WiFi MAC Models
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Talk outline

- Introducing the 802.11 CSMA/CA MAC.
- Finite load 802.11 model and its predictions.
- Issues with standard 802.11, leading to 802.11e.
- Finite load 802.11e model and its predictions.
- Beyond infrastructure mode networks.
- Why do these models work?

The 802.11 MAC

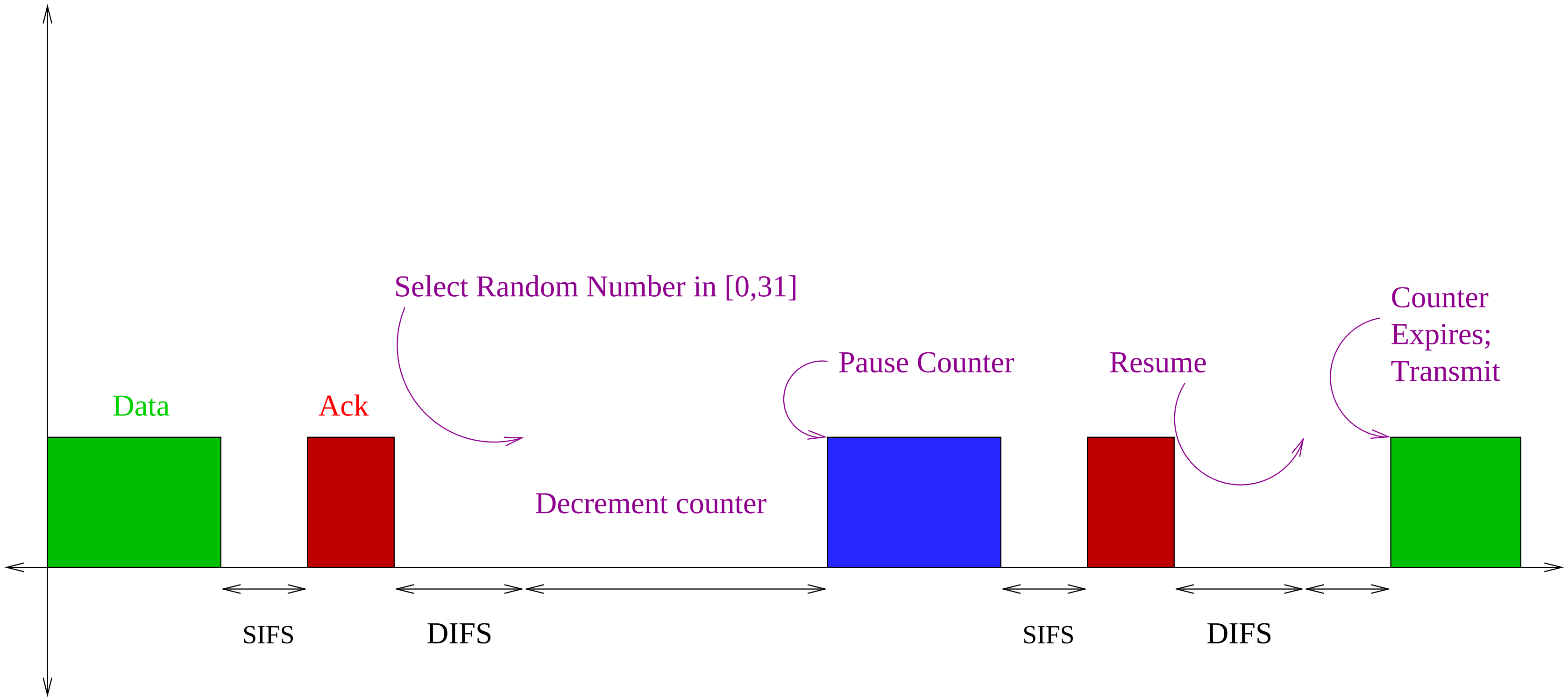


Figure 1: 802.11 MAC operation

802.11 MAC Summary

- After transmission choose $\mathrm{rand}(0, \mathrm{CW} - 1)$.
- Wait until medium idle for $\mathrm{DIFS}(50\mu s)$,
- While idle count down in slots $(20\mu s)$.
- Transmission when counter gets to 0, ACK after SIFS $(10\mu s)$.
- If ACK then $\mathrm{CW} = \mathrm{CW}_{\mathrm{min}}$ else $\mathrm{CW} *= 2$.

Ideally produces even distribution of packet transmission.

Modelling approaches

- P-persistent: approximate the back-off distribution be a geometric with the same mean. Exemplified by Marco Conti and co-authors.
- Asymptotic full system analysis: Bordenave, McDonald and Proutiere + Sharma, Ganesh and Key.
- Bianchi's mean-field Markov model: treat stations individually; network relationship between stations gives a set of coupling equations.

In simplest form: constant transmission probability τ gives throughput

$$S = n\tau(1-\tau)^{n-1}, \tag{1}$$

and collision probability

$$1 - p = (1-\tau)^{n-1}. \tag{2}$$

Mean-field Markov Overview

Mean field approximation: each individual station's impact on overall network is small. Assume a fixed probability of collision given attempted transmission p.

Each station's back-off counter then a Markov chain. Stationary distribution gives the probability the station attempts transmission in a typical slot $\tau(p)$.

Network coupling then gives a system of equations relating all stations' p and τ, which determines everything.

Real-time quantities determined through a relation involving the average real-time that passes during a counter decrement.

Following to appear in IEEE/ACM ToN (Duffy, Leith, Malone).

