Effective Capacity: A Wireless Link Model for Support of Quality of Service

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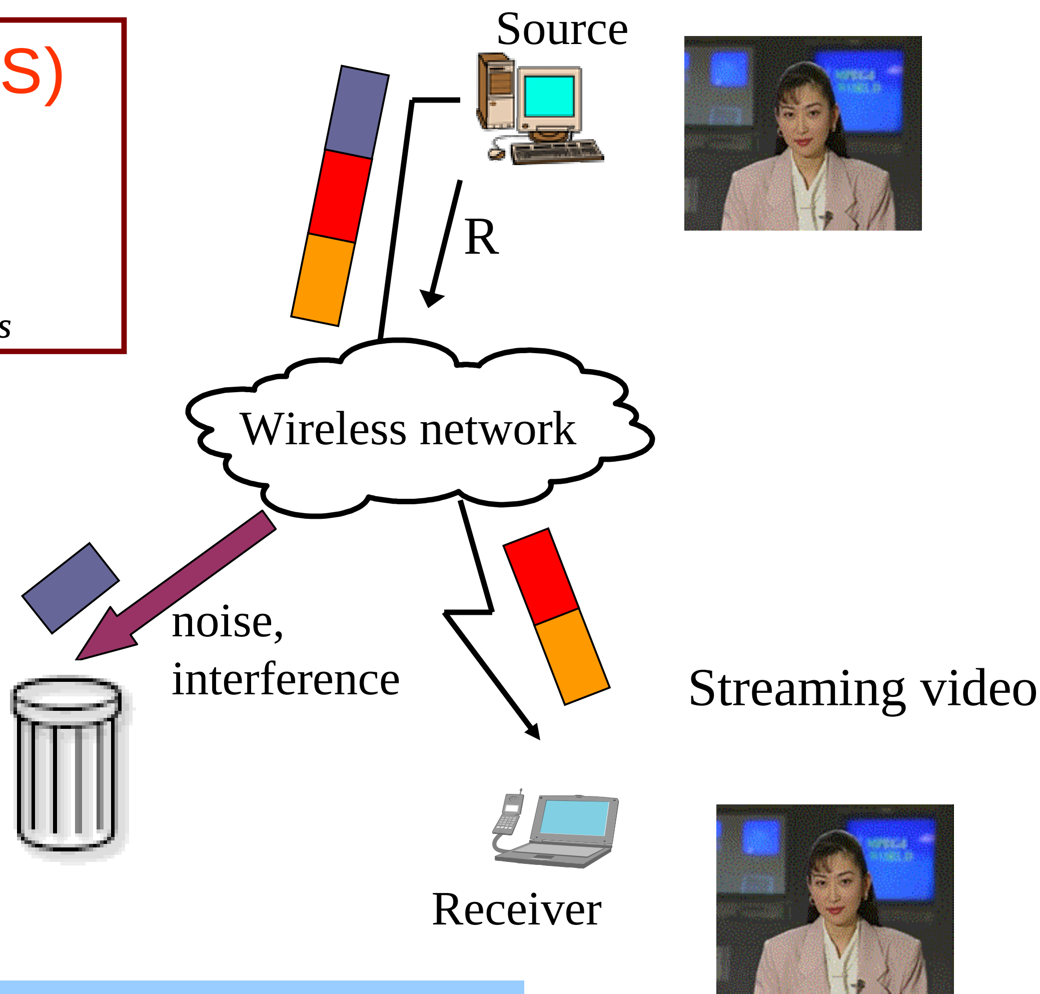
Outline

- Motivation of this paper
- Brief review of Effective Bandwidth
- New model used at upper layer to capture wireless channel quality
- Simulation
- Contribution & Limitations

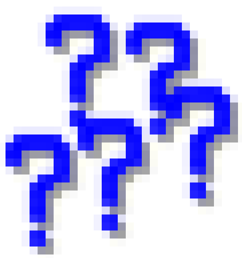
QoS Provisioning in Wireless Networks

Quality of Service (QoS)

- Data rate R
- Delay tolerable D_{max}
- Packet loss probability P_{loss}

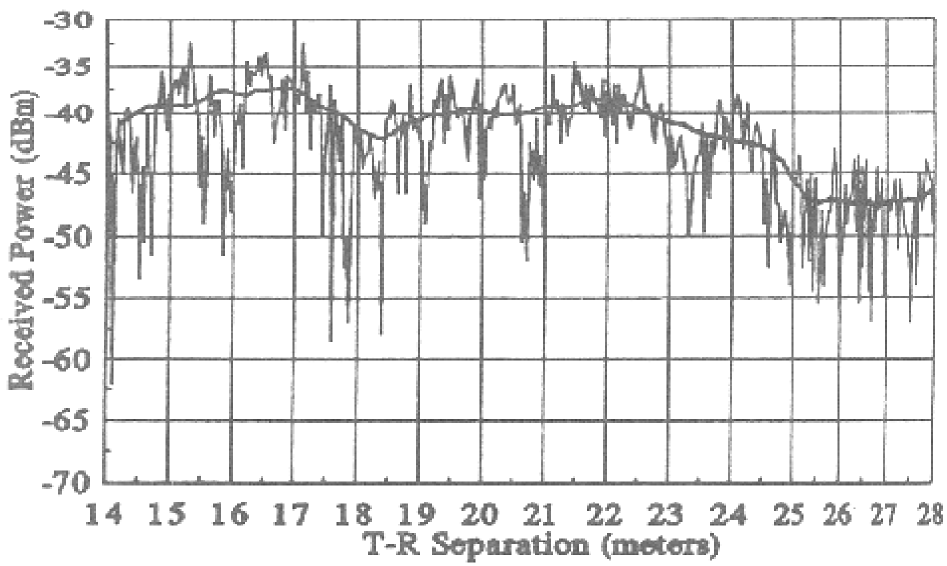


$$P_{loss} = \text{Prob}\{D(t) \geq D_{max}\}$$



How do we guarantee QoS to the user?

