Competition, Cooperation, and Optimization in Multi-Hop CSMA Networks

Zhefu Shi , Cory Beard , Kenneth Mitchell

Department of Computer Science Electrical Engineering,

University of Missouri-Kansas City

Background and Contribution

- Nodes using standardized, contention-based CSMA protocols can change parameters which will affect the othersŠ attempts to use the channel and the other nodesŠ quality of service (QoS).
- The first contribution is a new understanding of performance effects from competition and cooperation relationships among nodes in a CSMA network. 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 second 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.
- The average rate that Node i to go from the state that represents not using the channel to the state that represents using the channel.

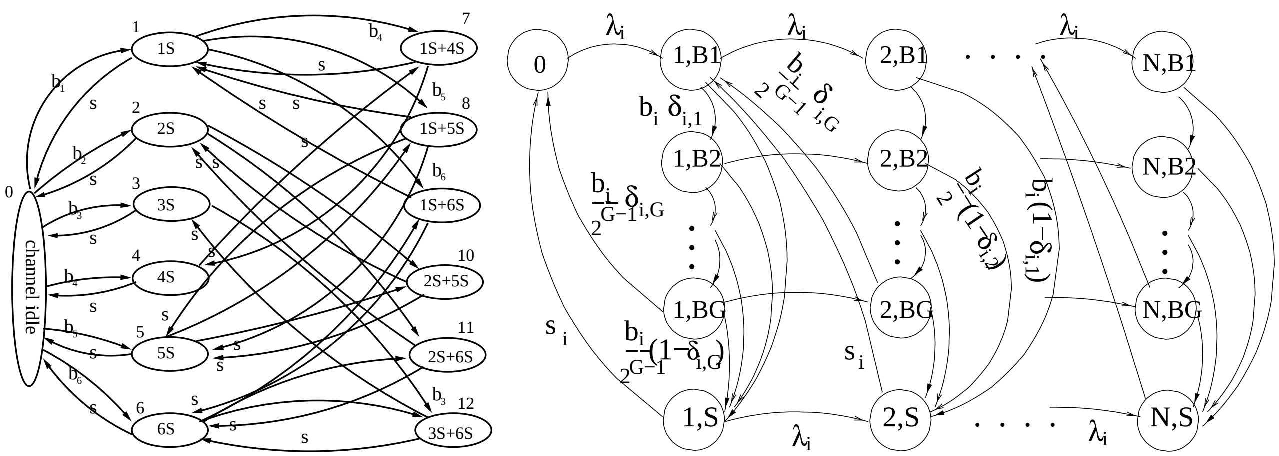
$$r_i = \frac{b_i \left(1 - \pi_{i,0} - \pi_{i,s}\right)}{1 - \pi_{i,s}}. \quad (1)$$

Definitions and Assumptions

- λ_i: The frame arrival rate at Node i to the MAC layer is exponentially distributed with average rate λ_i.
- b_i: The backoff rate is exponentially distributed at the first stage. Any random variable could be used in a MAC layer for random backoff.
- s_i: The packet service rate for Node i is exponential distributed.
- π_i: The state probability in a Markov Chain for state i.
- The propagation delay between neighboring nodes is zero.
- Under CSMA/CA, a node will transmit a scheduled packet if it detects an idle channel.
- Links are error free. A packet will be successfully transmitted only if there is no collision.
- The lengths of RTS and CTS are small enough so their transmission delay can be ignored. Acknowledgements are obtained instantaneously.
- The transmission interference range is two hops.

Network topology I

- 7-node Tandem Topology Channel Utilization Model and Node Analytical Model



-

$$\pi_{1,s} = \frac{b_1(s + b_4 + b_5 + b_6)}{D},\ \pi_{2,s} = \frac{b_2(s + b_5 + b_6)}{D},\ \pi_{3,s} = \frac{b_3(s + b_6)}{D},$$

$$\pi_{4,s} = \frac{b_4(s + b_1)}{D}, pi_{5,s} = \frac{b_5(s + b_1 + b_2)}{D},\ \pi_{6,s} = \frac{b_6(s + b_1 + b_2 + b_3)}{D}.$$

Where D is

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

Relationship Analysis–1

- $\pi_{i,s}, i = 1...6$ 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	$-\propto (\frac{1}{b_6})$	$*$	$\propto (\frac{1}{b_6})$	$-\propto (\frac{1}{b_6})$	$-\propto (\frac{1}{b_6})$	$\propto (\frac{1}{b_6})$

