Cooperative Communication and Networking

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We give an overview of our recent research in the area of cooperative communication and networking for military applications, focusing on radio resource management to maximize system efficiency and reliability. Specifically, we describe utility-based resource allocation techniques to maximize aggregate network utility and also to provide fairness among the nodes or users, presenting two representative results in this article. First, we describe one of our resource allocation techniques, called clique-based utility maximization, in a wireless mesh network with multihop transmission and multiple contention links. We constructed a clique-based method to generate a subgraph with efficient spatial reuse and then incorporated proportionally fair scheduling for fair resource allocation. We derived closed-form analytical results to quantify the system throughput and performance. Second, we present connectivity analysis in a cooperative ad hoc network with selfish nodes, considering a realistic cooperative network where not all nodes are willing to collaborate to relay other nodes' traffic. For such selfish, cooperative networks, we used stochastic geometry and percolation theory to analyze the connectivity and provide an upper bound of critical node density when the network percolates.

INTRODUCTION

The field of telecommunication networks involves exchange of information messages among a collection of terminals, links, and nodes that are connected together. The field has advanced tremendously and has generated many breakthroughs in research and technology innovations in the past century. The fundamental goals that have driven communications and networking research and technology developments are mainly to solve two problems: how to increase communication rates over a communication link connecting two nodes and how to increase the communication reliability to minimize the errors in information delivery. The first goal often refers to spectral efficiency, measured by bits per second per hertz. The second goal often refers to information capacity or channel capacity, measured by the bits per second that can be achieved with arbitrarily small error probability. Emerging classes of wireless networks, such as ad hoc and sensor networks and cellular networks with multiple hops, often consist of a large number of nodes in different geometric locations. Compared with classical point-to-point systems, these new types of networks are extremely difficult to analyze and optimize. Therefore, new theoretical and practical techniques are needed to augment classical communication and networking theory and practice.

Cooperative communication and networking is one of the emerging technologies that promises significantly higher reliability and spectral efficiency in wireless networks. Unlike conventional point-to-point communications, cooperative communication is a new form of diversity that allows users or nodes to share resources to create collaboration via distributed transmission and processing of messages. This cooperative diversity concept is similar to the multiple-input multiple-output (MIMO) system but is applied in a networked setting. As a result, it is often called a distributed MIMO or network MIMO. It represents a paradigm shift from a network of conventional point-to-point links to network cooperation.

Figure 1 shows an example of how cooperative diversity is used in a wireless network. A source node S needs to send messages to a destination node D. It needs the assistance of other nodes, i.e., n1, n2, n3, and n4, to forward and relay messages to reach the destination. This is shown as the noncooperative optimal route in traditional communication and networking design in Fig. 1a. Because of the broadcast nature of the wireless links, other nodes in the network (e.g., nodes a1, a2, and a3) can also receive the messages sent from the source node S. In Fig. 1a, the dashed circle indicates the broadcast area where the center node can be heard by other nodes. In this example, nodes a2 and a3 collaborate with node n1 to transmit the message to node n2, as shown in Fig. 1b. Similarly, nodes b1 and b2 collaborate with node n2 to transmit the message to node n3. Finally, nodes c2 and c4 collaborate with node n4 to transmit the message to the destination node D. The selection of nodes for collaboration is determined by node locations and preferred performance metrics.

Much work on cooperative communication networks in the international research community focuses on fundamental research in information theory and signal processing. Mathematical analysis and signal processing techniques have been developed to derive the capacity and efficiency gains or bounds. Some of the most representative work on this topic can be found in Refs. 1–5 and the references cited therein. Besides the theoretical analysis, standards activities in commercial industry have recently started to take practical design and network protocols into consideration in order to realize the potential gains of cooperative diversity. The IEEE 802.16j[6] and 802.16m[7] working groups have included cooperative relay as an optional feature for the next-generation WiMax systems. 802.16j, which provides a multihop relay specification, serves as an amendment to the existing WiMax standard IEEE 802.16e. It achieves cost-effective coverage extension via multihop relays and capacity enhancement by using cooperative diversity. 802.16m is an amendment targeting the upgraded performance requirements specified by IMT-Advanced. It is built on top of 802.16j and incorporates the MIMO capability at each relay node. It also incorporates the "shared relay" capability, where the relay node does intercell interference cancellation in addition to signal forwarding. Third Generation Partnership Project Long Term Evolution standards also include cooperative relay as one of the key features in the 4G/5G wireless cellular systems. Besides coverage extension, capacity enhancement, and interference cancellation, Long Term Evolution standards also incorporate Layer 3 relaying or self-backhauling to allow relaying in backhaul connection as well.

