Effects of Clustering in Ad Hoc Networks from Network Utility Maximization Aspect

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***Abstract* — In this paper, we study joint end-to-end congestion control and medium access control (MAC) in ad-hoc networks with fixed wireless channels as a utility maximization problem with constraints that arise from contention for channel access. Scheduling of the transmissions is used, although random access can be used too. We analyze the effects of clustering at both physical and application level on the maximum end-to-end throughput gained in the network. Our results show that the natural clustering tendency of the users works favorably and can improve network performance. Two types of network areas are being considered: square shaped and rectangle shaped. The rectangle shaped topology gave higher maximum end-to-end throughput.**

***Index terms* — Ad hoc wireless network, clustering, congestion control, medium access control, network utility maximization.**

I. INTRODUCTION

AFTER the publication of the seminal paper [1], the network utility maximization (NUM) framework has found applications in network rate allocation through congestion control protocols. In the NUM framework, each end-user has its utility function and link bandwidths allocated so that network utility is maximized. Network utility can be the sum of all users' utilities, but some other definitions are also possible. A utility function can be interpreted as the level of satisfaction attained by a user as a function of resource allocation. Different kinds of utility functions lead to different types of fairness. A family of utility functions is proposed in [2] .

In this paper we consider the problem of congestion control in a multihop wireless ad hoc network. Mobile ad hoc networks have been an active research area over the past years with many fascinating and complex issues like: mobility, channel estimation, power control, MAC, routing, etc. Unlike in wireline networks where links are disjoint resources with fixed capacities, in ad hoc wireless networks the link capacities are "elastic" [3]. Most routing schemes for ad hoc networks select paths that minimize hop count. This implicitly predefines a route for any source-destination pair of a static network, independent of the pattern of traffic demand and interference among links. This may result in congestion at some region while other regions are not fully utilized. To use the wireless spectrum more efficiently, multiple paths based on the pattern of traffic demand and interference among links should be considered [4].

Wireless channel is a shared medium and interference-limited. Link is only a logical concept and links are correlated due to the interference with each other. Under the MAC strategies such as time-division and random access, these links contend for exclusive access to the physical channel. Unlike in the wireline network where network layer flows compete for transmission resources only when they share the same link, in wireless network flows can compete even if they don't share a wireless link in their paths. Thus, in ad hoc wireless networks the contention relations between link-layer flows provide fundamental constraints for resource allocation.

TCP congestion control algorithms can be considered as distributed primal-dual algorithms which maximize aggregate network utility, where a user's utility function is (often implicitly) defined by its TCP algorithm, [1] and [5]. These works implicitly assumes a wireline network where link capacities are fixed and shared by flows that traverse common links. A natural formulation for the joint design of congestion and media access control is then the utility maximization framework with new constraints that arise from channel contention. There can be many alternative decompositions of these algorithms, leading to a choice of different layering architectures. In [6] is given a survey of the current status of horizontal decomposition into distributed computation, and vertical decomposition into functional modules such as congestion control, routing, scheduling, random access, power control, and channel coding.

Here we focus only on congestion control at the transport layer and channel contention at the MAC layer, and ignore all other issues. There are many works which are focused on these issues. For the MAC layer, in [3] and [7], random access is considered while in others scheduling and multi-channel networks are considered [4]. In this paper we use scheduling with time-division multiple access.

Ad hoc networks are usually formed by people in order to share information, and people are also part of some social network. Since most human communication takes place directly between individuals, such networks are

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crucially important for communications. This sociological concept is the basis for the small world research, which describes the tendency for each entity in a large system to be separated from any other entity in the system by only a few steps [8]. According to the small world research, the group of ad hoc network users can be modeled as a type of social network with a small average path length and high clustering coefficient and grouping affinity. From this point of view, most of the communication between the nodes is done inside the 'home' cluster while the necessity to communicate with an entity from an 'outside' cluster is scarcely rare. When considering clustering in ad hoc networks we must differentiate between the physical clusters that are created by the physical vicinity of the users, but also we have the cluster-oriented way of communication between the users in the network according to the small world pattern of behaviour. Of course, it is always expected that in many circumstances these two clustering based connections will be overlapping, that is the physical cluster will be formed by users that usually communicate between each other.