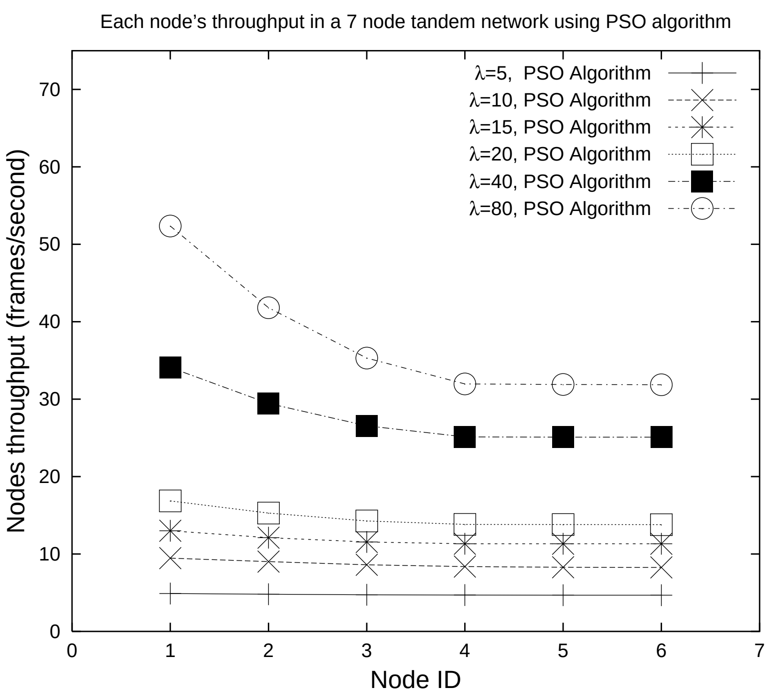
- If all of the nodes follow the same procedure for maximizing their own channel utilization, then the first derivative, $\frac{\partial \pi_{i,s}}{\partial b_j} \to 0$ for all nodes. This results that no node has the intention to change its backoff rate. Then equilibrium is attained.

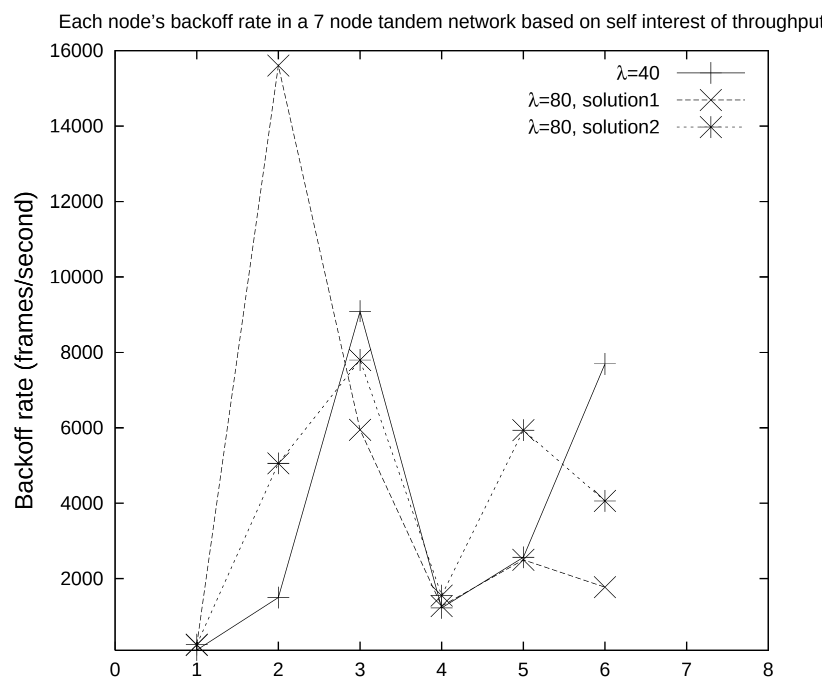
Relationship Analysis–2

- 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.
- 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.
  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.
- 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.

Optimization for Tandem Topology

- PSO technology is developed for optimization of nonlinear functions, which is specially useful for our problem. We modified the standard PSO algorithm. For example, about the dominance parameters, such as backoff rate in an upstream node, a broader region should be searched.
- The performance result for each candidate solution is calculated by using the node analytical model and channel utilization model.
- Application of PSO algorithm for throughput in a 7-node tandem network.





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 creating a channel utilization model with a new defined variable ri, the “channel access rate", which is applicable for all traffic loads. These models can be applied with different kinds of optimization methods. Also of 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. Further research will be focused in this direction.

References

[Bianchi00] G. Bianchi, “Performance analysis of the IEEE 802.11 distributed coordination function.” *IEEE JSAC*, Vol. 18, No. 3, March 2000.

[Boorstyn87] Robert R. Boorstyn, Aaron Kershenbaum, Basil Maglaris, Veli Sahin, “Throughput analysis in multihop CSMA packet radio networks”, *IEEE Transactions on Communications*, Vol.COM-35, No.3, pp.267-274, March 1987.

[Kar05] Xin Wang and Koushik Kar, “Throughput modelling and fairness issues in CSMA/CA based ad-hoc networks”, *INFOCOM 2005*, Vol. 1, pp. 23-24, March 2005.

[Pso95] Kennedy, J. and Eberhart, R., “Particle swarm optimization”, *Neural Networks, 1995. Proceedings., IEEE International Conference on.*, Vol. 4, pp.1942-1948, Nov/Dec 1995.

[Epfl05] M. Cagalj, S. Ganeriwal, I. Aad, and J. P. Hubaux, “On selfish behavior in CSMA/CA networks”, *INFOCOM 2005.*, Vol. 4, pp.2513-2524, March 2005.