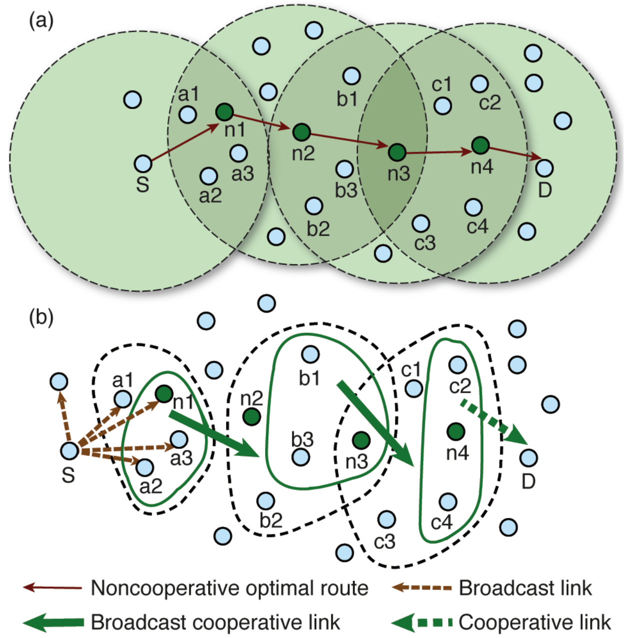

Figure 1. An example of cooperative diversity. (a) Noncooperative optimal route from source S to destination D. (b) Cooperative transmission along the optimal route from source S to destination D.

In FY2008 APL established an international collaboration with scientists at Imperial College London in London, UK, to conduct fundamental research in the area of cooperative communication and networking, supplementing our internal research project on assurable tactical networks. The team has been emphasizing fundamental research driven by the need to design robust wireless networks for infrastructure monitoring and/or for command and control. Specifically, our team has been focusing on theoretical analysis for maximizing the network utility function over a cooperative multihop path. We consider the energy efficiency issue in battery-operated wireless networks with sensor nodes and users with limited and nonreplenishable energy supplies. Finally, we study selfish node behavior and connectivity of a large cooperative ad hoc network where not all nodes are fully cooperative.

RADIO RESOURCE MANAGEMENT IN COOPERATIVE NETWORKS

Radio resource management refers to the system level of control and management of limited radio spectrum resources and network infrastructure to optimize the system efficiency and performance. Radio resources include the channels, data rates, transmission power, spreading codes (in a spread spectrum system), antenna elements, channel cards, etc. Radio resource management strategies involve algorithms and protocols for channel allocation, access control, frequency reuse, transmission scheduling, power control, interference mitigation, adaptive modulation and coding, etc., at a system level with multiple users. Therefore, it often relates to maximizing the system or network capacity and performance instead of maximizing a point-to-point link. In the context of cooperative networks, where nodes share their resources and collaborate in transmission and receiving, radio resource management has the same objective of utilizing the resources to maximize the system efficiency as much as possible. Obviously, the resource management becomes quite complicated and difficult to design in a cooperative network.

Resource allocation relies on a suitable performance metric. Broadly speaking, there are two types of performance metrics used in the context of resource allocation: the total rate-based performance metric and the utility-based performance metric. The total rate-based performance metric targets maximizing the aggregate system throughput or total rates of all links. It is known to cause unfairness among the nodes or users because nodes in good channel conditions are allocated more resources whereas nodes in bad channel conditions do not get much chance to be served. The most recent work on resource allocation has shifted to a utility-based framework. In utility-based resource allocation, the objective is to maximize the aggregate utility in the network and to provide a certain level of fairness criteria among the nodes. In our work, we adopt the utility-based framework for resource allocation in a cooperative wireless network.

In a utility-based framework, each link l is associated with a utility function $U_l(R_l)$ over the link throughput R_l. The function U is typically assumed to be concave and nondecreasing for all links. By defining $U(\cdot)$ appropriately, different fairness criteria of interest, such as proportional fairness (PF) or max-min fairness, can be achieved.[8,9] Radunović and Le Boudec[10] have proved that the max-min allocation has a fundamental efficiency problem and results in all links receiving the rate of the worst link. For fairness and efficiency, we consider the PF allocation method in the transmission scheduling design. In the following section, we describe a clique-based utility maximization technique designed for wireless mesh networks (WMNs).

