Competition, Cooperation, and Optimization in Multi-Hop CSMA Networks with Correlated Traffic

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The purpose of this paper is to present a new method for the study of the competition and cooperation relationships among nodes in a network using a CSMA (Carrier Sense Multiple Access) protocol implemented with an exponential backoff process. Self-organized behavior is proposed. Standard topologies, such as tandem, traffic splitting and merging, are studied with variables: 1) backoff rate, 2) topology position, 3) traffic splitting. Several interesting phenomena are reported. We propose a "Channel Utilization Model" with a new derived variable "channel access rate" which can be used for all traffic loads. These models are applied with different optimization methods. Special strategies, for example "MAC Friendliness" [Shi et al. 2007], are also presented for serving special traffic like emergency traffic.

Keywords: CSMA, QoS, Matrix Exponential, Wireless Mesh Networks

1. INTRODUCTION

For multihop wireless networks to support various applications, a balance of control overhead and traffic throughput must be obtained. A very simple approach to the MAC layer in such networks is to use a Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) mechanism. In such an approach, nodes sense the wireless channel then backoff and try again later according to some random process if they find the channel busy. This type of approach minimizes the need for a central controller, reservation protocols, or transmission of control packets. In some situations, a centralized controller is not even possible. The main drawback of CSMA/CA, however, is concerns about the level of throughput that can be obtained for general network topologies. The behavior of a node in the network will affect the communication capabilities of other nodes in its interference range, most notably because the radio communication channel must be shared in wireless networks. Changing each node's parameters will affect the others' attempts to use the channel and the other nodes' quality of service (QoS). In some special situations, e.g., natural disasters and battlefields, the nodes will have self-organized behavior and could be divided into different groups based on different QoS requirements, such as end-to-end throughput or end-to-end delay. The groups can then implement special strategies to adapt their transmission rate or CSMA backoff processes.

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1.1 Contributions of this work

First of all, this work provides a new understanding of performance effects from competition and cooperation relationships among nodes in a CSMA network based on the QoS requirements on different nodes/paths. Definitions of "dominance", "friends", "enemies", and "pendulums" are presented from first derivative and clique methods so nodes can know the relative effects that changing parameters would have on other nodes. Furthermore, analysis shows there exists self-organized behavior in nodes' competition and cooperation. A set of variables: 1) backoff rate in each node, 2) topology position, 3) traffic distribution on different paths, are used in this analysis. The topology position is defined as a relative position, such as, node 1 is 3 hops away from node 4.

The second contribution is that this work provides a detailed investigation of tandem, splitting, and merging topology elements within a network. Several interesting phenomena are reported. Actual networks may have a combination of these elements and the insights from our work can be combined for those topologies.

In the tandem topology, the backoff process at each node can substantially influence the overall throughput. Certain nodes, like the first node and, interestingly, the first node that is more than two hops away from the first node, must have carefully chosen parameters. We analyze the backoff process at each node, mainly in terms of the engineered backoff rates, and provide optimizations for the end-to-end throughput. Contrary to what might be assumed, the total length of a tandem network is not the limiting factor in overall throughput. Instead, what has the main effect is the number of nodes in interference ranges of each other.

In a splitting and merging topology, the effect of unbalanced traffic distribution on different interfering paths and the effect of downstream or upstream node relationships within a topology is analyzed. A strategy for traffic distribution on different paths is presented. In all topologies, parameter settings in the upstream nodes have more effect on end-to-end throughput than the downstream nodes; the same is true with bottleneck nodes.

The third main contribution is the development of tractable mathematical models. These models can then be used either by network designers or even the network elements themselves to control the above three variables. Extended from [Shi et al. 2009], a channel utilization model with a new defined variable "channel access rate" which is presented in this paper, is applicable for all traffic loads. This model is an improvement compared to other works which only assume heavy load. The Markov chains provided in this paper are specific to the related topologies. However, using the same methodology, a similar Markov chain can be created for any topology.

The models that are presented here can be applied with Particle Swarm Optimization (PSO) and Game Theory to find optimal solutions. Other heuristic algorithms can also be applied based on our model. Choice of which one to use would depend on differences in their implementation complexity, desired modeling accuracy, and computation time. Meanwhile, these models has strong extensibility because more variables, such as power cost, can be included. Finally, we build on the concept of "MAC Friendliness" to extend it to a multi-hop topology.

The main purpose of this paper is to analyze competition, cooperation, self-organization, and optimization in a Multi-Hop CSMA Networks. We follow most of assumptions in [Boorstyn et al. 1987] and [Wang and Kar 2005], for example, interference comes from nodes less than or equal to two hops from a given node. This paper assumes nodes are either in range or out of range. Follow on work, however, could easily incorporate physical layer models that depend on distance, modulation schemes, or fading.

1.2 Related work

Bianchi [Bianchi 2000] first proposed a two dimensional discrete Markov Chain to model the CSMA/CA IEEE 802.11 protocol, with many follow-up papers. The key approximation in the model assumes heavy traffic load, which means at each transmission attempt, and regardless of the number of retransmissions suffered, each frame collides with constant and independent probability. Many papers use game theory to analyze the performance of CSMA networks and still use the same assumption, e.g., [M. Cagalj and Hubaux 2005] by Cagalj, Ganeriwal, Aad, and Hubaux. In [Lauwens et al. 2010], Ben Lauwens, Bart Scheers, and Antoine Van de Capelle proposed a novel analytical model for the saturation throughput of an unslotted CSMA/CA protocol. The models, presented in [Shi et al. 2009] and [Shi et al. 2008], is not just for heavy traffic, but also for light and medium traffic loads, and the collision probability varies at different backoff stages. Also the model in [Shi et al. 2008] captures the space, backoff and flow correlation in CSMA wireless networks, which is specially useful in game theoretic analysis. In this paper, we extend the node analytical model presented in [Shi et al. 2008] to an optimization channel utilization model for optimization purposes. This extended optimization channel utilization model is similar with the model presented in [Boorstyn et al. 1987] in appearance, but the improvement is the new derived formula to calculate the packet arrival rate to the "channel" under all traffic loads. The performance can be accurately predicted under different traffic loads, instead of using the heavy load assumption used in many other papers.

In [Xu and Saadawi 2001], Xu and Saadawi concluded that the current version of the IEEE 802.11 CSMA wireless LAN protocol does not function well in multi-hop ad hoc networks. So how to optimize it is the next problem. In [Boorstyn et al. 1987], Boorstyn, Kershenbaum, Maglaris, and Sahin claimed that an upper bound on throughput is $\frac{1}{5}$ in a chain topology. In [Medepalli and Tobagi 2006], Medepalli and Tobagi found that Exponential Backoff (EB) plays a much smaller role in flow starvation when compared to the minimum contention window (CWmin). In [Li et al. 2001], Li, Blake, De Couto, Lee, and Morris showed that achievable capacity depends on network size, traffic patterns, and detailed local radio interactions. This paper follows this direction and studies optimal solutions for several factors, e.g., back off process and routing strategy, to network performance. We study tandem, traffic merging, and traffic splitting topologies and the steady state conditions of the network. Also the dominance of the upstream nodes over the network is analyzed. And the competition among different paths is addressed. The preliminary work is available in [Shi et al. 2011].

In [Luo et al. 2000], Luo, Lu, and Vaduvur proposed new centralized packet scheduling models to ensure fair allocation of basic channel service while seeking to maximize spatial reuse. Then they design a backoff-based distributed implementation which closely emulates the ideal centralized algorithm. In [Wang and Kar 2005], Wang and Kar proposed a throughput model based on Markov analysis, and throughput approximations based on local topology information. In [Rajagopalan et al. 2009], Shreevatsa Rajagopalan and Devavrat Shah and Jinwoo Shin developed a distributed algorithm building upon a Metropolis-Hastings sampling mechanism along with selection of 'weight' as an appropriate function of the queue-size with a novel adiabatic like theorem. M. Brahma, K. W. Kim, A. A Bouaissa, and P. Lorenz present a load-balancing and push-out scheme to support Quality of Service in [Brahma et al. 2005]. In [Ashraf et al. 2011], Usman Ashraf, Slim Abdellatif, and Guy Juanole propose a novel routing metric Expected Link Performance for wireless mesh networks to select the best end-to-end route. In this work, we presented optimal solutions based on distributed self organized strategies.