Key issue: time varying wireless channel



Receiver moves

↓

Power fluctuates

↓

Data capacity changes

↓

Packets get loss

↓

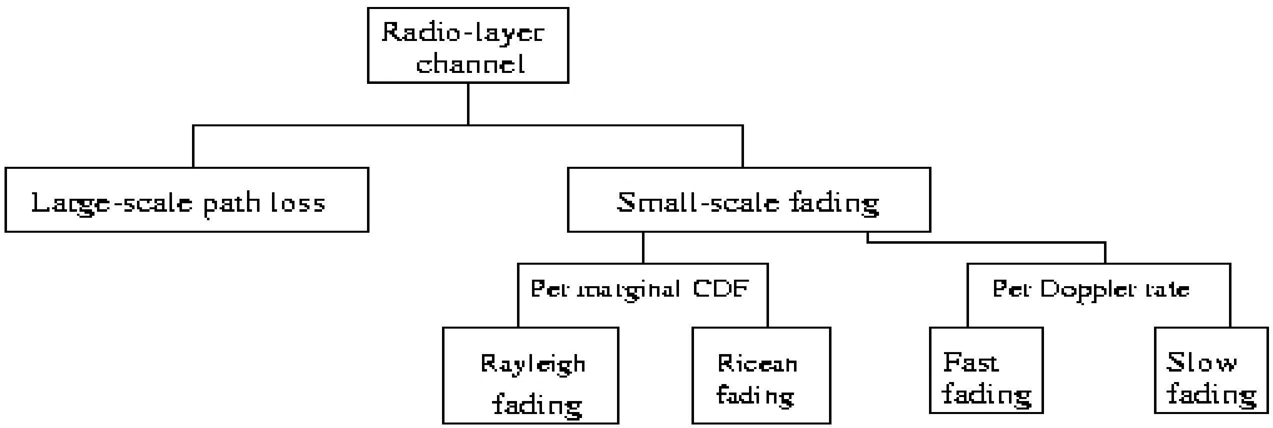
$$P_{loss} = \text{Prob}\{D(t) \geq D_{\max}\}$$

So ???

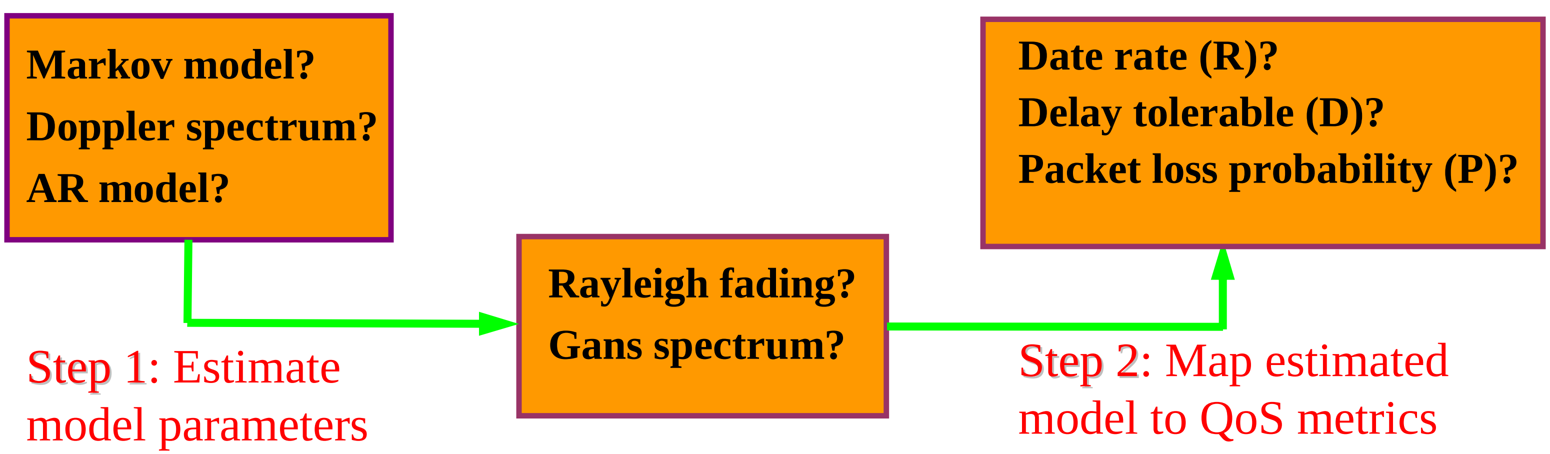
How do we estimate wireless channel capacity?