Mean-field Markov Model's Chain

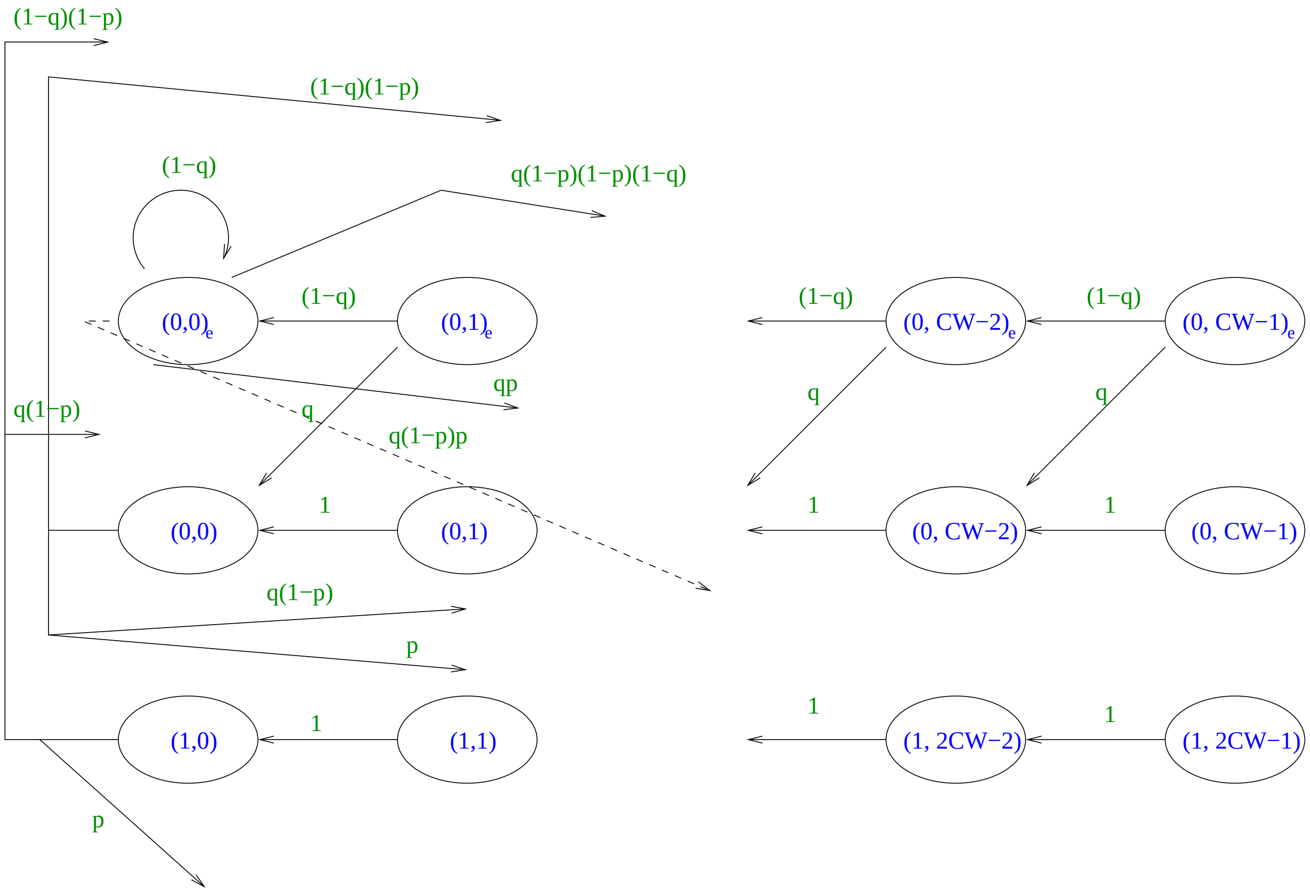


Figure 2: Individual's Markov Chain

Mean-field Markov Model Solution

Stationary distribution of Markov chain gives:

$$\tau(p, q, W_0, m) = \eta^{-1} \left(\frac{q^2 W_0}{(1-p)(1-q)(1-(1-q)^{W_0})} - \frac{q^2(1-p)}{1-q} \right), \qquad (3)$$

where

$$\begin{aligned} \eta &= (1-q) + \tfrac{q^2 W_0 (W_0+1)}{2(1-(1-q)^{W_0})} + \tfrac{q(W_0+1)}{2(1-q)} \left(\tfrac{q^2 W_0}{1-(1-q)^{W_0}} + p(1-q) - q(1-p)^2 \right) \\ &+ \tfrac{pq^2}{2(1-q)(1-p)} \left(\tfrac{W_0}{1-(1-q)^{W_0}} - (1-p)^2 \right) \left(2W_0 \tfrac{1-p-p(2p)^{m-1}}{1-2p} + 1 \right). \end{aligned}$$

Network coupling

For given loads $q_1, \ldots, q_n$, define $\tau_j = \tau(p_j, q_j, W_0, m)$ and then n coupling equations:

$$1 - p_i = \prod_{j \neq i} (1 - \tau_j).$$

Solve to determine $(p_1, \tau_1), \ldots, (p_n, \tau_n)$.

If all packets are the same length, L bytes taking T_L time on the medium, then

$$S_i = \frac{\tau_i (1 - p_i) L}{\prod_{i=1}^{n} (1 - \tau_i) \delta + (1 - \prod_{i=1}^{n} (1 - \tau_i)) T_L}.$$

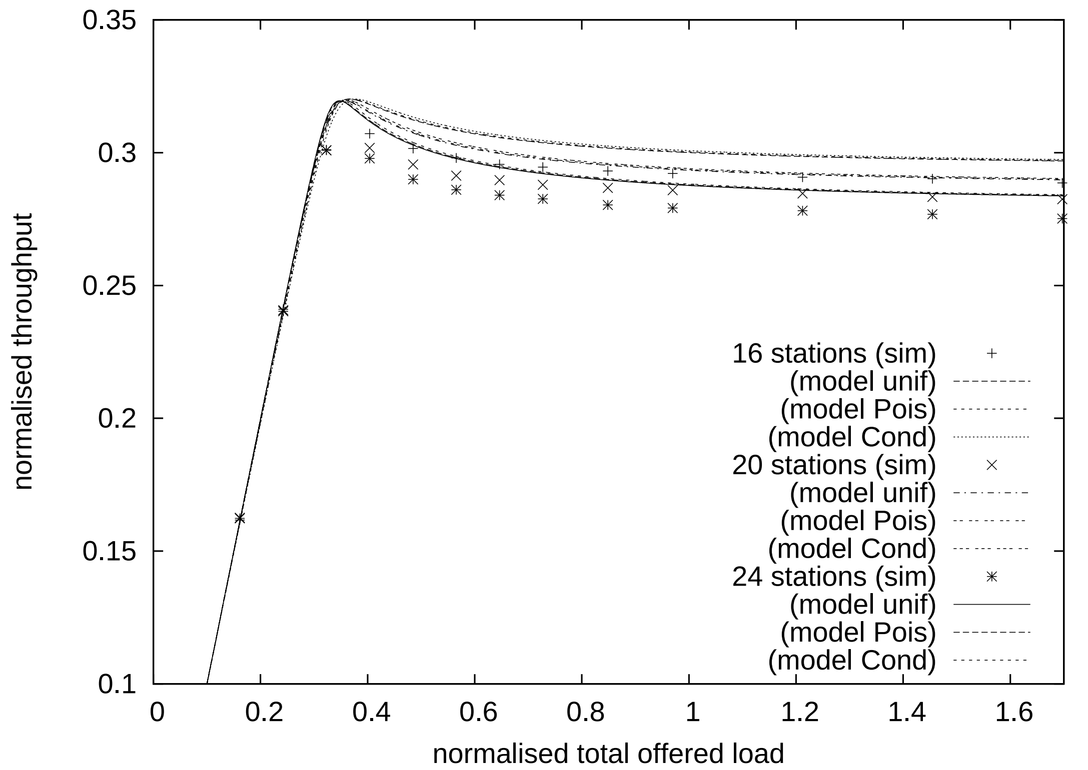
Relating q to offered load

- Taking $\lim_{q \to 1}$ models saturation.
- For small buffers, a crude approximation:

