Distributed Uplink Scheduling in EV-DO Rev. A Networks

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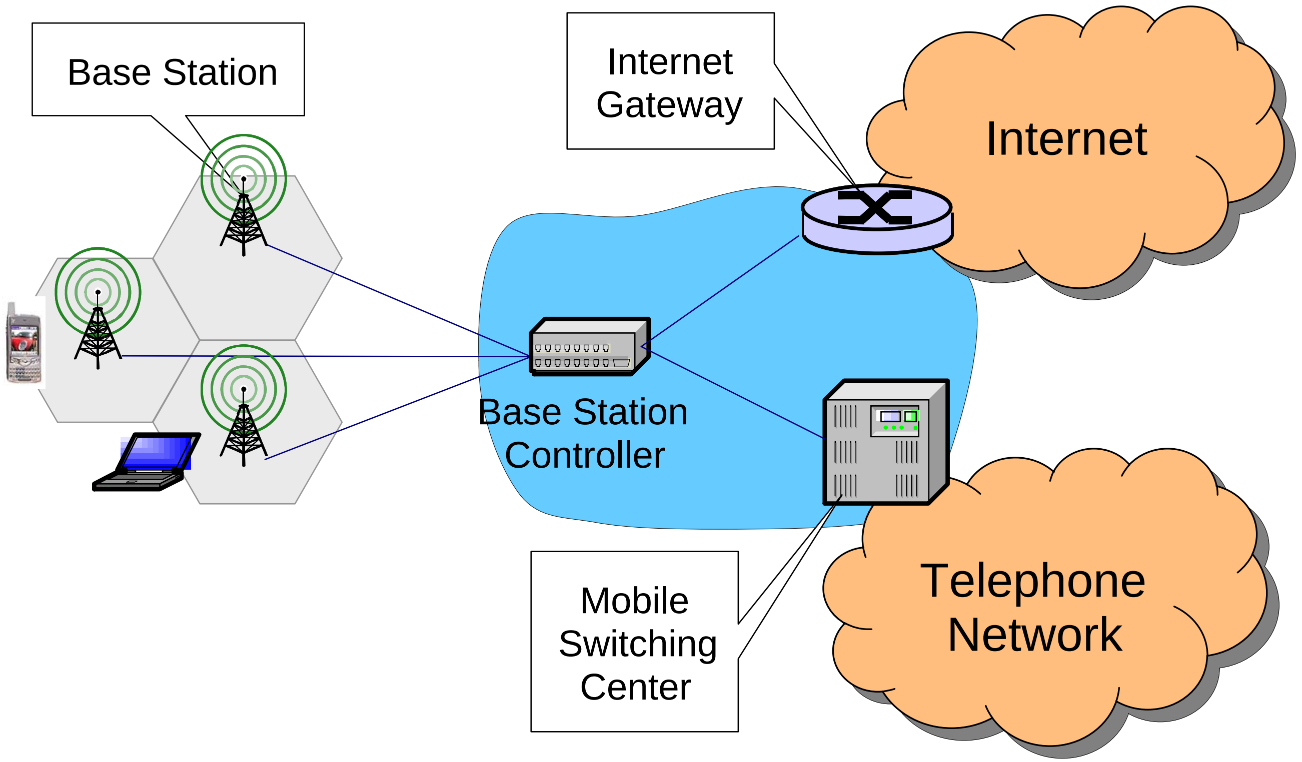
Overview of Problem