Need for a novel wireless channel model

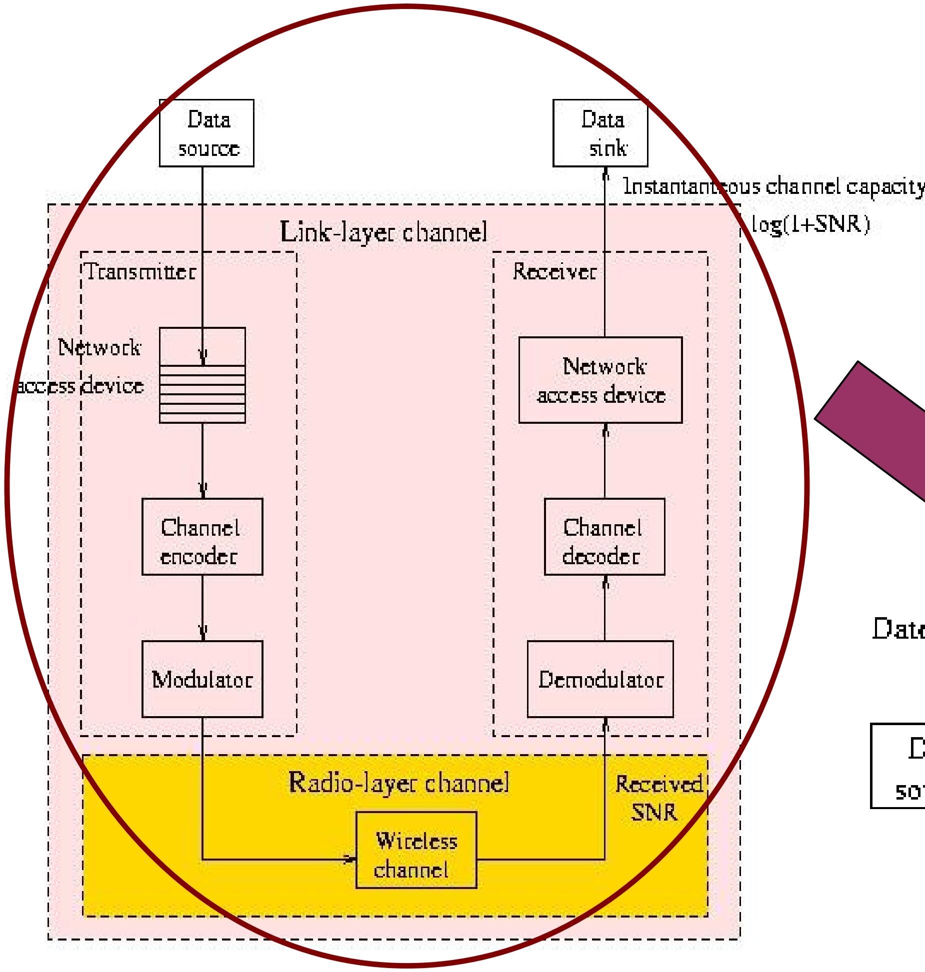
- "Radio layer" channel models represent power fluctuations

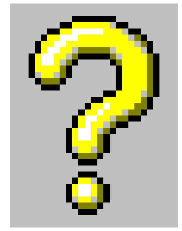


- Hard/impossible to extract $\{R, D_{max}, P_{loss}\}$ QoS metrics



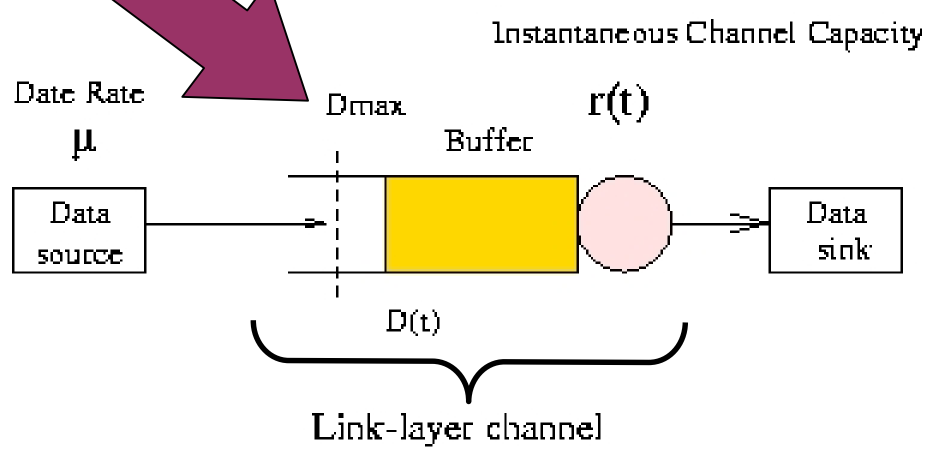
A “link-layer” channel model





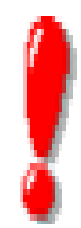
What is channel “capacity”, when QoS is accounted for?

Model as time-varying server



link-level channel model

Easily computes delay constrained capacity



Motivation of This Paper

- Model wireless channel in terms of upper-layer QoS metrics such as data rate, delay, and delay-violation probability to facilitate support of QoS in next-generation wireless networks
  - easy of translation into QoS guarantees
  - simplicity of implementation
  - accuracy

Main Idea

Statistical Service Curve

+

Effective Bandwidth Theory

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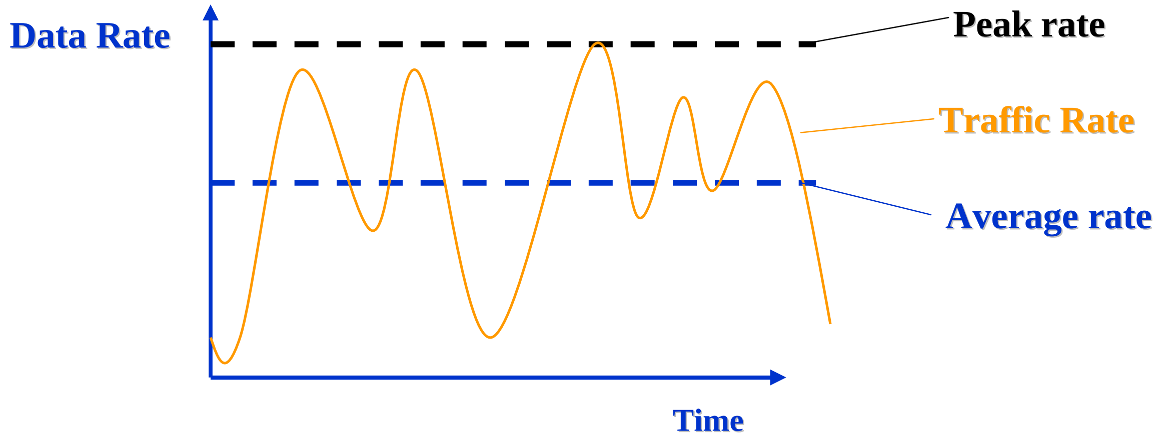
New Channel Capacity Model

What is Effective Bandwidth ?