CLIQUE-BASED UTILITY MAXIMIZATION IN WMNs

Wireless Mesh Networks

We consider the network resource management and optimization problem in WMNs. A WMN is a communication network consisting of radio nodes connected in a mesh topology. Different from a cellular network, where each radio node communicates to other nodes through a base station, nodes in a WMN can communicate with each other directly or through one or more intermediate nodes. A WMN is a special type of mobile ad hoc network. It often has a more "planned" network configuration and relatively "static" topology instead of an "ad hoc" network formulation and highly "dynamic" topology, typical of most mobile ad hoc networks. A WMN has a hierarchical architecture with regular nodes as the clients and special nodes as the mesh routers and gateways. Resource allocation in such networks needs to take this particular network architecture into consideration.

The "Clique" Concept

We address the resource allocation and optimization issue in a cooperative WMN, focusing on the throughput and fairness criteria. As discussed in the *Radio Resource Management in Cooperative Networks* section, the utility-based approach has been widely used in resource allocation for its efficiency and fairness properties. We adopt the PF criterion for transmission scheduling design and analysis. For a WMN, multiple transmission links may be activated at the same time because of spatial reuse. This makes the transmission scheduler design more difficult and complicated than the scheduler for a single link transmission. To facilitate the design and analysis, we introduce the concept of a clique from graph theory. Given a graph, a clique is defined as a complete subgraph that is not contained in any other complete subgraph. A WMN is considered a connected graph. Each clique represents a maximum number of concurrent and noncontending links. The WMN is divided into multiple nonoverlapping cliques. These cliques are scheduled in a proportionally fair manner.

Clique for Spatial Reuse in the Network

We define a link contention model as having undesirable interference and resource competition. Two links contend if their concurrent transmissions need to access the same radio resource. There are five kinds of link contention: multiple links transmitting to the same node,

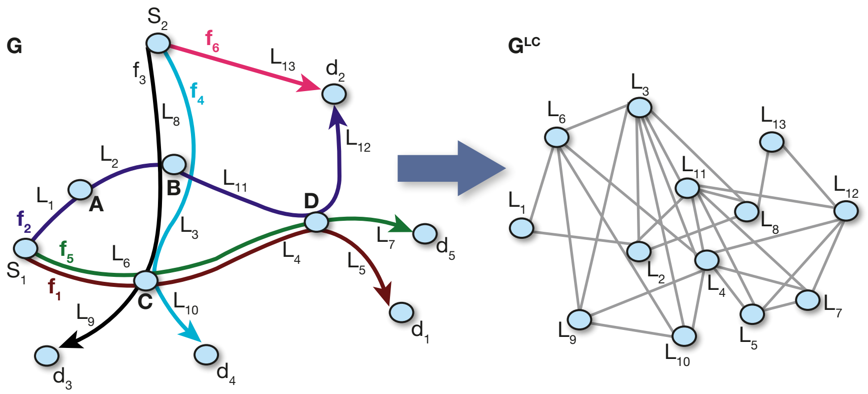

Figure 2. Generation of a link contention graph G^{LC}. s1 and s2, source nodes 1 and 2; d1, d2, d3, d4, and d5, destination nodes 1, 2, 3, 4, and 5.

multiple links receiving from the same node, a transmitting link and a receiving link interacting with the same node, intraflow link contention where different links of the same flow heavily interfere with each other, and interflow link contention where different links of different flows heavily interfere with each other. The level and size of the contention in a WMN is determined by the node position and each node's communication, interference, and sensing range.

As shown in Fig. 2, the network topology is represented by a graph G (left). The connectivity is represented by a link L_{ij}, from node i to node j. There are six flows, e.g., $f_1, f_2, \ldots, f_6$, each of which is illustrated by a route from the source to the destination. On the basis of the link connectivity, we generate a link contention graph G^{LC} that captures the contentions among the links in such a way that each link is a vertex in this graph, and two links that contend are adjacent, as shown on the right side of Fig. 2. According to the definition of link contention, link L_1 contends with links L_2 and L_6; link L_8 contends with links L_2, L_{11}, L_3, and L_{13}. The edge between L_1 and L_6 indicates an intraflow link contention over flow f_2; the edge between L_1 and L_8 indicates an interflow link contention.

Using the link contention graph G^{LC}, we construct the complement (or inverse) graph G^I of G^{LC} in such a way that two vertices in G^I are adjacent if and only if they are not adjacent in G^{LC}. From the complement graph G^I, we generate a clique allocation graph G^{CA}, which is the maximum clique of G^I, as shown in Fig. 3. A maximum clique V is simply the set of vertices in the clique allocation graph and represents a maximum number of concurrent links in the network.