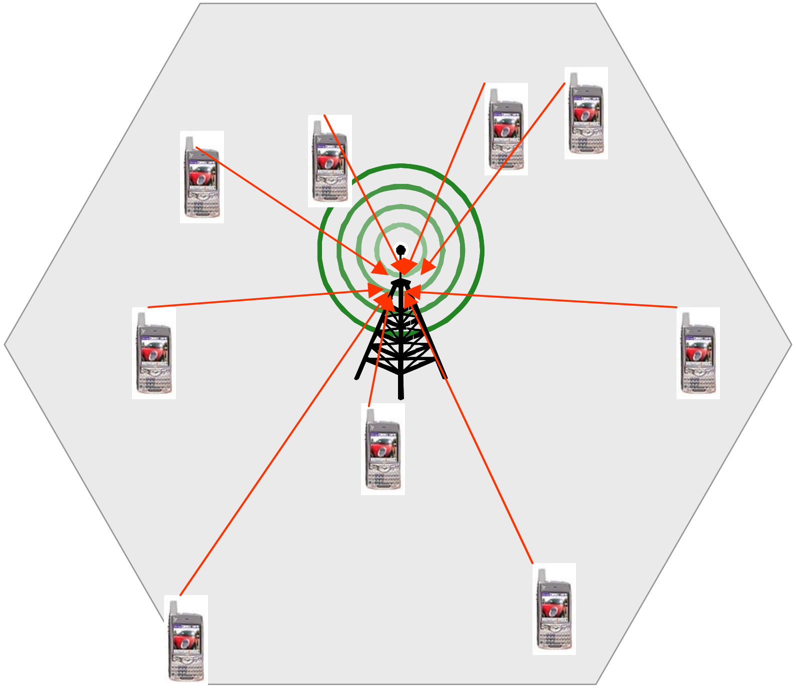
- Most modern wireless systems
  - Deliver high performance through tight control of transmissions by the Base Station (which devices, when & at what power)
- Most modern wireless devices
  - Run a broad range of applications with different communication needs (voice, video, web, email, SMS)
- Centralizing all decisions at the base station lacks flexibility and scalability
  - Latest wireless standards include mechanisms for partially delegating transmission decisions to devices
- But there is a cost in giving devices autonomy in making independent transmission decisions?
  - Sub-optimal resources sharing can impact overall throughput

- How big is the problem?
- What policies/mechanisms to best mitigate those effects?

System Overview



Our Focus



Overview of Results

- Assessing the impact of independent (uplink) user transmissions
  - Saturated, homogenous users
  - Randomized policies (transmission probability p)
  - Optimal value for p with significant impact on throughput
    - Threshold behavior as a function of system load
- Realizing optimized distributed transmissions in token bucket controlled systems
  - Selecting transmission probabilities to approximate optimal policies under bucket constraints

Outline of Talk

- A short primer on wireless transmissions
  - CDMA uplink
  - EV-DO Rev. A operation
- Previous works
- Modeling distributed transmission decisions
  - Analysis of randomized policies
- Emulating optimal policies
  - Token-bucket controlled systems
- Extensions of results and future work

Overview of CDMA Uplink

- CDMA uplink is interference limited
  - Each user has a spreading "orthogonal" code
    - Allows *simultaneous* transmissions
    - However, users interfere due to multi-path effects
- Users can select among multiple (discrete) transmission rates
  - Control loop based on pilot signal equalizes channel among users
  - Transmitted power is proportional to pilot strength AND selected rate

Uplink Operation

- Pilot P_i transmitted by device i=1,...,n+1
  - Pilot signals are power controlled by BS to all be received with the ***same*** target SINR $1/\Phi$

$$\frac{1}{\phi} = \frac{G^i_{loss} P_i}{\sigma^2 + \theta_{Pilot} \sum_{j \neq i} G^j_{loss} P_j} \Rightarrow G^i_{loss} P_i = \Delta = \frac{\sigma^2}{\phi - n\theta_{Pilot}}, \forall i = 1, \ldots, n+1$$

    - G^i_{loss} : Path loss; θ_{Pilot}: Orthogonality factor; σ^2 : Noise
- User i transmit power = $P_i \cdot TxT2P[R]$
  - $R \in \Re$: Target data rate from discrete set $\Re$
  - $TxT2P[R]$: Proportionality factor relative to Pilot
    - User spends $TxT2P[R]$ power *tokens* to transmit at rate R

Sample $TxT2P[R]$ Values

Target Data Rate	$TxT2P[R]$ dB
0	-∞
9.6 kbps	4.5
19.2 kbps	6.75
38.4 kbps	9.75
76.8 kbps	13.25
153.6 kbps	18.5