Minimum data rate needed for arrival traffic to meet its QoS requirements

Effective Bandwidth was proposed by Gibbens& Hunt, Guerin, and Kelly in 1991

Definition of Effective Bandwidth

- A(t) (total arrival traffic during [0,t)) has stationary increments

$$\alpha(\theta, t) = \frac{1}{\theta t} \log E[e^{\theta A(t)}] \quad \theta, t \in [0, \infty)$$

$\alpha(\theta, t)$ is called as effective bandwidth of arrival traffic

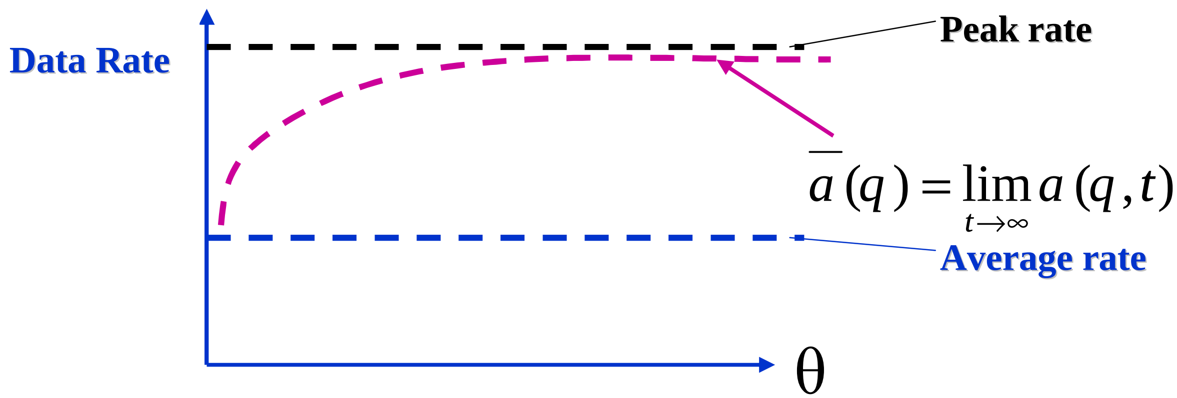
- Range:

$$\text{average rate} \leq \alpha(\theta, t) \leq \text{peak rate}$$

$$\alpha(\theta, t) \to \text{average rate} \quad \text{as} \quad \theta \to 0$$

$$\alpha(\theta, t) \to \text{peak rate} \quad \text{as} \quad \theta \to \infty$$

Effective Bandwidth & QoS



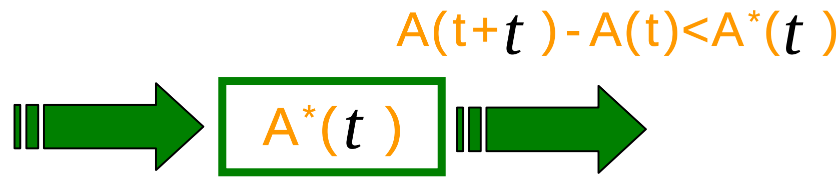
$$P\{\text{delay} \geq D\} \leq \varepsilon$$

Large ε Small e

Small θ Large θ

Small $\alpha(t, \theta)$ Large $\alpha(t, \theta)$

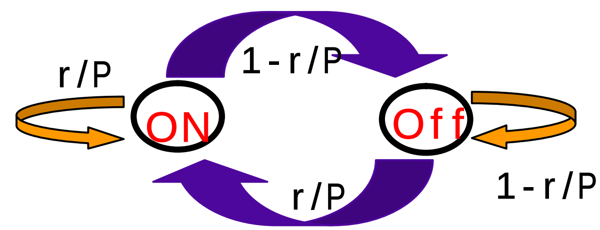
Examples



- Regulated Traffic

$$\alpha(\theta,t) = \frac{1}{\theta t}\log[1+\frac{\rho t}{A^*(t)}(e^{\theta A^*(t)}-1)]$$

$$\text{where} \quad \rho = \lim_{t\to\infty}\frac{A^*(t)}{t}$$



- On-Off Traffic

$$a(q,t) = \frac{1}{q}\log(1+\frac{r}{P}(e^{Pq}-1))$$

- FBM Traffic

$$a(q,t) = r + \frac{1}{2}bqt^{2H-1}$$

$A(t) = rt + \beta Z_t$ r = mean traffic rate

1. $Z_0 = 0.$ 2. $EZ_t = 0$

3. $EZ_t^2 = t^{2H}$, Hurst Paramter $H \in (0,1)$

Extended Definition of Effective Bandwidth

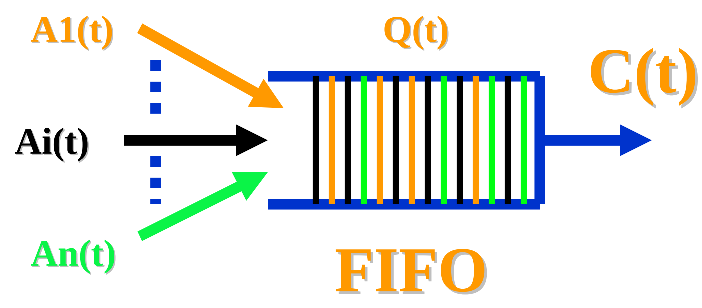
- For a stochastic process $\{X(t), t>0\}$ with stationary and nonnegative increments

$$\alpha_X(q,t) = \frac{1}{|\theta| t} \log E[e^{\theta X(t)}], q \in (-\infty, \infty), t \in [0, \infty)$$