In [Michele Garetto and Knightly 2006], Garetto, Salonidis and Knightly showed that the fundamental cause is not merely differences in the number of contending neighbors, but a generic coordination problem of CSMA-based random access in a multi-hop environment. But they only consider the case in which all traffic produced or relayed by a node is directed to a single neighboring node. In [Shi et al. 2008], Shi, Gurewitz, Mancuso, Camp, and Knightly identified severe throughput imbalances between one-hop flows and two-hop flows for gateway access.

In [Srivastava et al. 2005], V. Srivastava and other authors proposed game theory to be a very good tool for performance analysis and optimization in CSMA networks like ours because it captures the effects of the interaction among the nodes. Also in [Felegyhazi and Hubaux 2006], Felegyhazi and Hubaux introduced the most fundamental concepts of non-cooperative game theory in wireless networks. In [M. Cagalj and Hubaux 2005], Cagalj, Ganeriwal, Aad, and Hubaux use a game-theoretic approach to investigate the problem of selfish behavior of nodes in IEEE 802.11. They characterize two families of Nash equilibria in a single stage game, one of which always results in a network collapse. They develop a simple, localized and distributed protocol that successfully guides multiple selfish nodes to a Pareto-optimal Nash equilibrium. In our work, we analyze the competition among nodes in a continuous time CSMA/CA network in which the network collapse can be avoided. Also some cooperative strategies are proposed to improve the end-to-end QoS.

Kennedy and Eberhart first propose a Particle Swarm Optimization (PSO) algorithm in [Kennedy and Eberhart 1995] for the optimization of a nonlinear function, which is useful for our problem since the equations are iterative and non-linear. Also [Clerc and Kennedy 2002] analyzes a particle's trajectory as it moves in discrete time (the algebraic view), then progresses to the view of it in continuous time (the analytical view). PSO algorithm is applied to search for the optimal backoff rate to maximize the end-to-end throughput. PSO is a useful algorithm in this work because of 1)multi-variant, 2)non-linear characteristics in this problem.

In Section 2, we introduce a node analytical model of a continuous-time protocol which was published in [Shi et al. 2008] and a channel utilization model with a new variable, "channel access rate", which works for all traffic loads. This node analytical model and channel utilization model are very useful because they capture the space, backoff, and flow correlation in CSMA wireless networks. For different topologies, the same methodology can be applied to generate the corresponding Markov chains for performance analysis. This methodology can be applied to any topology. In Section 3, the competition and cooperation relationship among nodes in a tandem and a traffic splitting topology are deeply studied. Two methods, one is "first derivative" and another one is "flow and resource contention graph" are presented to analyze the competition and cooperation relationship.

Then we apply node analytical model and channel utilization model as the calculation kernel for the algorithms presented in Section 4 and 5. In Section 4, a PSO algorithm is used to provide numerical optimal solutions for performance of a tandem topology. In Section 5, the traffic splitting and merging topologies are considered with numerical optimal solutions, along with how to set $p_{i,j}$, the ratio of the traffic to go through node i for path j. These results are particularly fascinating. In Section 6, a new concept, "MAC Friendliness" in a multihop environment, is proposed. The purposes of "MAC Friendliness" are: 1) optimize the channel utilization, and 2) guarantee fairness and priority among different types of traffic. Section 7 concludes our work.

2. NODE ANALYTICAL MODEL AND CHANNEL UTILIZATION MODEL

In this section, we first present a node analytical model based on continuous-time protocols that provides a close approximation to discrete-time CSMA/CA systems like IEEE 802.11 [Shi et al. 2007]. Then we provide a channel utilization model. Both of node analytical model and channel utilization model will be used as the calculation kernel for optimization algorithms in later section.

2.1 Node Analytical Model

Nodes sense the channel and wait a random backoff time then try again. After trying G times, the node drops of the packet if unsuccessful. The reciprocal of the backoff time is the backoff rate, which can be understood as the rate at which the node tries to use the channel after backoffs; this is the main parameter of interest in this paper. Both a single node Markov chain and a channel Markov chain are created, then an iterative solution method is used to find a common solution. This model, and variations of it, will be used to obtain insights for various network topologies.

We use a continuous-time model, one benefit of which is its resistance to misbehaving nodes [Shi et al. 2009]. In [M. Cagalj and Hubaux 2005], it was shown that if there exist two cheaters in a discrete-time system like IEEE 802.11 who set their contention window size equal to one, the network throughput will collapse. One advantage of continuous-time CSMA/CA over a time-slotted network is that even if there exist multiple cheaters who set their backoff rates comparatively high, the network will not collapse because no two events can occur at the same time. This prevents the situation where a node can monopolize the channel.

Now we specify the following notation and assumptions:

1) λ_i: The frame arrival rate at Node i to the MAC layer is exponentially distributed with average rate λ_i.

2) b_i: The backoff rate is exponentially distributed with average rate b_i, where i is the node id. Random backoff in the MAC layer could be implemented according to any random variable, but it is advantageous here to use the exponential random variable to facilitate analysis. Besides, in [Kleinrock and Tobagi 1975] Kleinrock and Tobagi have shown for CSMA that "only the first moment of the *retransmission delay distribution* has a noticeable effect on the average

throughput-delay performance". So in our paper, the exponential distribution is used for the backoff process.

3) s_i: The frame service rate for Node i is exponential with average rate s_i. For simplicity, we set all s_i equal to each other, with notation s. But if one wishes to incorporate wireless channel conditions (distance, shadowing, fading), one would only need to set s_i to the service rate a channel would attain.

4) $\delta_{i,g}$ is the probability that the channel is busy when one node finishes the current backoff stage and tries to access the channel, so is defined as the collision probability. Different backoff stages have different collision probabilities which are denoted as $\delta_{i,g}$ for each node. Here i is the node id, $g = 1 \cdots G$ is the backoff stage. Many papers assume that the collision probability is the same at each backoff stage, but we do not make this assumption. If in a second backoff stage, a node has already collided with another node and is likely to collide with that node again.

5) Q_i is the queue length of the ith node.

6) γ_i is the probability that Node i starts a new backoff process immediately after having a collision in the last backoff stage (i.e., the frame is dropped) for the current backoff process. So, $1 - \gamma_i$ is the probability that Node i goes into idle state immediately after having a collision in the last backoff stage for the current backoff process.

7) ζ_i is the probability that Node i starts a new backoff process immediately after finishing *sending* the current frame. So, $1-\zeta_i$ is the probability that Node i goes into idle state immediately after sending the current frame.

8) π_i is the state probability in a Markov Chain for state i.

The other assumptions following [Boorstyn et al. 1987] and [Wang and Kar 2005] are:

1) The propagation delay between neighboring nodes is zero.

2) Under CSMA/CA, a node will transmit a scheduled packet if it detects an idle channel.

3) Links are error free. A packet will be successfully transmitted only if there is no collision.

4) The lengths of RTS and CTS are small enough so their transmission delay can be ignored. Acknowledgements are obtained instantaneously.

5) The transmission interference range is two hops.

Fig. 1(a) illustrates the a Markov chain that models idle, backoff and sending states in a 3-node tandem (straight-line) wireless network topology. For each node there is a single backoff stage. Each node can be in state 0(idle), $B1$(backoff), or S(sending). For example, state "$(B1, S)$" indicates the network state where Node 1 is in its first backoff stage and Node 2 is sending. The third node is the sink, so those states are not shown here. Notice that state (S, S) doesn't exist because Nodes 1 and 2 are in the interference range of each other. In the wireless network environment, any pair of nodes in the interference range of each other cannot be in sending state at the same time.