CDMA Uplink Interference Model

$$SINR_i(R_i) = \frac{G(R_i)\cdot G^i_{loss}\cdot P^i_D(R_i)}{\sigma^2 + \theta\sum_{j\neq i} G^j_{loss}\cdot P^j_D(R_j)}, \theta:$$ Data orthogonality factor

$G(R_i) = \frac{W}{R_i}$: Processing Gain and $P^i_D(R_i) = P_i \cdot TxT2P[R_i]$

$$\Rightarrow SINR_i(R_i) = \frac{G(R_i)\cdot TxT2P[R_i]\cdot\Delta}{\sigma^2 + \theta\sum_{j\neq i} TxT2P[R_j]\cdot\Delta}, \Delta = \frac{\sigma^2}{\phi - n\theta_{Pilot}}$$

- Interferences from other users
  - The higher the rate a user chooses, the more interference it creates!

No Channel Effects (Perfect Power Control)

Our Problem

$$SINR_i(R_i) = \frac{G(R_i) \cdot TxT2P[R_i] \cdot \Delta}{\sigma^2 + \theta \sum_{j \neq i} TxT2P[R_j] \cdot \Delta}, i = 1, \ldots, n+1$$

- Users make independent transmission and rate selection decisions
  - Greedy behavior by individual users can affect overall performance
- What guidelines to mitigate negative impact of independent decisions

Previous Work

- Extensive work on rate allocation and power control
  - Assumes continuous transmission (no scheduling).
- Scheduling in CDMA ad-hoc networks
  - Assumes synchronization, contention resolution.
- Closest work that of [3], [4]
  - Scheduling in cellular CDMA.
  - Solves centralized global allocation numerically.

Our Initial Model

- Homogenous, unconstrained users
  - All users (n+1 users in a sector) employ the same policy
  - Users always have data and are able to transmit whenever the policy schedules a transmission
- Probabilistic On-Off transmission policy
  - Transmit at rate R in a slot with probability p
    - Transmit power is therefore 0 with probability 1-p and ~$TxT2P[R]$ with probability p
- Simple but useful model
  - Similar to Aloha
  - But with a contention model based on soft interferences (CDMA) rather than "collisions"
- Questions
  - At what rate R should a user transmit?
  - How often (what p value) should a user transmit?

Main Results

- There exists an optimal p^* (maximizes $\hat{C}(p)$)
  - If $\delta \geq 1$ then $p^*=1$
  - If $\delta < 1$ then $p^* < 1$

