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Bandwidth and Available Bandwidth Concepts for Wireless Ad Hoc Networks

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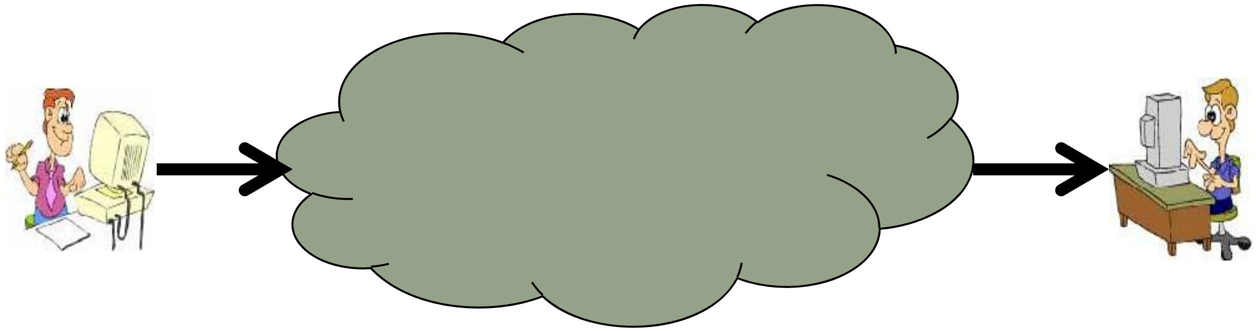
Schedule

- Introduction : Bandwidth (*BW*) and Available Bandwidth (*ABW*) concepts in wired point-to-point networks
- The “Spatial Channel”
- Link and path bandwidth
- Link and path available bandwidth
- An example: IEEE 802.11b
- Conclusions

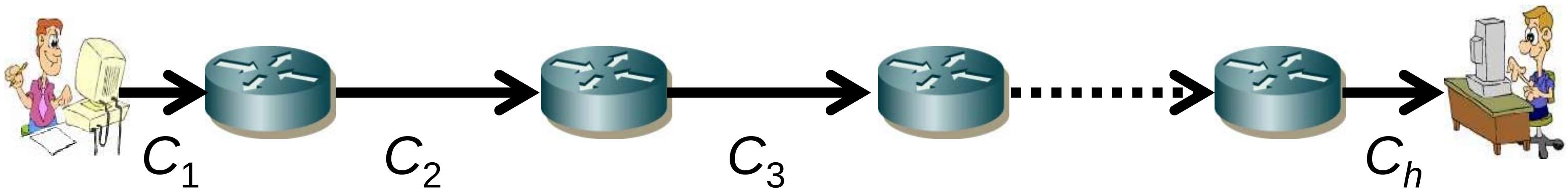
Basic Bandwidth and Available Bandwidth Concepts



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

Available BandWidth (BW) : What is the Maximum Transmission rate I can achieve given the current load within the network?

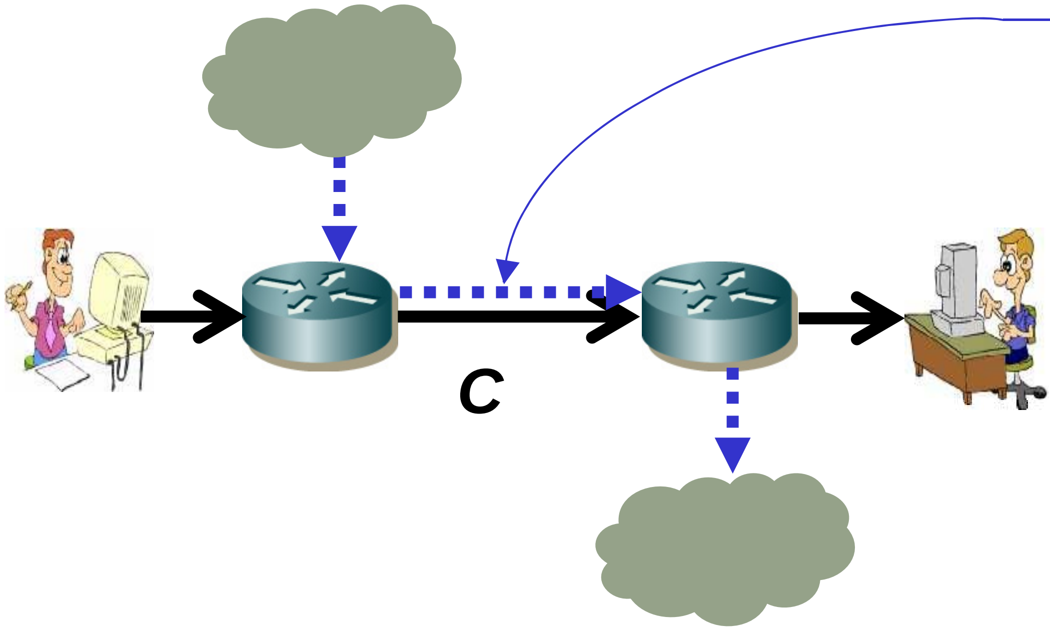
Bandwidth of a wired point-to-point path