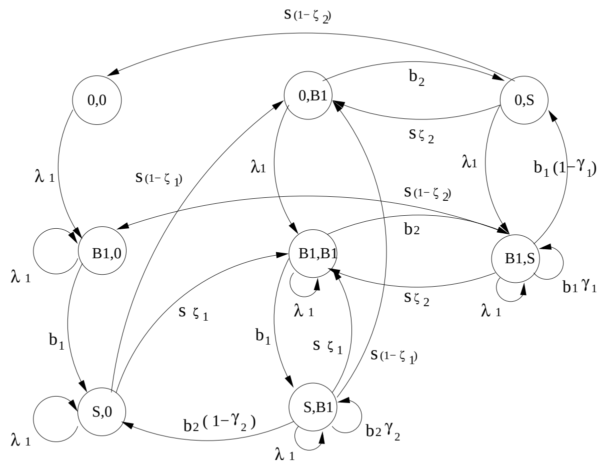
Fig. 1(b) illustrates the Markov chain for one node using the CSMA process modeled in our paper. Queue fill increases horizontally to the right, and backoff stages increase downward. Each state signifies number of frames in the system, backoff or sending state. The operation of the model is illustrated, for example, by considering state "$(q, B1)$". In this state, q frames are in the system, and the node is in the first backoff stage. The node transfers to the sending state "(q, S)" if when it finishes backoff the channel is idle.

A iterative method is used to calculate the collision probability, then the queue fill probability by using this node analytical model. Detailed formulas can be seen in [Shi et al. 2008].

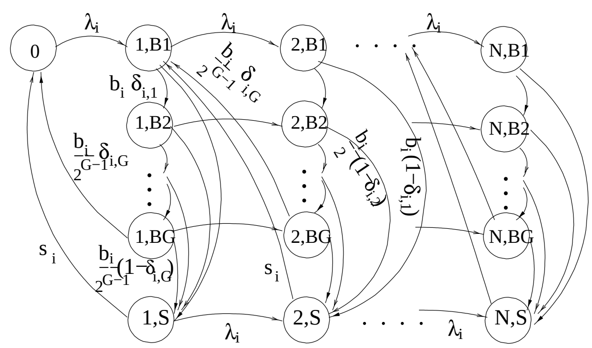
2.2 Channel Utilization Model

In this subsection we will introduce a channel utilization model. The node analytical model introduced in subsection 2.1 is used to calculate the queue fill probability and channel utilization for each node. They are the basis for the channel utilization model. The channel utilization model is used to describe how the nodes share the channel and its variations can be used for competition, cooperation and self-organization analysis.

We first define a new variable r_i, which is the average rate that Node i to go from the state



(a) Channel markov chain with idle, backoff and sending states.



(b) Single node markov chain with the multi-stage back off process.

. Markov chain of node analytical model

that represents not using the channel to the state that represents using the channel.

$$r_i = \frac{b_i \ (1 - \pi_{i,0} - \pi_{i,s})}{1 - \pi_{i,s}}, \tag{1}$$

Formula (1) could be used in all ranges of traffic loads.

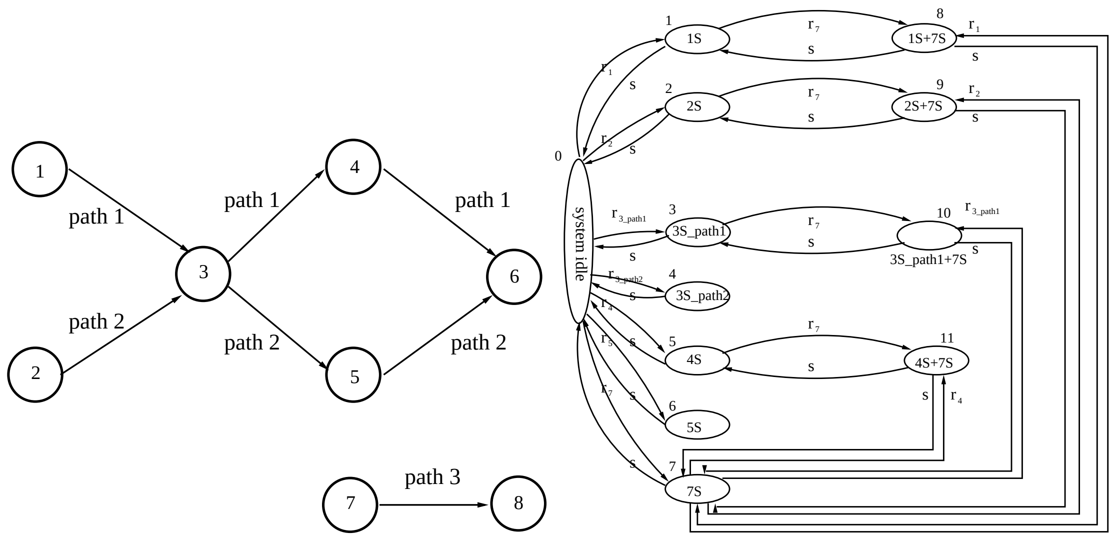
In Fig. 2(a), we show an 8-node 3-path network topology. Fig. 2(b) is the corresponding channel utilization model. This shows how the channel goes from idle to busy from activity of the different nodes. The variable r_i, "channel access rate", is the average rate that Node i goes from not using the channel to using the channel which is defined in formula (1). The sending rate is s. The state "channel idle" means no node is using any channel. State "1S" represents only Node 1 is sending, also "1S+7S" represents Nodes 1 and 7 are using the channel. Define $\boldsymbol{\pi}_{i,s}$ as the probability Node i is sending (Node i's channel utilization), which can be found from each $\boldsymbol{\pi}_j$, the state probability in Fig. 2(b) (j values are from the small numbers above each state).

In Fig. 2(b), we have:

$$\boldsymbol{\pi}_{1,s} = \boldsymbol{\pi}_1 + \boldsymbol{\pi}_8,$$

$$\boldsymbol{\pi}_{2,s} = \boldsymbol{\pi}_2 + \boldsymbol{\pi}_9,$$

$$\boldsymbol{\pi}_{3,s} = \boldsymbol{\pi}_3 + \boldsymbol{\pi}_4 + \boldsymbol{\pi}_{10},$$



(a) 8-node, 3-path topology.

(b) Channel Utilization Model in a 8-node, 3-path network.

. Network topology I

$$\boldsymbol{\pi}_{4,s} = \boldsymbol{\pi}_5 + \boldsymbol{\pi}_{11},$$

$$\boldsymbol{\pi}_{5,s} = \boldsymbol{\pi}_6,$$

$$\boldsymbol{\pi}_{7,s} = \boldsymbol{\pi}_7. \tag{2}$$

Those packets that are successful are those that do not fail over G backoff stages at any node on a path. G is the number of backoff stages. $\delta_{i,1}, i = 1...N$ are defined as the collision probability in the first backoff stage at each node i as follows:

$$\delta_{1,1} = \boldsymbol{\pi}_{2,s} + \boldsymbol{\pi}_{3,path1,s} + \boldsymbol{\pi}_{3,path2,s} + \boldsymbol{\pi}_{4,s} + \boldsymbol{\pi}_{5,s}, \tag{3}$$

$$\delta_{2,1} = \boldsymbol{\pi}_{1,s} + \boldsymbol{\pi}_{3,path1,s} + \boldsymbol{\pi}_{3,path2,s} + \boldsymbol{\pi}_{4,s} + \boldsymbol{\pi}_{5,s}, \tag{4}$$

$$\delta_{3,1,path1} = \boldsymbol{\pi}_{1,s} + \boldsymbol{\pi}_{2,s} + \boldsymbol{\pi}_{4,s} + \boldsymbol{\pi}_{5,s}, \tag{5}$$

$$\delta_{3,1,path2} = \boldsymbol{\pi}_{1,s} + \boldsymbol{\pi}_{2,s} + \boldsymbol{\pi}_{4,s} + \boldsymbol{\pi}_{5,s} + \boldsymbol{\pi}_{8,s}, \tag{6}$$

$$\delta_{4,1} = \boldsymbol{\pi}_{1,s} + \boldsymbol{\pi}_{2,s} + \boldsymbol{\pi}_{3,1,path1} + \boldsymbol{\pi}_{3,1,path2} + \boldsymbol{\pi}_{5,s}, \tag{7}$$

$$\delta_{5,1} = \boldsymbol{\pi}_{1,s} + \boldsymbol{\pi}_{2,s} + \boldsymbol{\pi}_{3,1,path1} + \boldsymbol{\pi}_{3,1,path2} + \boldsymbol{\pi}_{4,s} + \boldsymbol{\pi}_{7,s}, \tag{8}$$

$$\delta_{7,1} = \boldsymbol{\pi}_{3,1,path2} + \boldsymbol{\pi}_{5,s}. \tag{9}$$

$\delta_{i,g}$ for backoff stages $g > 1$ can be approximated related by formula (10).

$$\delta_{i,g} = \delta_{i,1}\frac{s}{s+b_i} + \frac{b_i}{s+b_i}, \tag{10}$$

Based on the above description, (3) to (9) are for collision probability $\delta_{i,g}$. If desired, the constraints could also include bounds for end-to-end delay for specific paths.

