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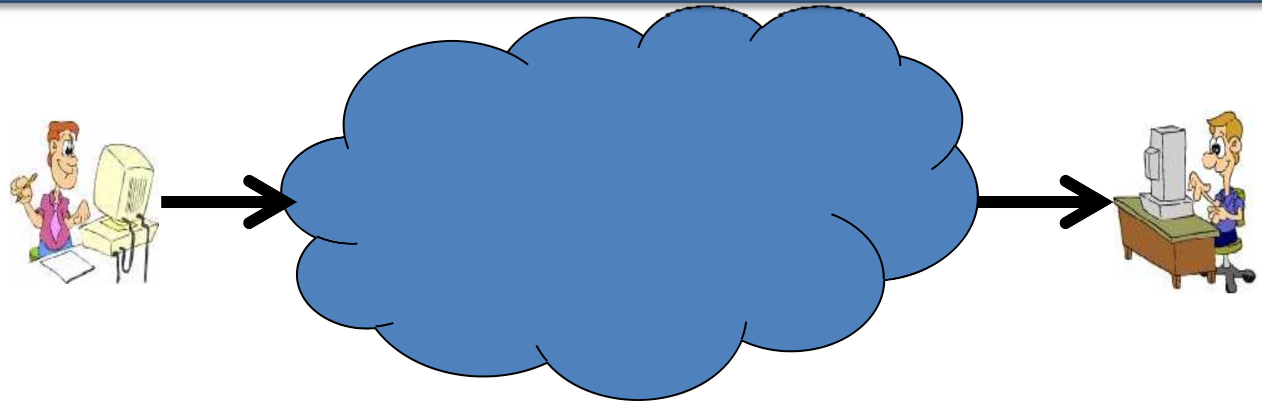
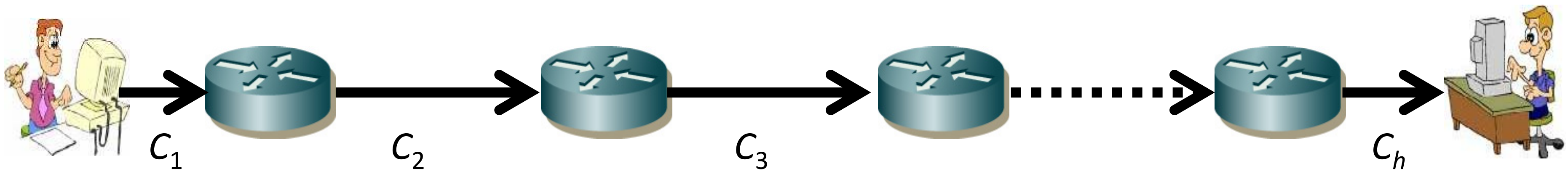
End-to-End Bandwidth and Available Bandwidth Estimation in Multi-Hop IEEE 802.11b Ad Hoc Networks

Marco A. Alzate	José C. Pagán	Néstor M. Peña	Miguel A. Labrador
Universidad Distrital F.J.C. Bogotá, Colombia	Universidad de Puerto Rico Mayagüez, PR	Universidad de los Andes Bogotá, Colombia	University of South Florida Tampa, FL

BandWidth of a Route



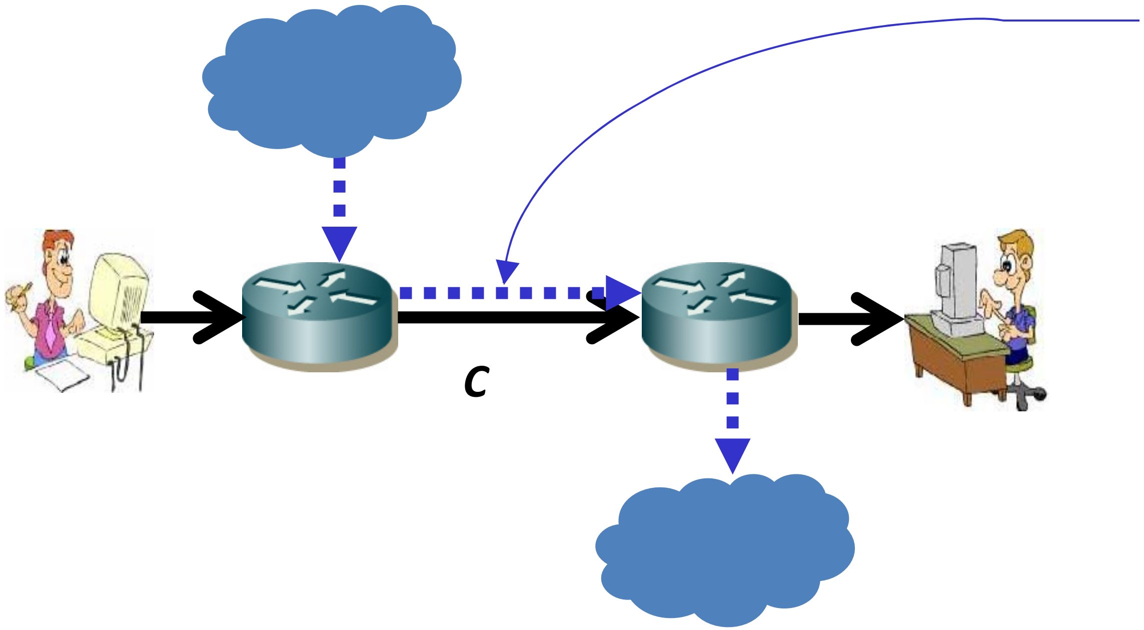
BandWidth (BW) : What is the Maximum Transmission rate I can achieve when nobody competes with me for using the network resources?

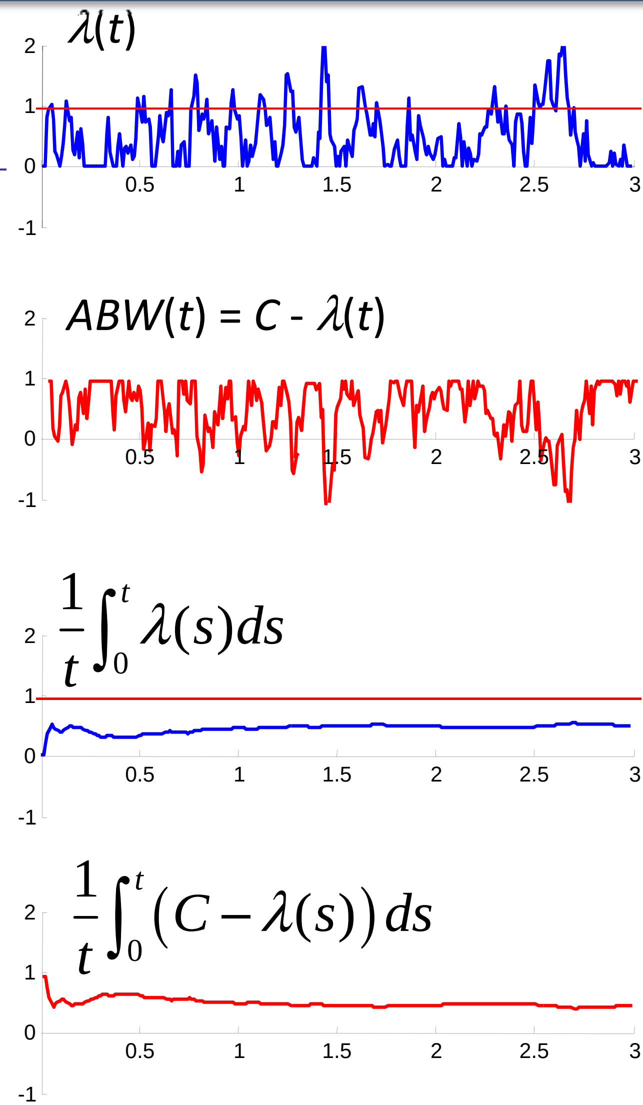


$$BW = \min_{i=1\ldots h} C_i$$

$$\text{"Narrow Link"} = \arg\min_{i=1\ldots h} C_i$$

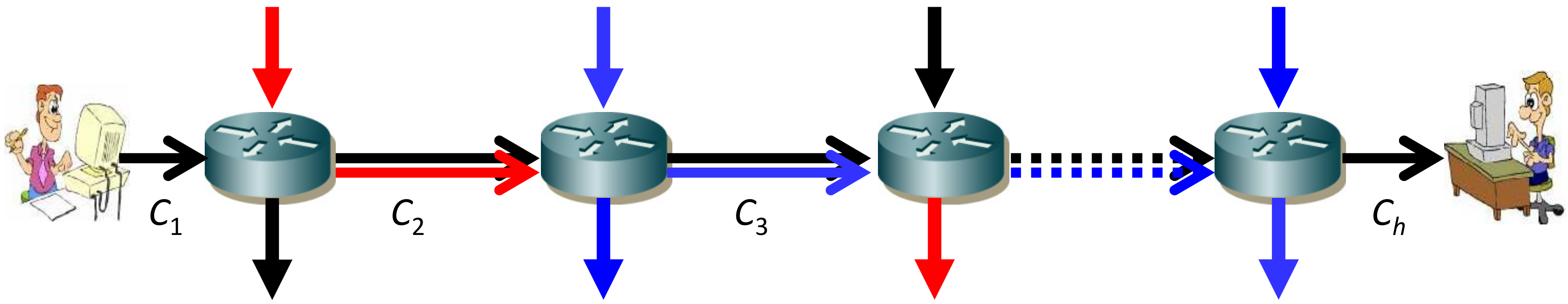
Available BandWidth on a Link



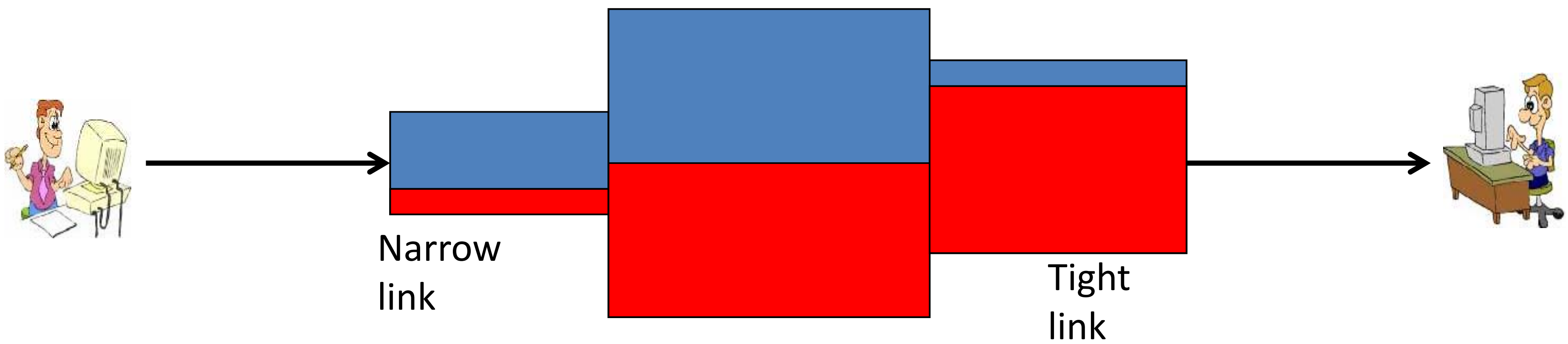


$$ABW(t-\tau,t) = \frac{1}{\tau}\int_{t-\tau}^{t}(C-\lambda(s))\,ds$$

Available BandWidth on a Route



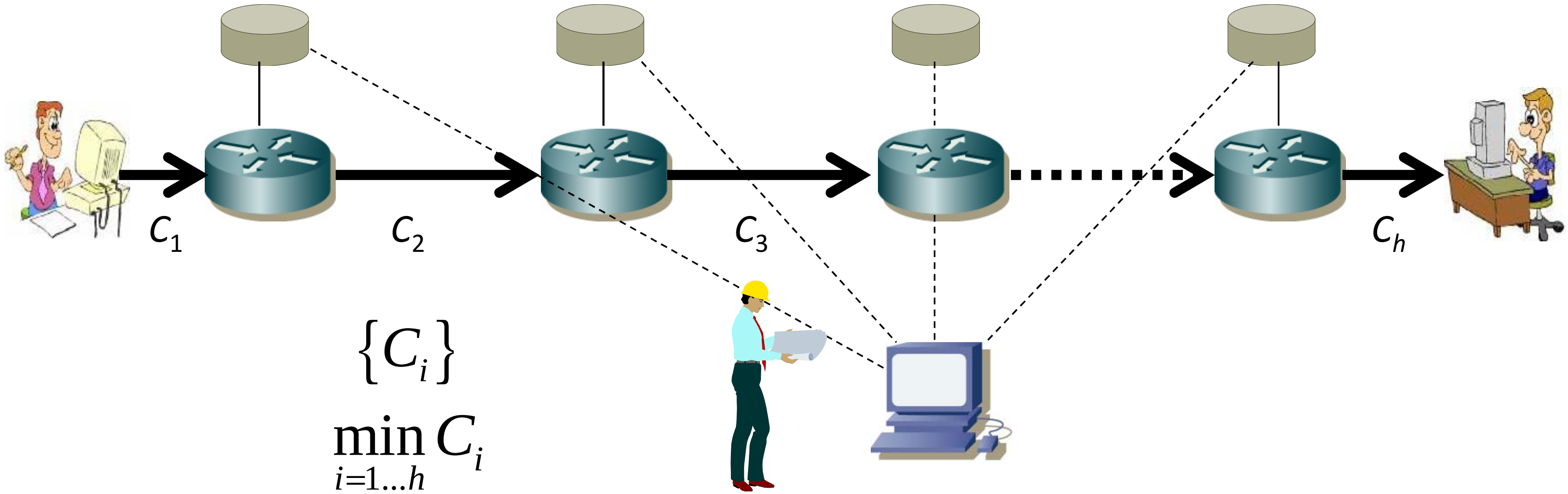
$$ABW = \min_{i=1\ldots h} ABW_i \qquad \text{"Tight Link"} = \arg\min_{i=1\ldots h} ABW_i$$



Why Is It Important to Know BW and ABW?

- Source transmission rate adjustment
  - ¿At which rate should I transmit in order to take the maximum advantage of network resources, without degrading the service received by current sessions?
- Admission Control
  - ¿Is the current ABW on the selected route greater than the required bandwidth announced in the admission request?
- Optimal routing
  - ¿Which one, among the possible routes, has the required bandwidth and minimize the routing metric?
- Traffic Engineering
  - ¿How to distribute the traffic among different alternate routes in order to optimally balance the load over the links?
- QoS verification
  - ¿Is the service provider delivering the BW we agreed?
- P2P service discovery
  - ¿With which of the possible pairs do I have a greater available bandwidth to minimize the file transfer time?

