MobileGrid: Capacity-aware Topology Control in Mobile Ad Hoc Networks

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Abstract—
Since wireless mobile ad hoc networks are arbitrarily and dynamically deployed, the network performance may be affected by many unpredictable factors such as the total number of nodes, physical area of deployment, and transmission range on each node. Previous research results only focus on maximizing power efficiency through dynamically adjusting the transmission range on each node. Via extensive performance evaluations, we have observed that the network performance is linked with a single parameter, the network *contention index*, which each node may estimate in a fully distributed fashion. This paper introduces the definition of such a parameter, which is derived from relevant parameters such as the number of nodes and the transmission range on each node. With the presence of node mobility, we present a detailed study of the effects of contention index on the network performance, with respect to network capacity and power efficiency. We have observed that the capacity is a concave function of the contention index. We further show that the impact of node mobility is minimal on the network performance when contention index is high. Based on these important observations, we present *MobileGrid*, a fully distributed topology control algorithm that attempts to achieve the best possible network capacity, by maintaining optimal contention index via dynamically adjusting the transmission range on each of the nodes in the network.

I. Introduction

In mobile ad hoc networks, since nodes are autonomic, it is practically impossible to predict the state of many important parameters with tractable mathematical models, including (1) the total number of nodes; (2) the physical area of deployment; and (3) the transmission range on each node. However, such parameters dramatically affect the network topology over time, and consequently have a considerable impact on the network performance, such as network capacity and power efficiency.

Maximizing power efficiency is primarily achieved in previous work by dynamically adjusting the nodal transmission range. They require a stationary ad hoc network without node mobility, in order to use a tractable mathematical model to derive the relationship between energy consumption and nodal transmission ranges. Such mathematical models may be used to optimize the topology to conserve power. However, we argue that, the absolute value of transmission range itself is *not* an independent driving force that affects power efficiency and network capacity. The fluctuating number of nodes in the network and the physical area of deployment also play a role. In order to identify one single parameter in controlling the network performance, we present a generic notion in ad hoc networks, the *contention index*, which represents the number of contending nodes within the interference range. In this work, via extensive performance evaluations, we contend that the *contention index*, rather than the *transmission range* on each node, is the primary and independent driving force that influences the network performance.

Indeed, simulation results show that network capacity is a *concave function* of contention index. As such, we argue that optimal values of contention index do exist to achieve the best possible performance. Based on the above critical findings from performance evaluation results, we propose *MobileGrid*, a distributed topology control algorithm to ensure every node in a mobile ad hoc network adjust the transmission range to maintain an optimal contention index which may lead to a topology that yields optimal performance in terms of network capacity.

The most significant and novel contribution in this paper that distinguishes it from previous works is that, we perform online dynamic range adjustments not only for the purpose of conserving power, but also for the purpose of keeping other network Quality of Service (QoS) parameters checked, hopefully around their optimal values achievable in the network. There exists previous work that considers throughput or delay when tuning transmission ranges, but none of them has offered insights on the *forward path* of the "closed loop", i.e., how to adjust the ranges to achieve a *better*, or *best possible*, throughput or delay. What we have contributed is the characterization of one of the inherent network properties, the *contention index*, that affects the network performance single-handedly, yet straightforward to monitor and estimate with a fully distributed algorithm.

The remainder of the paper is organized as follows. After discussing related work (Sec. II) and preliminaries (Sec. III), we divide the paper into two stages. In the first stage (Sec. IV), we present extensive and convincing simulation results to show the bond between the contention index and network performance. In the second stage (Sec. V), we formally present *MobileGrid*, a simple, yet effective, distributed algorithm to control the topology in order to achieve better performance. Section VII concludes the paper and points out possible future directions.

II. Related Work

Previous studies on capacity of wireless networks have been reported in [1], [2]. The network examined is stationary, with uniform node density and fixed transmission range. It has been shown that the per-node capacity may be estimated in the order of $O(1/\sqrt{n})$, n being the number of nodes in the network. However, the compensating effects of local per-node transmission range adjustments on the network performance (e.g. capacity) has yet to be studied.