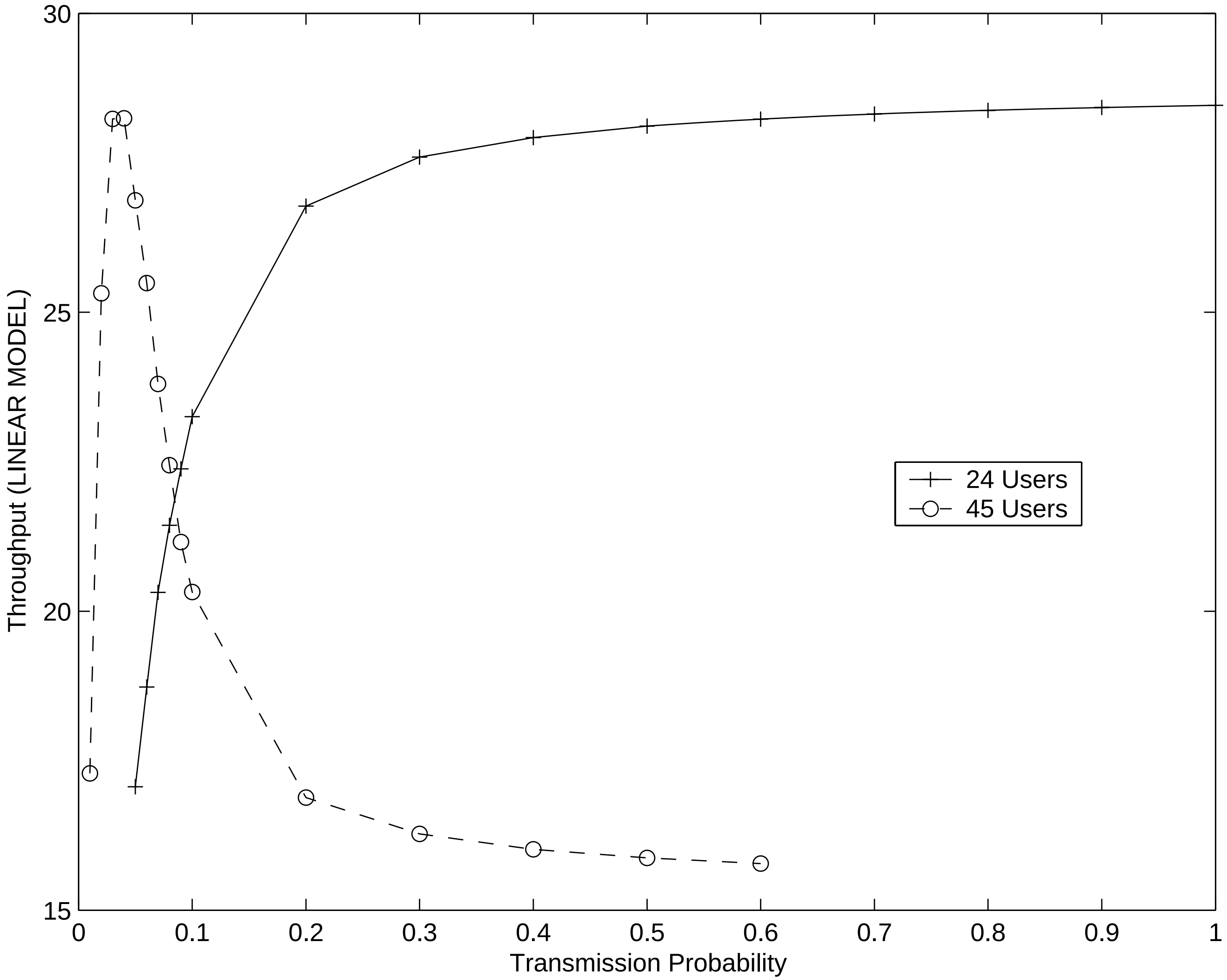
$$\delta = \frac{\phi - n\theta_{Pilot}}{\theta \cdot TxT2P[R]}$$