Measurement / Estimation



$$\{C_i\}$$

$$\min_{i=1\ldots h} C_i$$

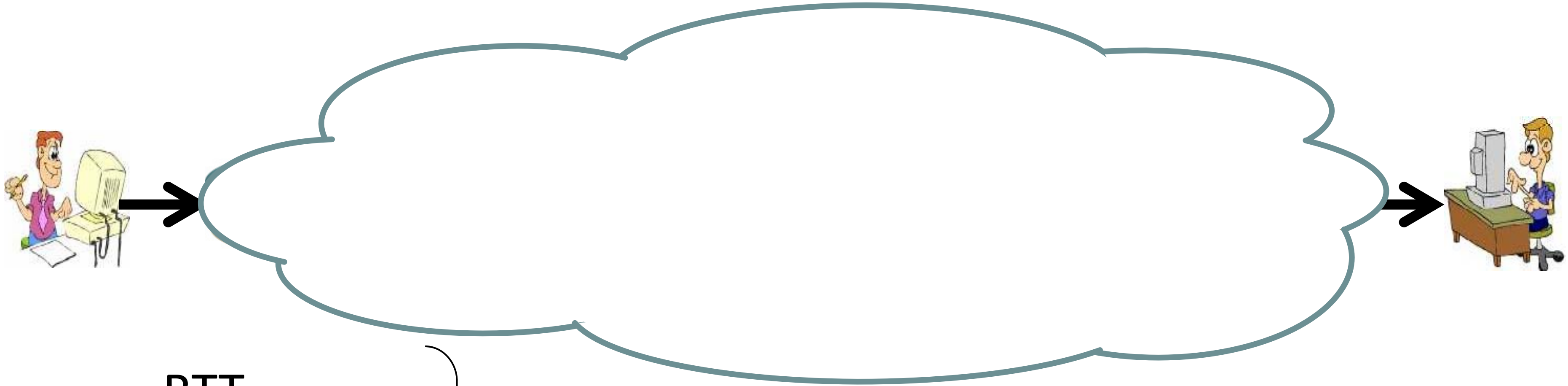
$$\frac{1}{\tau}\int_{t-\tau}^{t} \lambda_i(s)ds$$

$$\frac{1}{\tau}\int_{t-\tau}^{t} \left(C_i - \lambda_i(s)\right) ds$$

$$\min_{i=1\ldots h} ABW_i$$

As the network manager, I can measure the previously defined quantities

Measurement / Estimation



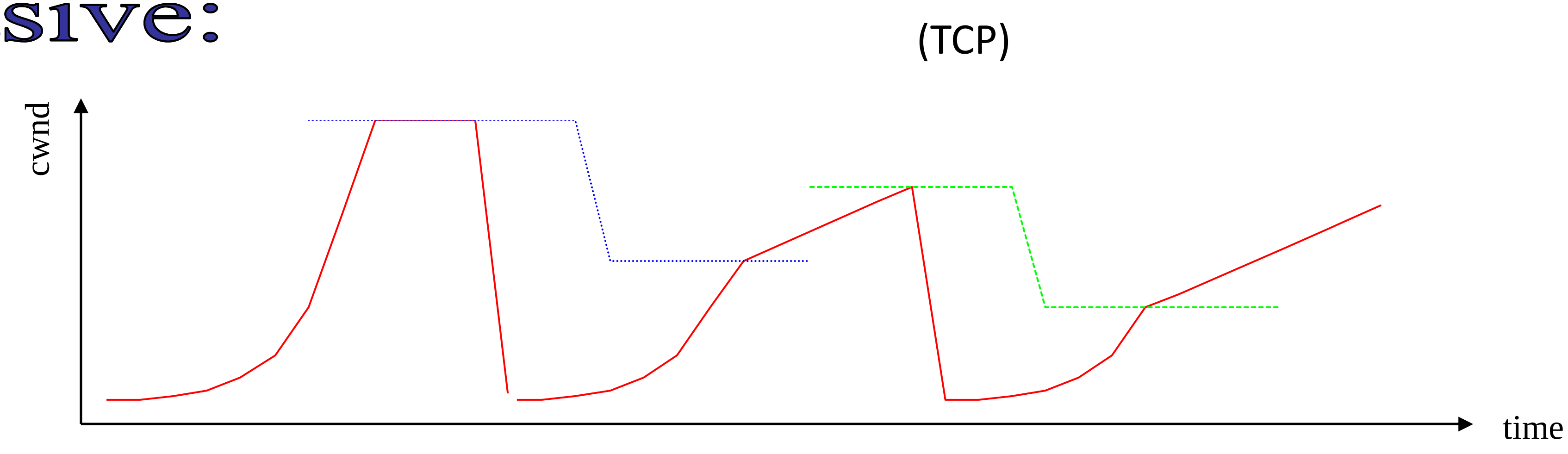
RTT
P[*Loss*]
(λ,γ)
OWD
...
$\{\theta_i\}$

$$ABW = ABW'(\theta_1, \ldots, \theta_n) + \varepsilon$$

Estimator based on
-Local measurements
-End-to-end measurements

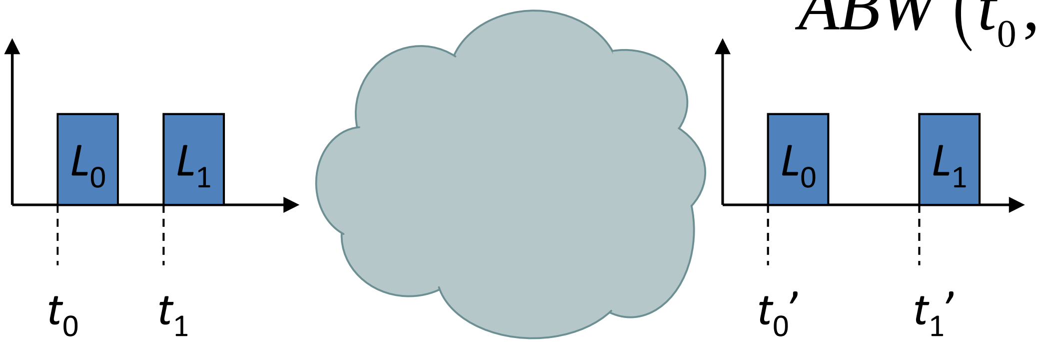
Estimation Techniques

Pasive:



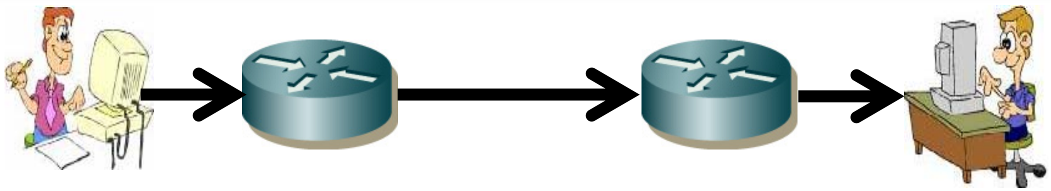
Active:

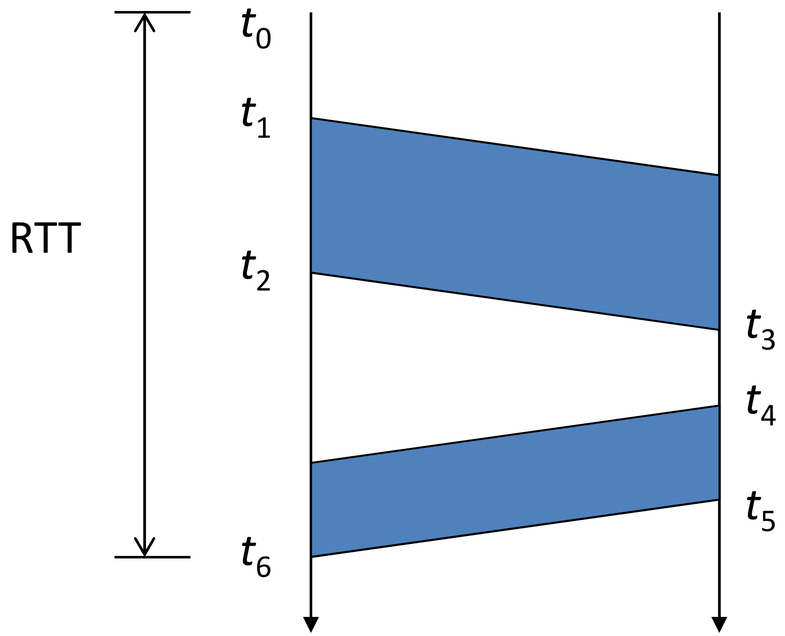
$$ABW\left(t_0, t_1\right) = f\left(t_0, t_0', t_1, t_1', L_0, L_1\right) + \varepsilon$$



Based on a dynamic model of the network

A Simple Example: VPS -Variable Packet Size-





RTT = $(t_1 - t_0)$ + ...	waiting in queue
$(t_2 - t_1)$ + ...	Transmission, L/C
$(t_3 - t_2)$ + ...	Propagation
$(t_4 - t_3)$ + ...	Processing
$(t_5 - t_4)$ + ...	Trans. ACK, L_{ack}/C
$(t_6 - t_5)$	Propagation

$$RTT = \frac{1}{C} L + T_0 + T_x$$

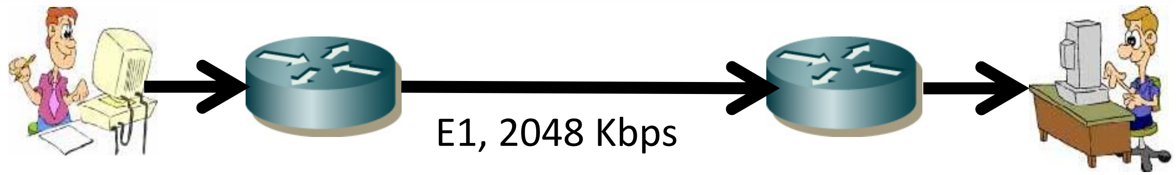
Link capacity, BW → C

Packet Size → L

Fixed delay, $(t_3 - t_2) + (t_5 - t_4) + (t_6 - t_5)$ → T_0

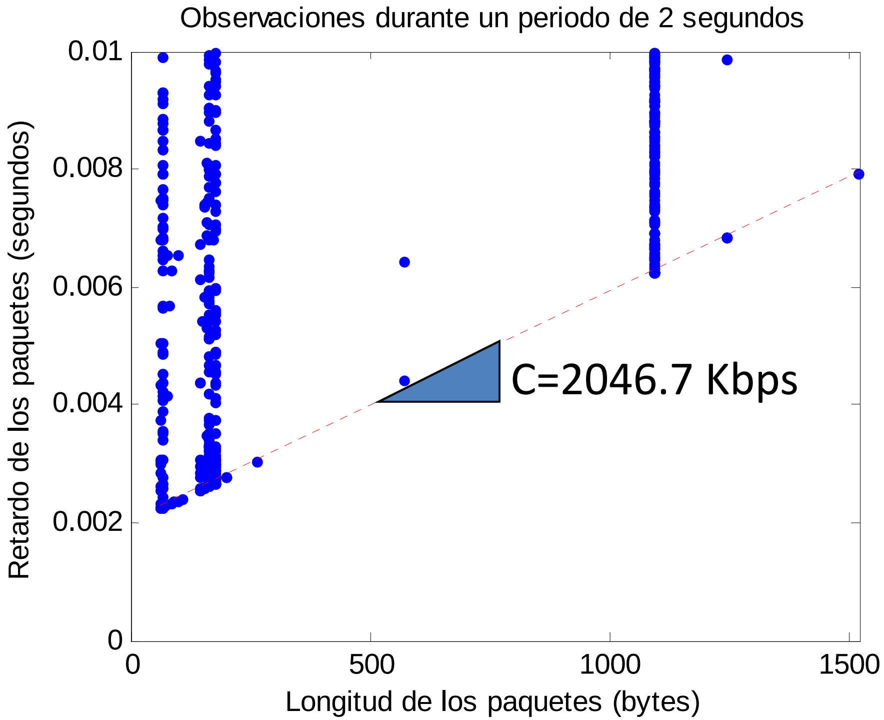
Random delay, $(t_1 - t_0) + (t_4 - t_3)$ → T_x

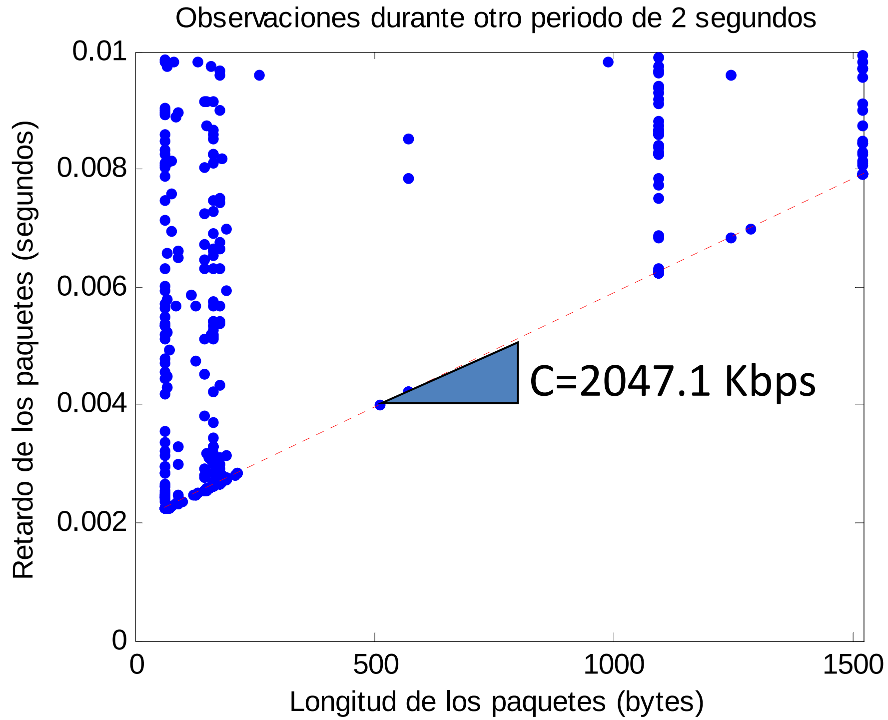
A Simple Example: VPS -Variable Packet Size-



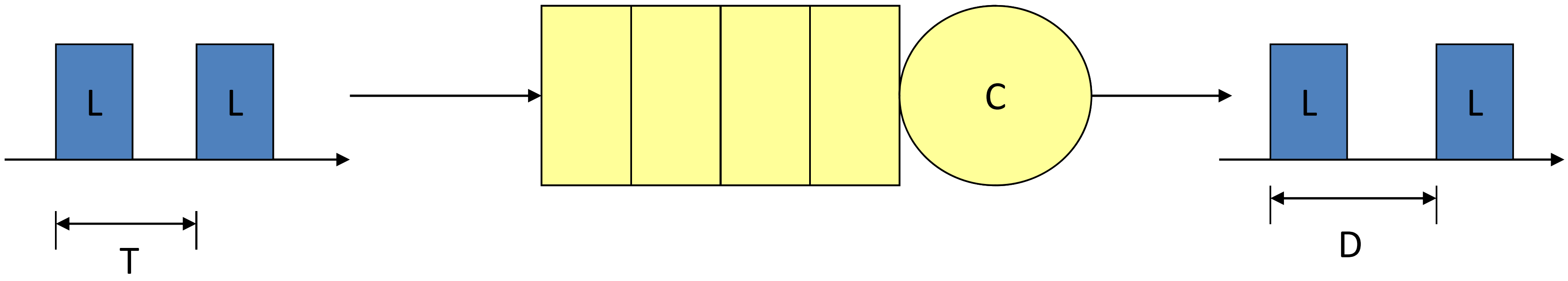
$$RTT = \frac{1}{C} L + T_0 + T_x$$

The model suggests to send packets of different length and to use linear regression on those packets that experienced the minimum RTT





Another Simple Example: Probing Packet Pair Dispersion



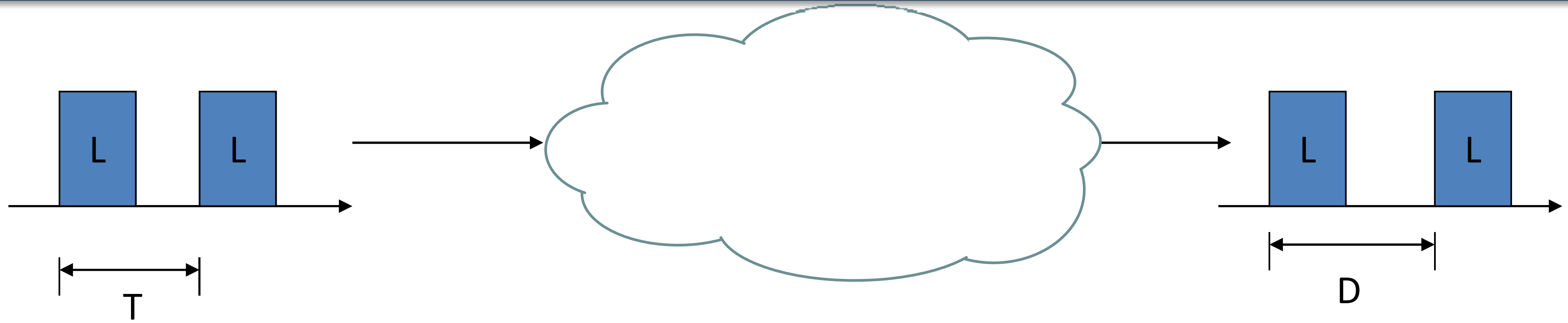
1. If there is not additional traffic and $T < L/C$, then $D = L/C$