Elbatt *et al.* [3] attempt to dynamically reach a near-optimal operating power level to maximize the end-to-end throughput. By increasing a node's transmission power until the throughput starts decreasing, it works based on the assumption that the throughput is a concave function of transmission power. However, there is no theoretical analysis or simulation studies in [3] to validate this assumption. The instantaneous throughput needs to be measured on an ongoing basis using an online algorithm, and the dynamic adjustments may be affected by short-term throughput variations. In comparison, we believe that *network capacity* has an inherent bonding relationship with the contention index. Rather than adjusting the range to increase instantaneous throughput, it may be more advantageous to find an optimal operating point that increases the capacity, even with a network without much ongoing packet transmissions present.

Bansal *et al.* [4] shows that in a stationary ad hoc network, the overall power assumption is a convex function of the number of hops for end-to-end TCP sessions and in some cases, network capacity is a concave function of transmission range. Though the insights are interesting, they are not used to direct the design of new protocols, leading to a lack of the "forward path" to close the "feedback loop". Towards this end, we identify a parameter, the *contention index*, that may be locally measured, rather than the node density in the previous work, which may not be estimated locally. Further, rather than a stationary ad hoc network, we consider node mobility in all of our performance evaluations.

Grossglauser *et al.* [5] focus on a mobile ad hoc network where the mobility pattern ensures that each node has the chance to eventually visit all other nodes in the network. As a result, at the expense of increased (possibly infinite) end-to-end delay, node mobility may be used to achieve multi-user diversity, which increases per-node throughput. In this work, we do not study the issue of "delayed deliveries", i.e., increasing network capacity at the expense of end-to-end delay.

The issue of topology control has been extensively addressed by previous work. As one example, Wattenhofer et al. [6] have proposed a fully distributed algorithm that only relies on directional information between nodes to decide the minimum transmission power required to ensure the connectivity of the network. However, the work does not consider other QoS parameters other than power efficiency and basic network connectivity. All existing work on topology control focus on power optimization in stationary wireless ad hoc networks, and do not consider the impact on other performance parameters. In comparison, the emphasis on optimal performance and consideration of node mobility are the highlights of our work.

III. The Contention Index

In our performance evaluations, we consider n *mobile* nodes (equipped with omni-directional antennas), each using the transmission range R, in a network deployed in an L by L square.

We formally define the *contention index* as *the number of nodes within the transmission range* (or the interference range, if different). This parameter is referred to as the contention index since it represents the potential congestion level in the local neighborhood. For the sake of simplicity and a functional MAC protocol, we assume that the transmission ranges on all nodes are identical. As such, the *contention index* is related to three parameters in the simulation setup: (1) the total number of nodes n; (2) the physical area of deployment L^2; and (3) the nodal transmission range R. Naturally, the contention in the network increases when there are more nodes in the network, or each node adopts a larger transmission range, or the network area size decreases.

With the *node density* D calculated as n/L^2, the contention index, CI, is the product of node density and area size of local transmission range:

$$CI = D\pi R^2 = \frac{n\pi R^2}{L^2} \tag{1}$$

We vary the *contention index* in the performance evaluations as a primary driving force, in order to measure its impact on the performance of the network in terms of network capacity and power efficiency.

IV. Performance Evaluation

We begin our studies by evaluating the bonding relationships between varying contention indices and QoS parameters in a mobile ad hoc network. The ns 2.1b8a network simulator is used to carry out the evaluations. There are 36 nodes randomly deployed in an L by L area. The nodes move following the random waypoint mobility model supported by ns2, where the nodes move at a bounded speed to a randomly selected destination with a pause time of 10 seconds. The traffic load in such a network is set to be 36 ftp sessions on top of the TCP protocol such that node 0 sends packets to node 1, node 1 to node 2, and so on, till node 35 to node 0. The power consumption of the wireless interface is set to be 0.395 W for receiving at all cases, 0.66 W for transmitting when the transmission range is 250 meters, and varies linearly with the transmission power.