$\alpha_X(q,t)$ is called as effective bandwidth of the stochastic process

Effective Bandwidth & QoS

- Assume aggregated traffic arrival process A(t) and link capacity process C(t) are stationary, then



$$Q(t) = \max_{0 \le s \le t}[A(t) - A(s) - C(t) + C(s)]$$

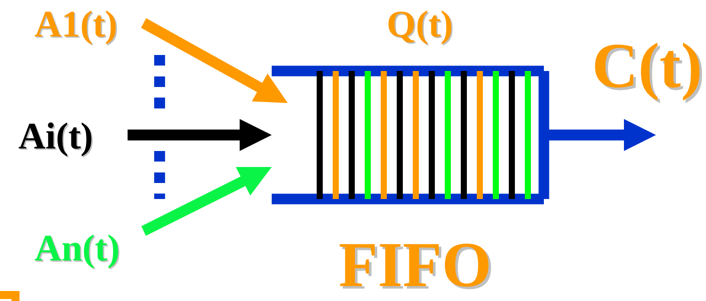
$$P[Q \ge x] = \sup_{t} P[Q(t) \ge x]$$

$$a_A(q^*, t) + a_C(-q^*, t) \to 0 \text{ as } t \to \infty$$

$$\Downarrow$$

$$\lim_{x \to \infty} \frac{1}{x} \log P\{Q \ge x\} \le -q^* \quad \Leftrightarrow \quad P\{Q \ge x\} \approx g e^{-xq^*}$$

Special Cases



A(t)=A1(t)+A2(t)+…+An(t)

C(t)=r*t è $a_C(-q,t) = -r$

$$\sup_{t} \Pr[\mathrm{D(t)} \geq \mathrm{x}] \approx g(r) \times e^{-r \times g^{-1}(r)x}$$

$$g(r) = \Pr[D(t) \geq 0] \quad g(q) = \lim_{t \to \infty} a_A(q,t)$$

$$\mathrm{Q(t)} = \max_{0 \leq s \leq t}[\mathrm{A(t)} - \mathrm{A(s)} - \mathrm{C(t)} + C(\mathrm{s})]$$

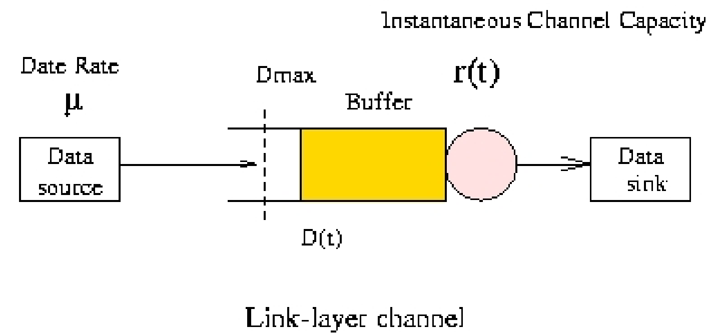
$$\mathrm{P[Q} \geq \mathrm{x]} = \sup_{t} \mathrm{P[Q(t)} \geq \mathrm{x]}$$

A(t)=u*t è $a_A(q,t) = u$

$$\sup_{t} \Pr[\mathrm{D(t)} \geq \mathrm{x}] \approx g(u) \times e^{-u \times h^{-1}(u)x}$$

$$g(u) = \Pr[D(t) \geq 0] \quad h(q) = -\lim_{t \to \infty} a_C(-q,t)$$

Proposed Link-level channel model



- **According to**:

$$\sup_t \Pr\{D(t) \geq D_{max}\} \approx g(u) \times e^{-u \times h^{-1}(u) \times D_{max}}$$

$\{g(u), h^{-1}(u)\}$ is called link-layer wireless channel model

- Interpretation
  - Probability of delay, experienced by CBR traffic with rate u, more than D is bounded by

$$g(u) \times e^{-u \times h^{-1}(u) \times D_{max}}$$

Simple Estimation Algorithm

$$\Pr\{D(t) \geq D_{\max}\} \approx \text{[redacted]}) \times e^{-u\times \text{[redacted]} \times D_{\max}}$$

$$E[D(t)] = \frac{g(u)}{u \times h^{-1}(u)} \qquad E[D(t)] = t_s(u) + E[Q(t)]/u \qquad h^{-1}(u) = \frac{g(u)}{u \times t_s(u) + E[Q(t)]}$$

average remaining time of a packet being served

- Taking N samples over an interval with length T
  - S(n) indicates whether a packet is in service at the n-th sample
  - Q(n) indicates queue length at the n-th sample
  - T(n) indicates the remaining service time of the packet at the n-th sample

$$\overline{g} = \frac{1}{N}\sum_{n=1}^{N} S(n) \qquad \overline{Q} = \frac{1}{N}\sum_{n=1}^{N} Q(n) \qquad \overline{t_s} = \frac{1}{N}\sum_{n=1}^{N} T(n) \qquad \overline{h^{-1}(u)} = \frac{\overline{g}}{u \times \overline{t_s} + \overline{Q}}$$

$$\Pr\{D(t) \geq D_{\max}\} \approx \overline{g} \times e^{-u \times \overline{h^{-1}(u)} \times D_{\max}}$$

Summary of EC Link Model

EC link model:

1. $\{g(u), h^{-1}(u)\}$ is the EC link model, which exists if the log-moment generating function $h(q) = \lim_{t\to\infty} \alpha_C(-q,t)$ in (11) exists [e.g., for a stationary Markov-fading process $C(t)$].