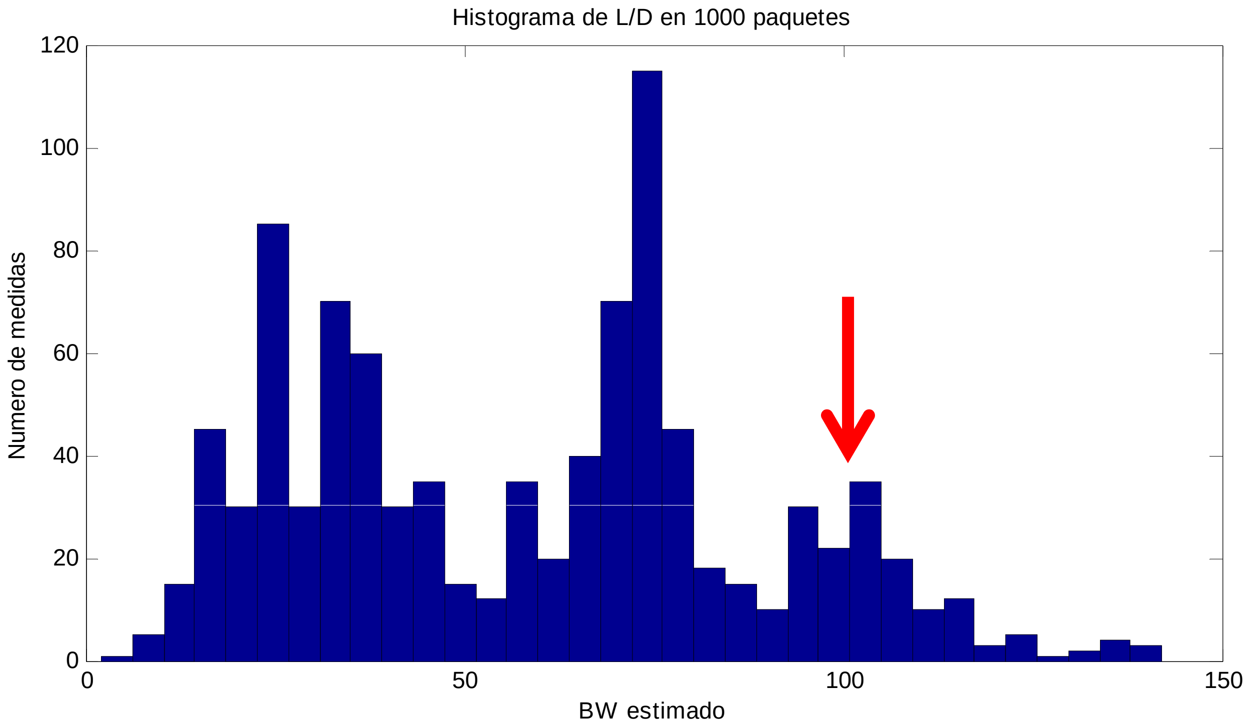
$$BW = L / D$$

2. If the additional traffic generates an average of λ bps during T, in such a way that both probing packets belong to the same link occupation period, then D = (λT + L)/C

$$ABW(T) = C\left(1 - \frac{D - L/C}{T}\right)$$

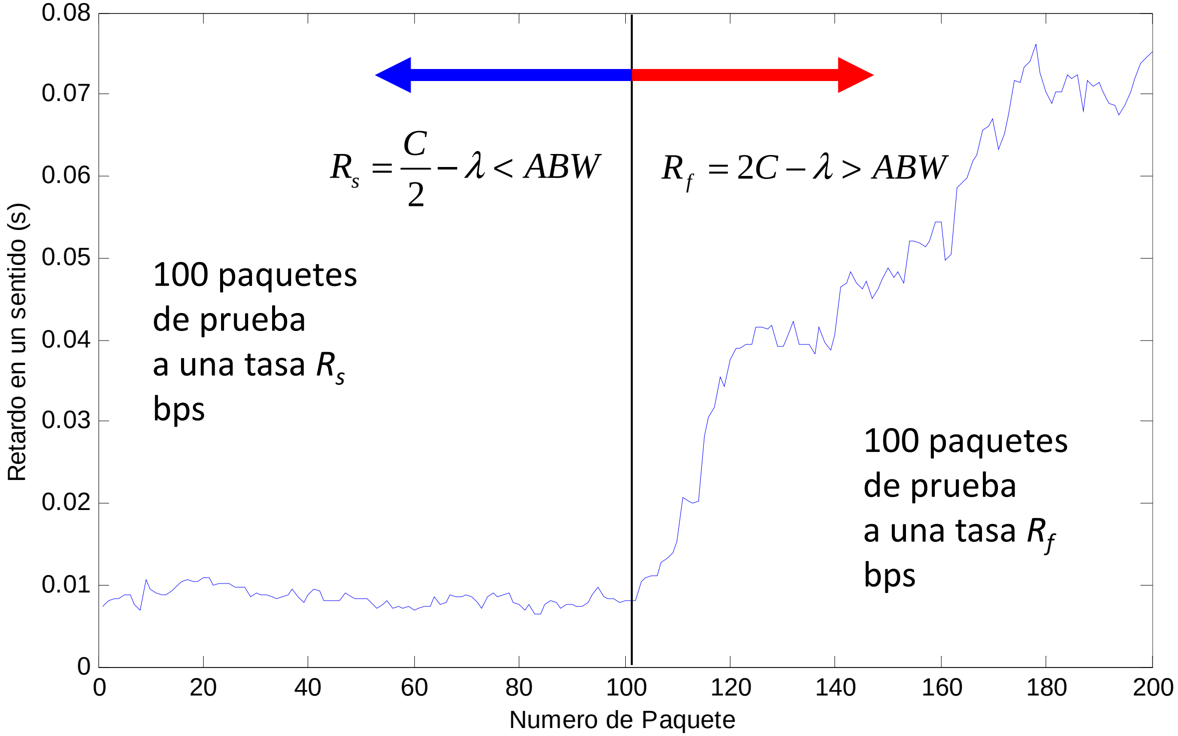
Another Simple Example: Probing Packet Pair Dispersion



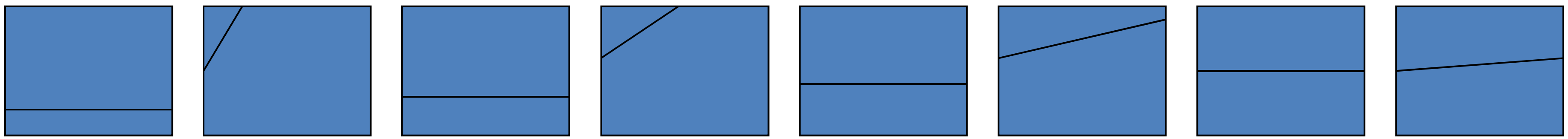


Most measurements subestimate the BW and a few of them overestimate it because the correct measurement forms a modest local mode in the histogram $\Rightarrow$ Different statistical analysis techniques.

Example: Self-induced Congestion



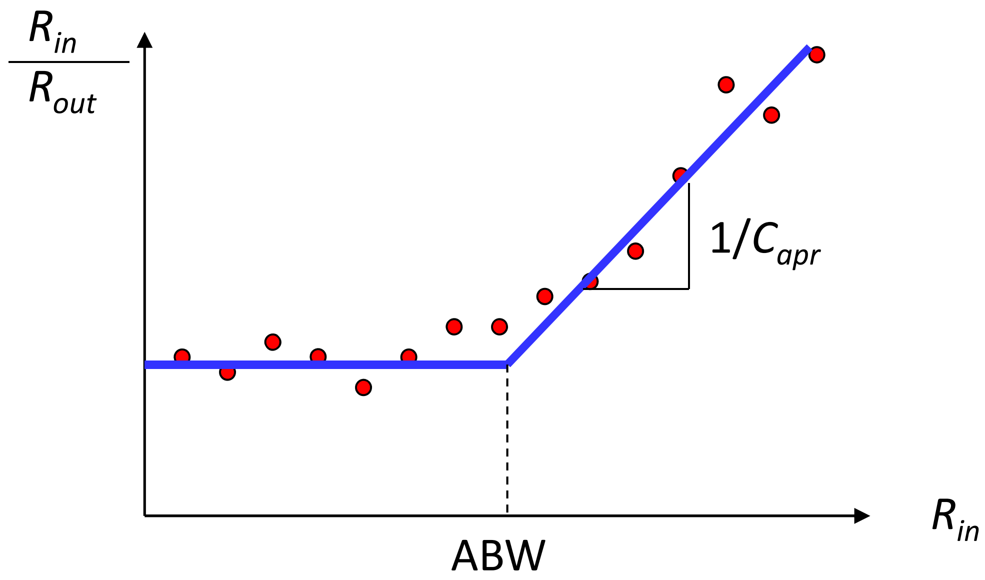
SLoPS (*Self Loading Periodic Stream*) : Tx sends a periodic flow of probing packets at a rate *R*. Rx measures the *OWD* of each probing packet and returns the tendency. Tx adjusts R in a binary search.



$$R_7 < ABW < R_8, \quad R_7 \approx R_8 \Rightarrow ABW \approx \frac{R_7 + R_8}{2}$$

Example: Self-induced Congestion

ToPP : Train of packet pairs

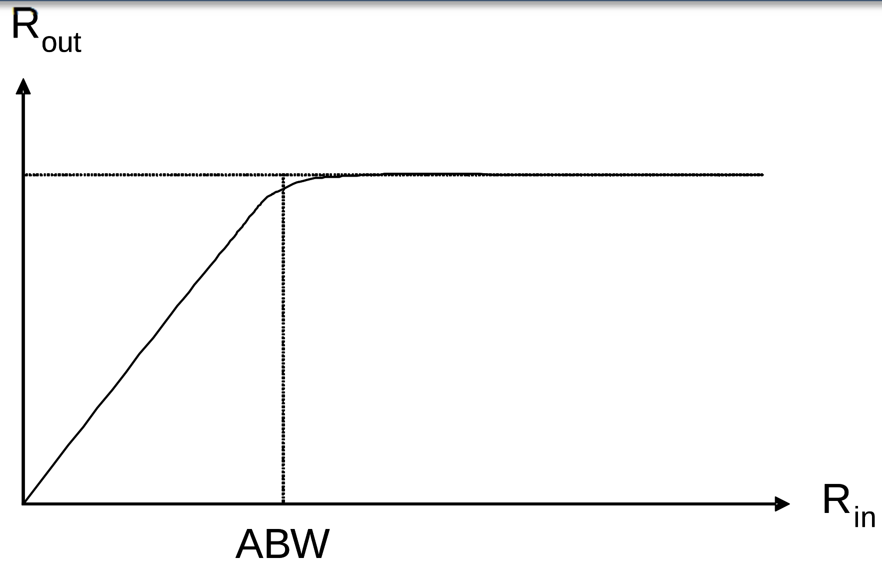


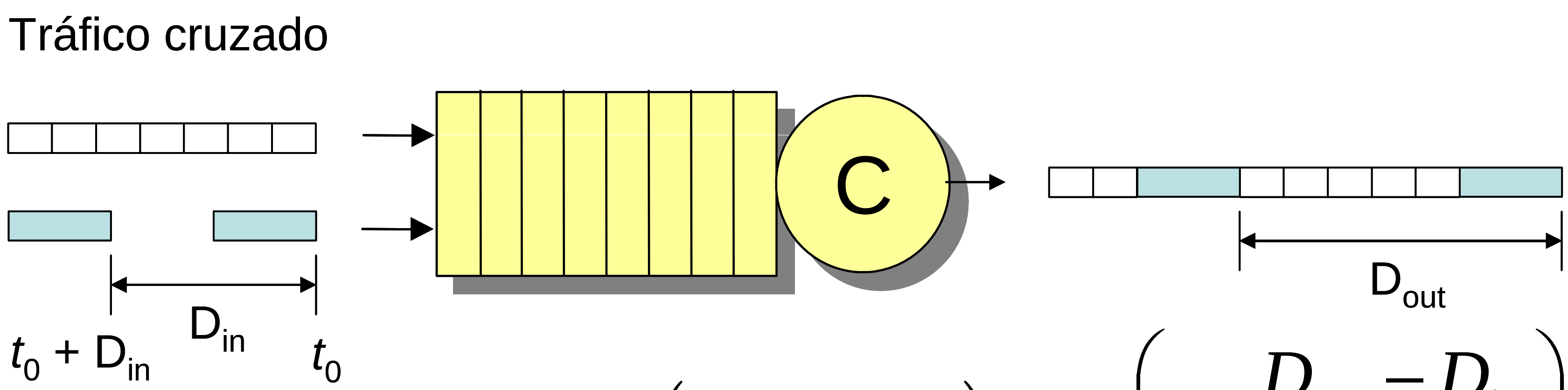
$$ABW(t-\tau,t)=\frac{1}{\tau}\int_{t-\tau}^{t}\left(C_{apr}-\lambda(s)\right)ds \overset{?}{=} \arg\max_{R}\left(R \,\middle|\, R+\frac{1}{\tau}\int_{t-\tau}^{t}\lambda(s)ds<C_{apr}\right)$$

Some Tools

- PathChar (VPS)
- Pathrate (PPD)
- Cprobe (ToPP)
- PathLoad (SLoPS)
- IGI/PTR (PPD & ToPP)
- PathChirp (PPD / ~ToPP)
- Delphi (PPD)
- Spruce (PPD / ~ToPP)
- etc

Two Basic Principles



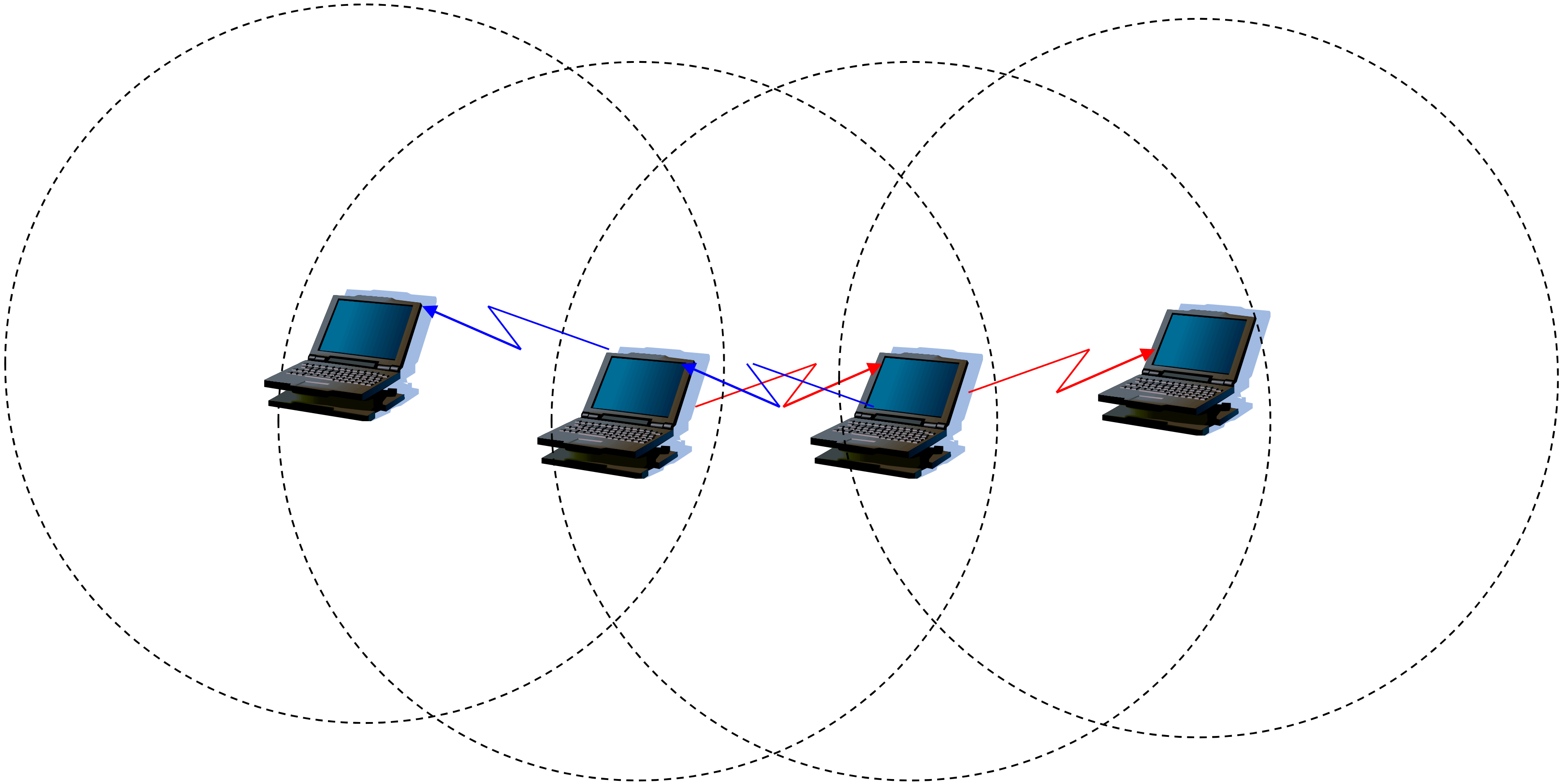


$$ABW\left(t_0, t_0 + D_{in}\right) = C \cdot \left(1 - \frac{D_{out} - D_{in}}{D_{in}}\right)$$