The tested arrival rate and resulting throughput are presented in Table I. To verify the accuracy of these results, we compare them with simulation results. The channel transmission rate in our simulator, s, is 200 frames/sec.

Table I. Total Network Throughput with Respect to Different λ

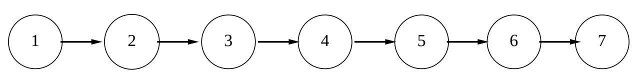
$\lambda 1$	$\lambda 2$	$\lambda 7$	Model total thp	Simu total thp	Path 1 thp	Path 2 thp	Path 3 thp
5	15	22.5	38.18	37.04	4.45	12.46	20.12
10	10	22.5	38.44	37.26	8.71	8.37	20.18
15	5	22.5	38.79	34.65	9.73	4.83	20.09

The channel utilization model is developed specifically from a specific topology (in this case it is a Tandem topology). However, this methodology can be applied to any topology. The node analytical model and channel utilization model are applied as the kernel calculation models in optimization algorithms presented in later section.

3. COMPETITION, COOPERATION AND SELF-ORGANIZATION

In this section, a study on the competition, cooperation and self-organization characteristics is provided. A "first derivative" method is provided for a 7-node tandem topology. Flow contention graph and resource contention graph are presented for a traffic splitting topology. New concepts, such as "friend" and "enemy", are defined.

3.1 Throughput analysis in the tandem topology with arrivals at each node



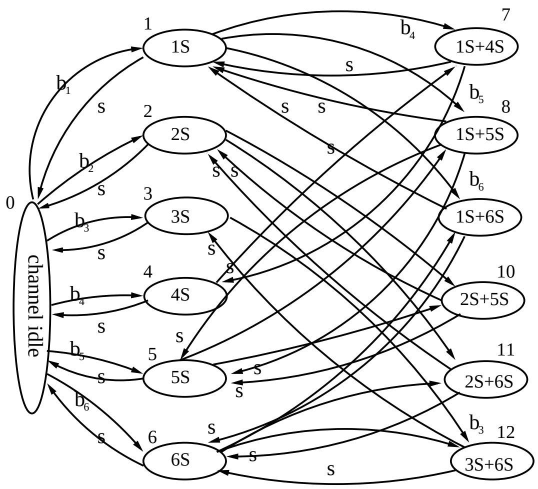
. 7-node tandem topology.

Fig. 3 shows a 7-node tandem topology. In this example, we use a simplified queueing model that each node only has two states: backoff(b) or sending(s). This means nodes only undergo a single backoff stage and then drop the packet if not successful. This allows us to view the channel states of a 7-node tandem network according to the channel utilization model given in Fig. 4. The state "channel idle" means no node is using the channel. State "1S" represents only Node 1 is sending, also "1S+4S" represents Nodes 1 and 4 are using the channel. The states represent combinations of how one or two nodes can be sending simultaneously. It assumes that each node uses "rational selfishness", which means each node changes its backoff rate while only being concerned with maximizing its own throughput. For this model, we also assume that each node has its own arrival traffic and is in a heavy traffic condition, thus each node always has frames in its queue. Combined with formula (1), $\pi_{i,0} = 0$ because of heavy traffic condition (i.e., it is never idle), which makes $r_i = b_i$. The channel utilization model is developed for a specific topology (in this case it is a Tandem topology). However, this methodology can be applied to any topology. This model is similar to Fig. 1(a), that to make the model tractable, backoff states are not included, only sending states.

The solution for this simplified system is:

$$\pi_{1,s} = \frac{b_1(s + b_4 + b_5 + b_6)}{D},\ \pi_{2,s} = \frac{b_2(s + b_5 + b_6)}{D},$$

$$\pi_{3,s} = \frac{b_3(s + b_6)}{D},\ \pi_{4,s} = \frac{b_4(s + b_1)}{D},$$



. Channel Utilization Model in a 7-node tandem network

$$\pi_{5,s} = \frac{b_5(s+b_1+b_2)}{D},\ \pi_{6,s} = \frac{b_6(s+b_1+b_2+b_3)}{D}. \tag{11}$$

Where D is

$$D = s^2 + s\ b_1 + s\ b_2 + s\ b_3 + s\ b_4 + s\ b_5 + s\ b_6$$

$$+b_5\ b_1 + b_6\ b_1 + b_4\ b_1 + b_6\ b_3 + b_6\ b_2 + b_5\ b_2 \tag{12}$$

If we set the optimization objective function for the tandem topology to address each node's channel utilization, respectively, there are six optimization problems:

$$Maximize\ \ \boldsymbol{\pi}_{i,s},\quad i = 1...6 \tag{13}$$

which means that each node tries to maximize its sending probability, and therefore utilization of the channel and throughput. With constraints:

$$\boldsymbol{\pi}_{j,s}\ > 0, j = 1...6 \quad b_j > 0 \tag{14}$$

Then perform optimization and the results are presented in Table II. From formula (11), each node will increase its backoff rate, b_i, to maximize its channel utilization, which will result in a choice of b_i which is comparatively larger than the channel sending rate, s. Node 1 is the dominant node and its backoff rate selection affects the throughput of all of the downstream nodes. It must, however, share the channel with Nodes 2 and 3. Because each node has its own arrival traffic, the distribution of channel utilization is symmetric from Nodes 1 to 3 then Nodes 4 to 6.

Table II. $\pi_{i,s}, i = 1...6$ Optimized channel utilization for rational selfish nodes

$\pi_{1,s}$	$\pi_{2,s}$	$\pi_{3,s}$	$\pi_{4,s}$	$\pi_{5,s}$	$\pi_{6,s}$
$\frac{1}{2}$	$\frac{1}{3}$	$\frac{1}{6}$	$\frac{1}{6}$	$\frac{1}{3}$	$\frac{1}{2}$

3.2 Competition analysis in a 7-node tandem topology

Now let us use this model to consider how all nodes maximize their own channel utilization by changing backoff rates respectively. We find the first derivatives of $\pi_{i,s}, i = 1...6$ with respect to $b_j, j = 1...6$ and the important characteristics are shown in Table III, which shows whether first derivatives are proportional to $\frac{1}{b}$ or $\frac{1}{b^2}$ and if the slopes are negative or positive. As we stated before, each node is "rationally selfish", each node increases its backoff rate b_i to values much larger than s, and we can assume all of the b_i are the same order of magnitude. For example, if b_1 increases then $\pi_{2,s}$, $\pi_{3,s}$, and $\pi_{6,s}$ decrease proportionally to $\frac{1}{b_1}$ and $\pi_{4,s}$ increases proportionally to $\frac{1}{b_1}$. A '*' in this table means it could be $\pm \propto (\frac{1}{b_i})$ or $\pm \propto (\frac{1}{b_i^2})$, depending on the values of b_i.

Table III. $\pi_{i,s}, i = 1...6$ First Derivatives with Respect to $b_j, j = 1...6$

	$\pi_{1,s}$	$\pi_{2,s}$	$\pi_{3,s}$	$\pi_{4,s}$	$\pi_{5,s}$	$\pi_{6,s}$
b_1	$\propto (\frac{1}{b_1})$	$- \propto (\frac{1}{b_1})$	$- \propto (\frac{1}{b_1})$	$\propto (\frac{1}{b_1})$	$*$	$- \propto (\frac{1}{b_1})$
b_2	$- \propto (\frac{1}{b_2})$	$\propto (\frac{1}{b_2})$	$- \propto (\frac{1}{b_2})$	$- \propto (\frac{1}{b_2})$	$\propto (\frac{1}{b_2})$	$*$
b_3	$- \propto (\frac{1}{b_3})$	$- \propto (\frac{1}{b_3})$	$\propto (\frac{1}{b_3})$	$- \propto (\frac{1}{b_3})$	$- \propto (\frac{1}{b_3})$	$\propto (\frac{1}{b_3})$
b_4	$\propto (\frac{1}{b_4})$	$- \propto (\frac{1}{b_4})$	$- \propto (\frac{1}{b_4})$	$\propto (\frac{1}{b_4})$	$- \propto (\frac{1}{b_4})$	$- \propto (\frac{1}{b_4})$
b_5	$*$	$\propto (\frac{1}{b_5})$	$- \propto (\frac{1}{b_5})$	$- \propto (\frac{1}{b_5})$	$\propto (\frac{1}{b_5})$	$- \propto (\frac{1}{b_5})$
b_6	$- \propto (\frac{1}{b_6})$	$*$	$\propto (\frac{1}{b_6})$	$- \propto (\frac{1}{b_6})$	$- \propto (\frac{1}{b_6})$	$\propto (\frac{1}{b_6})$

From this, we find:

1) If all of the nodes follow the same procedure for maximizing their own channel utilization, then $b_i, i = 1...6$ will be a large value compared to s. So the first derivative, $\frac{\partial \pi_{i,s}}{\partial b_j} \to 0$ for all nodes, which means that even if a node changes its backoff rate, its throughput will not increase. This results that no node has the intention to change its backoff rate. Then equilibrium is attained.