The *contention index* CI varies with either one of the following: (1) the area size L which is in the range of $[210, 2658]$m while $R = 250m$; (2) the transmission range R which is in the range of $[80, 1000]$m while $L = 840m$. The total number of nodes, n, is set as 36 for both scenarios. In all simulations, we use IEEE 802.11 as the MAC protocol with a channel capacity of 2Mb/s and Dynamic Source Routing as the routing algorithm. We simulate for 600 seconds.

The network performance is evaluated by examining two metrics: (1) *network capacity* is defined as the total number of bytes of data successfully delivered to the destinations per time unit in the entire network; (2) *power efficiency* is measured by the energy (in Joules) consumed for each successfully delivered packet. We present the results of performance evaluation with respect to the the effects of *contention index* and *node mobility speed* on network performance.

A. Network Capacity

The bonding relationships between the contention index and the network capacity is presented in Fig. 1 and Fig. 2. Both diagrams use natural logarithmic scale to show the axis of contention index. As illustrated in the figures, we observe that the network capacity is a concave function of the contention index at a certain bounded speed.

It is observed that when *contention index* CI varies with L or R, the network capacity is maximized when CI is between 3 and 9. When CI is less than 3, the network is sparse such that many transmitted packets are dropped at the network layer due to non-existence of routes. Typically, when $CI = 1$, among the

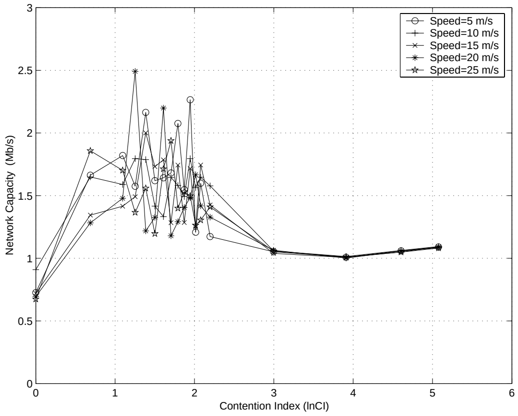

Fig. 1. Network Capacity vs. Contention Index (L varies)

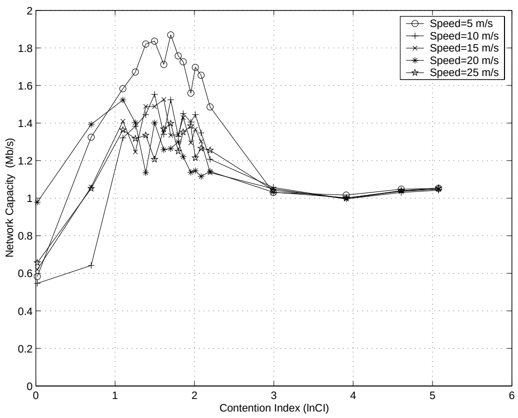

Fig. 2. Network Capacity vs. Contention Index (R varies)

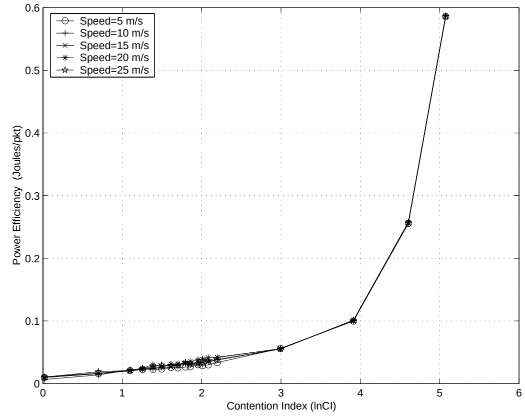

Fig. 3. Power Efficiency vs. Contention Index (R varies)