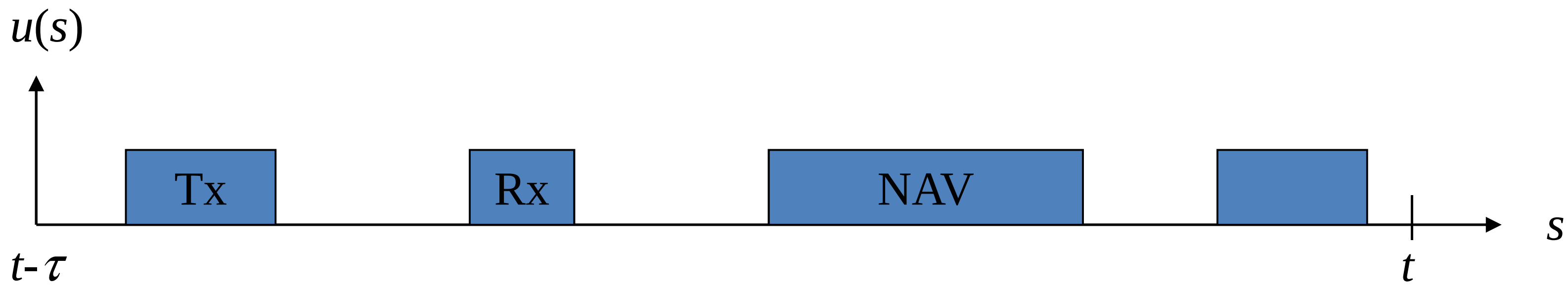
Some Problems with ABW Estimation

- ABW is not a constant parameter but a highly dynamic variable.
- ABW can exhibit high variability in a wide range of time scales.
- Accuracy and timeliness are opposed objectives.
- Probing traffic can alter network conditions

Mobile Ad Hoc Networks



ABW in Ad Hoc Networks

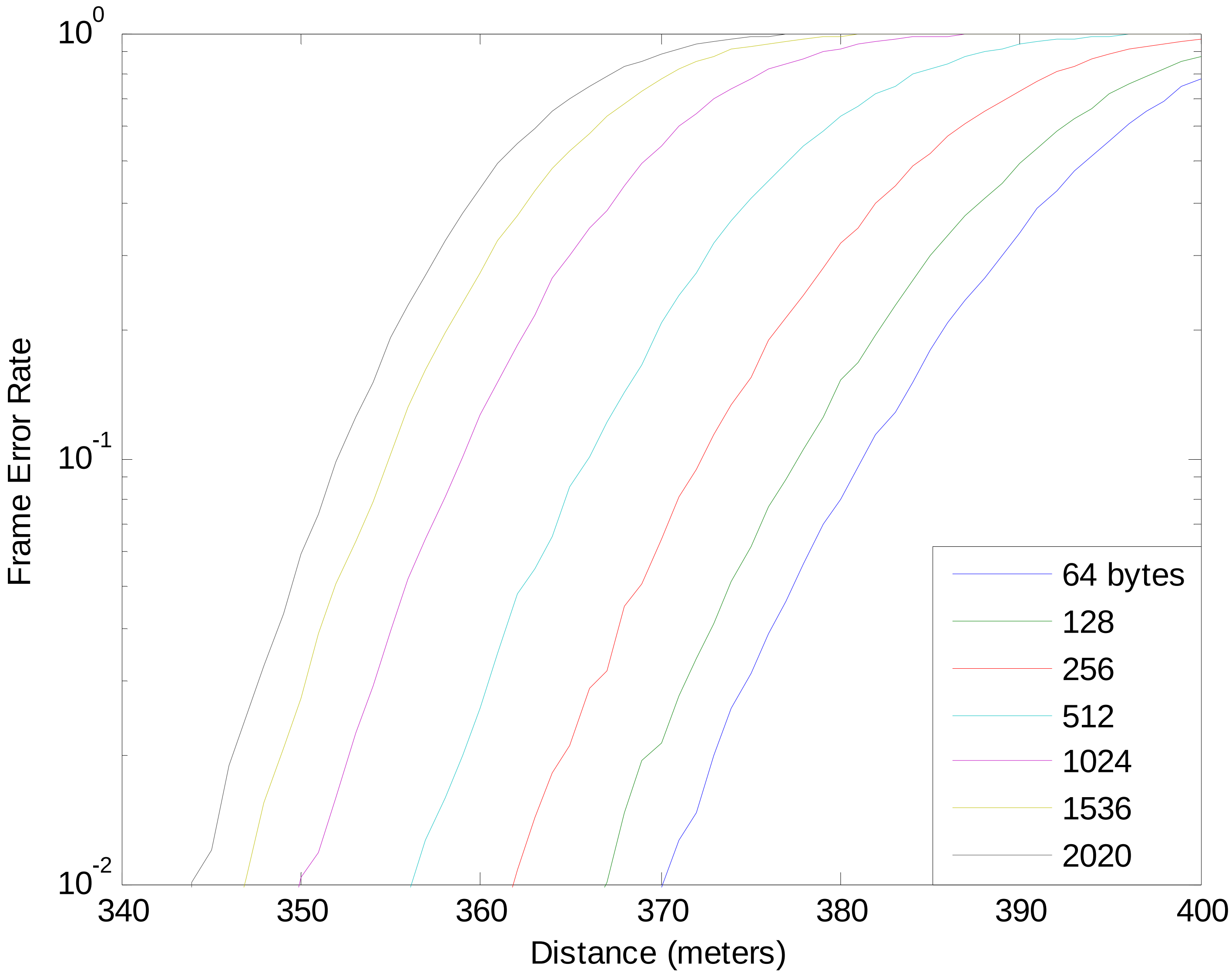


$$U(t-\tau,t)=\int_{t-\tau}^{t}u(s)ds$$

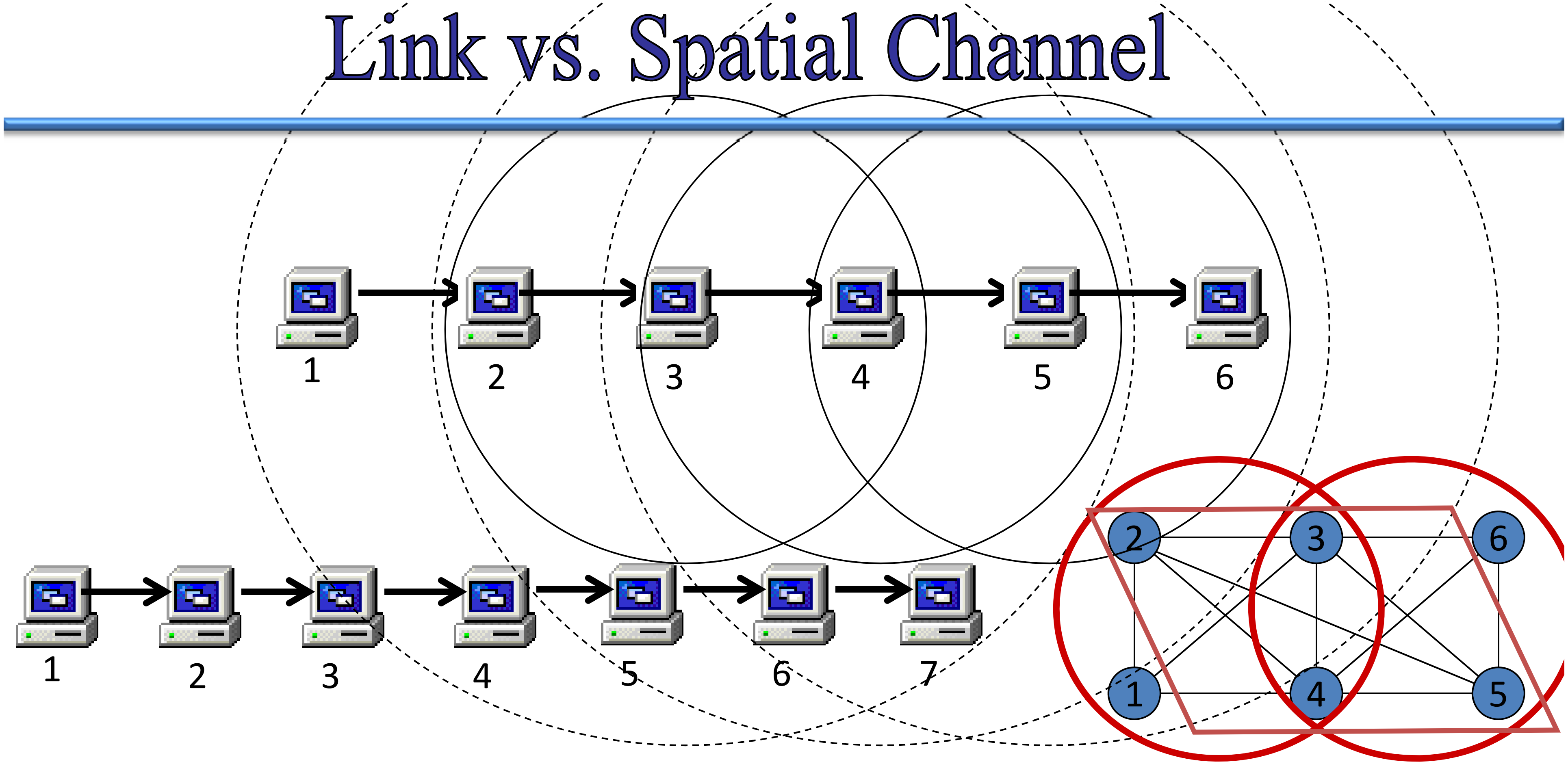
$$ABW(t-\tau,t)=C\left(1-U(t-\tau,t)\right)$$

$$ABW=\min_{i=1\ldots h}ABW_i$$

Is a Link a Precise Concept in an Ad Hoc Network?



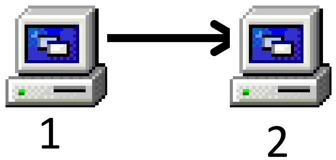
Link vs. Spatial Channel



Contention graph: The vertices are the links within the network
The edges represent the impossibility of simultaneous use

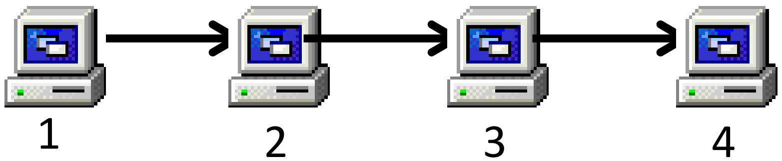
Spatial Channel: Completely interconnected subgraph not contained within another completely interconnected subgraph (“Maximal Clique”)

Capacity of a Link, a Spatial Channel and a Route



Transmission time of a single bit = $1/C_1$

Physical transmission rate = C_1



Transmission time of a single bit = $\sum_{i=1}^{n} \frac{1}{C_i}$

Physical transmission rate = $\frac{1}{\sum_{i=1}^{n} \frac{1}{C_i}}$

The end-to-end capacity of a multi-hop route that traverses *H* spatial channels, where the *i*th spatial channel is composed by n_i links with capacities $\{C_{i,j},\ i=1..H,\ j=1..n_i\}$, is defined as

$$C = \min_{i=1..H} C_i = \min_{i=1..H} \frac{1}{\sum_{j=1}^{n_i} 1/C_{i,j}}$$

Bandwidth of a Single Link

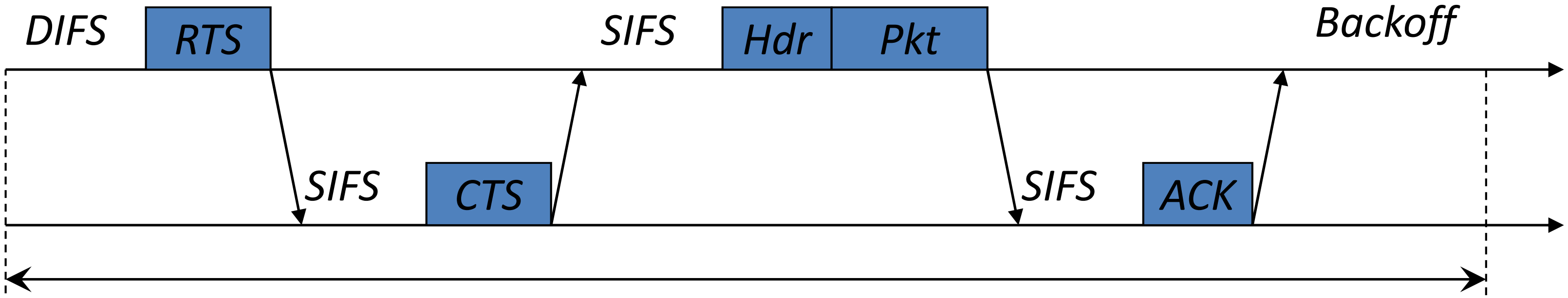
- Let us consider the individual experience of a single packet

$$t_{Tx} = T_0 + \frac{L_0}{C} + \frac{L}{C} + X$$

$$BW(L,C) = \frac{L}{\tau(L,C) + X} \quad \Bigg| \quad \tau(L,C) = T_0 + \frac{L_0 + L}{C}$$

$$f_{BW}(b) = \frac{L}{b^2} f_X\left(\frac{L}{b} - \tau\right)$$

BW Probability Distribution in an IEEE 802.11b DCF/(RTS,CTS) link



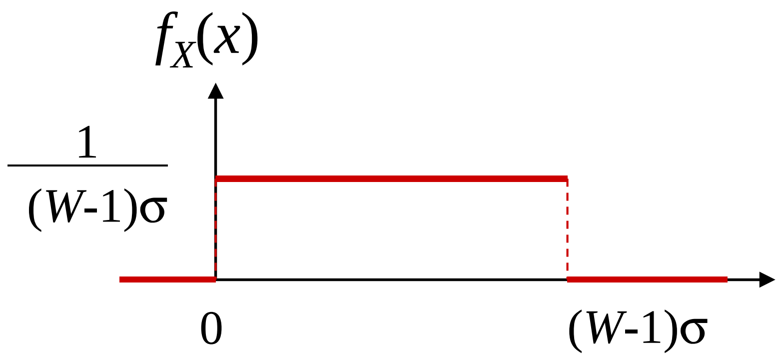
$$t_{Tx} = DIFS + \frac{RTS}{C} + t_p + SIFS + \frac{CTS}{C} + t_p + SIFS + \frac{Hdr}{C} + \frac{L}{C} + t_p + SIFS + \frac{ACK}{C} + t_p + n\sigma$$