2) Notice $\frac{\partial \pi_{1,s}}{\partial b_2} < 0$ and $\frac{\partial \pi_{1,s}}{\partial b_3} < 0$, but $\frac{\partial \pi_{1,s}}{\partial b_4} > 0$. In this game, Node 1 competes for the channel with Nodes 2, 3; Node 4 also competes with Nodes 2 and 3. Nodes 2 and 3 are the common "enemies" of Nodes 1 and 4. Based on the logic "an enemy's enemy is a friend", Nodes 1 and 4 can cooperate with each other. They should adjust their parameters, e.g., b_1 and b_4, in the same direction. We will use this logic in the following numerical analysis algorithm.

3) Nodes 2 and 3 have the same enemies, Nodes 1 and 4, but they are not "friends" because they compete for the channel with each other also. But each one can still find its friend, e.g., Node 5 for 2 and Node 6 for 3.

So we define a "Friend": 1) There is no competition among the friends, and 2) there can be found at least one common competitor. Obviously, the definition for "Enemy": A competitor who competes for the resource, which exacerbates one node to satisfy its QoS requirements.

4) Also notice $\frac{\partial \pi_{1,s}}{\partial b_5}$ could be positive or negative, and it could be $\propto (\frac{1}{b})$ or $\propto (\frac{1}{b^2})$. Although Nodes 1 and 4 are friends and Node 5 is an enemy of 4, Node 5 can still be a friend of Node 1. This is the logic: "a friend's enemy can be a friend or enemy", it depends on the benefits to each other. Node 5 can act like a "pendulum" for Node 1. The definition for "Pendulum": When one parameter's value is in an interval, the node is a friend; once the value changes to another interval, the node becomes an enemy.

The throughput formulas 11 and 12 are strictly derived from the channel utilization model and presented. The channel utilization model is developed from a specific topology (in this case it is a Tandem topology), so the dominance information, such as the effect from an upstream node, is already included in the throughput results in formulas 11 and 12. In a different topology, we can still use the same methodology to derive the channel utilization model and the throughput formula, furthermore to analyze the corresponding equilibrium.

3.3 The benefits of cooperation in a 7-node tandem topology

In the previous sections, nodes were selfish and only sought to optimize their own throughput. Now we consider whether there are benefits if the nodes work together. One might expect that cooperation would be beneficial, because upstream nodes need downstream nodes to successfully continue the transmission of frames to the final destination sink node.

We set the objective function to optimize the channel utilization of the next-to-last node in Fig. 3 into the sink.

$$\max_{b_j} \quad \boldsymbol{\pi}_{6,s} \tag{15}$$

with constraints:

$$\boldsymbol{\pi}_{i-1,s} \;>\; \boldsymbol{\pi}_{i,s},\; i = 2...6 \qquad \boldsymbol{\pi}_{j,s} \;> 0, j = 1...6 \quad b_j > 0 \tag{16}$$

This causes all nodes to try to work together to achieve the best throughput for the network. The upper bound is $Max\ \boldsymbol{\pi}_{6,s} \;\approx\; \frac{1}{5}$, and is shown in Table IV. Node 3 has a total of 5 nodes in its interference range (including itself), since Nodes 1, 2, 4, and 5 cannot transmit without affecting a transmission if Node 3 is also sending. Node 4 also has 5 nodes in its interference range. In this topology, there are a maximum of 5 nodes in anyone's interference range, so this makes the upper bound $\frac{1}{5}$. A very important implication of this result should not be missed. Nodes should carefully use power control so that only their upstream and downstream neighbors are in their interference range. If their interference ranges are larger, the throughput will degrade.

The assumptions of these results are that corresponding optimized parameters, the backoff rates, are comparatively much larger than the sending rate.

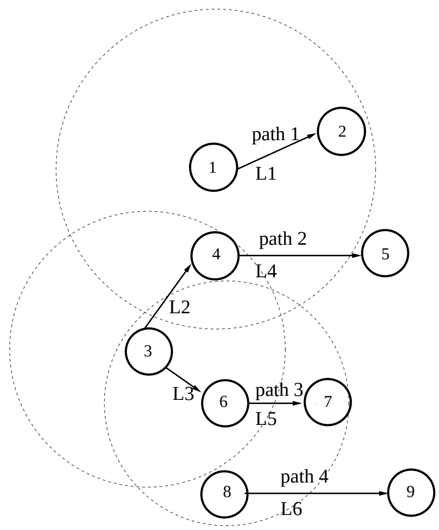
Table IV. $\pi_{i,s}, i = 1...6$ Node channel utilization for optimized end-to-end throughput

$\pi_{1,s}$	$\pi_{2,s}$	$\pi_{3,s}$	$\pi_{4,s}$	$\pi_{5,s}$	$\pi_{6,s}$
$\frac{1}{5}$	$\frac{1}{5}$	$\frac{1}{5}$	$\frac{1}{5}$	$\frac{1}{5}$	$\frac{1}{5}$

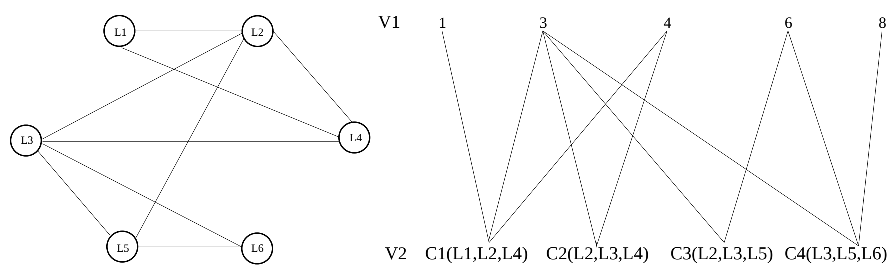
It is important to consider how nodes get information about each other so they can cooperate. In [Bianchi and Tinnirello 2003], a Kalman filter is used to estimate the competing number of nodes in the interference range. Piggybacking information onto the header of data frames is another method to share the topology information. Each node can periodically exchange information, e.g., topology, individual arrival rate. Using the shared information, each node can adjust its backoff rate and traffic splitting strategy based on the optimization objective.

3.4 Competition relationships in the traffic splitting network

The analysis of "friend" and "enemy" is helpful in the adaptive adjustment in the algorithm based on game theory [Shi 2010]. In Table III, we used differentiation to analyze the relationships among the nodes. Another method is to use a "clique" to represent the interference relationship. The "clique" is first introduced in [Nandagopal et al. 2000] and is a fully connected subset of vertices in a graph. One example is the flow (Fig. 6(a)) and resource contention (Fig. 6(b)) graphs for a 9-node, 4-path traffic splitting topology in Fig. 5. In Fig. 6(a), each vertex represents a link in Fig. 5, and each edge represents interference among those links. In Fig. 6(b), $V1$ represents the sending node for each link, $V2$ represents the cliques for the links in Fig. 5. There are four triangles (cliques), which are: 1) $L1$, $L2$, $L4$, 2) $L2$, $L3$, $L4$, 3) $L2$, $L3$, $L5$, and 4) $L3$, $L5$, $L6$. All of the links in a clique are in interference range of each other, so they are "enemies". Notice both links 1 and 2 are in clique 1, which means they are in interference range and "enemies" of each other. And links 2 and 3 are "enemies" because they are in clique 2. But links 1 and 3 do not co-exist in any clique and they have the common "enemy", link 2, so links 1 and 3 are "friends". The links in interference range of each other have direct effect on each other. But the links out of interference range have indirect effects on each other. In clique $C3$, $L5$ is the enemy of $L2$ and $L3$. But $L2$ is an enemy of $L1$, and $L3$ is a friend of $L1$, so in this case, it's hard to tell the relationship between $L1$ and $L5$. More research based on the numerical analysis needs to be done to further understand this relationship. With this rationality, nodes can use self-organized behavior and can be separated into different allies. Again, the flow and resource contention graphs can be applied to the analysis of any topology.