$$q = \min(\text{Expected slot length}/\text{mean inter-packet time}, 1).$$

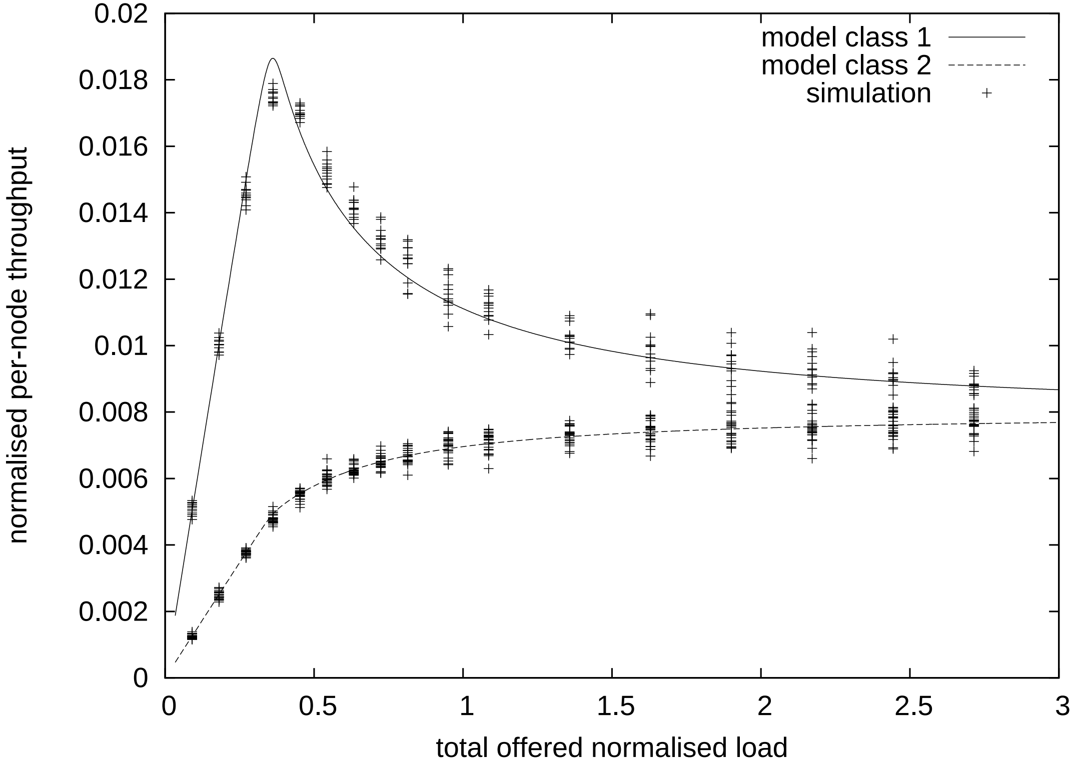
- If packets arrive a Poisson manner with rate λ_l, then q_l is $1 - \exp(-\lambda_l \text{Expected slot length})$.
- Possible to produce a relation of this sort that uses conditional information.

Model Predictions



Throughput as the traffic arrival rate is varied. Results for three load relationships (uniform, Poisson and conditional) shown.

Model Predictions



Normalized per-station throughput, where $n_1 = 12$, $n_2 = 24$. The offered load of a class 2 station is $1/4$ of a class 1 station.

TCP Upload Scenario

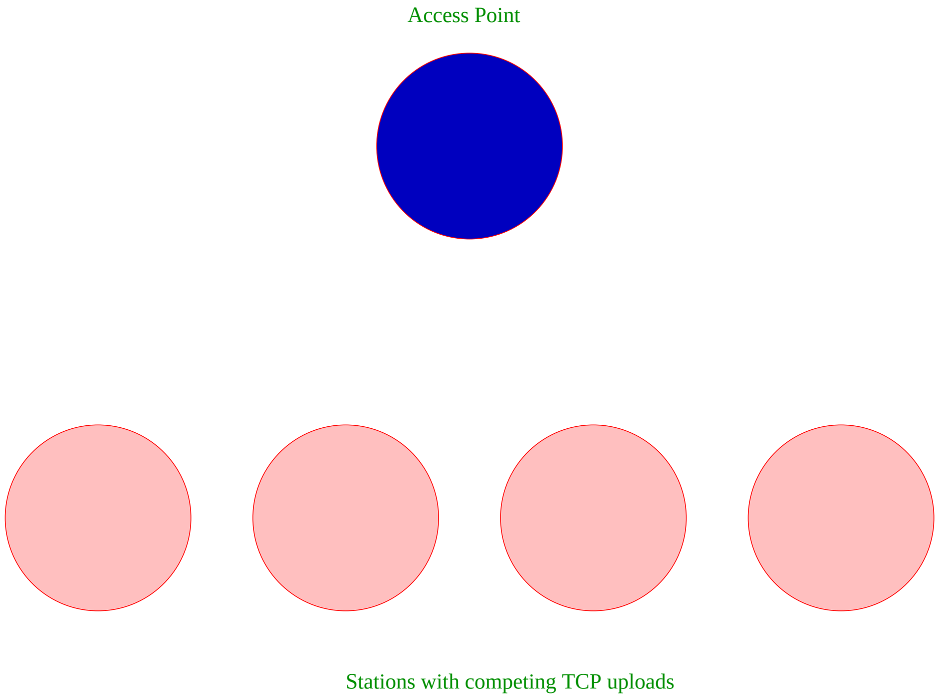


Figure 3: Competing TCP uploads.