  - In both cases p^* satisfies the following equality

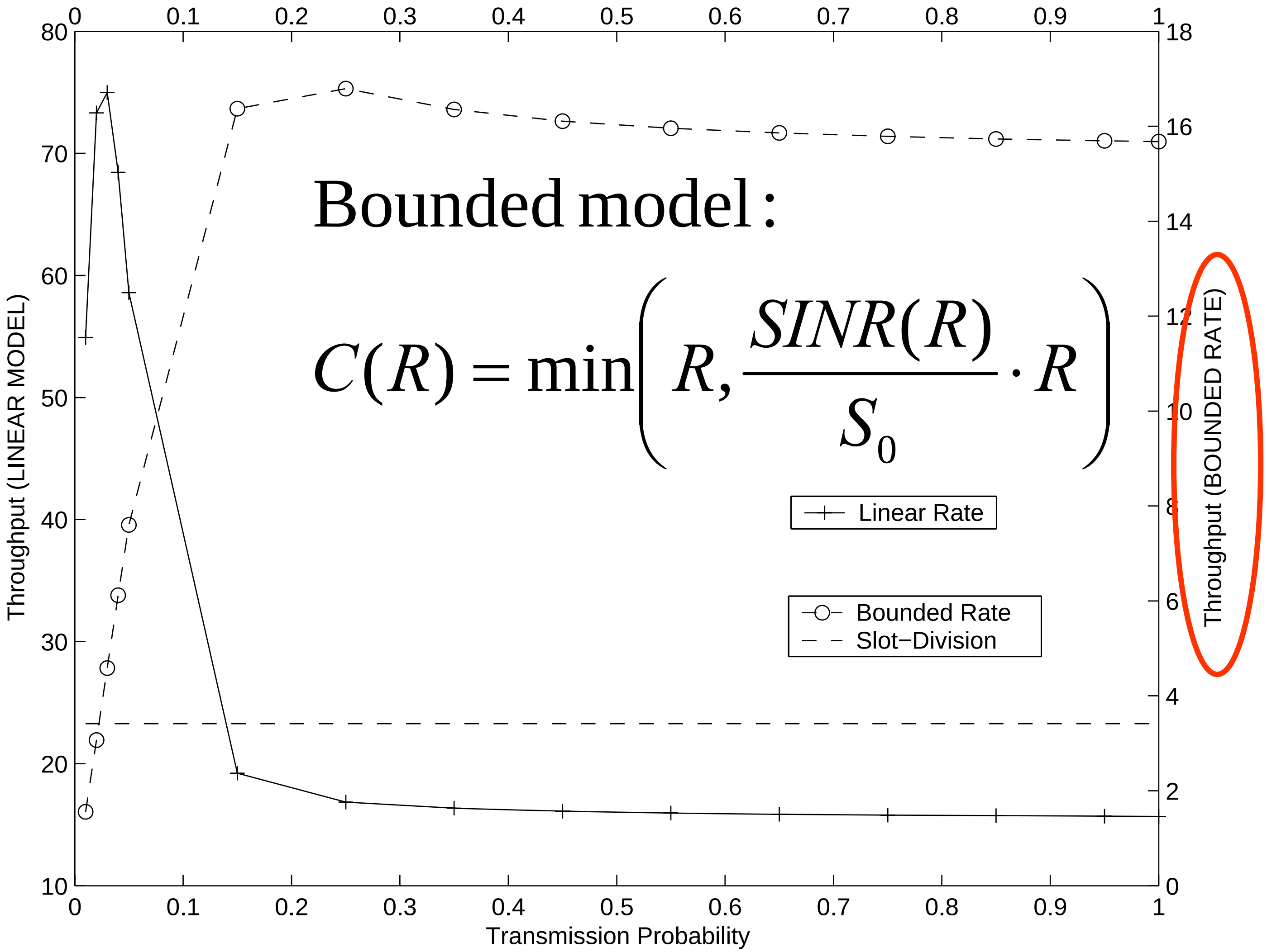
$$\sum_{j=0}^{n} \frac{1}{j+\delta} \binom{n}{j} p^{*j} (1-p^*)^{n-j} = \frac{1}{(n+1)p^* - 1 + \delta}$$

  - With few (many) users, and/or low (high) *target* rate R, users should transmit (in)frequently
- Higher target rates always achieve higher throughput, i.e., $\hat{C}(p_1^*, R_1) > \hat{C}(p_2^*, R_2)$, if $R_1 > R_2$
  - In the absence of other constraints

Impact of δ



Hybrid Slotted/CDMA



Bounded model:

$$C(R) = \min\left(R, \frac{SINR(R)}{S_0} \cdot R \right)$$

Distributed Control

- Token bucket mechanism available in EV-DO Rev. A and HSUPA to “control” device transmissions
  - Token bucket depth σ and token fill rate ρ are controlled by Base Station
  - A device needs $TxT2P[R]$ tokens to transmit at rate R
  - Aimed at limiting peak and average power to satisfy fairness and QoS constraints
- Question: How does the presence of a token bucket affect the choice of “good” transmission decisions by devices?

