noise, we derive closed-form expressions for the probability density function of the achievable rates under two decoding rules: treating interference as noise, and jointly detecting the strongest interfering signals treating the others as noise. Based on these rules and the bipolar model, we approximate the expected maximum spatial throughput, showing the best performance of the latter decoding rule. These results are also compared to the reference scenario where the transmitters do not have cognitive ability, coding their messages at predetermined rates that are chosen to optimize the expected spatial throughput – regardless of particular realizations – which yields outages. We prove that, when the same decoding rule and network density are considered, the cognitive spatial throughput always outperforms the other option.

1. Introduction

In the last few years, the demands for more efficient, reliable wireless systems induced network designers to think about alternative ways to supplement centralized cellular models. One interesting idea is to build a multi-tier network where macro-base-stations coexist with a great number of smaller cells, which in their turn operate in a more distributed fashion (e.g. the concept of femto-cell networks [1]). Departing from the centralized approach whose capacity are fairly well characterized by Shannon theory, the limits of distributed systems that work in interference-limited regimes are unknown except for few specific cases, as discussed in [2]. In the following, we will discuss the main results on interference networks and how the concept of cognitive radio introduced in [3] is important in this context.

1.1. Capacity of interference networks

In 1978 Carleial formally stated the interference channel problem using arguments from information theory [4]. Since then, several results have been proposed for the interference channel as discussed in [5, Ch. 6]. Although these works shed light on the problem, even the capacity region of the simplest two-source-two-destination setting is still an open problem. Moreover, when

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* Corresponding author.
E-mail address: nardelli@ee.oulu.fi (P.H.J. Nardelli).

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multiples sources and destinations are considered, such capacity regions become even more elusive.

Knowing such difficulties, some researchers began to investigate alternative approaches to better understand the limits of wireless networks with multiple communication pairs. Gupta and Kumar introduced in [6] the transport capacity metric to determine how many bits-meter a wireless network with uniformly distributed nodes can reliably sustain when its density grows to infinite (asymptotic analysis). After this milestone, many other papers have focused on a similar ideas, finding the transport capacity scaling laws for different scenarios and under different assumptions. The monograph [7] compiles some of such studies.

Franceschetti et al. presented another important result in [8], where they applied an unconventional method to find the physical limit of wireless networks by using laws of electrodynamics. The authors further extended this approach in [9] and determined the degrees of freedom of wireless networks based on the electromagnetic theory.

Nevertheless both Franceschetti's and Gupta's lines of research strongly rely on asymptotic behaviors when the number of nodes infinitely grows, which may give an unclear picture of the actual physical or medium access control network layers' design. Bearing this aspect in mind, Weber et al. applied in [10] a statistical approach to characterize the throughput of wireless networks and then defined the transmission capacity as the highest spatial throughput[1] achievable without exceeding a maximum link outage probability, using the density of active links as the optimization variable. An important aspect of this work is the use of stochastic geometry [13] to characterize the node spatial distribution as a Poisson point process (PPP). Thereafter different strategies used in the wireless communications have been investigated such as interference cancellation, threshold transmissions, guard zones, bandwidth partitioning amongst others; the Ref. [14] compiles these results.

In addition to them, we find in the literature other contributions using a similar approach. For example, Vaze studied in [15] the throughput-delay-reliability trade-off in multi-hop networks using the metric random access transport capacity, which is an extension of the transmission capacity for multi-hop systems [14, Section 4.2]. In [16], the authors derived closed-form expressions for the throughput optimization under packet loss and queue stability constraints. In [17] a revisited version of the transmission capacity was proposed to compare different modulation-coding schemes. The work [18] presented the transmission capacity optimization in term of the number of allowed retransmissions considering different medium access control protocols, which can be either synchronous or asynchronous. Ganti et al. generalized in [19] the transmission capacity for different fading and node distributions for the high signal-to-interference regime.

Apart from these papers that focus on the statistic quantification of the spatial throughput of wireless networks, the use of models from stochastic geometry dates back the early 80s, when Takagi and Kleinrock firstly introduced the idea of evaluating the aggregate interference power of Poisson distributed interfering nodes [20]. Thereafter, the subject has greatly developed and we can cite [21–24] as relevant tutorials on how to apply stochastic geometry when analysing wireless systems. Considering the above discussion, this approach is important when dealing with cognitive networks, where self-organizing solutions are employed in a distributed manner.

1.2. Complex systems and cognitive radio

Let us start presenting a brief description of complex systems from [25]: "A complex system consists of diverse entities that interact in a network or contact structure – a geographic space, a computer network, or a market. These entities' actions are interdependent – what one protein, ant, person, or nation does materially affects others. In navigating within a complex system, entities follow rules, by which I mean prescriptions for certain behaviors in particular circumstances".

For example, the tragedy of the commons problem described in [26] illustrates a counter-intuitive feature of many independent and rational agents sharing a common pool of limited resources. In this scenario, the agents optimize their own pay-offs in a selfish manner, i.e. find their individual global optimum, regardless of the others. Consequently, if every single agent takes the same rational decision, the shared resource will fade away after some time. This problem is very context-dependent; for example, both fishing in a lake and forest harvesting can be viewed as a tragedy of the commons class of problem, but the solution applied for each case tends to differ as the internal constraints of each system are different. For wireless networks, the authors in [16] showed that the spatial throughput optimization under packet loss and queue stability constraints can be also viewed as a tragedy of the commons problem.

Another issue related to complex systems refers to the interplay between coordination and cooperation. In game theory, the prisoners' dilemma is a good example of how coordination based on side information is important to optimize the system [27]. In this game, rational agents, which cannot communicate to each other, should choose whether to cooperate or not. If both cooperate, they get a higher pay-off than do not. However, if one cooperate and the other does not, the non-cooperative agent will obtain a higher pay-off. This fact leads to both agents not cooperating, which in turn provides lower pay-offs. One interesting work was recently proposed by Nowak [28], where the author describe different ways that cooperative behavior can emerge in evolutionary systems.

Cooperative solutions are also important when dealing with co-channel interference in wireless networks. For example, the authors in [29] employed game theory to build an algorithm to find coalitions of femto-cells that are willing to cooperate. In [30] distributed coordination mechanisms were employed to control the aggregate interference level in stand-alone femto-cell networks.

Interestingly, these examples are based on self-organizing solutions, which refers to decentralized systems that are functional even without any central controlling entity

[1] In the literature, spatial throughput can be also referred to as area spectral efficiency [11] or density of throughput [12].