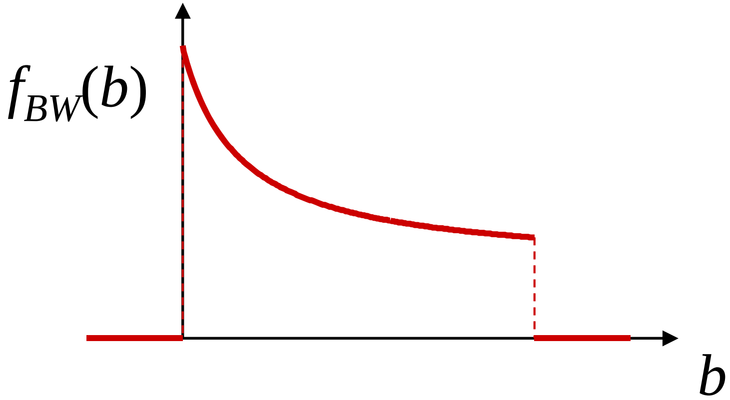
$$T_0 = DIFS + 3SIFS + 4t_p$$

$$L_0 = RTS + CTS + Hdr + ACK$$

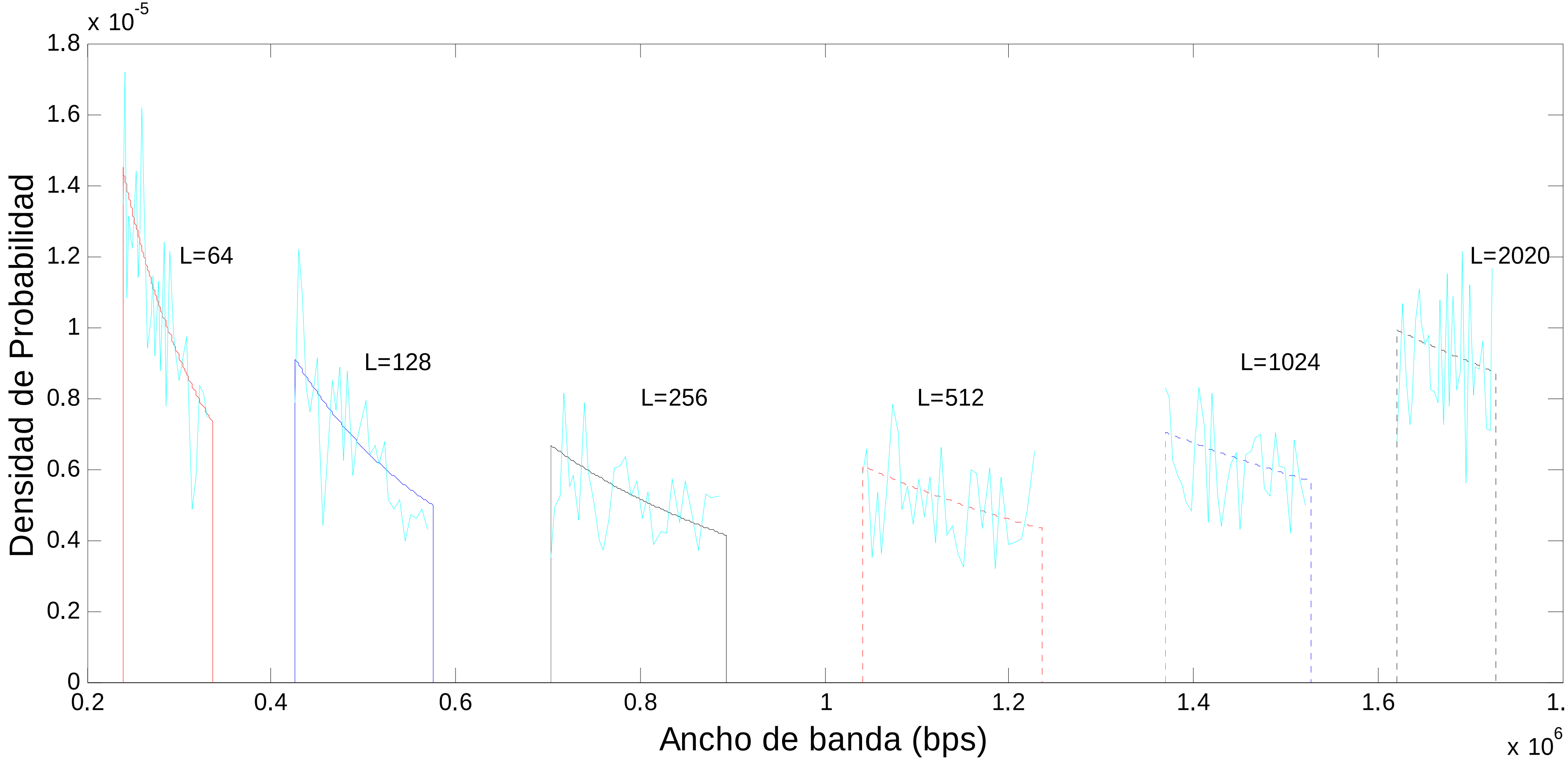
$$X = n\sigma, n \sim U(0, W-1)$$

$$f_{BW}(b) = \begin{cases} \dfrac{L}{b^2\sigma(W-1)} & b \in \left[\dfrac{CL}{L + L_0 + C(T_0 + \sigma(W-1))}, \dfrac{CL}{L + L_0 + CT_0}\right] \\ 0 & \text{Otherwise} \end{cases}$$





Link BW is a Random Variable



…!That depends fundamentally on packet length!

Spatial Channel Bandwidth

Time to acquire and release the channel in the n_i hops of channel *i*:

$$T_i = \sum_{j=1}^{n_i}\left(T_0 + \frac{L_0}{C_{i,j}}\right) + \sigma\sum_{j=1}^{n_i} BO_j$$

Bandwidth of channel *i*:

$$BW^{ch_i}(L) = \frac{C_i \cdot L}{L + C_i \cdot T_i}$$

If we assume the sum of *BOs* is a normal random variable,

$$f_{BW^{ch_i}(L)}(b) = \frac{L}{\sqrt{2\pi} s_i b^2}\exp\left[-\frac{1}{2}\left(\frac{b - L/m_i}{s_i b/m_i}\right)^2\right]$$

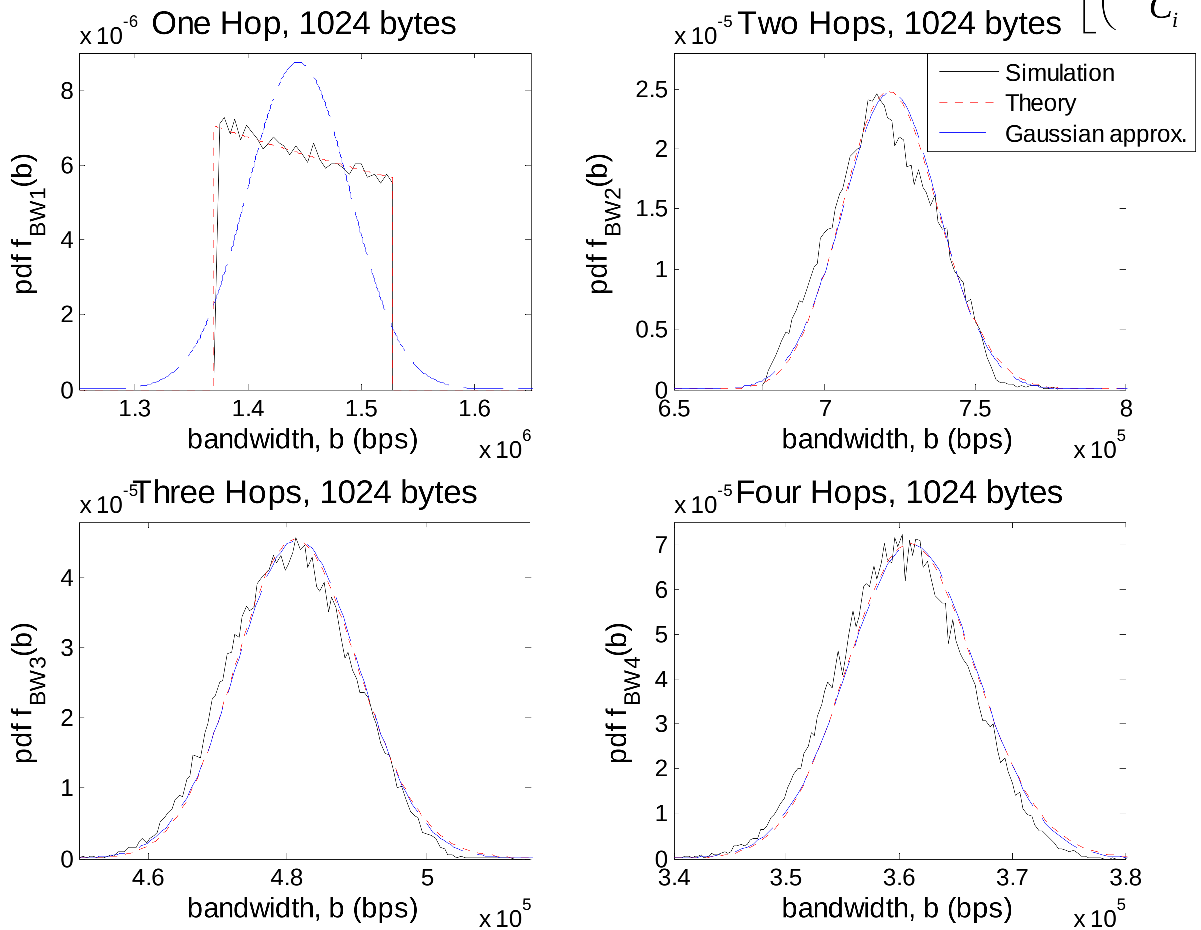
$$m_i = \frac{L + L_0}{C_i} + n_i\left(T_0 + \sigma\frac{W-1}{2}\right)$$

$$s_i^2 = n_i\sigma^2\frac{(W-1)^2}{12}$$

Spatial Channel Bandwidth

$$E\left[BW^{ch_i}(L)\right]=\frac{L}{\frac{L+L_0}{C_i}+n_i\left(T_0+\sigma\frac{W-1}{2}\right)}$$

$$V\left[BW^{ch_i}(L)\right]=\frac{n_i}{3}\left[\frac{L\sigma\frac{(W-1)}{2}}{\left(\frac{L+L_0}{C_i}+n_i\left(T_0+\sigma\frac{W-1}{2}\right)\right)^2}\right]^2$$



Route Bandwidth

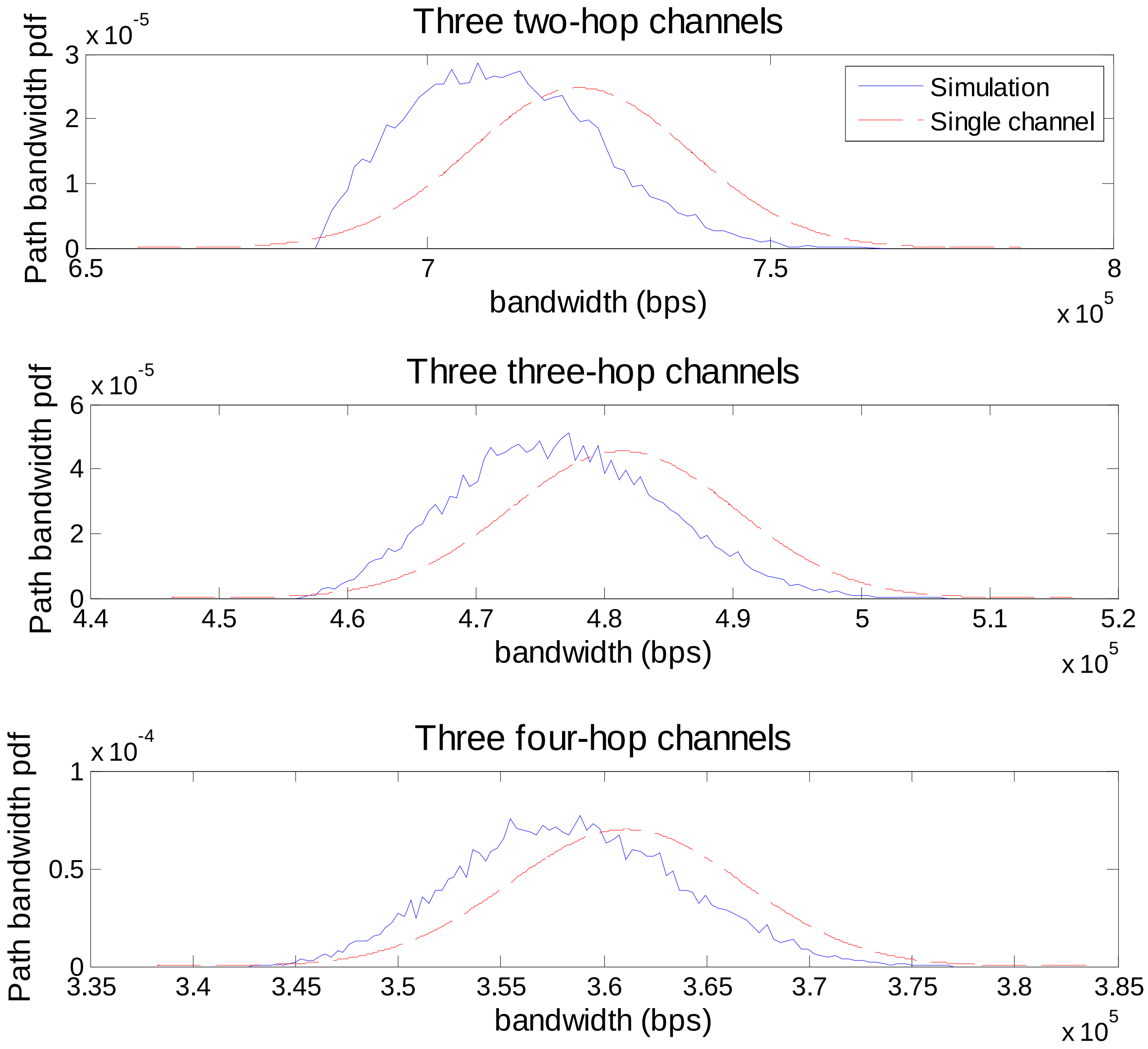
$$BW^{path}(L) < \min_{i=1..H} BW^{ch_i}(L)$$

$$\mathrm{E}\left[BW^{path}(L)\right] < \mathrm{E}\left[\min_{i=1..H} BW^{ch_i}(L)\right] < \min_{i=1..H} \mathrm{E}\left[BW^{ch_i}(L)\right]$$

The average end-to-end bandwidth of a multi-hop route traversing H spatial channels, where spatial channel i is composed of n_i links with capacities $\{C_{i,j},\ i=1..H,\ j=1..n_i\}$, and where the time it takes a packet to acquire and release the medium at link j of channel i is $T_{i,j}$, is defined as

$$\mathrm{E}\left[BW^{path}(L)\right] < \min_{i=1...H} \frac{L}{\sum_{j=1}^{n_i}\left(\frac{L}{C_{i,j}} + \mathrm{E}\left[T_{i,j}\right]\right)}$$

Route Bandwidth



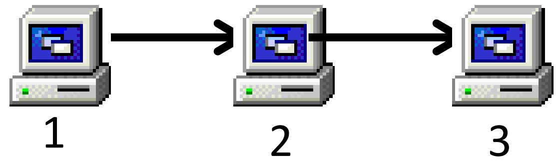
L = 1024 bytes

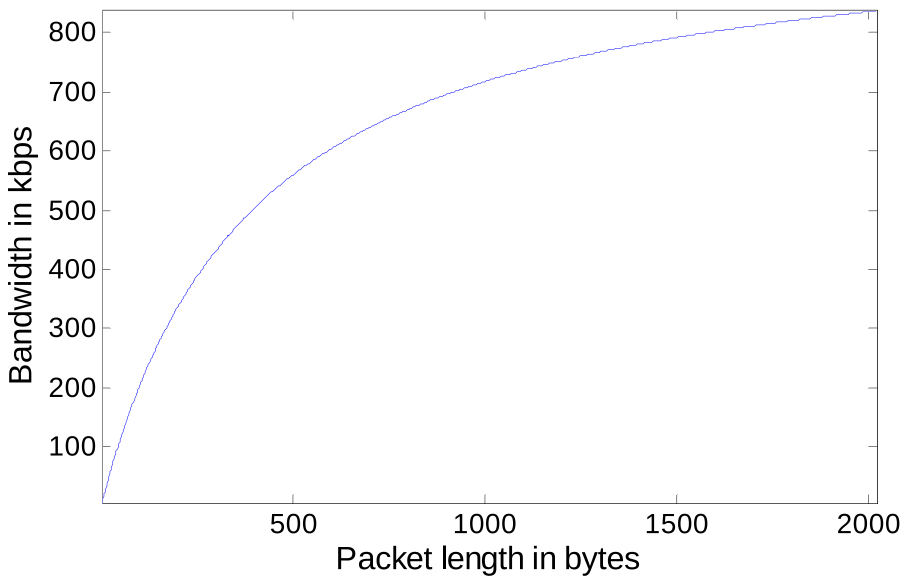
Unused Bandwidth in a Multi-Channel Route