Clique-Based Scheduling Algorithm

We propose a clique-based proportionally fair scheduling (CBPFS) algorithm that maximizes the aggregate utility of cliques. Each clique contains a number of concurrent and noncontending links and has a sum of rates accordingly. Using the notion of cliques, CBPFS achieves spatial reuse and maximizes efficiency by allowing concurrent link transmissions within a clique. This CBPFS algorithm is a general extension to the PF scheduling algorithm for a multihop wireless network. It becomes the PF scheduling algorithm when used in a single-hop cellular network where each clique contains only one link.

Given a graph, there could be multiple maximum cliques of the same size. We could maximize the spatial reuse of the network by scheduling one of these maximum cliques. However, this method has two major problems. The first issue has to do with fairness. Different maximum cliques may have overlapped links, which will be scheduled more frequently than those nonoverlapping links. Links that are not covered by the maximum cliques will not be served at all. The second issue has to do with complexity. This method requires enumerating all maximum cliques, which is nondeterministic polynomial-time hard. To solve the fairness problem and reduce the complexity, we propose the following greedy algorithm:

- Generate the first link connection graph G^{LC} as shown in Fig. 2. Then generate the first clique allocation graph G^{CA} as shown in Fig. 3 and obtain the maximum clique V_1.
- Generate the Kth link contention graph G^{LC} by removing V_{K-1} from the $(K-1)$th link contention graph. Then generate the Kth clique allocation graph G^{CA} and obtain the maximum clique V_K.
- Repeat the above procedure for $K = 2, 3, \ldots,$ until all links are in cliques.

In the above greedy algorithm, if there are $n = |L|$ links in the network, K is at most n, i.e., there are $O(n)$ link contention graphs. Obviously, this greedy algorithm has polynomial-time complexity if we limit

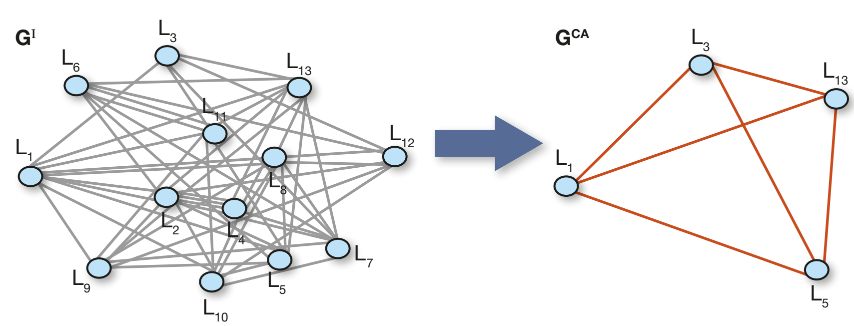

Figure 3. Generation of a clique allocation graph G^{CA}.

the maximum degree of the clique allocation graph and thus has a much less complexity than finding all maximum cliques.

With the above algorithm, we divide the network into K cliques $\{V_i, i = 1, 2, \ldots, K\}$. We schedule one of the K cliques for transmission in different time slots. Each clique V_i represents a maximum number of noncontending links. When it is scheduled, all links in the clique can transmit simultaneously. This way, we achieve the spatial reuse to maximize the system efficiency. To add the PF criterion, the aggregate logarithmic utility function of all K cliques should be maximized. Formally we have the following maximization problem,

$$\max \sum_{i=1}^{K} ln(\gamma_i[t]) \tag{1}$$

s.t.

$$\gamma_i[t] = \sum_{\forall l \in V_i} R_l[t], \tag{2}$$

where V_i is determined by the greedy algorithm; γ_i is the throughput of clique V_i; and for each link $\forall l \in V_i$, the link throughput R_l is updated by

$$R_l[t+1] = \left(1 - \tfrac{1}{k}\right) R_l[t] + I_i[t+1] \times \frac{C_l[t+1]}{k}, \tag{3}$$

where $C_l[t + 1]$ is the estimated capacity of link l at time slot $t + 1$; constant $k \geq 1$ is the smoothing factor; and $I_i[t + 1]$ is the indicator event function of the event that clique V_i is scheduled in slot $t + 1$. Following detail derivations, we have the solution to the optimization problem defined in Eq. 1 and Eq. 2,

$$V_i = arg \max_{\forall V_j} \frac{\sum_{\forall l \in V_j} C_l[t+1]}{\sum_{\forall l \in V_j} R_l[t+1]}. \tag{4}$$

We call the algorithm described by Eq. 4 a CBPFS algorithm.