. 9-node, 4-path, traffic splitting topology.



(a) Flow contention graph. (b) Resource contention graph.

. Flow and resource contention graphs in the 9-node, 4-path, traffic splitting topology

For the topology in Fig. 5, besides the backoff rates, the probability parameter, σ_2 for dividing the arrival rate of Node 3 to paths 2 and 3, also needs to be considered. For the heavy load situation, the value is $\frac{1}{2}$. But in the light or medium traffic load situation, this probability needs to be adjusted. In fact, from our experiment, we found that three effects will have more impact on the quality of service: 1) upstream nodes, 2) the nodes have higher arrival rates, e.g., bottleneck links, and 3) the nodes which have more paths going through them. We define these nodes as "dominant nodes". For example, the bottleneck links are those with comparatively higher loss ratios.

4. OPTIMIZATION FOR A TANDEM TOPOLOGY

In this section we provide numerical optimal solutions for a tandem topology.

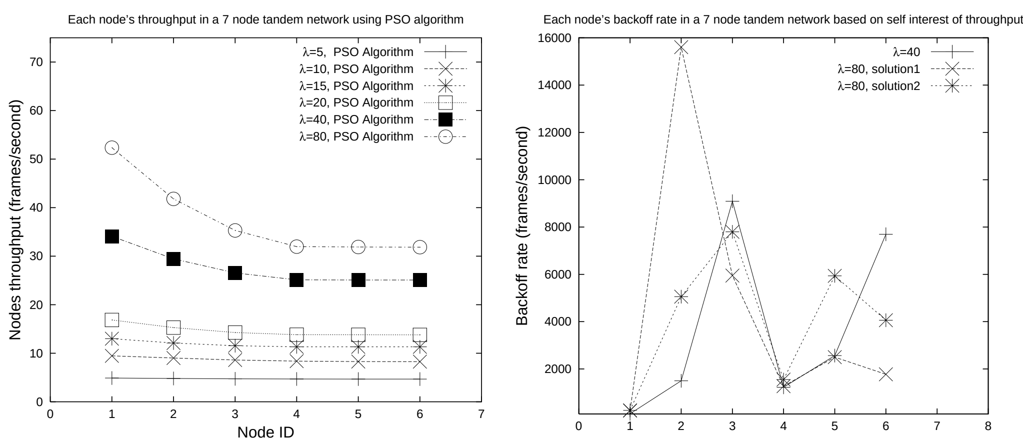
4.1 Application of particle swarm optimization algorithms

Now we want to see how to optimally assign backoff rates among cooperative nodes in all load conditions for a 7-node tandem topology.

We apply a Particle Swarm Optimization (PSO) searching algorithm to find the backoff rates. PSO is a stochastic, population-based evolutionary computer algorithm for problem solving, which was first described by James Kennedy and Russell C. Eberhart [Kennedy and Eberhart 1995]. It takes a set of "particles" that are each trying to find a solution for a certain parameter. At each iteration, the global and local bests are computed for the particles, then these results are used to move in the next iteration for each particle (with some randomness). PSO technology is developed for optimization of nonlinear functions, which is specially useful for our problem. We modified the standard PSO algorithm specially for network performance optimization. For example, about the dominance parameters, such as backoff rate in a upstream node, a broader region should be searched. Details of the modification can be found in [Shi 2010]. PSO optimizes a problem by having a population of candidate solutions. In our PSO algorithm, the performance result for each candidate solution is calculated by using the node analytical model and the channel utilization model. Node analytical model and channel utilization model are the calculation kernel for PSO algorithm. Our PSO algorithm will choose the optimal solution from the candidate solution set.

We use a model with 3 backoff stages per node and a queue size of 50, and Fig. 7 shows the PSO results for throughput and backoff rates at each node. Fig. 7(a) shows results for different traffic loads λ_1. At each node, a certain amount of traffic is lost because of channel contention or full queues. When the traffic load is low, e.g., $\lambda_1 = 5$, the throughput is higher (compared to the input rate) than in the high load traffic situation, $\lambda_1 = 80$.

Note that the results for backoff rates for Nodes 1 and 4 (see in Fig. 7(b)) are the same between different PSO runs, but results for the other nodes change a lot. This means that the selection of backoff rates for Nodes 1 and 4 are critical to the optimization, but for the other nodes their backoff rates do not matter so much.

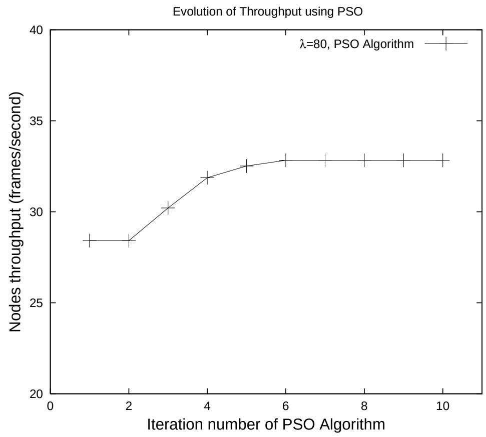


(a) Each node's throughput in a 7-node tandem network using a PSO algorithm.

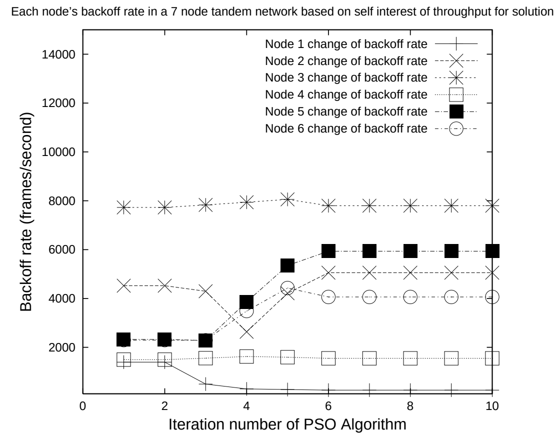
(b) Each node's backoff rate in a 7-node tandem network using a PSO algorithm.

. Application of PSO algorithm for throughput in a 7-node tandem network.

The progress of the PSO steps is seen in Figures 8(a) for overall throughput and 8(b) for individual backoff rates. The throughput changes most when b_1 is adjusted, once again showing it to be a dominant node. This was confirmed by simulation results (not shown here). From Fig. 7(a) the loss ratio is high in the tandem network, as mentioned in [Xu and Saadawi 2001].



(a) Progress of end-to-end throughput for 7-node tandem network.



(b) Progress of backoff rate for 7-node tandem network.

. Application of PSO algorithm for throughput in a 7-node tandem network.

With $\lambda_1 = 80$ and the optimized throughput at about 32 frames/sec, the throughput ratio is about 0.40.

4.2 Description of some interesting load transfer situations in a tandem network

From the above discussions, there are some interesting phenomena observed from the backoff rate selections among the nodes in the 7-node Tandem topology. One cannot expect to optimize the backoff rate values simply through trial-and-error simulation attempts, so these optimization approaches are needed.

The first phenomenon is shown in Fig. 7(b), where the backoff rates of Nodes 1 and 4 are very close among different calculations from the PSO algorithm, although it is not true for the backoff rates of Nodes 2, 3, 5. For $\lambda_1 = 80$, $b_1 \approx 200$, and $b_4 \approx 1400$. The reasons are as follows: first, Node 1 is the first node in the Tandem network; its output is the input of the downstream nodes, so it has what we call "traffic dominance" over the network. As shown in Table III, Node 4 is a "friend" of Node 1 and they have common interest, which means Nodes 1 and 4's throughputs change the same way when they change their backoff rates. Nodes 2 and 3 are the "enemies" of Nodes 1 and 4 and they interfere with Nodes 1 and 4's throughput.