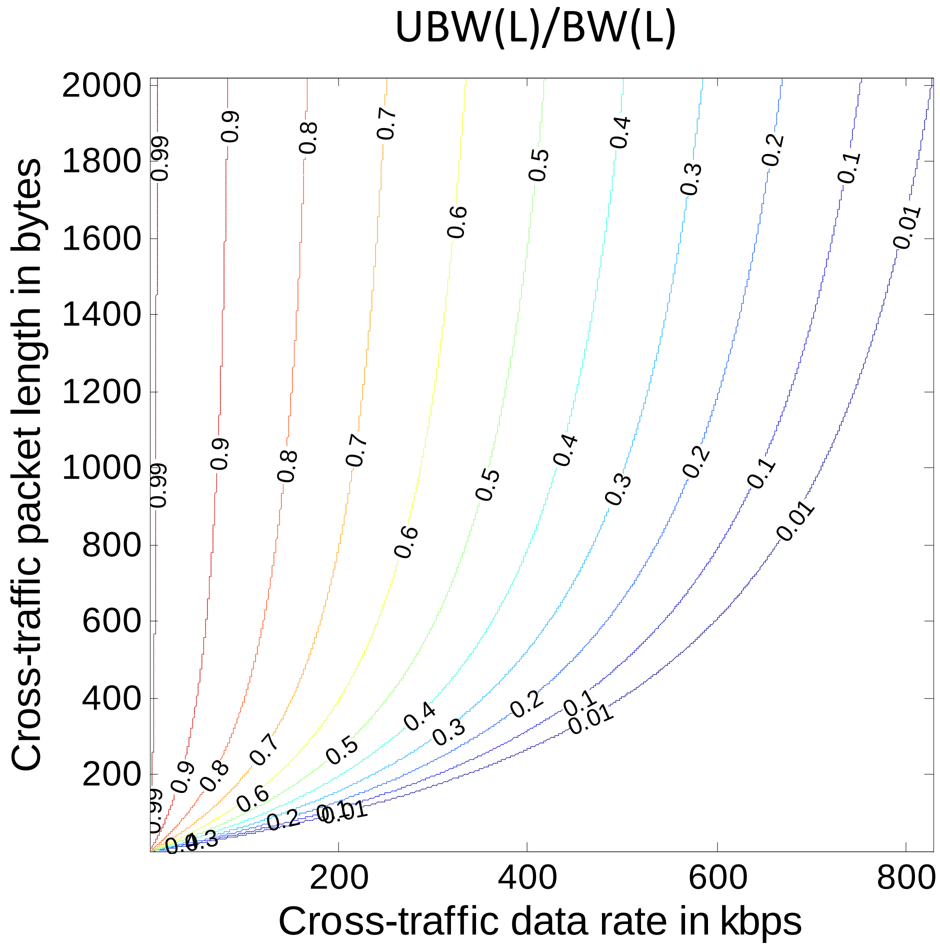
Consider a multi-hop route that traverses H spatial chanels, where channel i is composed of n_i nodes with capacities $\{C_{i,j},\ i=1, \ldots, H,\ j=1, \ldots, n_i\}$. Among the n_i nodes within channel i, a subset $\{x_{i,l},\ l=1, \ldots, m_i\} \subseteq \{1, \ldots, n_i\}$ belongs to the multi-channel route. The time it takes a single packet to acquire and release the medium in order for channel i to send it through link j is a random variable $T_{i,j}$. Node j of spatial channel i sends (either as a source or as an intermediate router) $\lambda_{i,j,k}$ k-bit packets per second, $k = 1,2,\ldots$ The average unused end-to-en bandwidth for L-bit long packets in the route is bounded above as follows:

$$\mathrm{E}\left[UBW^{path}(L)\right] < \min_{i=1\ldots H} \frac{L}{\sum_{l=1}^{m_i}\left(\frac{L}{C_{i,x_{i,l}}} + \mathrm{E}\left[T_{i,x_{i,l}}\right]\right)} \left(1 - \sum_{j=1}^{n_i}\sum_{k=1}^{\infty}\lambda_{i,j,k}\left(\frac{k}{C_{i,j}} + \mathrm{E}\left[T_{i,j}\right]\right)\right)$$

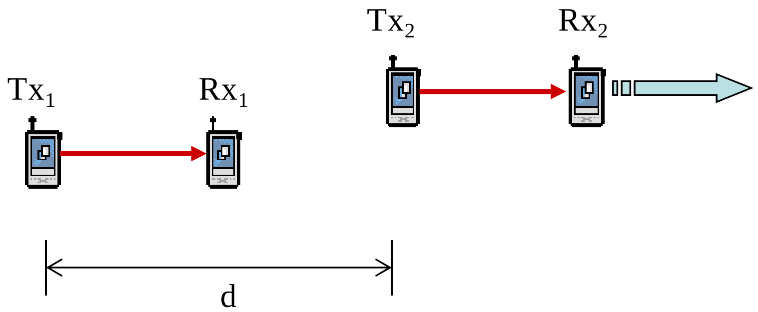
Single Channel Example

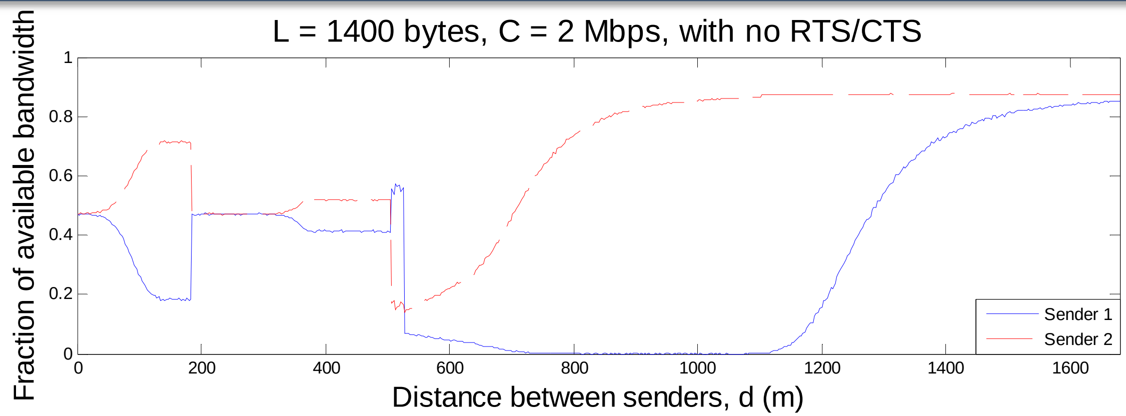


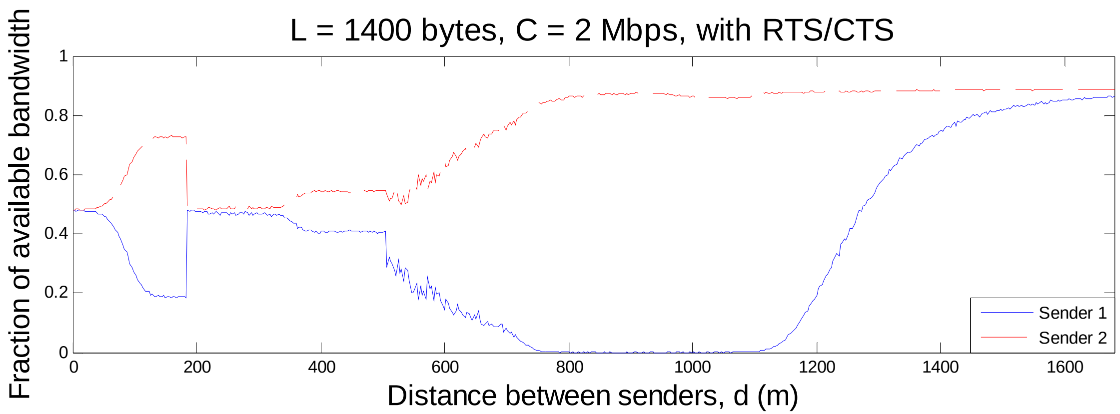




Is it Unused Bandwidth Equal to Available Bandwidth?

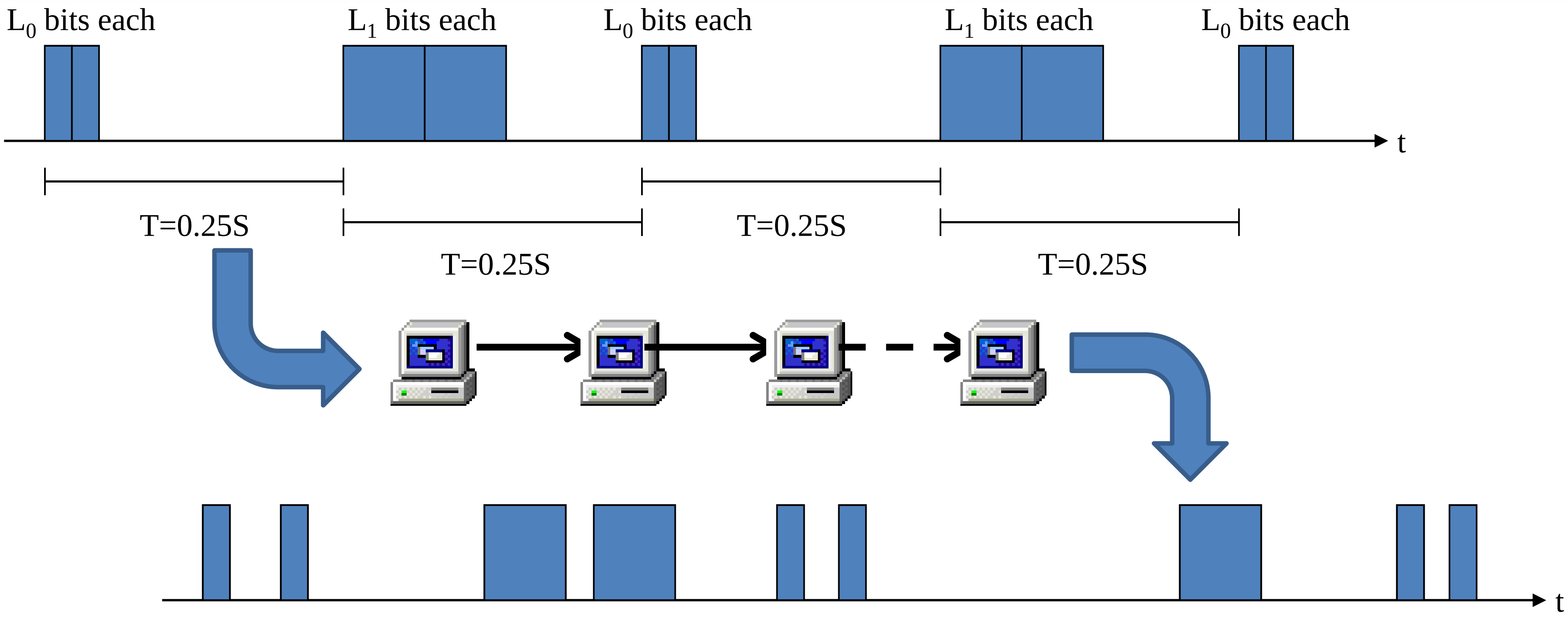






$$ABW(L) = \max_{\lambda > 0} \left[\lim_{t \to \infty} \frac{(n(t)-1)L}{t - t_1} \right]$$

Measuring Procedure

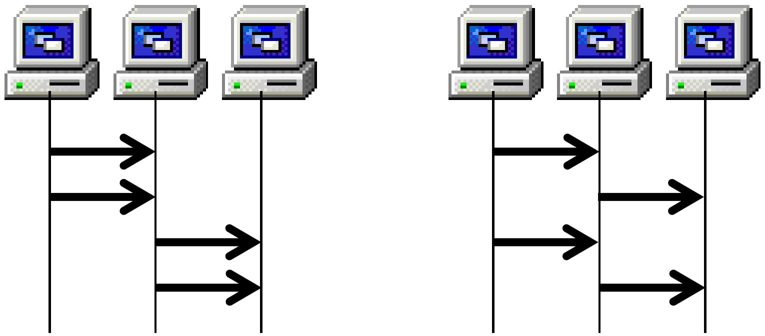


One-Way-Delays, OWD

Packet pair dispersion, Gap

(+fraction of lost packets, correlation between consecutive OWD, etc.)

Packet Pair Dispersion Measurements



The gap between packets of the pair that have the minimum sum of OWD (SOWD) represents the effective time it takes a packet of the given length to get the destination.

