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HierHybNET: Capacity scaling of ad hoc networks with cost-effective infrastructure

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ABSTRACT

In this paper, we introduce a large-scale *hierarchical hybrid network (HierHybNET)* consisting of both n wireless *ad hoc* nodes and m base stations (BSs) equipped with l multiple antennas per BS, where the communication takes place from wireless nodes to a remote central processor (RCP) through BSs in a hierarchical way. To understand a relationship between capacity and cost, we deal with a general scenario where m, l, and the backhaul link rate can scale at arbitrary rates relative to n (i.e., we introduce three scaling parameters). In order to provide a cost-effective solution for the deployment of backhaul links connecting BSs and the RCP, we first derive the minimum backhaul link rate required to achieve the same capacity scaling law as in the infinite-capacity backhaul link case. Assuming an arbitrary rate scaling of each backhaul link, a generalized achievable throughput scaling law is then analyzed. Moreover, *three-dimensional* information-theoretic operating regimes are explicitly identified according to the three scaling parameters. We also characterize an *infrastructure-limited* regime where the throughput is limited by the backhaul link rate.

1. Introduction

1.1. Related work

Gupta and Kumar's pioneering work [1] introduced and characterized the sum throughput scaling law in a large wireless *ad hoc* network. For the network having n nodes randomly distributed in a unit area, it was shown in [1] that the aggregate throughput scales as $\Theta(\sqrt{n/\log n})$.[1] This throughput scaling is achieved by the nearest-neighbor multihop (MH) routing strategy. In [3–5], MH schemes were further developed and analyzed in the network, while their average throughput per source–destination (S–D) pair scales far slower than $\Theta(1)$—the total throughput scaling was improved to $\Theta(\sqrt{n})$ by using percolation theory [3]; the effect of multipath fading channels on the throughput scaling was studied in [4]; and the tradeoff between power and delay was examined in terms of scaling laws in [5]. Together with the studies on MH, it was shown that a hierarchical cooperation (HC) strategy [6,7] achieves an almost linear throughput scaling, i.e., $\Theta(n^{1-\epsilon})$ for an arbitrarily small $\epsilon > 0$, in dense networks of unit area. As alternative approaches to achieving a linear scaling, novel techniques such as networks with node mobility [8], interference alignment [9,10], directional antennas [11–13], and infrastructure support [14] have been proposed.

Since long delay and high cost of channel estimation are needed in ad hoc networks with only wireless connectivity, the interest in study of more amenable networks using infrastructure support has greatly been growing. Such hybrid

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[1] We use the following notation: (i) $f(x) = O(g(x))$ means that there exist constants C and c such that $f(x) \le Cg(x)$ for all $x > c$, (ii) $f(x) = \Omega(g(x))$ if $g(x) = O(f(x))$, (iii) $f(x) = \omega(g(x))$ means that $\lim_{x\to\infty} \frac{g(x)}{f(x)} = 0$, and (iv) $f(x) = \Theta(g(x))$ if $f(x) = O(g(x))$ and $g(x) = O(f(x))$ [2].

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networks consisting of both wireless ad hoc nodes and infrastructure nodes, or equivalently base stations (BSs), have been introduced and analyzed in [14–18]. In a hybrid network where the number of antennas at each BS can scale at an arbitrary rate relative to the number of wireless nodes, the optimal capacity scaling was characterized by introducing two new routing protocols, termed infrastructure-supported single-hop (ISH) and infrastructure-supported multihop (IMH) protocols [18]. In the ISH protocol, all wireless source nodes in each cell communicate with its belonging BS using either a single-hop multiple-access or a single-hop broadcast. In the IMH protocol, source nodes in each cell communicate with its belonging BS via the nearest-neighbor MH routing.[2]

In hybrid networks with ideal infrastructure [14–18], BSs have been assumed to be interconnected by infinite-capacity wired links. In large-scale ad hoc networks, it is not cost-effective to assume a long-distance optical fiber for all BS-to-BS backhaul links. In practice, since the backhaul link rate becomes an important factor to determine a cost of operators when the infrastructure is deployed, it is rather meaningful to consider a cost-effective finite-rate backhaul link between BSs. One natural question is what are the fundamental capabilities of hybrid networks with *rate-limited* backhaul links in supporting n nodes that wish to communicate concurrently with each other. To in part answer this question, the throughput scaling was studied in [20,21] for a simplified hybrid network, where BSs are connected only to their neighboring BSs via a finite-rate backhaul link—lower and upper bounds on the throughput were derived in one- and two-dimensional networks. However, in [20,21], the system model under consideration is comparatively simplified, and the form of achievable schemes is limited only to MH routings. In [22], a general hybrid network deploying multi-antenna BSs was studied in fundamentally analyzing how much rate per BS-to-BS link is required to guarantee the optimal capacity scaling achieved for the infinite-capacity backhaul link scenario [18].