2. In addition to its stationarity, if $r(t)$ is also ergodic, then $\{g(u), h^{-1}(u)\}$ can be estimated by (19) through (22).

3. Given the EC link model, the QoS $\{\mu, D_{\max}, \varepsilon\}$ can be computed by (23), where $\varepsilon = \sup_t \Pr\{D(t) \geq D_{\max}\}$.

4. The resulting QoS $\{\mu, D_{\max}, \varepsilon\}$ corresponds directly to the SC specification $\{\lambda_s^{(c)}, \sigma^{(c)}, \varepsilon'\}$ with $\lambda_s^{(c)} = \mu$, $\sigma^{(c)} = D_{\max}$ and $\varepsilon' \leq \varepsilon$.

Simulation Results

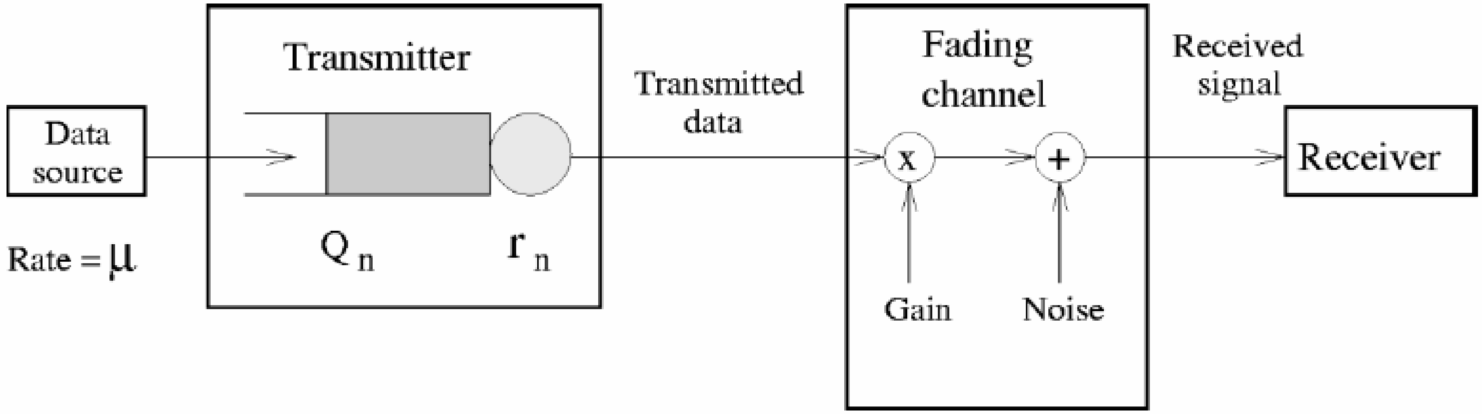


TABLE II
SIMULATION PARAMETERS

Channel	Maximum Doppler rate f_m	5 to 30 Hz
	AWGN channel capacity r_{awgn}	100 kb/s
	Average SNR	0/15 dB
	Sampling-interval T_s	1 ms
Source	Constant bit rate μ	30 to 85 kb/s