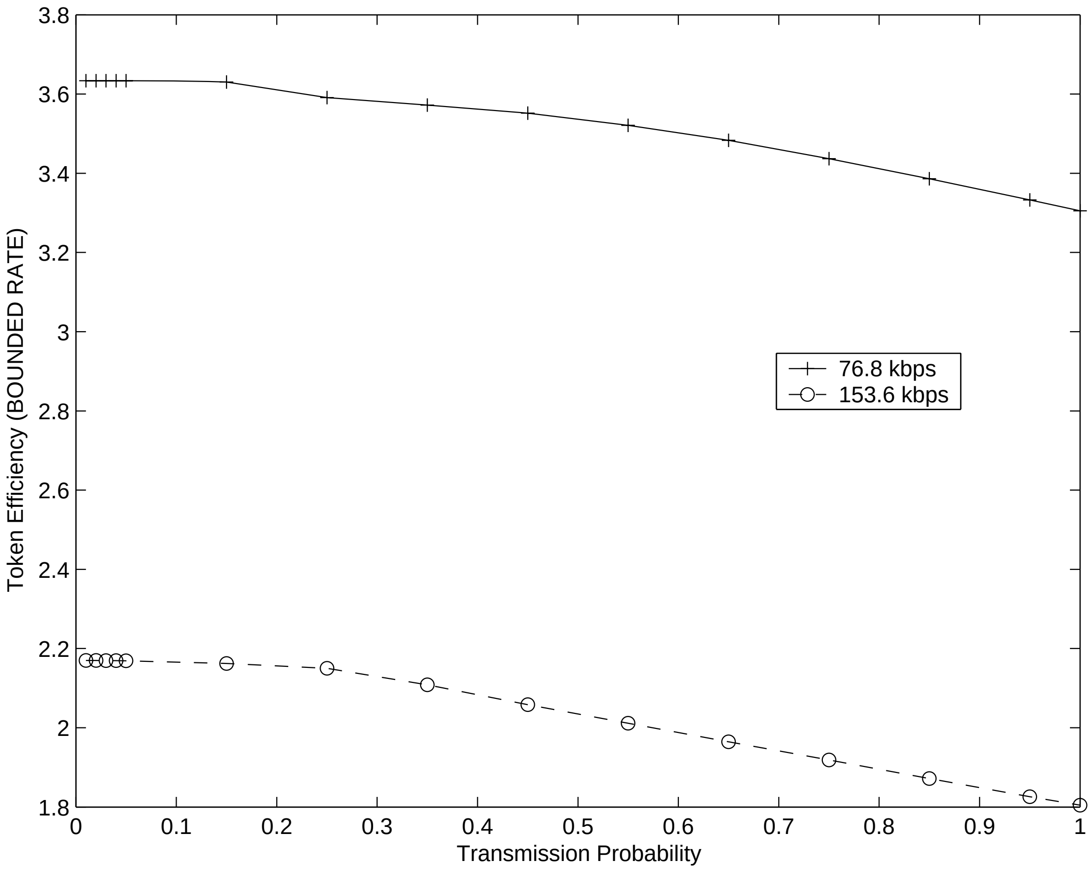
Accounting for Token Buckets

- Given a token bucket configuration (σ,ρ)
  - What are the optimal p^* and K values?