We analyze the performance of the CBPFS algorithm by using results of stochastic approximation and abstracting the underlying fading processes with stochastic estimates. We obtain the closed-form expression of the average throughput of each link for Rayleigh fading scenarios. The detailed analysis and proofs can be found in our published papers.[11,12] We also develop simulations to show quantitative performance results of throughputs and fairness among the nodes.

CONNECTIVITY ANALYSIS IN SELFISH AND COOPERATIVE NETWORKS

While connectivity is arguably the most critical performance metric for a wireless network to ensure end-to-end delivery, one cannot assume that any two nodes can always keep connected all the time. Channel fading, interference, and mobility, etc., may cause link disruptions and disconnection. This is especially true for the emerging type of wireless networks such as ad hoc networks, where highly dynamic changes in network topology and link connectivity occur frequently and unexpectedly. Among various approaches to ensure connectivity in wireless networks, cooperative communication shows great potential. Various cooperative communication and networking techniques, as presented in many publications in recent years, have shown the concrete advantages and potential of node cooperation and sharing resources. However, there remain challenges to achieve the full potentials of cooperation. Besides the technical challenges of finding practical solutions to implement cooperation, there are issues in other disciplinary areas such as the user's social behavior and willingness to join a cooperative network. It is of great interest to investigate the connectivity in cooperative networks with selfish nodes, treating the cooperative diversity and node's selfish behavior jointly.

The above rationale motivates our research on this specific aspect for cooperative communication networks. Our objective is to quantify the connectivity for cooperative ad hoc networks with user selfishness defined as a p-selfishness probability model, as a first step. We derive an upper bound of critical node densities for such systems to percolate.

System Model

In the general notion of ad hoc networks, nodes are randomly distributed and/or moved; thus full connectivity of the whole network is often not possible. Practically speaking, it is sufficient for a network operator to ensure that some fraction of the nodes instead of all nodes in the network are connected for a functional network. The occurrence of connected nodes in infinitely large networks is mathematically defined as percolation.[13] By Kolmogorov's zero-one law, a network of infinite size will percolate once the node density λ or node range r is above some threshold. The density or range threshold for percolation to occur is called the critical density or range, denoted by λ_c or r_c.

Consider a cooperative ad hoc network shown in Fig. 4. We assume that k nodes $n_0 \sim n_{k-1}$ transmit to node n_k in a cooperative manner, i.e., transmit the same message to node n_k simultaneously. These k nodes form a k-collaborative cluster. Because of the diversity gain obtained through cooperative transmission, the node distance between n_k and n_i ($i = 0 \sim k$) could be greater than node range r, which is the transmission range without any cooperation. We assume that node n_k and $k - 1$ nodes out of the $n_0 \sim n_{k-1}$ nodes together form another k-collaborative cluster to reach node n_{k+1}. In this cooperative transmission, because the node distance could be greater than the reachable range without any cooperation, the critical node density or range is expected to be reduced.

In most work on cooperative communication, it is assumed that nodes in a collaborative cluster are expected to cooperatively transmit at all times, no matter whether the transmitted messages are their own or belong to other nodes. This assumption may not be true, especially when the nodes have intelligence or knowledge of the transmitted information, or self-awareness. For example, nodes may become selfish and may not be willing to relay other nodes' traffic if it means consuming their own resources (e.g., battery and time). Therefore nodes may not cooperatively transmit at some time. Our objective is to analyze the connectivity for a cooperative network with selfish nodes. More specifically, we would like to obtain the critical node density needed for percolation to occur in a cooperative network.

Critical Node Density

In Fig. 4, nodes are distributed across an infinite region according to a Poisson Point Process with node density by $\lambda > 0$. k-collaborative connectivity is defined as the existence of one cluster chain containing an infinite number of connected clusters, each of which has k nodes cooperatively transmitting. As a first step, we consider a simple model to define the selfish behavior. A node in a k-collaborative cluster will cooperatively transmit with a probability of p when relaying other nodes' traffic. This model is likewise used in Ref. 14 to study cooperation in ad hoc networks. We call it p-selfishness. With p-selfishness, the extreme case of $p = 0$ corresponds to noncooperation scenario and $p = 1$ corresponds to the traditional cooperation scenario.