The different ways of modeling users and their actions in the ad hoc network is presented in [12]. The way the application and physical clustering are affecting ad hoc networks has been studied in [9]. The impact of the small world phenomena on the ad hoc network performances is presented in [10] and [11]. From this past work it can be concluded that the application layer clustering and physical node dissemination have large impact on the ad hoc network performances. When taken into consideration the small world clustering effect the ad hoc network performances rise several times than their estimated values according to the traditional random engines.

Therefore, the main goal in this paper is to investigate how grouping affects the maximum end-to-end throughput gained in the network, in order to get a better view of what is the expected maximum performance of the ad hoc network can tend to achieve when used in a real world, that is 'small-world', situations.

The rest of the paper is organized as follows. In Section 2, we give a model of the ad hoc network and define the network utility maximization problem with its constraints and appropriate utility function. After that, in Section 3, we define the performance metrics, the methodology of small world clustering on the two different layers which will be considered. Simulation results and analysis are given in Section 4, and Section 5 concludes the paper.

II. NETWORK MODEL

We consider an ad hoc wireless network represented by a undirected graph $G(V,E)$, where V is the set of nodes and E is the set of logical links. Each source node s has its utility function $U_s(x_s)$, which is a function of its transmitting data rate x_s and we assume it is continuously differentiable, increasing, and strictly concave. For its communication, each source uses a subset $L(s)$ of links.# We define S as the set of all sources and $S(l)$ as the subset of sources that are traversing link#l. We assume static topology (the nodes are in a fixed position). Also, each link has finite capacity c_l when it is active, i.e. we implicitly assume that the wireless channel is fixed or some underlying mechanism masks the channel variation.

Wireless channel is a shared medium and therefore interference-limited. All logical links transmit at rate c_l for the duration they hold the channel. We assume that nodes can communicate with at most one other node at any given time, because node cannot transmit and receive simultaneously. Two links will interfere with each other, if either the sender or the receiver of one of the links is within the interference range of the sender or receiver of the other link. This is because we use TCP connections so the receiver has to send acknowledgment packets. For dealing with the contention among links, we use time-division multiple access, in other words we will use scheduling as in [4].

For simplicity, we avoid building contention graphs and then finding maximal cliques as in [3] and [4]. Instead, we consider contention in regions defined by a single link. Interference region of a link is defined by the interference radius around the two nodes which compose the link. With *I(l)* we denote the set of links which have at least one node in the interference region of link *l*. The fraction of time that each link can transmit is *f(l)*. So the sum of these fractions of all the links in an interference region defined by a single link cannot be greater than one.

As a utility function, we will use a function which provides proportional fairness among the end users:

$$U(x_s) = \log x_s \qquad (1)$$

From the concavity of the utility function it follows that the optimal rates $\{\hat{x}_s\}$ satisfy the following condition:

$$\sum_s \frac{x_s - \hat{x}_s}{\hat{x}_s} \leq 0, \qquad (2)$$

This means that if rate of one transmitter rises, the rate of another transmitter will drop, and the drop will be proportionally larger than the rise.

So we have the following utility maximization problem:

$$\max_{x_s} \sum_{s\in S} U_s(x_s) \qquad (3)$$

subject to:

$$\sum_{s\in S(l)} x_s \leq c_l\, f(l), \forall l \in E$$

$$\sum_{l'\in I(l)} f(l') \leq 1, \forall l \in E$$

After some reformulations and relaxations, this problem can be decomposed both horizontally and vertically. Vertically it can be decomposed in separate TCP and MAC layer algorithms, and these algorithms can further be horizontally decomposed and solved in distributed manner as in [5] and [1]. For simplicity, in our analysis we will solve the problem in a centralized manner.