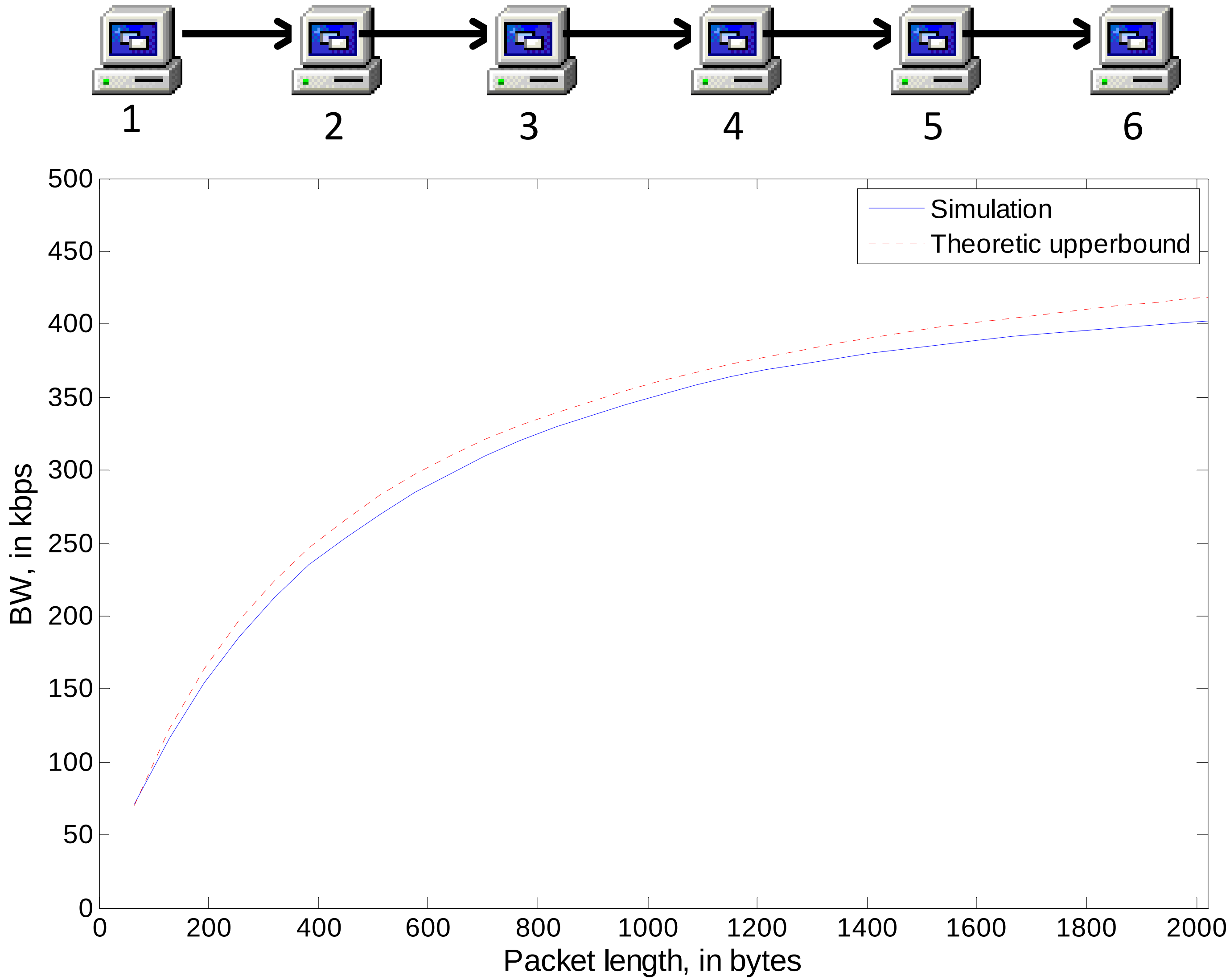
$$BW(L_0) = \frac{L_0}{gap_0}$$

$$BW(L_1) = \frac{L_1}{gap_1}$$

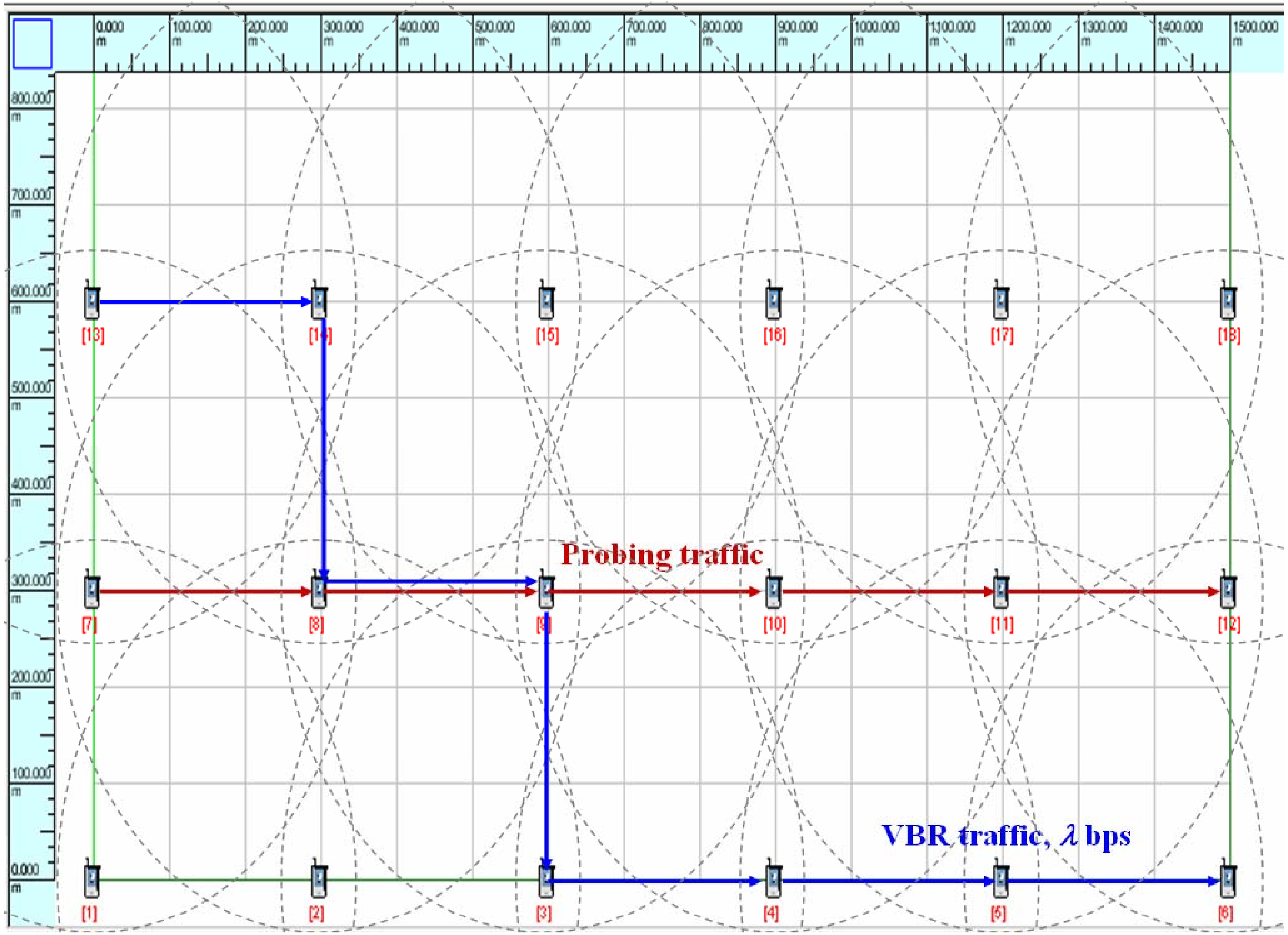
$$BW(L) = \frac{L}{\alpha L + \beta}$$

$$\begin{bmatrix} \alpha \\ \beta \end{bmatrix} = \begin{bmatrix} L_0 & 1 \\ L_1 & 1 \end{bmatrix}^{-1} \begin{bmatrix} gap_0 \\ gap_1 \end{bmatrix}$$

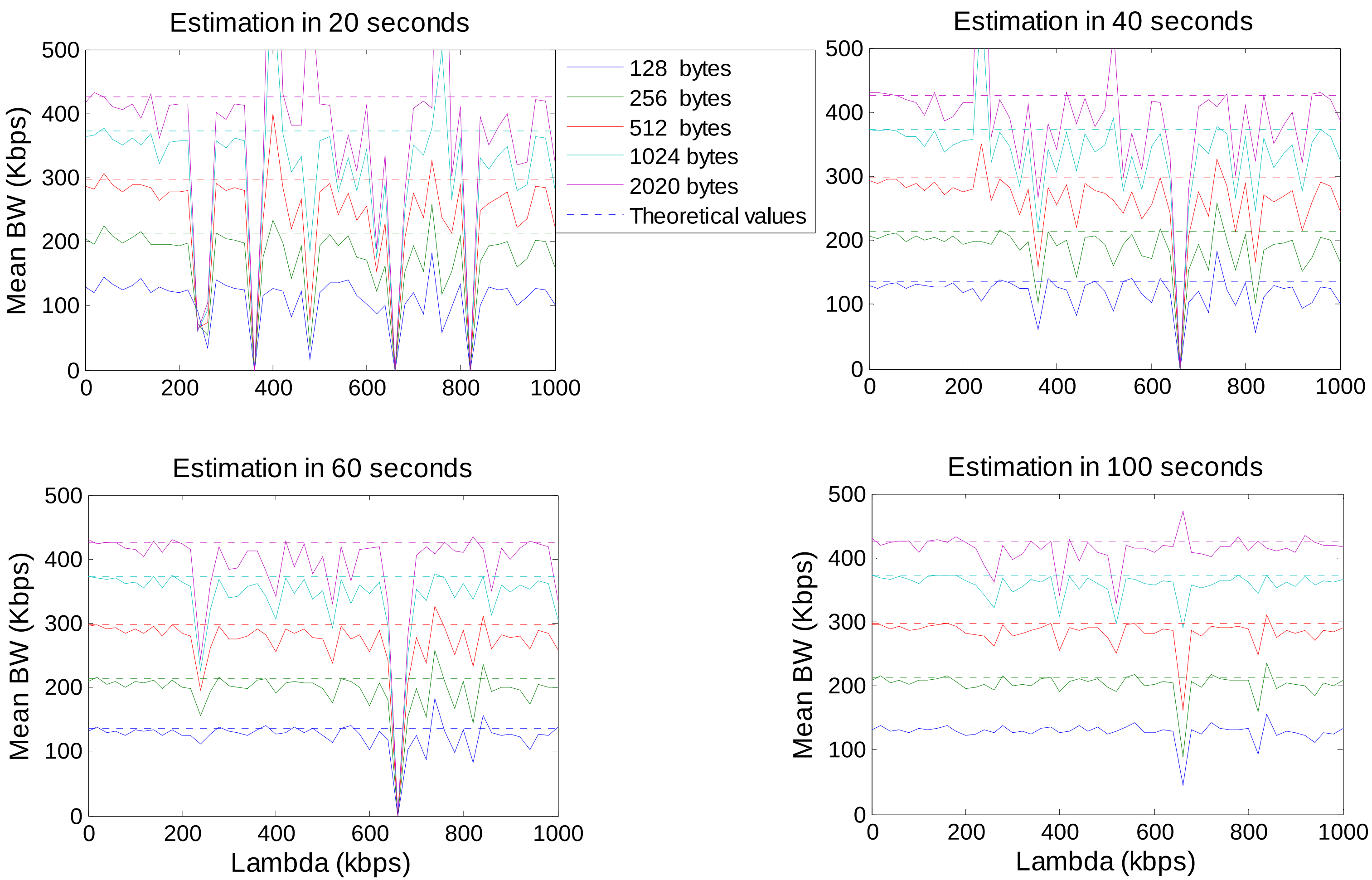
Some Results



An Scenario with Cross-Traffic



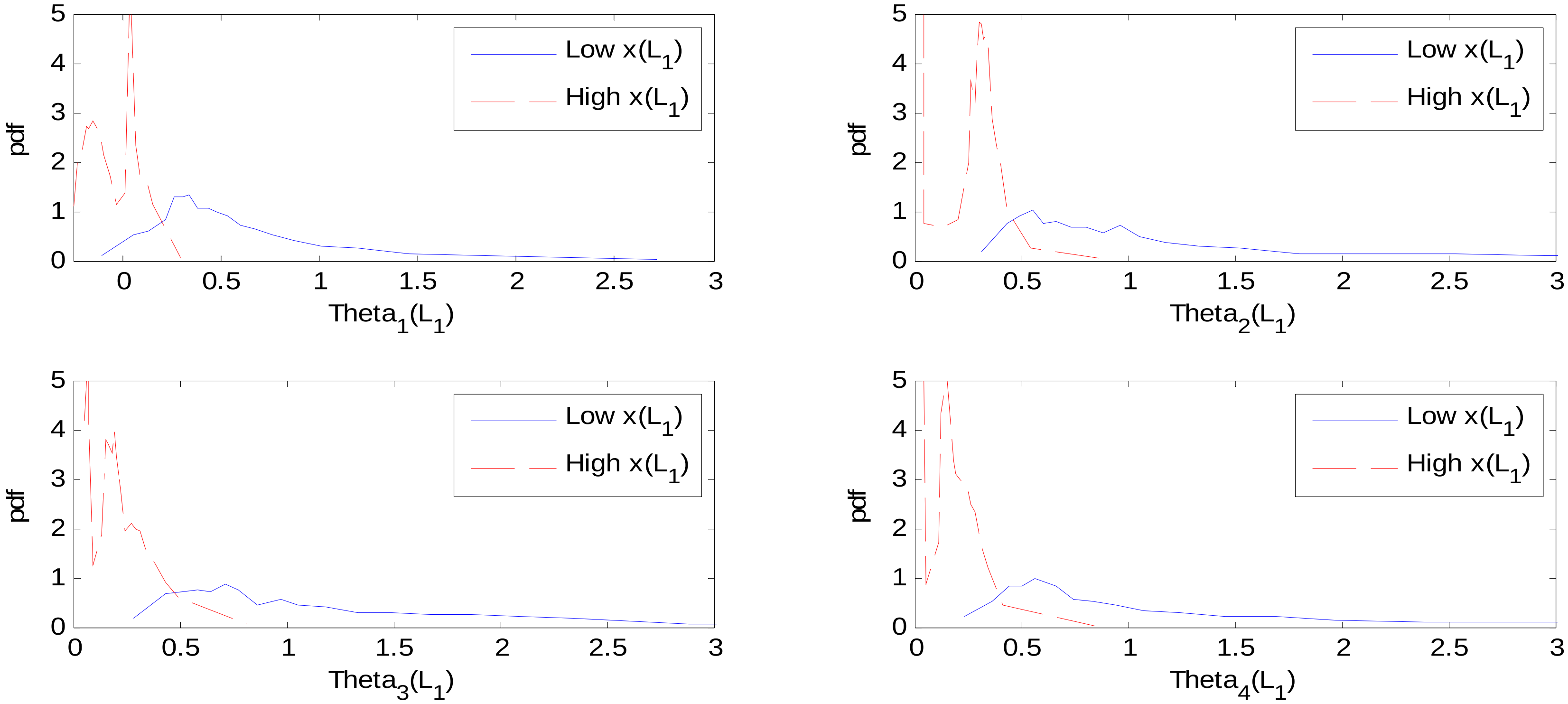
An Scenario with Cross-Traffic



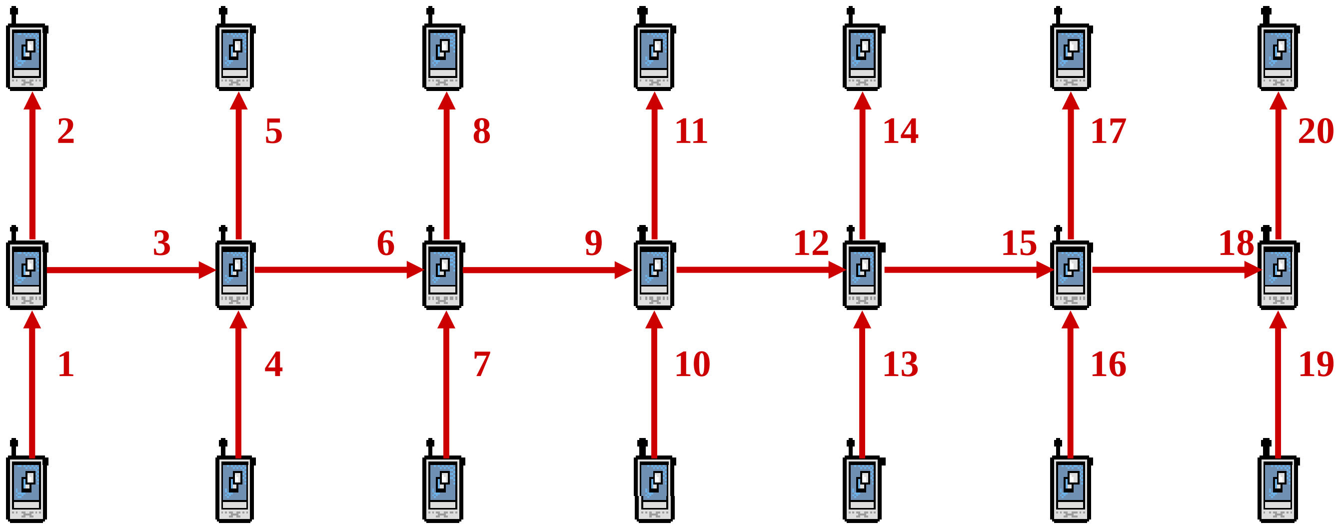
Availability Factor, $x(L)=ABW(L)/BW(L)$

Estatistics from the dispersion trace for L_0 and L_1:

$\theta_1(L_i)$ = mean *gap* between packets of a pair of L_i bits
$\theta_2(L_i)$ = Standard deviation of the *gap* between packets of a pair of L_i bits
$\theta_3(L_i)$ = mean *sowd* of the packets of a pair of L_i bits
$\theta_4(L_i)$ = Standard deviation of the *sowd* of the packets of a pair of L_i bits



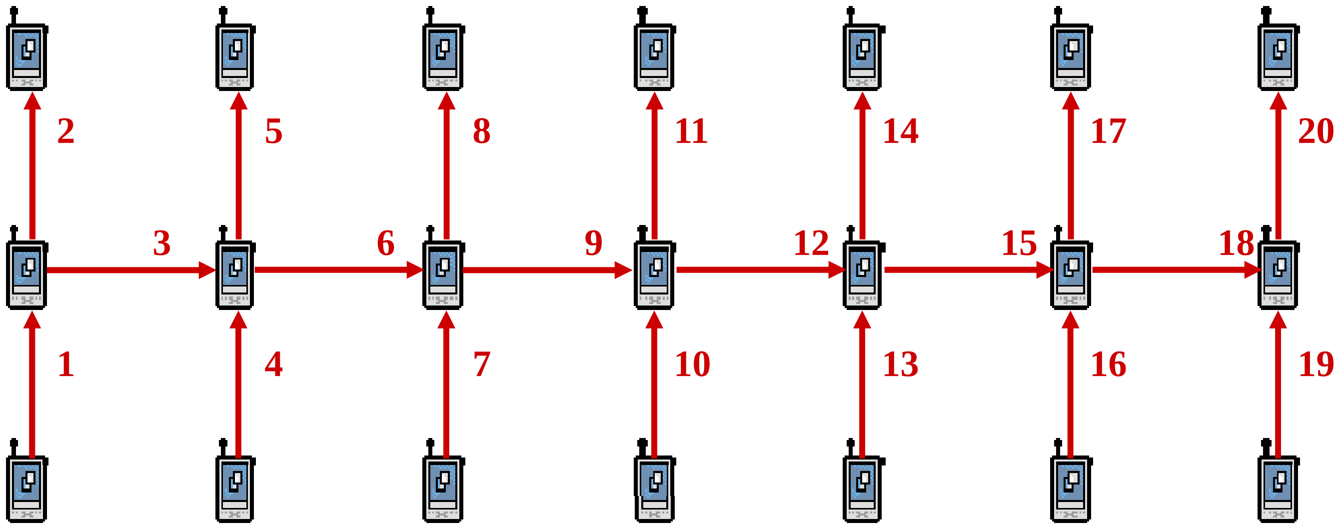
Training Scenario



We explore it by changing the following parameters:

- The distance between nodes
- The physical transmission rate,
- The use of the RTS/CTS mechanism,
- The number of cross-traffic flows,
- The origin and destination of each flow,
- The effective transmission rate of each flow,
- The packet length of each flow,
- The buffer size in the IP queues.