Accuracy

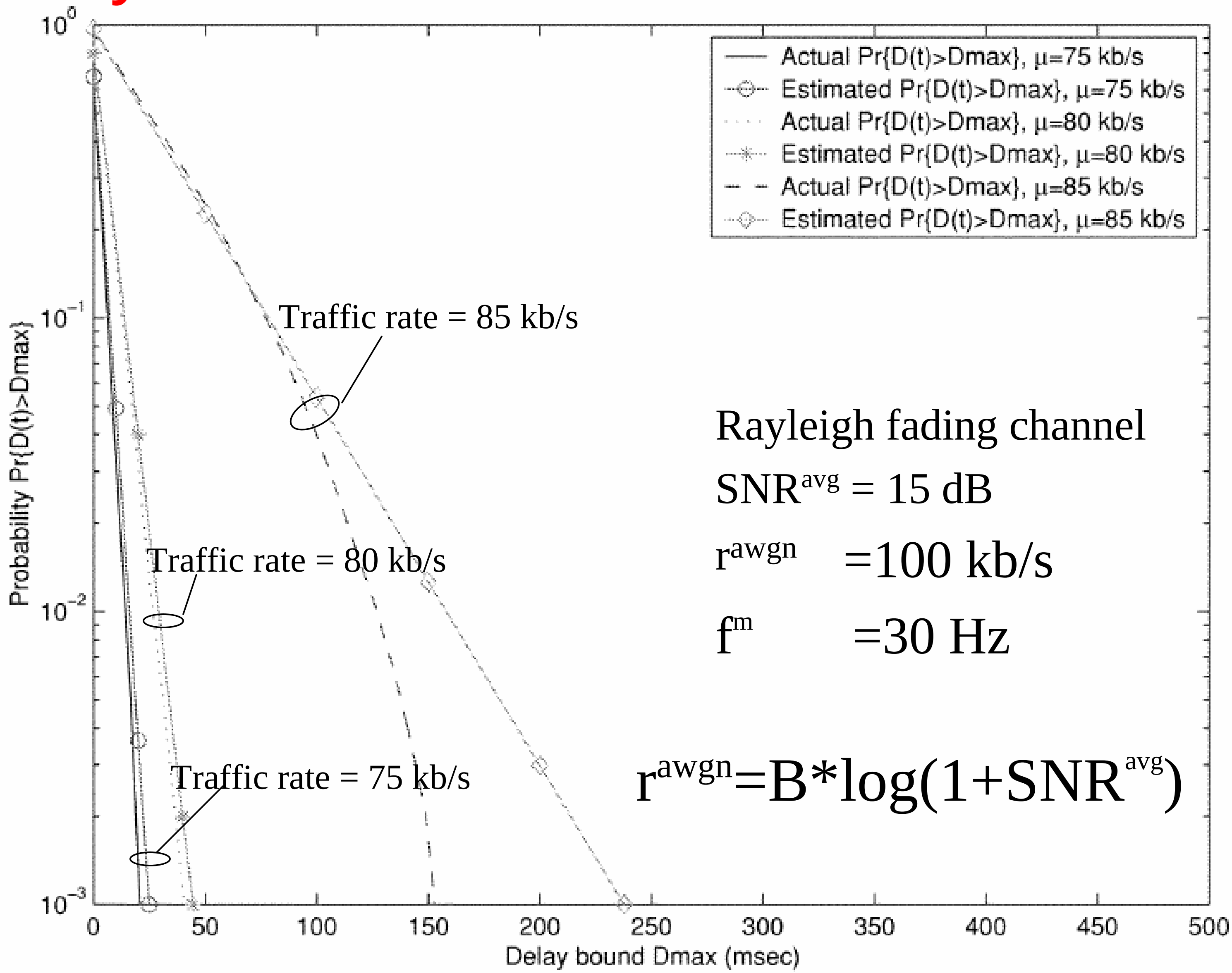


Fig. 9. Prediction of delay-violation probability when the average SNR is (a) 15

Accuracy

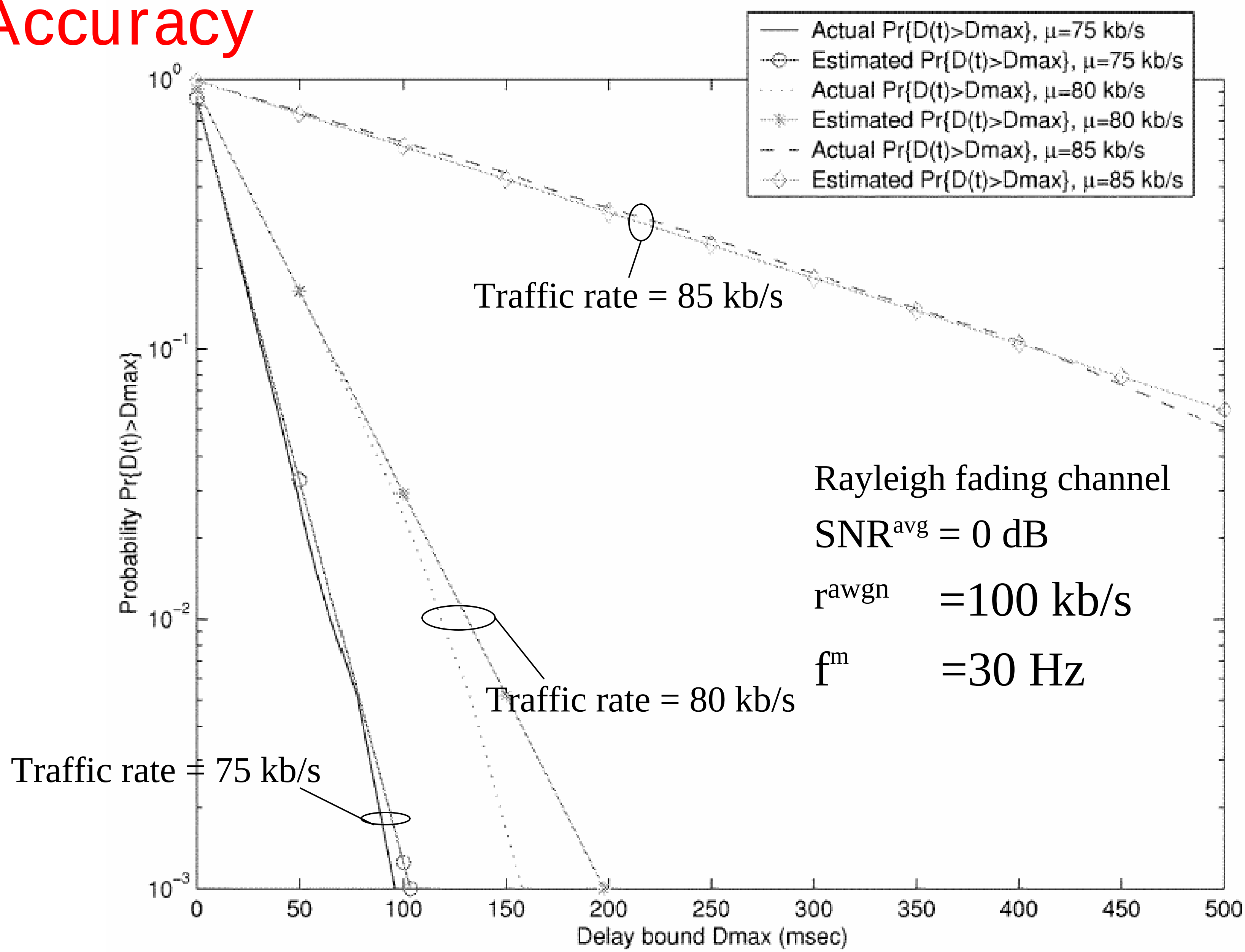


Fig. 9. Prediction of delay-violation probability when the average SNR is (b) 0 dB.