TCP Uploads

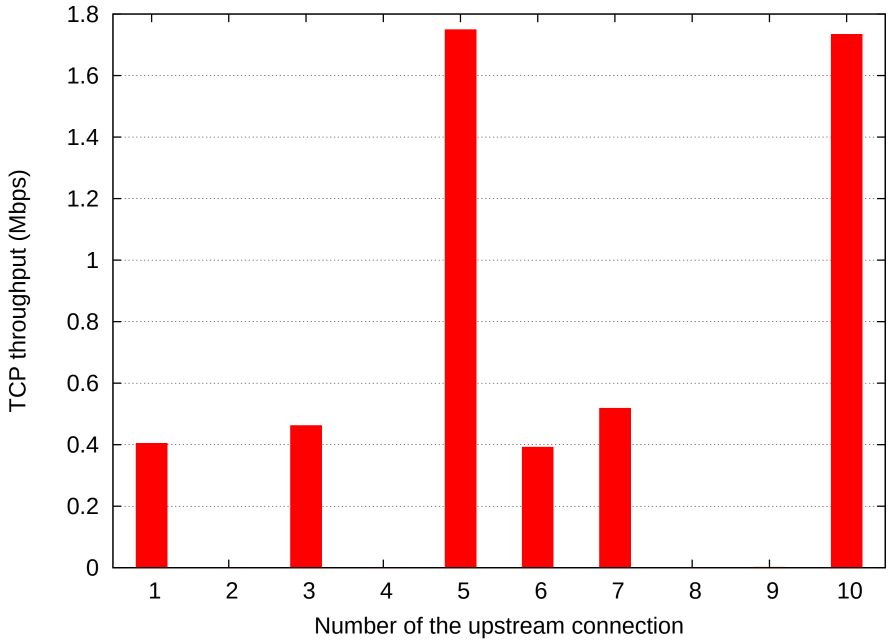


Figure 4: Competing TCP uploads, 10 stations (NS2 simulation, 802.11 MAC, 300s duration).

The 802.11e MAC

The three most significant 802.11e MAC parameters on traffic prioritization are TXOP, W_0 and AIFS.

- Four traffic classes per station.
- Station transmits for max duration TXOP (one packet without 802.11e).
- Per class, W_0 is 2^n, $n \in \{0, 1, \ldots\}$.
- Per class, AIFS $=$ DIFS $+ k\delta$, $k \in \{-2, -1, 0, 1, \ldots\}$.

The 802.11 MAC

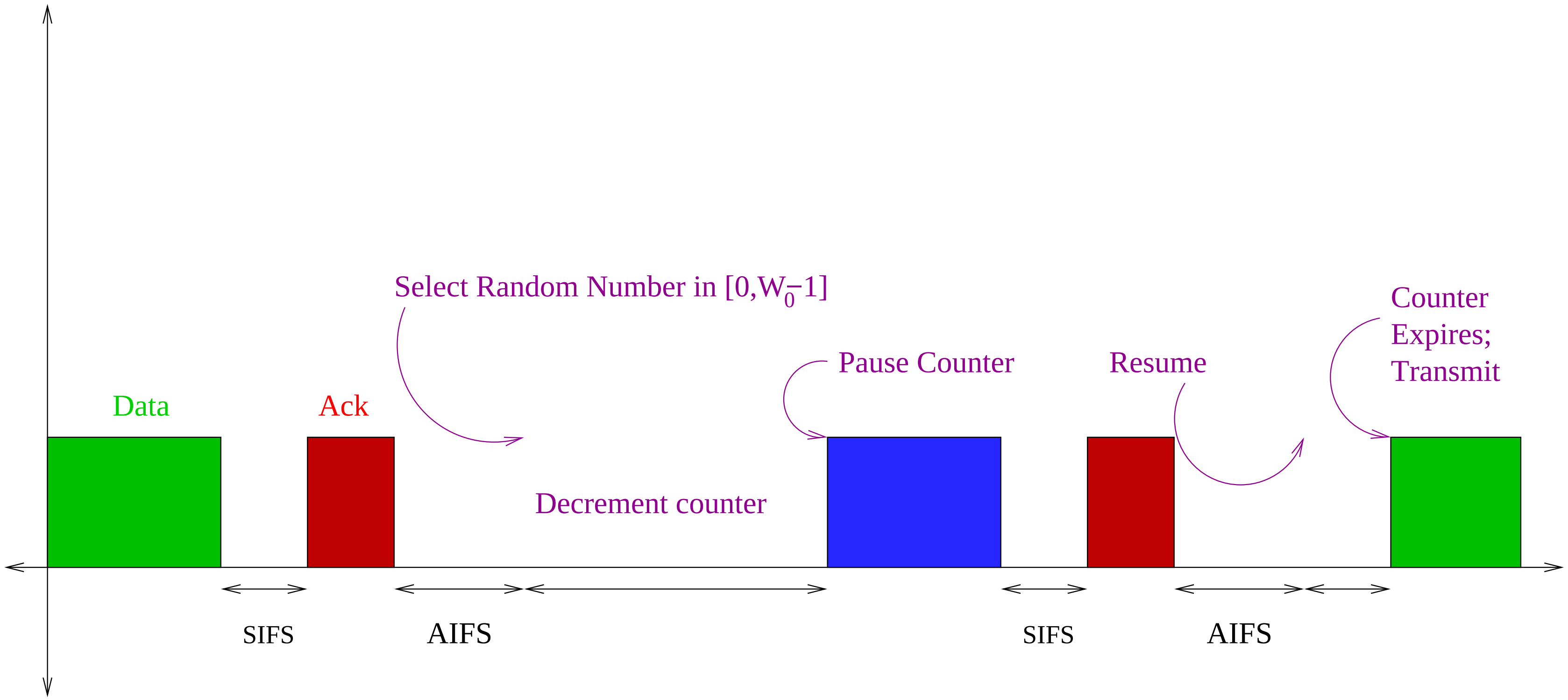


Figure 5: 802.11 MAC operation

Existing 802.11e models

Saturated 802.11e multi-class models.

- R. Battiti and Bo Li, University of Trento Technical Report DIT-03-024 (2003).
- J.W. Robinson and T.S. Randhawa, IEEE JSAC 22:5 (2004).
- Z. Kong, D. H.K. Tsang, B. Bensaou and D. Gao, IEEE JSAC 22:10 (2004).

Following (maybe!) to appear in IEEE Trans. Mob. Computing, with Clifford, Duffy, Foy, Leith and Malone.

Modelling 802.11e

Added complications: Need hold states for $AIFS$.