We conducted rigorous mathematical analysis to derive the critical node density in the following steps.

1. Derive the received power level at each node in the cluster chain considering k-collaborative transmission from the previous cluster.
2. Derive the critical node distance that the k-collaborative cluster with p-selfishness can cooperatively transmit to each node in the cluster chain.
3. Define the critical node density that incurs percolation in the network and two lemmas using the percolation theory and stochastic geometry.
4. Finally, obtain an upper bound of node density for the network to percolate in the following theorem.

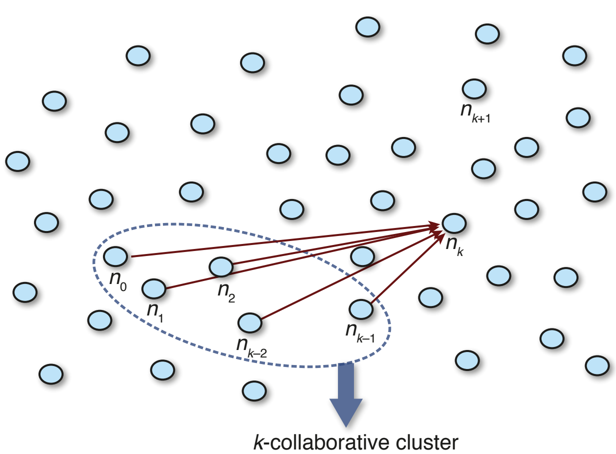

Figure 4. Cooperative networks: k-collaborative cluster.

Theorem 1. *For a* k*-collaborative network with* p*-selfishness, the critical node density is bounded by*

$$\lambda_c^* \leq \frac{\lambda_c}{\left(1 + \sum_{i=0}^{k-2} p \times (i+2)^{-\alpha}\right)^{\frac{2}{\alpha}}}, \tag{5}$$

where λ_c is the critical node density for the noncooperative network, and α is the path loss exponent.

Numerical Results

We compute the critical density for a k-collaborative network with selfish nodes to percolate. In this numerical calculation, the critical node density for the noncooperative network is normalized to 1. Figure 5 shows the plot of the numerical results of the upper bound of the critical density for various k and path loss exponent α using Theorem 1.

The results shown in Fig. 5 verify that node cooperation helps decrease the system cost in terms of reduced node density. When cooperation instead of selfishness dominates, i.e., cooperative transmission probability $p > 0.5$, the number of nodes needed in a cooperative network will be less than 77% of the number needed in a noncooperative network, for the configuration of $k = 20$, $\alpha = 2.0$.

SUMMARY

In this article, we give an overview of the fundamental research conducted by APL and Imperial College London in the area of cooperative communication and networking. This emerging technology has become a paradigm shift in wireless communication research. It promises significant improvement in reliability and spectral efficiency. We focus our research on the general topic of radio resource management. Specially, we develop utility-based resource allocation techniques to maximize the system efficiency while providing nodes/users fairness as well. Our resource allocation techniques include a clique-based utility maximization in a WMN. Furthermore, we analyze the connectivity issue in a cooperative ad hoc network with selfish nodes and derive an upper bound on critical node density for the network to percolate. We highlight the clique-based utility maximization algorithm and the connectivity analysis in this article. For more details of our other related work, the readers can refer to our publications.[11, 15–20]

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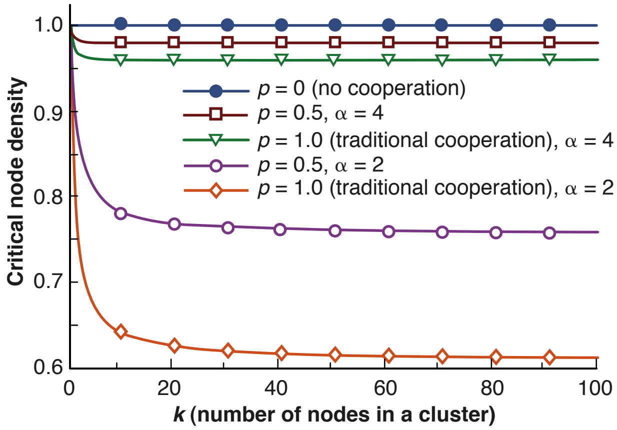

Figure 5. Critical node density in a k-collaborative cooperative network with p-selfishness. p, transmission probability; α, path loss exponent.

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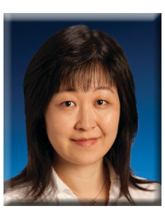

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