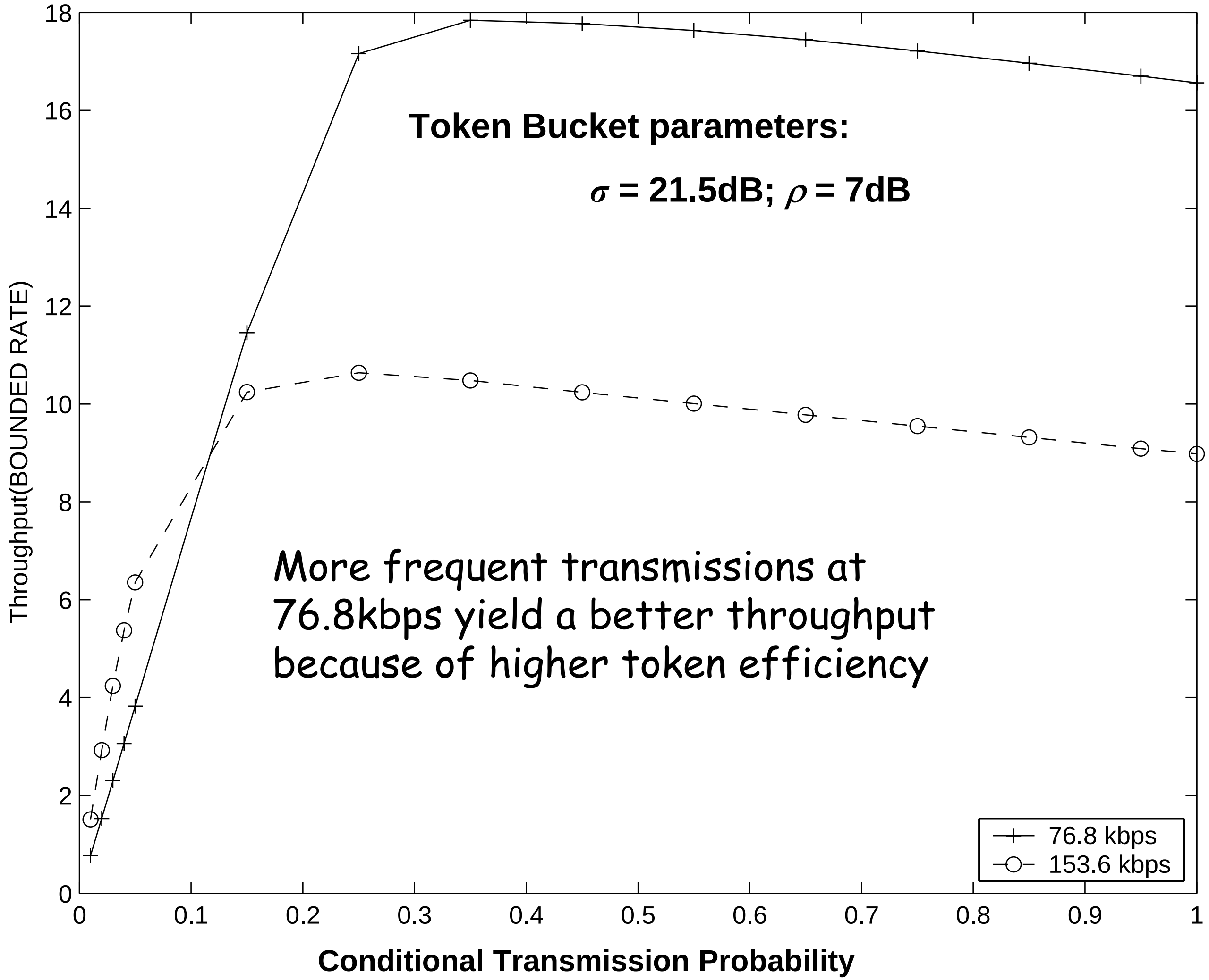
- Two-step formulation
  1. Account for impact of token bucket on transmission decisions
     - Transmissions conditioned on having at least K tokens
  2. Explore possible combinations of p and K values
     - Note that optimality of higher rates need not hold any more because of token constraints (token efficiency)

Token Efficiency

- With 24 users transmission at 153.6kbps yields a higher throughput but a lower token efficiency than transmission at 76.8kbps



Impact of Token Bucket



Analysis vs. Reality

	Token Bucket: $\sigma = 21.5$dB; $\rho = 7$dB				
Rate (kbps)	Analysis		Simulations (bounded rate model)		
	p^*_{A}	C^*_A	p^*_{sim}	$\mathrm{C}^*_{\mathrm{sim}}$	$\mathrm{C}_{\mathrm{sim}}(p^*_A)$
76.8	1.0	26.4	0.35	17.84	16.56
153.6	0.21	42.9	0.25	10.63	10.59

- Expected inaccuracies because of bounded rate
  - But actual impact on throughput is small

Extensions & Future Work

- Recent results
  - Established that similar results also hold for the *bounded* rate model
  - Characterized optimum *centralized* schedule
    - A benchmark against to compare distributed policies
    - A combinatorial problem because of discrete rate values
- Extensions
  - Investigating the impact/use of token bucket for its "original" purpose, namely, service differentiation
    - Rate vs. delay performance targets

Relevant References

1. P. Venkitasubramaniam, S. Adireddy, and L. Tong, "Opportunistic ALOHA and cross-layer design in sensor networks." Proc. IEEE MILCOM, Boston, MA, October 2003.
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