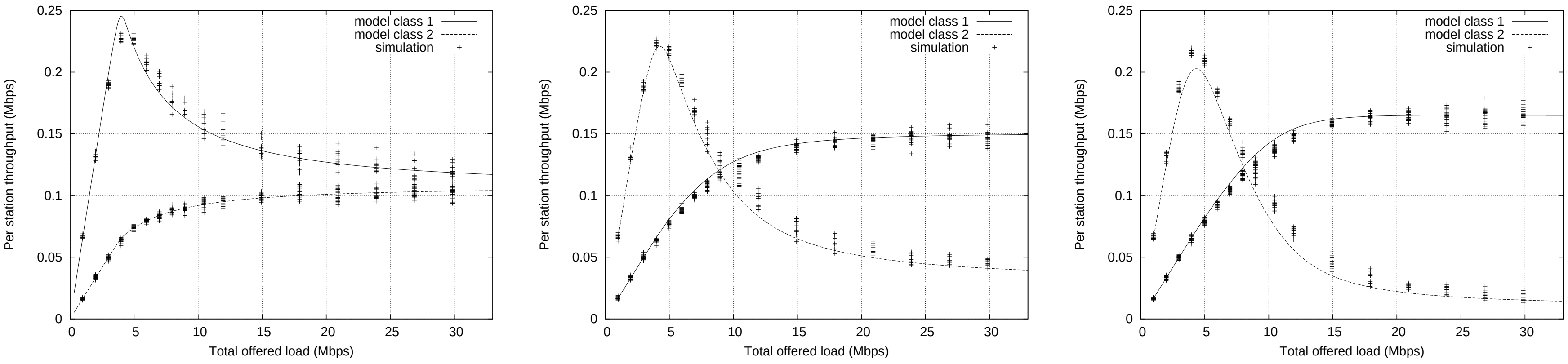
$$P_{\mathrm{h}} = \frac{(1 - \prod_{j=1}^{n_1}(1-\tau_j^{(1)})\prod_{j=1}^{n_2}(1-\tau_j^{(2)}))\displaystyle\sum_{i=1}^{D} P_{S_1}^{-i}}{1 + (1 - \prod_{j=1}^{n_1}(1-\tau_j^{(1)})\prod_{j=1}^{n_2}(1-\tau_j^{(2)}))\displaystyle\sum_{i=1}^{D} P_{S_1}^{-i}}. \tag{4}$$

New coupling equations

$$1 - p_i^{(1)} = \prod_{j \neq i} (1 - \tau_j^{(1)}) (P_\mathrm{h} + (1 - P_\mathrm{h}) \prod_{j=1}^{n_2} (1 - \tau_j^{(2)})) \tag{5}$$

$$1 - p_i^{(2)} = \prod_{j=1}^{n_1} (1 - \tau_j^{(1)}) \prod_{j \neq i} (1 - \tau_j^{(2)}). \tag{6}$$

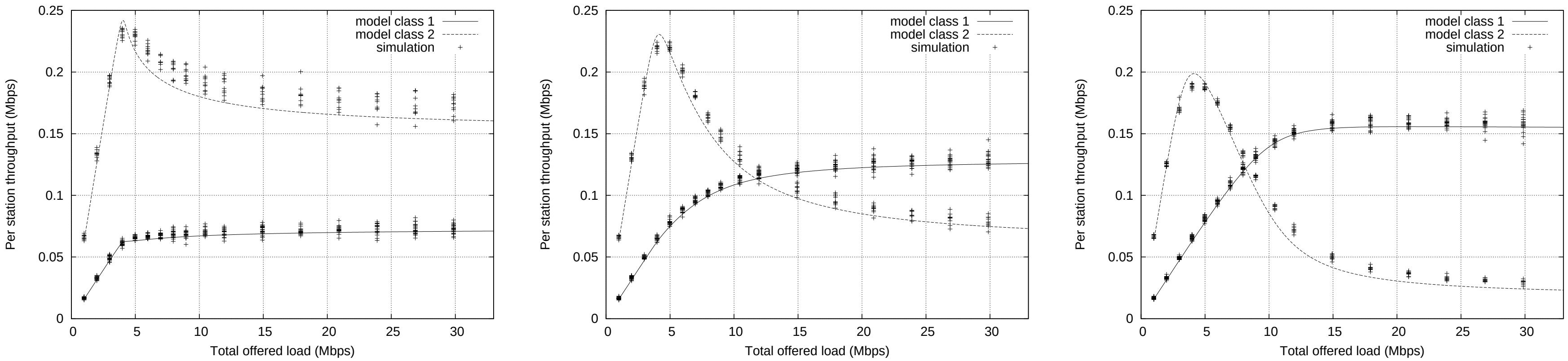
How good is it?



(a) $D = 0$ (b) $D = 2$ (c) $D = 4$

Throughput for a station in each class vs. offered load. 10 class 1 stations offering one quarter the load of 20 class 2 stations. Range of D values, the difference in AIFS between class 2 and class 1 (NS2 simulation and model predictions, 802.11e MAC, 11Mbps PHY, 100s duration.).

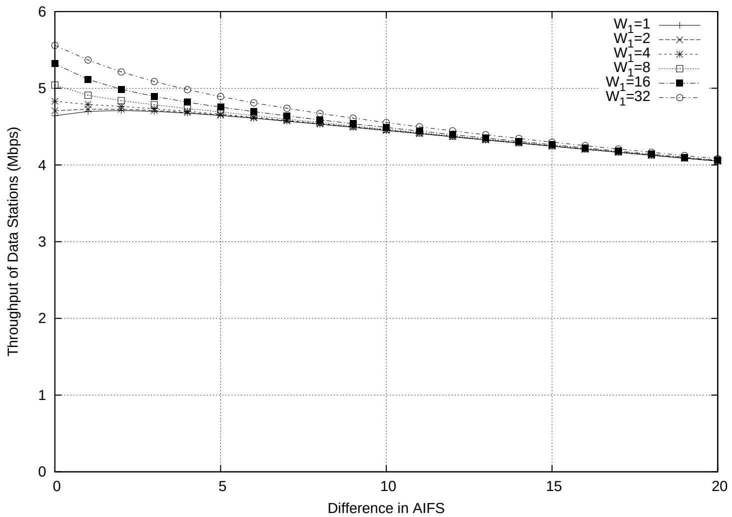
How good is it?