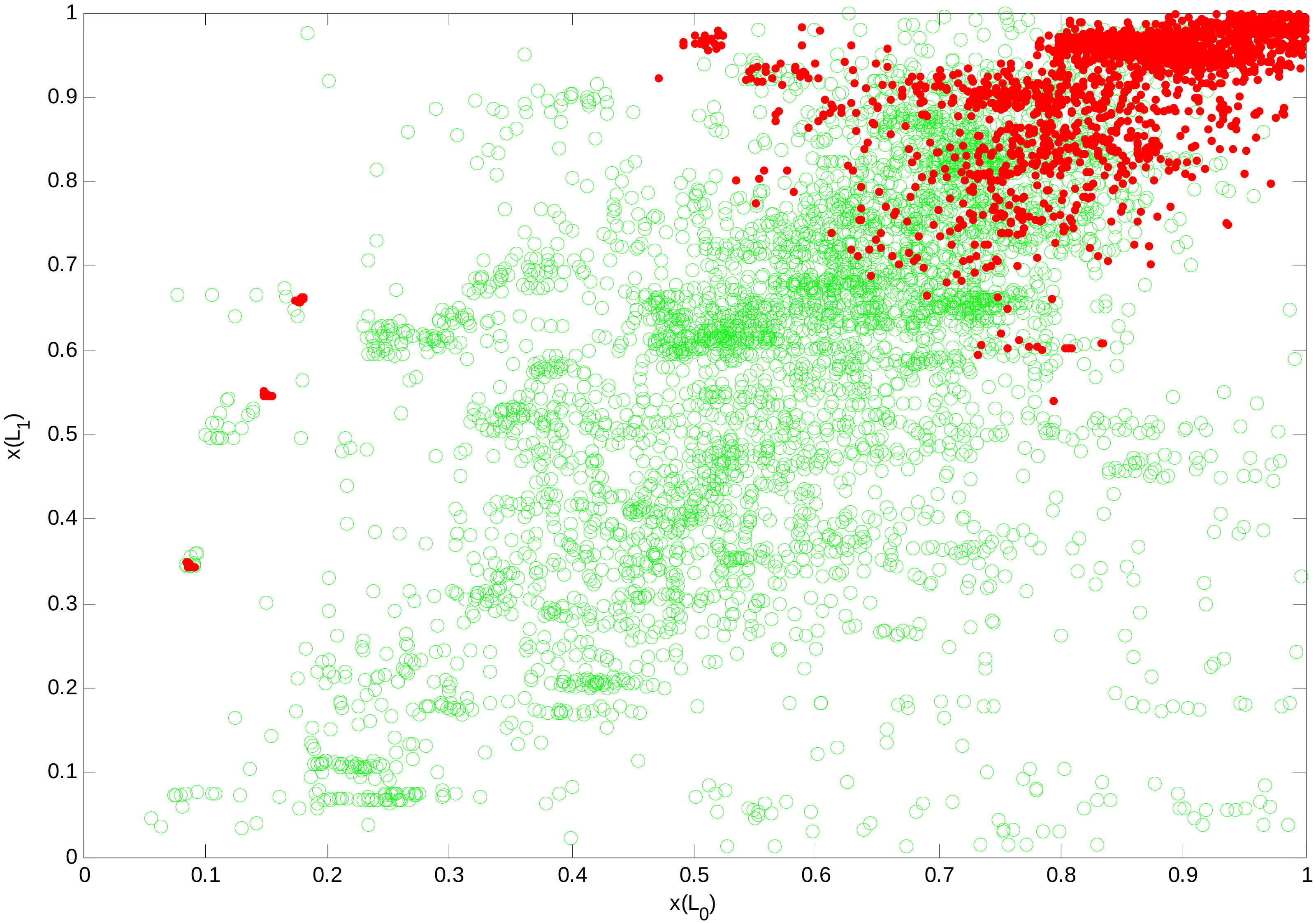
Training Scenario



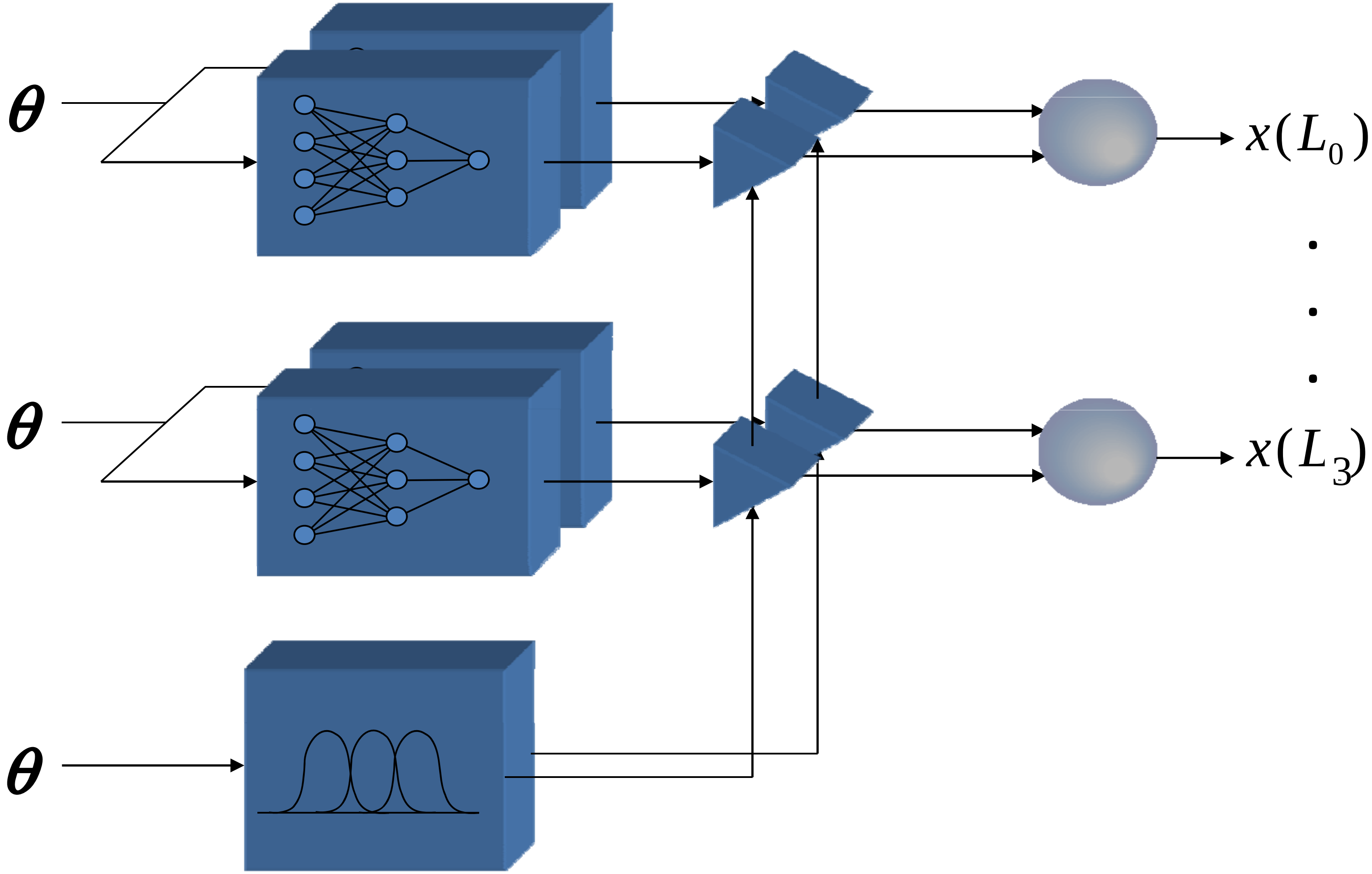
For each set of configuration parameters we did the following:

- Generate a dispersion trace of probing packet pairs between each of the 21 pairs of nodes of the middle row
- Find the maximum achievable throughput, through bracketing. Repeat as many independent experiments as necessary to obtain a ±5% interval with a 95% confidence.
- Construct a large set of training data consisting of a set of dispersion statistics and a corresponding availability factor.

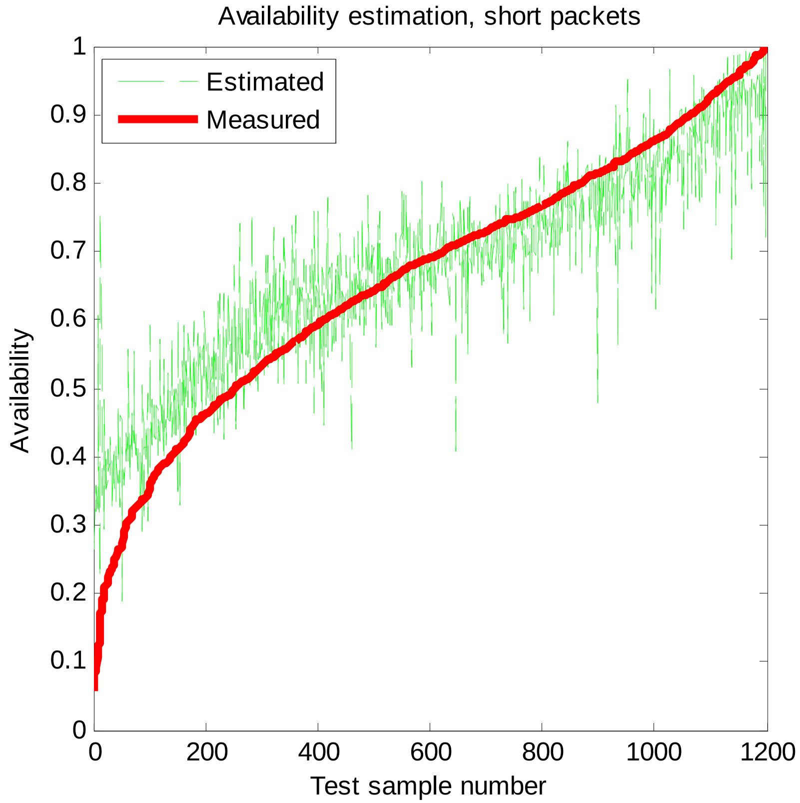
Fuzzy Clustering of the Training Data

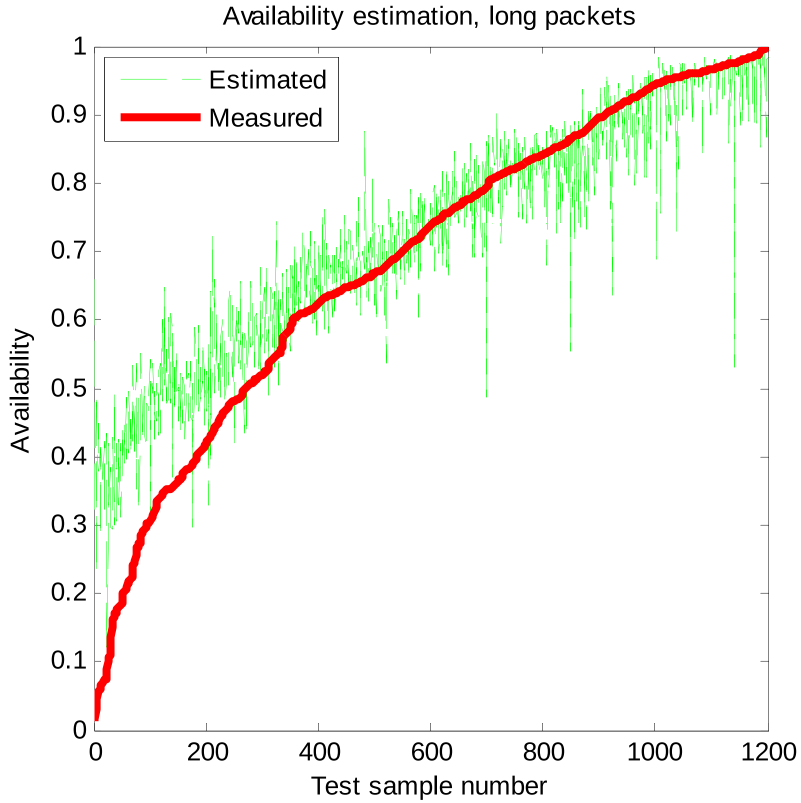


Availability Factor Estimation

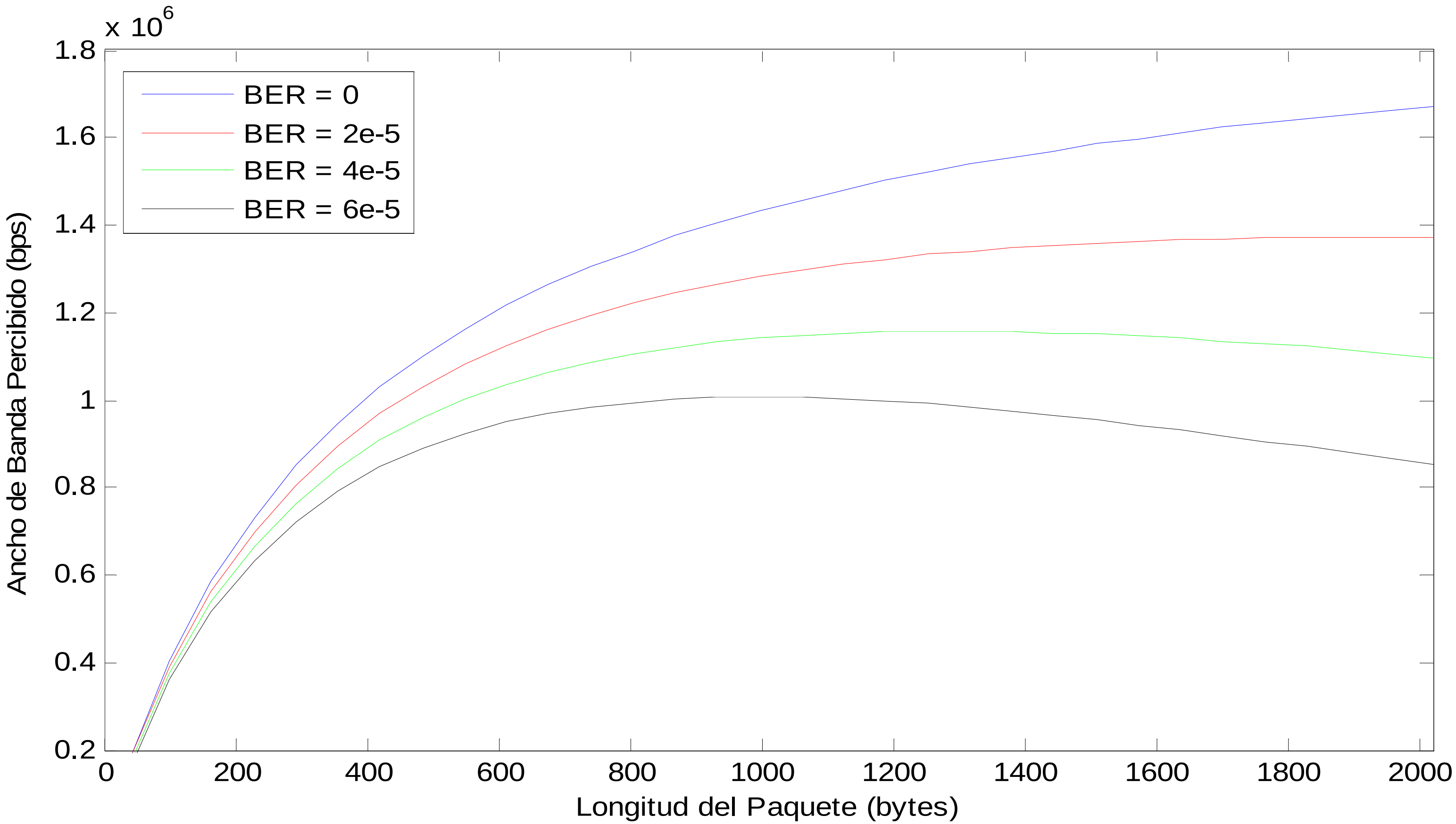


Availability Factor Estimation





Available Bandwidth Interpolation



$$ABW(L) = a\frac{L}{\phi L + \delta} + (1-a)\gamma L \exp(-\lambda L)$$

Simulation Results

Matlab Movies

Conclusions

• We have proposed new definitions for capacity, bandwidth, unused bandwidth and available bandwidth, which consider the multiple interdependencies in a mobile ad hoc network. They generalize the widely accepted definitions and put on solid grounds the search for appropriate estimators.

• We developed a simple, accurate and timely bandwidth estimator that returns the mean bandwidth as a function of packet length.

• This estimator was extended with a neurofuzzy system identification approach to model the dependence between dispersion variability and bandwidth availability.

• This led to a combined end-to-end bandwidth and available bandwidth estimation method that is been tested at the laboratory of unmanned vehicles of University of South Florida.