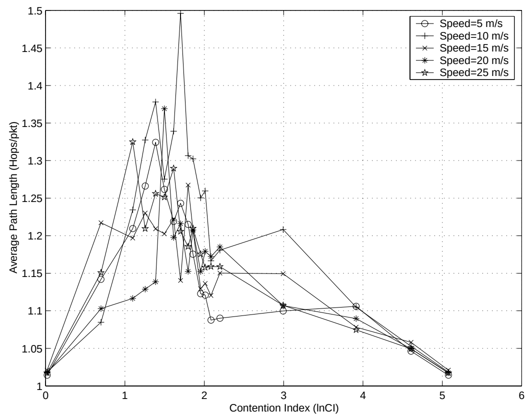

Fig. 4. Average Path Lengths vs. Contention Index (R Varies)

dropped packets, 90% occurs during routing and only 10% happens at the link layer. In comparison, when $CI = 50$, 12.5% of dropped packets are at the network layer and 87.5% occurs at link layer. This illustrates the trade-off between having weak connection at low CI and high contention in the shared channel at high CI. The optimization is achieved when CI is in $[3, 9]$ such that the network capacity is maximized. The above observation holds when CI is varied with either L or R, which leads to the conclusion that *contention index* is the primary driving force to affect network capacity rather than transmission range R itself.

Additional simulation results have shown that, despite that fact that network capacity decreases with the higher mobility speed when CI is low, the mobility speed tends to have minimal impact on network capacity when CI is higher than 20. No matter what the speed is, the network capacity is maximized when CI is in $[3, 9]$.

B. Power Efficiency

Fig. 3 depicts the relationship between contention index (in $\ln CI$) and power efficiency. It is perceived that when CI is in $[3, 9]$ such that network capacity is maximized, the power efficiency is close to optimal. In addition, when CI is lower than 3, the power consumption is the lowest at the cost of a low network capacity. This is because when $CI < 3$, the average hops of packet traverse is in $[1, 1.1]$ as in Fig. 4, which means it is impossible to establish a multi-hop path between source and destination in such a sparse network with the presence of node mobility. Successful packet transmission may only occur between two nearby nodes. Moreover, the transmission range at this state is short. As a result, the power efficiency is pretty high. On the other hand, when $CI > 9$, the average path length of successfully transmitted packet is also in the range $[1, 1.1]$ as in Fig. 4. However, this minimal length is achieved by having nodes employ a large transmission power which also cause collisions at the network link layer and subsequently more re-transmissions. As a result, power efficiency is low.

From the above results, we can conclude with the following observations. First, the network capacity is a concave function of the contention index and is maximized when contention index is in $[3, 9]$. Second, the power efficiency is a half convex function of contention index, and is close to optimal when the contention index is the same range $[3, 9]$. Third, the range of optimal contention indices does not change with mobility speed. Finally, the mobility speed of nodes do have minor impact on network performance with respect to network capacity and power efficiency when $CI \geq 20$.

We conclude with the statement that, *it is the contention index, rather than the transmission range on each node, that is the primary and independent driving force that influences the network performance*. This result holds for QoS parameters such as the network capacity and power efficiency. We note that, in real-world ad hoc networks, due to the diversity of the physical, MAC and routing layer protocols and parameters, the actual optimal contention index may not be identical as was observed in this section. However, our conclusion still holds in that: (1) there exist an optimal value of contention index corresponding to a specific QoS parameter; and (2) such optimal value may be measured using off-line experiments, and is an inherent property that will not change over the lifespan of the network. Such insights promote our work to design a fully distributed topology control algorithm to achieve the best possible network performance, with respect to at least one of the network parameters. By tuning the transmission ranges on each of the nodes, we have effectively adjusted and maintained the contention index around its optimal values. With this idea, we next present the MobileGrid algorithm.

V. MOBILEGRID ALGORITHM

We now propose a simple, yet effective, distributed topology control algorithm, *MobileGrid*, for nodes in mobile ad hoc networks to make fully localized decisions on the optimal transmission range to maintain an optimal contention index, so that the network capacity is optimized.

It is hard for a node to compute the network contention index using Eq. (1) accurately, due to the lack of *global knowledge* on either the number of nodes or the physical area of deployment. Even if it manages to obtain such knowledge, the communication and computation cost of dynamically updating the knowledge is overwhelming, which the nodes can ill afford. That said, since n/L^2 is the number of nodes per unit area and πR^2 is the radio coverage area of a node, we know that the average number of nodes in a node's transmission range, N, is given by $N = n/L^2 * \pi R^2 - 1 = CI - 1$. Thus, by knowing how many neighbors a node has, the node can estimate the contention index. Based on this observation, our distributed topology control algorithm, *MobileGrid*, is implemented as a three-phase protocol, executed at each node periodically (by the end of each time window) to accommodate node mobility.