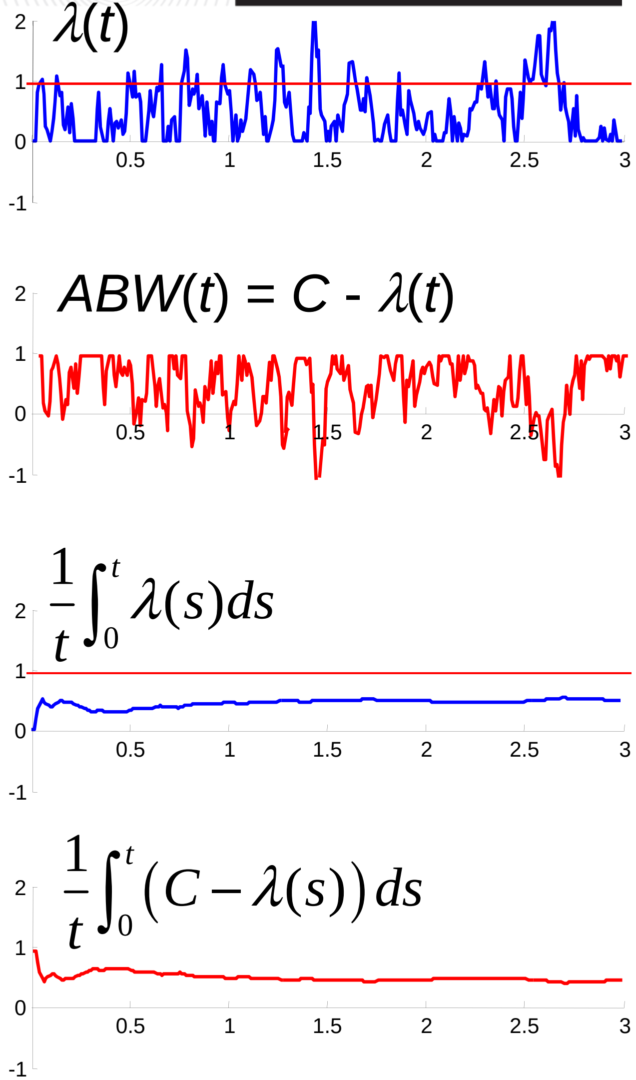


$$BW = \min_{i=1\ldots h} C_i$$

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

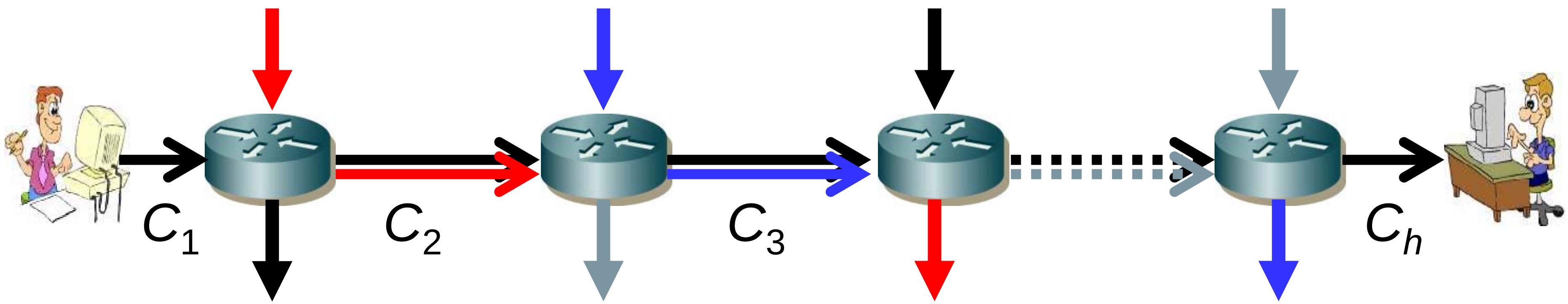
Available Bandwidth in a point-to-point wired link