III. SIMULATION METHODOLOGY

A. Performance metrics

For ad hoc network performance measuring using the small world application layer the end-to-end throughput is used as performance factor. The end-to-end throughput represents the total amount of bits received by all nodes per second and is measured in Mega bits per second (Mbps). Because in this paper we maximize the performance we will call it the maximum end-to-end throughput (MET).

B. *Network clustering*

In order to analyze how clustering at both application and physical level affects the maximum end-to-end throughput gained in the network we group the nodes in four clusters at both, application and physical layer.

At application level we are modeling the end-to-end communication via the percentage of in-cluster communications a is varied from 0% to 100%. For a=0% all the communications are taking place between nodes from different clusters, while for a=100% all the communications are taking place between nodes from the same cluster.

Clusters at physical level are formed according to clusters at application level, so that we can simulate the natural overlapping of these two types of views of the network. That means that nodes in cluster “C1” (Fig. 1) are in the same clusters at both physical and application level. When there is no clustering at physical level, all of the nodes from different clusters at application level are placed randomly in the network area using a uniform distribution.

C. *Network area*

From aspect of the shape, we will consider two types of network areas: square and rectangle (Fig. 1). It is natural to expect that the maximum end-to-end throughput gained in these two topologies will differ.

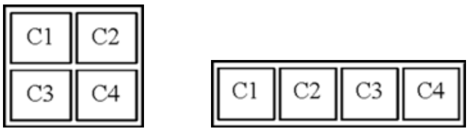

Fig. 1. Clustering at physical level in square and rectangle shaped topology.

IV. SIMULATIONS AND RESULTS

We use CVX [13] for solving our network utility maximization problem defined with (3). CVX is a modelling system for disciplined convex programming (DCP). DCP is a methodology for constructing convex optimization problems and is meant to support the formulation and construction of optimization problems that the user intends from the outset to be convex. DCP imposes a set of conventions or rules. Problems which follow the rules can be rapidly and automatically verified as convex and converted to solvable form. Some problems can be reformulated to be made convex and then solved by appropriate methods for convex problems.

For our simulations, we used an ad hoc network with 100 wireless nodes spread out in 1000x1000m area in the square shaped area and 500x2000m in the rectangle shaped area. We assume that every node is equipped with IEEE 802.11b radio, therefore each of the logical links has a capacity of 2Mbps. Fixed routing is used with the path with minimum hops between the sender and the receiver chosen as a route. The network has one channel that means the whole bandwidth is used for all communications. Every maximum end-to-end throughput (MET) shown in the results is average of the METs obtained for five different networks with same characteristics.

First, we will consider the influence of clustering on the MET in a square shaped topology. From Fig. 2, it can be seen that for not clustered network on physical level MET doesn’t change drastically for different percentage of in-cluster communications and is approximately same as with random traffic. Without any clustering (random traffic and randomly placed nodes), the MET in the network is 1.36Mbps.

In a network clustered at physical level MET constantly increases as the percentage of in-cluster communications increases (Fig. 2). For 0% of in-cluster communications, MET is even smaller than in network with random traffic, because most of the connections include more hops and have to compete with more connections than in other cases. On the other hand, as percentage of in-cluster communications increases, the average number of hops in a connection and number of competing connections decrease, so the MET increases.

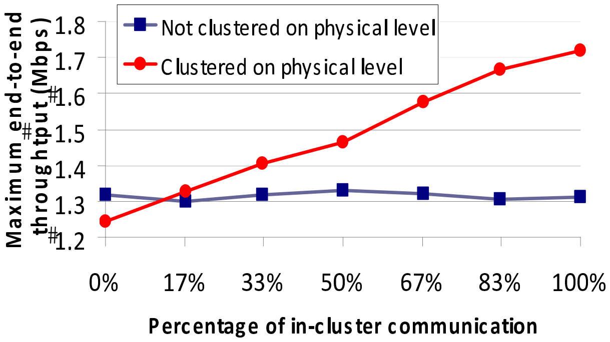

Fig. 2. MET in square shaped network for different percentage of in-cluster communications, for clustered and not clustered network at physical level.