More practically, packets arrived at a certain BS in a radio access network (RAN) are delivered to a core network (CN) in a hierarchical way, and then are transmitted from the CN to other BSs in the RAN, while neighboring BSs have an interface through which only signaling information is exchanged between them [23]. The *hierarchical hybrid network (HierHybNET)* operating based on a remote central processor (RCP) to which all BSs are connected is well suited to this realistic scenario [24–28]. In [27], the set of BSs connected to the RCP via limited-capacity backhaul links was adopted in studying the performance of cooperative cellular systems using Wyner-type models. An achievable rate for the uplink channel of such a network model was analyzed using a joint multi-cell processing. To the best of our knowledge, characterizing an information-theoretic capacity scaling law of large hybrid networks (i.e., more general version than the Wyner-type model) with finite-capacity backhaul links in the presence of the RCP has never been conducted before in the literature.

[2] Note that the performance analysis is performed by assuming that the number of antennas at each BS may tend to infinity. In practice, however, the number of antennas that can be deployed at each BS may be limited due to the limited size of each BS. Nevertheless, we can obtain valuable insights even for a finite-size system from the large-system analysis [19].

1.2. Main contributions

In this paper, we introduce a more general HierHybNET with unit node density (i.e., an extended HierHybNET), consisting of n wireless ad hoc nodes, multiple BSs equipped with multiple antennas, and one RCP, in which wired backhaul links between the BSs and the RCP are *rate-limited*. This new type of network, consisting of multiple nodes, multiple BSs, and one RCP, was originally introduced in [29] by the same authors. In this paper, with detailed descriptions and proofs, we completely establish our main theorem in which the minimum backhaul link rate required to achieve the same capacity scaling law as in the infinite-capacity backhaul link case is derived. To understand a fundamental relationship between capacity and cost, we take into account a general scenario where three scaling parameters of importance including (i) the number of BSs, (ii) the number of antennas at each BS, and (iii) each backhaul link rate can scale at arbitrary rates relative to n. Inspired by the achievability result in [18], for our achievable scheme, we use one of pure MH, HC, and two different infrastructure-supported routing protocols.

Our network model is well-suited for the cloud RAN (C-RAN) that has recently received a lot of attention as some functionalities of the BSs are moved to a central unit [30]. However, the usefulness of the C-RAN may be limited due to high CAPEX (capital expenditures) as well as high OPEX (operational expenditures) associated with high backhaul costs. That is, in our problem setup, the cost is referred to as the expenditures that are costed only by designing backhaul links. It is thus vital to significantly dimension the backhaul bandwidth (or equivalently, the backhaul capacity) to reduce the cost of operators while guaranteeing the optimal throughput. In this regard, our results present a *cost-effective* approach for the deployment of backhaul links. We first derive the minimum rate of a BS-to-RCP link (or equivalently, an RCP-to-BS link) required to achieve the same capacity scaling law as in the HierHybNET with infinite-capacity infrastructure.

Assuming an arbitrary rate scaling of each backhaul link, we then analyze a new achievable throughput scaling law. Moreover, we identify *three-dimensional* information-theoretic operating regimes explicitly according to the aforementioned three scaling parameters. Besides the fact that extended networks of unit node density are fundamentally power-limited [31], we are interested in further finding the case for which our network, having a power limitation, is in the *infrastructure-limited* regime, where the performance is limited by the rate of backhaul links. In other words, in such an infrastructure-limited regime, the throughput can be improved by increasing the backhaul link rate (i.e., investing more in backhaul infrastructure). The infrastructure-limited regime in a HierHybNET has never been characterized before in the literature. From our results, one can know when the network throughput can be improved by increasing the backhaul link rate. We thus characterize these qualitatively different regimes according to the three scaling parameters.