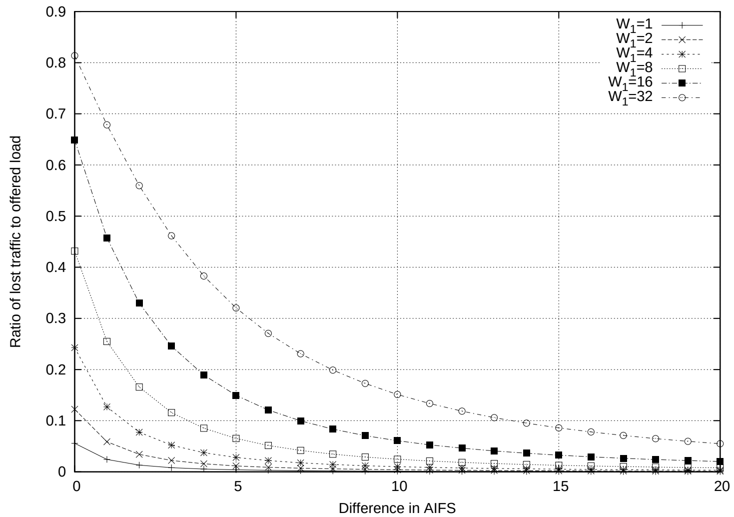
(d) $W_0^{(1)} = 32,\ W_0^{(2)} = 16$ (e) $W_0^{(1)} = 32,\ W_0^{(2)} = 64$ (f) $W_0^{(1)} = 32, W_0^{(2)} = 256$

Throughput for a station in each class vs. offered load. There are 10 class 1 stations each offering one quarter the load of 20 class 2 stations. Range of W_0 values (NS2 simulation and model predictions, 802.11e MAC 11Mbps PHY, 100s duration).

How do you use it?



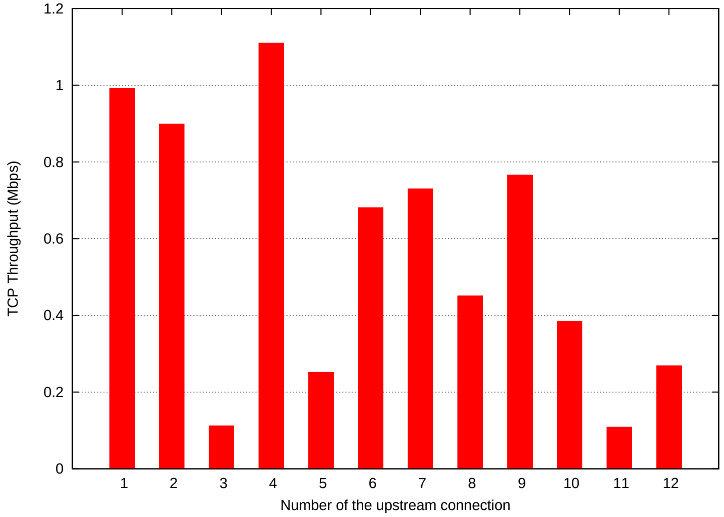
(g) Data throughput

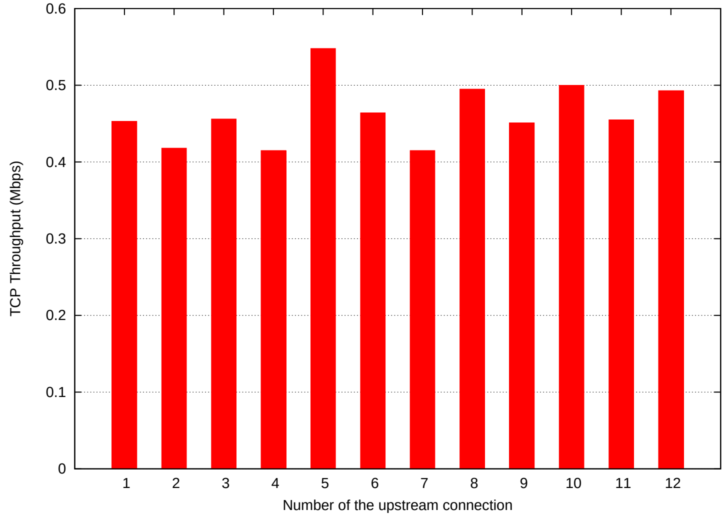


(h) ACK loss

10 stations (1500 byte packets) and AP transmitting (60 byte packets) at half achieved data rate.

Does it work?



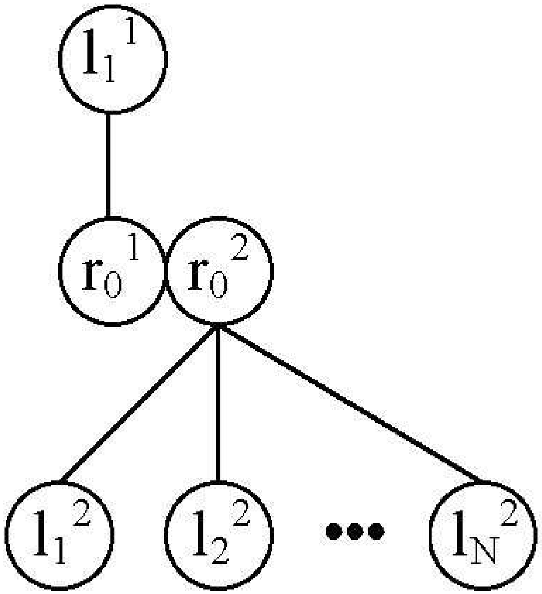


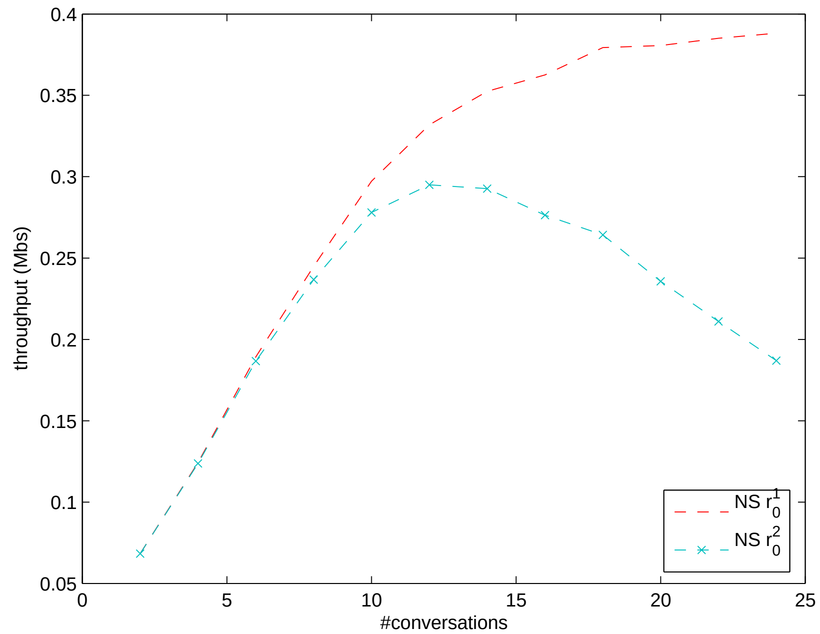
Competing TCP uploads, 12 stations **experiment** without and with prioritization (802.11e MAC, 300s duration).