However, the assumptions of the analysis in Table III were that all of the nodes always had frames to transmit, which meant all of the nodes were always either in backoff states or sending states. In more realistic situations, idle states will be introduced to the nodes, which is the situation for this subsection and the results in Fig. 7 and 8, which is more complicated. Still, Node 1 has the traffic dominance. However, it has one more interference which is from Node 4, as well as the interferences from Nodes 2 and 3. The reason is that now Node 4's throughput not only depends on its backoff rate, but also Node 3's throughput, further, Node 2's throughput. So now even if Node 1 maximizes its own throughput, which interferes with the Nodes 2 and 3's throughput, Node 4's throughput will also be affected. In this case, Node 4 is still a "friend" of Node 1, but Node 4 makes decisions for the value of its backoff rate based on: 1) maximizing its arrival rate, which comes from the throughput of Nodes 2 and 3, and 2) maximizing its own throughput. So Node 4 needs to balance these competing factors.

The second interesting phenomenon comes from the fact that the ranges of backoff possible solutions for rates (in Fig. 7(b)) for Nodes 2 and 3 are much wider than Nodes 1 and 4. The reason is the traffic is correlated. Because of the traffic dominance, Node 1 has the priority to choose the best value for its backoff rate. When Node 1 finishes the transmission, it either goes to idle state or the first backoff state. For Node 2 to avoid the collision, its backoff rate must be greater than the rate of Node 1 so Node 2 transmits before Node 1 tries the next attempt for transmission. That's why the backoff rates for Node 2 are larger. The range is also wider, since any value much larger than b_1 keeps collision probability low. Obviously in the 7-node Tandem topology, Node 2 also needs to consider the relationships with Nodes 3 and 4. The same explanation applies for Node 3, so it also can finish before Node 1. Because Nodes 2 and 3 have a wider range of backoff rates, Node 4 can choose the optimized value of its backoff rate.

5. OPTIMIZATION FOR A TRAFFIC SPLITTING AND MERGING TOPOLOGY

In this section we provide numerical optimal solutions for a traffic splitting and merging topology.

5.1 Application of static games with complete information

A static game with complete information is a game where 1) each player chooses an action without knowing what the other players have chosen for this step, and 2) every player will know the payoff that each agent will obtain depending on what actions have been taken. The sets of rational strategies in a static game with complete information are obtained by an iterative deletion procedure where decisions by some players remove possible choices for other players. In the wireless network we are studying, each node can be seen as a player. The payoff is the objective function, and it can be defined based on each node's, or each end user's QoS requirement, e.g., the throughput of each node or the loss ratio of the whole path. The game strategy is to change the traffic ratio onto the downstream link or change the backoff rate. The information in the wireless system is known by all of the nodes, including the arrival rates, backoff rates, etc. In [M. Cagalj and Hubaux 2005], a mechanism to detect aggressive behavior is developed. Also the interference relationship analysis, e.g., "friend" and "enemy", is helpful in the decision of traffic distribution among the paths and the direction to change the backoff rates.

Based on the model for continuous-time protocols, we apply a game theory algorithm [Shi 2010] to select routes and adjust the backoff rate at specific paths to guarantee the QoS for specific users. The topology in Fig. 5 is studied. Nodes 1 and 4 are in the interference range of each other, same as Nodes 3 and 4, Nodes 3 and 6, Nodes 6 and 8. Nodes 4 and 6 are not in interference range of each other. In our game theory algorithm, the performance result for each candidate solution is calculated by using node analytical model and channel utilization model. Node analytical model and channel utilization model are the calculation kernel for game theory algorithm. Game theory algorithm will choose the optimal solution from the candidate solution set.

5.2 Balance of traffic in traffic splitting topology

From the result of the Game Theory algorithm [Shi 2010], an interesting phenomenon is considered. In Fig. 5, if the arrival rates of Nodes 1 and 8 are the same, then Node 3 should split its traffic equally to Nodes 4 and 6 to avoid traffic congestion. But what should Node 3 do when the arrival rates of Nodes 1 and 8 are unequal to maximize Node 3's throughput? Is it correct that Node 3 should proportionally split $\lambda_{3,2}$ from Node 3 onto path 2 and $\lambda_{3,3}$ from Node 3 onto path 3 according to the following?

$$\frac{\lambda_{3,2}}{\lambda_{3,3}} = \frac{\lambda_8}{\lambda_1} \tag{17}$$

The answer is "No". The results are shown in Table V for setting traffic splitting to achieve maximum throughput. This means load balancing is not a simple linear function, but a nonlinear function. From observation of the simulation results, it seems that Node 3's throughput is maximized when the end-to-end throughput ratios are the same for paths 2 and 3, which means

$$\frac{s\ \pi_{4,s}}{\lambda_{3,2}} \approx \frac{s\ \pi_{6,s}}{\lambda_{3,3}}. \tag{18}$$

So the traffic splitting strategy of Node 3 can be based on the above formula. Because of a nonlinearity relationship between arrival rate and end-to-end throughput, formula (17) is not correct. The optimal splitting results are shown in Table V for different λ_1 and λ_8 where load is strongly distributed away from one side with even if it only has slightly higher λ. For example, even if $\lambda_1 = 72$ and $\lambda_8 = 68$, $25/30 = 83.3\%$ of the load is pushed toward path 3.

Table V. Simulation results for optimal traffic splitting

.

Maximum throughput Description	$\frac{\pi_{4,s}}{\lambda_{3,2}}$	$\frac{\pi_{6,s}}{\lambda_{3,3}}$	$\frac{\lambda_{3,2}}{\lambda_{3,3}}$	Path 2 and 3 maximum $e2e$ thp
$\lambda_1 = 80$, $\lambda_{3,2} = 1$, $\lambda_{3,3} = 29$, $\lambda_8 = 60$	0.5608	0.6389	0.0345	19.0886
$\lambda_1 = 77$, $\lambda_{3,2} = 0$, $\lambda_{3,3} = 30$, $\lambda_8 = 63$	0/0	0.6234	0	18.70
$\lambda_1 = 75$, $\lambda_{3,2} = 0$, $\lambda_{3,3} = 30$, $\lambda_8 = 66$	0/0	0.6164	0	18.49
$\lambda_1 = 72$, $\lambda_{3,2} = 5$, $\lambda_{3,3} = 25$, $\lambda_8 = 68$	0.5946	0.6063	0.2000	18.13
$\lambda_1 = 30$, $\lambda_{3,2} = 5$, $\lambda_{3,3} = 55$, $\lambda_8 = 10$	0.6430	0.6964	0.0909	41.51
$\lambda_1 = 20$, $\lambda_{3,2} = 5$, $\lambda_{3,3} = 45$, $\lambda_8 = 10$	0.7146	0.7368	0.1111	36.727

6. MULTIHOP MAC FRIENDLINESS

Based on the above analysis, we can introduce a new concept, called "MAC Friendliness" in a multihop environment. The purposes are: 1) optimize the channel utilization in each interference range, and the end-to-end QoS, especially for emergency users, and 2) guarantee fairness with channel utilization by removing traffic dominance introduced from the upstream nodes and unfairness from asymmetric position, e.g., bottleneck nodes.