In a rectangle shaped topology (Fig. 3) it can be seen that for not clustered network on physical level MET doesn’t change drastically for different percentage of in-cluster communications and is approximately same as with random traffic. With random traffic and nodes randomly positioned the MET is 1.6Mbps.

In a network clustered at physical level MET constantly increases as the percentage of in-cluster communications increases (Fig. 3). For 0% of in-cluster communications, MET is drastically smaller than in network with random traffic from the same reasons it dropped slightly in square shaped network, noting that in this case the multihop paths are going to be longer. However, when the in-cluster percentage starts to rise, we have a steady boost of MET which is now almost twice as large, because we can now have cases of undisturbed parallel communication in distant clusters that do not affect some of the other parts of the network via interference.

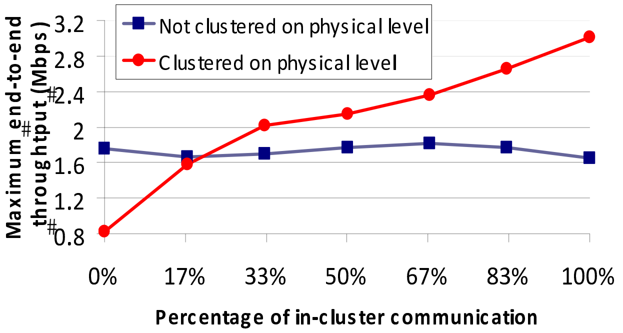

Fig. 3. MET in rectangle shaped network for different percentage of in-cluster communications, for clustered and not clustered network at physical level.

On Fig. 4, we give a comparison of the differently shaped topologies, by analyzing the ratio of their maximum end-to-end throughput.

$$R/S=\frac{MET(\mathrm{Re}c\tan gle)}{MET(Square)}$$

There are two main aspects considering this ratio. First R/S is smaller then one for a network clustered at physical level, with 0% percentage of in-cluster communications. The MET of a rectangle shaped topology is smaller than the MET of a square shaped topology. The reason for this is that the rectangle is wider, so the clusters are more mutually far-away. Because most of the connections in this case are between nodes from different clusters, the average number of hops per connection is bigger in this topology. Bigger number of hops per connection means bigger interference between connections.

Second R/S is greater than one for all other kinds of traffic, including random traffic. The reason for this is that the rectangle is wider and the nodes are more mutually far-away, so the number of nodes which are placed in the interference region of each node is smaller.

In both topologies for network not clustered at physical level MET doesn't change as the percentage of in-cluster communications increases, and is approximately same as with random traffic.

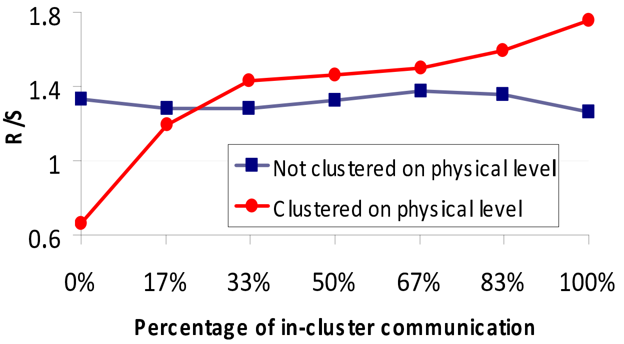

Fig. 4. METs ratio of rectangle and square shaped topologies, for different percentage of in-cluster communications, for physically clustered and not clustered network

Data rates obtained in our analysis are different than in previous analysis because we assume the existence of a centralized body which schedules the transmissions. If we use random access, and solve the problem in decentralized manner, the rates will probably be a bit lower.

V. CONCLUSION

This paper has studied the effects of clustering at application and physical level in ad hoc networks using the network utility maximization framework.

Although the network model here is quite distinct than in other analysis, we get similar conclusion: by taking in consideration the impact of the grouping formed by the ad hoc users the performance of the network is significantly changed when compared to the random scenarios.

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