Why stop with single infrastructure mode network?

Basic behavior of individual stations is independent of the network in which they exist. Change the network coupling, change the network.

Typical mesh issue





Example of aggregate throughput vs number of voice calls for the multi-hop 802.11b WLAN topology. Voice packets are transported between l_1^1 and $l_1^2, \ldots, l_N^2$ by node r_0^1/r_0^2 which denotes a relay station with two radios.

Mesh

Following in IEEE Comms. Letters (2006), (Duffy, Leith, Li and Malone).

M distinct local zones on common frequency. For $n \in \{1, \ldots, M\}$ local stations $\mathcal{L}_n = \{l_1^n, \ldots\}$ and relay stations $\mathcal{R}_n = \{r_0^n, \ldots\}$. Mean field gives for each station $c \in \mathcal{R}_n \cup \mathcal{L}_n$:

$$1 - p_c = \prod_{b \in \mathcal{R}_n \cup \mathcal{L}_n,\ b \neq c} (1 - \tau_b). \tag{7}$$

The stationary probability the medium is idle is $p_{idle} = \prod_{b \in \mathcal{R}_n \cup \mathcal{L}_n} (1 - \tau_b)$. The mean state length is $E_n = p_{idle}\sigma + L(1 - p_{idle})$, where each packet takes L seconds and idle slot-length is σ seconds.

Added difficulty: for each $n, l \in \mathcal{L}_n$, q_l is given, but q_r is not known a priori for each relay station.

Mesh

The parameter q_r is determined through relay traffic.

- For each n, $l \in \mathcal{L}_n$, a fixed route f_l from its zone to a destination zone.

$$f_l = \{l, s_1 \ldots, s_m, d\}.$$

- If $m = 0$, then l and d are in the same zone and no relaying occurs.
- We assume routes are predetermined by an appropriate wireless routing protocol.

Mesh

For each $s \in \mathcal{L}_n \cup \mathcal{R}_n$, let $E(s) = E_n$. For $k \in \{1, \ldots, m\}$ Let Q_{l,s_k} be offered load from l arriving at s_k and Q_{s_k} be the total load offered to s_k. From these we calculate:

$$S_{s_k} = \frac{\tau_{s_k}(1 - p_{s_k})}{E_n}$$

and then assume:

$$Q_{s_{k+1}} = \sum \frac{Q_{l,s_k}}{Q_{s_k}} S_{s_k}$$

to calculate the load in the next network.

Buffering

- Limitations of small buffers particularly apparent in mesh.
- Need to introduce queue empty probability to model queue: r_n.
- Model queues as M/G/1.

$$\mathbf{E}(B(p)) = \frac{W_0}{2(1-2p)}(1 - p - p(2p)^m). \tag{8}$$

$$r_n = \min(1, -B(p_n)\log(1 - q_n)) \tag{9}$$

Simply replaces $\tau(p)$ relation.

To appear, IEEE Comms. Letters (2007), (Duffy, Ganesh).

Seeing some interaction between buffering and service.