Phase 1. *Estimating Contention Index*

A node starts to discover its neighbors at the MAC layer with its current transmission power (or maximum power at $0th$ time window) by overhearing both control (e.g. RTS/CTS/ACK) and data messages. Since the header of each message contains the source node ID, the node may compute the number of unique node IDs that it may overhear over the time window. Such a set of unique node identifiers forms the set of *neighbors* that the node may find. Such a passive approach does not introduce additional overhead to the existing network traffic. Obviously the node may not be able to detect "silent" nodes in the neighborhood that did not transmit any control or data messages. We argue that, since such silent nodes did not inject network traffic in the current time window, the possibility that they start to transmit in the next time window is low. In this case, the calculation of contention index may safely ignore such nodes.

As discussed earlier, if the discovered number of neighboring nodes is N, the estimated contention index CI is $N + 1$.

Phase 2. *Looking up Optimal Values of the Contention Index*

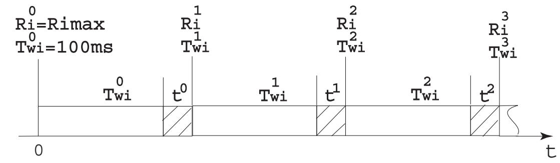

Fig. 5. Time Sequence at Node i

Each node looks up in a particular *optimization table* to determine if it is operating around an optimal value of contention index. The table stores the optimal values of *contention index* to maximize the network capacity, which we may obtain from off-line experiments using identical physical, MAC and routing layer characteristics and parameters. Since the optimal contention index is an inherent property that does not vary much when changing node mobility, we may safely assume that such an optimization table may not need to be updated frequently.

With respect to an interested QoS parameter such as network capacity, if the contention index it has estimated from the first phase does not fall into the specific optimal range in the table, the node proceeds to the next phase to adjust its transmission range. Otherwise, the current transmission range is adopted for the next time window.

Phase 3. *Transmission Range Adjustments*

If, in the second phase, a node decides that its current transmission range is not optimal by a table look-up, it uses the following scheme to eventually keep it checked within the range of optimal contention index values. If the contention index CI calculated in the first phase is out of the optimal range in the optimization table (either smaller than the lower bound or higher than the upper bound), the node tunes the transmission power R as illustrated in Eq. (2):

$$R_{\text{new}} = \min\left(\sqrt{\frac{CI_{optimal}}{CI_{current}}} * R_{current}, R_{max}\right) \qquad (2)$$

where R_{max} is the maximum transmission range decided by the physical layer and radio characteristics, and CI_{optimal} is chosen as the median point of the optimal range in the table. This scheme guarantees convergence towards either the maximum range R_{max}, or the optimal range of contention indices, whichever appears earlier.

Fig. 5 illustrates the time sequence at node i. The notation R_i^k represents the transmission power of node i at kth time window; T_{wi}^k stands for the length of time window at node i at the kth time window; t_i^k is the execution time of Phase 2 and Phase 3 MobileGrid algorithm at node i by the end of kth time window.

Initially, at time 0, node i uses the maximum transmission power R_{imax} to build its neighbors list over the initial time window T_{wi}^0 which is a random number between $100ms$ and $200ms$ (or other representative values). Upon the expiry of T_{wi}^0, node i spends t_i^0 time on the table look-up and adjusting the transmission power according to the MobileGrid algorithm. Meanwhile, it calculates the duration of the next time window. Sequentially, node i uses the resulted R_i^1 as transmission range, and T_{wi}^1 as time window for next iteration.