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

Available Bandwidth in a point-to-point wired multi-hop path



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

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

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?*

BW and ABW Estimation

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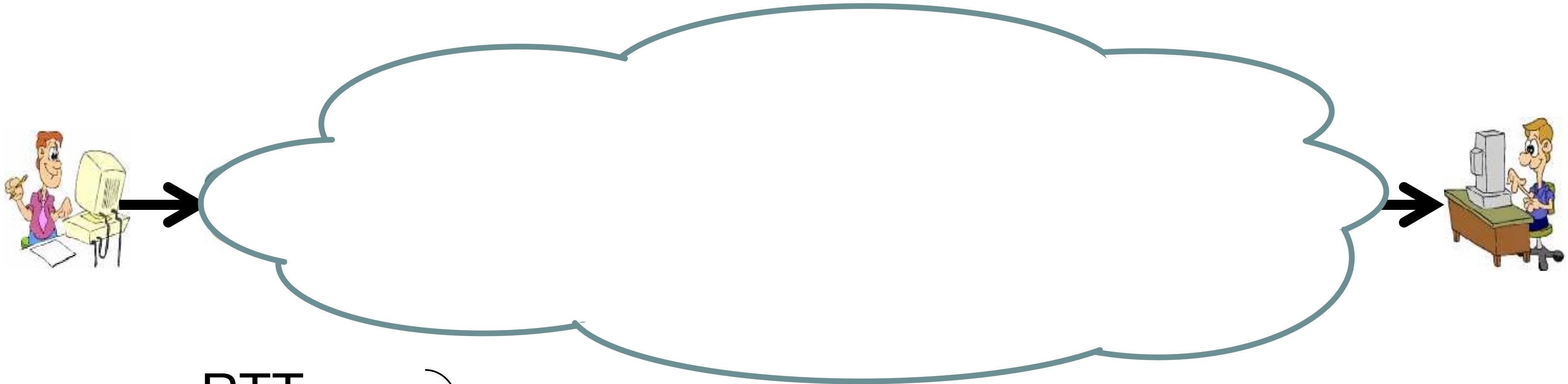

RTT

P[*Loss*]

(λ,γ)

OWD

…

$\{\theta_i\}$

$$BW = \widehat{BW}(\theta_1, \ldots, \theta_n) + \varepsilon$$

$$ABW = \widehat{ABW}(\theta_1, \ldots, \theta_n) + \delta$$

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Two Basic Principles

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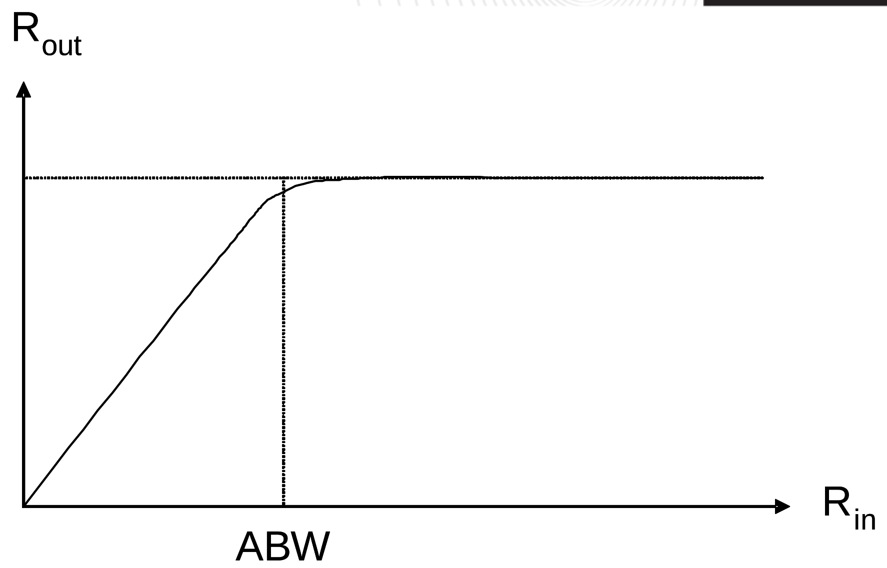
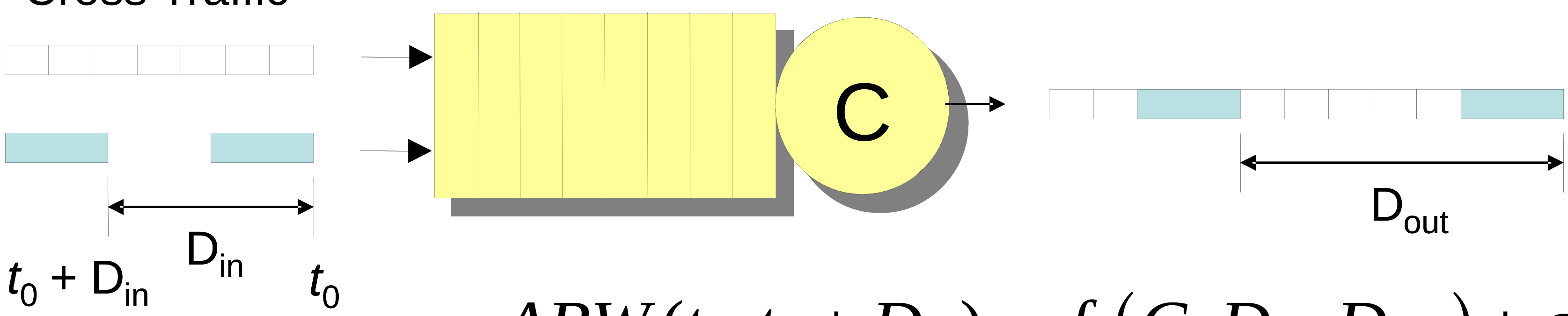