A general topology is the 8-node, 3-path topology shown in Fig. 2(a). Assume λ_1 is the arrival rate to Node 1 for path 1, λ_2 the arrival rate to Node 2 for path 2, and λ_7 the arrival rate to Node 7 for path 3. We first assume no loss in the traffic path. Besides the relationships in formula (2), to optimally satisfy the traffic requirement, the following considerations should be satisfied from the states in Fig. 2(b). First of all, as we have seen with the tandem case, the best throughput occurs when all of the nodes on the path have the same throughput and no packets are lost. This can be accomplished using the following equations that can serve as stopping conditions when searching for a solution.

$$\lambda_1 = s(\boldsymbol{\pi}_1 + \boldsymbol{\pi}_8) = s(\boldsymbol{\pi}_3 + \boldsymbol{\pi}_{10}) = s(\boldsymbol{\pi}_5 + \boldsymbol{\pi}_{11}),$$

$$\lambda_2 = s(\boldsymbol{\pi}_2 + \boldsymbol{\pi}_9) = s\boldsymbol{\pi}_4 = s\boldsymbol{\pi}_6, \tag{19}$$

The basic idea of "MAC Friendliness" is to allocate each node a $\boldsymbol{\pi}_{i,s}$, then let it modify its traffic parameters (namely λ and b) to meet its QoS requirements. There are many ways to allocate $\boldsymbol{\pi}_{i,s}$, but one might choose to use the following equations that allocate $\boldsymbol{\pi}_{i,s}$'s in proportion to the path arrival rates.

$$\frac{\lambda_1}{\lambda_2} = \frac{\boldsymbol{\pi}_{1,s}}{\boldsymbol{\pi}_{2,s}} = \frac{\boldsymbol{\pi}_{4,s}}{\boldsymbol{\pi}_{5,s}},$$

$$\frac{\lambda_2}{\lambda_3} = \frac{\boldsymbol{\pi}_{5,s}}{\boldsymbol{\pi}_{7,s}}. \tag{20}$$

"MAC Friendliness" could also be used to guarantee the performance for emergency traffic or other types of priority traffic. For example, if path 2 is to be used for emergency traffic, then channel allocation should be first guaranteed on a priority basis for path 2, which means Nodes 2, 3, and 5 will have their channel utilization determined first. Note that "MAC Friendliness" might not be based on nodes, but rather based on paths, which means "MAC Friendliness" would be used to define the channel allocation along the entire traffic path, whether it be emergency or normal traffic.

7. CONCLUSION

This paper first provides a new understanding of the competition and cooperation relationships among nodes in a multi-hop wireless network. New concepts, “dominance,” “friends”, “enemies”, and “pendulums” are defined and self-organizing behavior is studied.

The second contribution is that this work provides a detailed investigation of tandem, splitting, and merging topology elements within a network. Performance effects are investigated from a set of variables: 1) backoff rate in each node, 2) topology position, and 3) traffic distribution on different paths. Several interesting phenomena are reported. We build on the concept of “MAC Friendliness” to extend it to a multi-hop topology.

The third contribution extends the work in [Shi et al. 2008] by creating a channel utilization model with a new defined variable r_i, the “channel access rate”, which is applicable for all traffic loads. Node analytical model and channel utilization model can be applied as the calculation kernel in different kinds of optimization methods. Channel utilization model is developed specifically for a specific topology, but this methodology can be used for any topology. Also these models can be extended with other variables, such as traffic cost, in optimization objective functions and constraints.

The self-organizing behavior and heuristic algorithms are helpful to optimize the performance in a large size CSMA multi-hop network when central scheduling algorithms are difficult to be implemented. Combined with Algorithm 1 in [Shi et al. 2012], the model in this paper can be applied to large sized topologies for competition, cooperation, and optimization analysis. This work is applicable to fixed topology, but it can be extended to dynamic topologies with the models used at each point in time. Further research will be focused in this direction.

REFERENCES

Ashraf, U., Abdellatif, S., and Juanole, G. 2011. Route selection in ieee 802.11 wireless mesh networks. *Telecommunication Systems*.

Bianchi, G. 2000. Performance analysis of the IEEE 802.11 distributed coordination function. IEEE JSAC *18*, 535547.

Bianchi, G. and Tinnirello, I. 2003. Kalman filter estimation of the number of competing terminals in an ieee 802.11 network. INFOCOM.

Boorstyn, R. R., Kershenbaum, A., Maglaris, B., and Sahin, V. 1987. Throughput analysis in multihop CSMA packet radio networks. IEEE Transactions on Communications *35,* 3 (March), 267–274.

Brahma, M., Kim, K. W., Abouaissa, A., and Lorenz, P. 2005. A load-balancing and push-out scheme for supporting qos in manets. *Telecommunication Systems 30,* 1-3, 161–175.

Clerc, M. and Kennedy, J. 2002. The particle swarm - explosion, stability, and convergence in amultidimensional complex space. Evolutionary Computation, IEEE Transactions on *6,* 1 (Feb), 58–73.

Felegyhazi, M. and Hubaux, J.-P. 2006. Game theory in wireless networks: A tutorial. EPFL Technical report.

Kennedy, J. and Eberhart, R. 1995. Particle swarm optimization. Neural Networks, 1995. Proceedings., IEEE International Conference on *4*, 1942–1948.

Kleinrock, L. and Tobagi, F. 1975. Packet switching in radio channels: Part i–carrier sense multiple-access modes and their throughput-delay characteristics. IEEE Transactions on Communications *23,* 12 (December), 1400–1416.

Lauwens, B., Scheers, B., and de Capelle, A. V. 2010. Performance analysis of unslotted csma/ca in wireless networks. *Telecommunication Systems 44,* 1-2, 109–123.

Li, J., Blake, C., De Couto, D. S. J., Lee, H. I., and Morris, R. 2001. Capacity of ad hoc wireless networks. Proceedings of the 7th ACM International Conference on Mobile Computing and Networking, 61–69.

Luo, H., Lu, S., and Bharghavan, V. 2000. A new model for packet scheduling in multihop wireless networks. Proceedings of ACM MOBICOM, 76–86.

M. Cagalj, S. Ganeriwal, I. A. and Hubaux, J. P. 2005. On selfish behavior in CSMA/CA networks. INFOCOM 2005 *4*, 2513–2524.

Medepalli, K. and Tobagi, F. A. 2006. Towards performance modeling of IEEE 802.11 based wireless networks: A unified framework and its applications. INFOCOM 2006. 25th IEEE International Conference on Computer Communications. Proceedings, 1–12.

Michele Garetto, T. S. and Knightly, E. W., Eds. 2006. *Modeling Per-Flow Throughput and Capturing Starvation in CSMA Multi-Hop Wireless Networks. Proceedings of IEEE INFOCOM*, Barcelona, Spain.

Nandagopal, T., eun Kim, T., Gao, X., and Bharghavan, V. 2000. Achieving mac layer fairness in wireless packet networks. *MOBICOM*, 87–98.

Rajagopalan, S., Shah, D., and Shin, J. 2009. Network adiabatic theorem: an efficient randomized protocol for contention resolution. SIGMETRICS '09 Proceedings of the eleventh international joint conference on Measurement and modeling of computer systems.

Shi, J., Gurewitz, O., Mancuso, V., Camp, J., and Knightly, E. W. 2008. Measurement and modeling of the origins of starvation in congestion controlled mesh networks. INFOCOM, 1633–1641.

Shi, Z. 2010. Stochastic modeling, correlation, competition, and cooperation in a csma wireless network. Ph.D. thesis, University of Missouri-Kansas City, Kansas City, Missouri.

Shi, Z., Beard, C., and Mitchell, K. 2007. Misbehavior and MAC friendliness in CSMA networks. IEEE Wireless Communications and Networking Conference WCNC., 355–360.

Shi, Z., Beard, C., and Mitchell, K. 2008. Tunable traffic control for multihop csma networks. Military Communications Conference (MILCOM '08), 1–7.

Shi, Z., Beard, C., and Mitchell, K. 2009. Analytical models for understanding misbehavior and mac friendliness in csma networks. Performance Evaluation *66*, 469–487.

Shi, Z., Beard, C., and Mitchell, K. 2011. Competition, cooperation, and optimization in multi-hop csma networks. Accepted by The Eighth ACM International Symposium on Performance Evaluation of Wireless Ad Hoc, Sensor, and Ubiquitous Networks (PE-WASUN).

Shi, Z., Beard, C., and Mitchell, K. 2012. Analytical models for understanding space, backoff, and flow correlation in csma wireless networks. doi: 10.1007/s11276-012-0474-8. Wireless Networks, Springer.

Srivastava, V., Neel, J., MacKenzie, A. B., Menon, R., DaSilva, L. A., Hicks, J. E., Reed, J. H., and Gilles, R. P. 2005. Using game theory to analyze wireless ad hoc networks. IEEE Communications Surveys and Tutorials *7*, 46–56.

Wang, X. and Kar, K. 2005. Throughput modelling and fairness issues in CSMA/CA based ad-hoc networks. INFOCOM 2005 *1*, 23–34.

Xu, S. and Saadawi, T. 2001. Does the IEEE 802.11 mac protocol work well in multihop wireless adhoc networks? Communications Magazine, IEEE *39,* 6 (June), 130–137.

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