The calculation of time window T_w^{k+1} by the end of kth

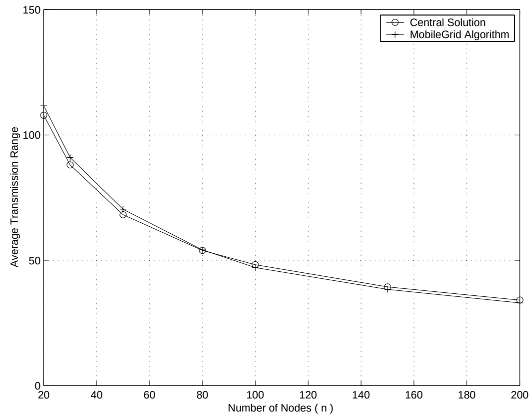

Fig. 6. Centralized Solution vs. MobileGrid (Average Transmission Range)

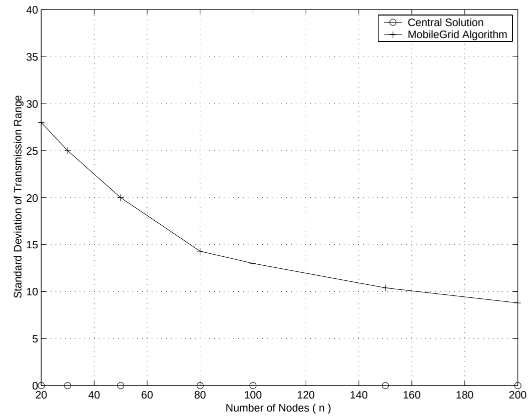

Fig. 7. Centralized Solution vs. MobileGrid (Standard Deviation of Transmission Ranges)

time window is to minimize the probability of occurrences of the race condition between itself and neighboring nodes, denoted as P_{conf}. Given that node i has N neighboring nodes, $P_{conf} = \sum_{j=1}^{N} (\frac{t_j^{k+1}}{T_{wj}^{k+1}+t_j^{k+1}} * \frac{t_i^{k+1}}{T_{wi}^{k+1}+t_i^{k+1}})$. To simplify the problem and reduce overhead, node i assumes it requires the same t_i during different iterations and surrounding nodes employ similar T_w and t_i as itself. It may be derived that

$$T_{wi}^{k+1} \approx (\frac{\sqrt{N}}{\sqrt{P_{conf}}} - 1) t_i^k$$

To conclude, regarding the transmission range adopted by node i in various iterations running the MobileGrid algorithm, we have:

$$R_i^k = \begin{cases} R_{imax} & k = 0; \\ \min(\sqrt{\frac{CI_{optimal}}{CI_i^{k-1}}} * R_i^{k-1}, R_{imax}) & k \geq 1. \end{cases}$$

VI. Experiments on the MobileGrid Algorithm

In order to evaluate if *MobileGrid* works as effective as the centralized solution in previous performance evaluations (Sec. IV), we use a snapshot of a wireless ad hoc network in an area of 350 meters by 350 meters where each node's maximum transmission range is 200 meters. The number of nodes in such a network varies from 20 to 200. Network capacity is chosen to be optimized and the optimal contention index CI is set to be 6.

Both the *average transmission power* and *standard deviation of transmission powers* are measured in the experiments, where *average transmission power* is calculated as the sum of transmission powers at each node divided by number of nodes in the network, the *standard deviation of transmission powers* is calculated to demonstrate how diverse are the transmission ranges among all network nodes.

Fig. 6 demonstrates the respective *average transmission range* in the resulted topology based on the *centralized solution* and *MobileGrid algorithm*, respectively. We observe that the two curves are very close to each other, which means that MobileGrid performs nearly as well as the centralized solution. Furthermore, this observation does not change with the total number of nodes.

In the *centralized solution*, all nodes are supposed to adopt a uniform transmission range. Hence, in Fig. 7, the curve for the centralized solution is flat with values of 0. However, in MobileGrid, the standard deviation of transmission powers is always positive — since the network is not evenly distributed, different nodes adopts different powers to cover the same number of neighboring nodes. As we may observe, the standard deviation of transmission powers tends to decline with the denser nodes in the network.

VII. Conclusions

In this paper, we introduce an interesting decisive parameter, *contention index*, within the scope of mobile ad hoc networks. Via extensive performance evaluations, it is found that the *contention index* is the primary driving force that influences the network performance with respect to *network capacity* and *power efficiency*. Furthermore, optimal values of the contention index does exist to optimize the network performance. MobileGrid, a distributed topology control algorithm, is proposed to ensure optimality regarding the contention index. It is proved to be effective by our simulation results.

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