Accuracy

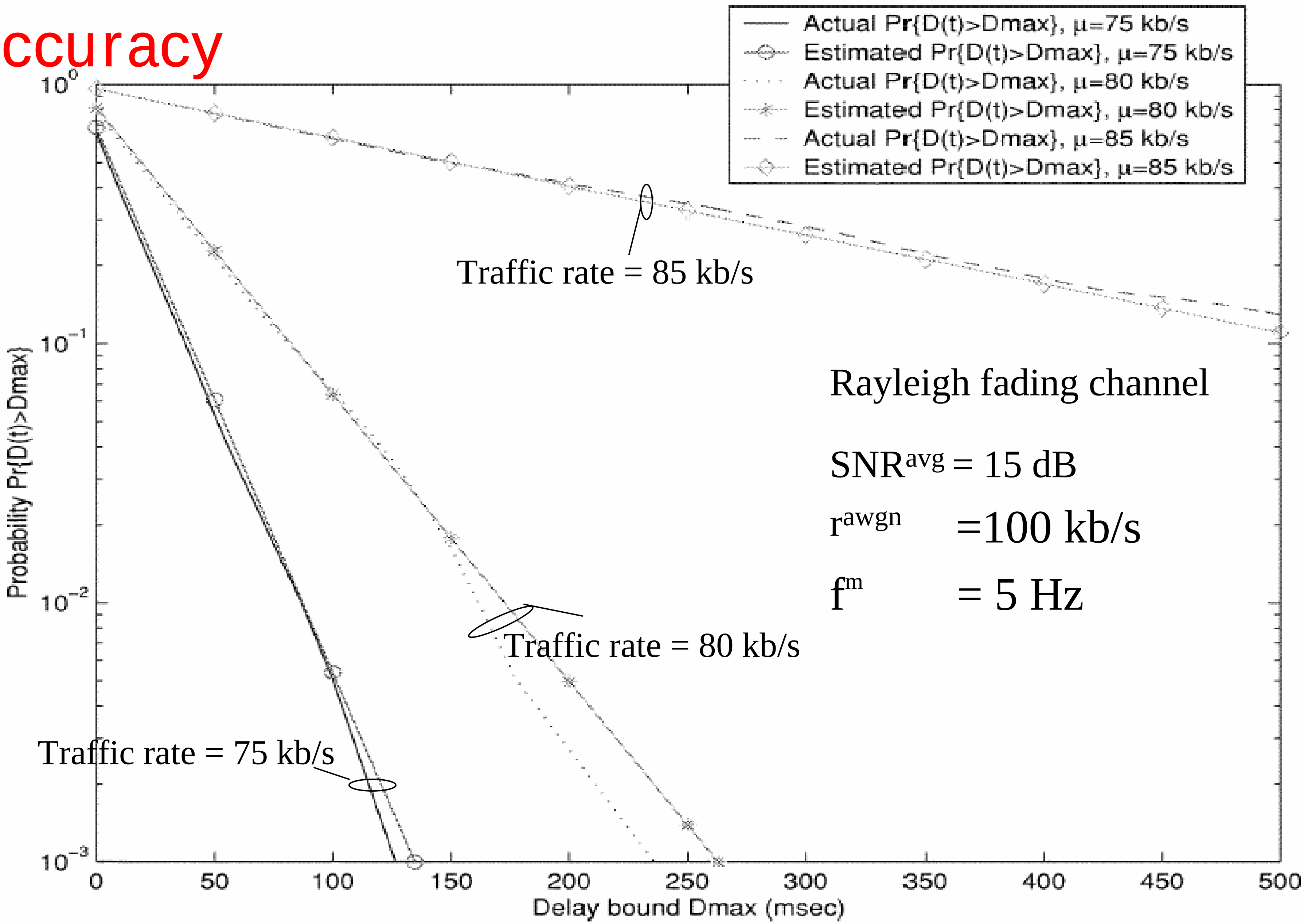


Fig. 10. Prediction of delay-violation probability, when $f_m = 5$ Hz.

Contribution of This Paper

link-layer wireless channel model $\{g(u), h^{-1}(u)\}$

for QoS Guarantees

$$\sup_t \Pr\{D(t) \geq D_{\max}\} \approx g(u) \times e^{-uh^{-1}(u) \times D_{\max}}$$

Limitation of This Paper

- Not solid theoretical foundation

$$a_A(q^*, t) + a_C(-q^*, t) \to 0 \text{ as } t \to \infty$$
$$\Downarrow$$
$$\lim_{x\to\infty} \frac{1}{x} \log P\{Q \geq x\} \leq -q^* \quad \Leftrightarrow \quad P\{Q \geq x\} \approx g e^{-xq^*}$$

- Are the algorithms based on sampling accurate and simple?

$$\overline{g} = \frac{1}{N}\sum_{n=1}^{N} S(n) \quad \overline{Q} = \frac{1}{N}\sum_{n=1}^{N} Q(n) \quad \overline{t}_s = \frac{1}{N}\sum_{n=1}^{N} T(n) \quad \overline{h^{-1}(u)} = \frac{\overline{g}}{u \times \overline{t}_s + \overline{Q}}$$

$$\Pr\{D(t) \geq D_{\max}\} \approx \overline{g} \times e^{-u \times \overline{h^{-1}(u)} \times D_{\max}}$$

- Are the algorithm easy to use?
- Only for CBR traffic
- Does not explicitly take modulation and channel coding into account

Future Work

- More deeply use effective bandwidth theory
- Take its advantage but avoid it disadvantage
- Build a more power channel capacity model for QoS provisioning
- Implementation in 3G or 4G