Unfairness

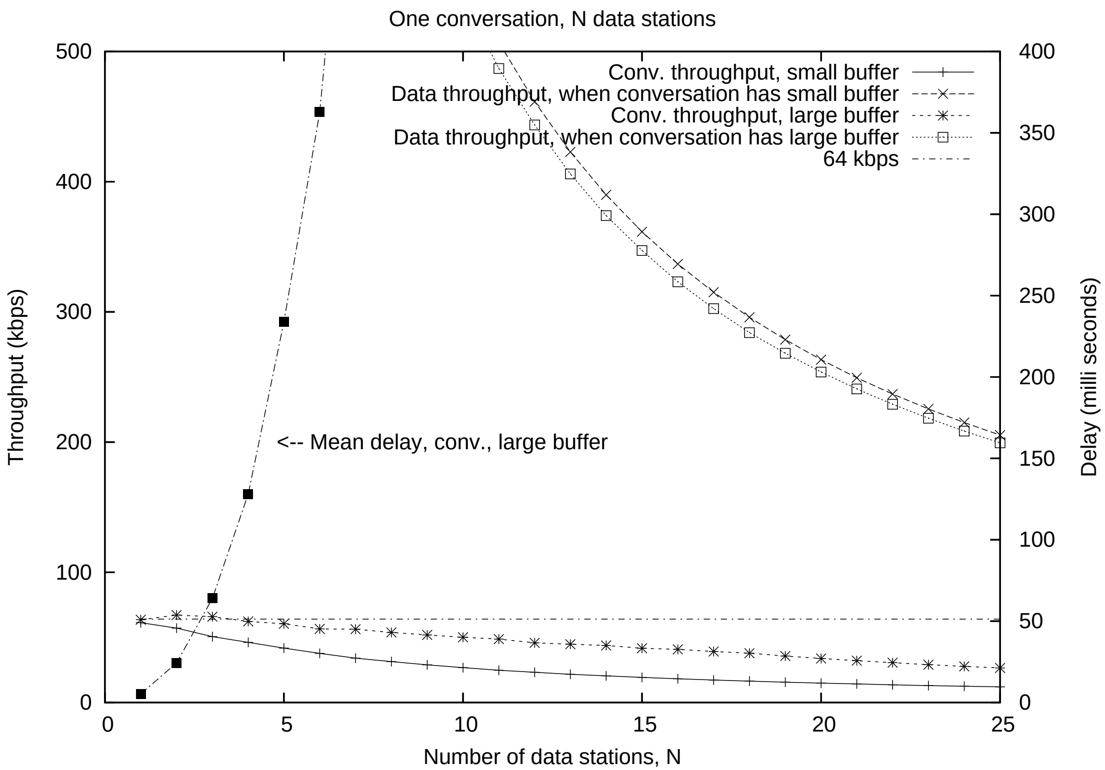
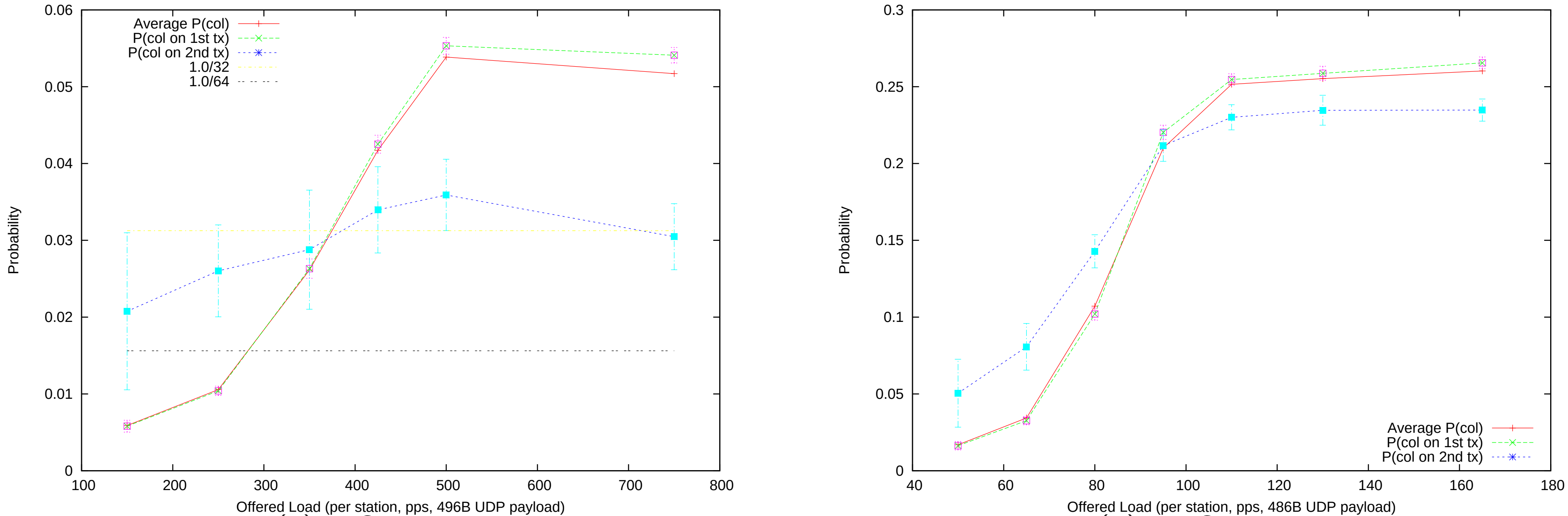


Figure 6: NS packet-level simulation results and model predictions

Understanding the Models

- Models are inexact in several ways.
- Constant p replaces complex Markov chain with direct sum.
- Throughput relationship assumes independent.
- Do assumptions hold or are stationary distributions similar?

Is p constant?



(a) 2 Stations

(b) 10 Stations

Figure 7: Measured collision probabilities as offered load is varied.

Independence of Transmissions

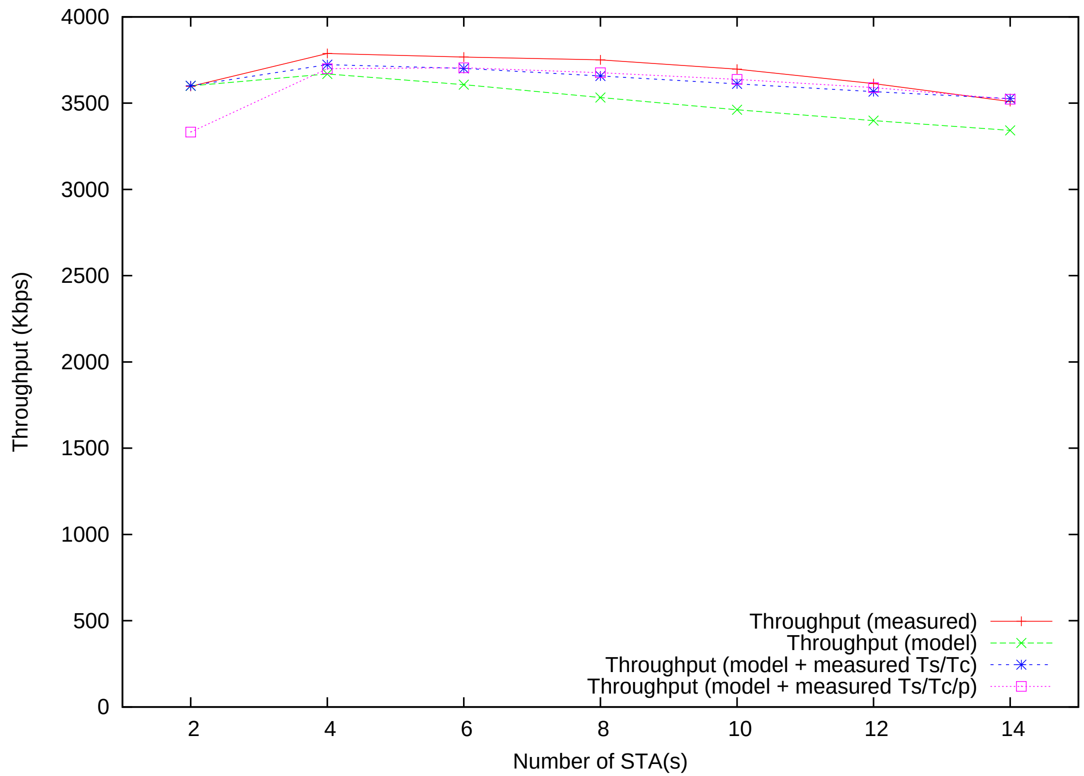


Figure 8: Overall throughput in a network of saturated stations as the number of stations is varied. The measured values are compared to model predictions.

Conclusions

- 802.11/802.11e CSMA/CA models that are simple, solvable, yet complex enough to predict data throughput.
- Model gives insight into 802.11 MAC behavior.
- Model gives insight into effect of 802.11e parameters.
- Prioritization schemes can now be designed quickly based on the model.
- Extensible to network scenarios.
- Interesting questions on buffering and foundations remain to be answered.