Cross Traffic



$$ABW(t_0, t_0 + D_{in}) = f\left(C, D_{in}, D_{out}\right) + \varepsilon$$

Probe Traffic

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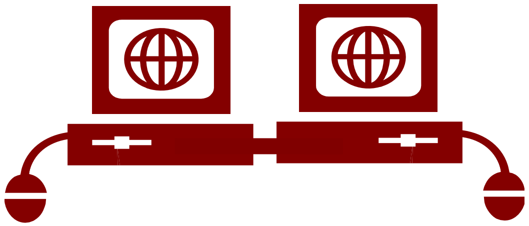
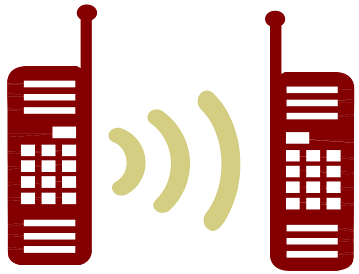
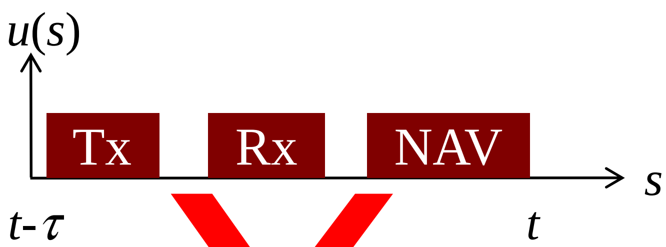
Some tools



- PathChar
- Pathrate
- Cprobe
- PathLoad
- IGI/PTR
- PathChirp
- Delphi
- Spruce
- CapProbe
- Netperf
- etc



- Many tools based on the same concept!



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

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

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

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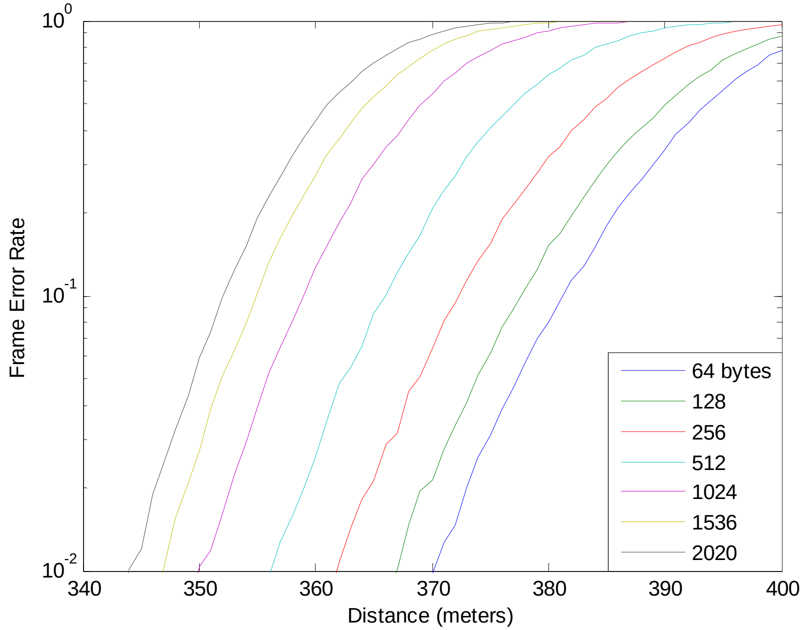
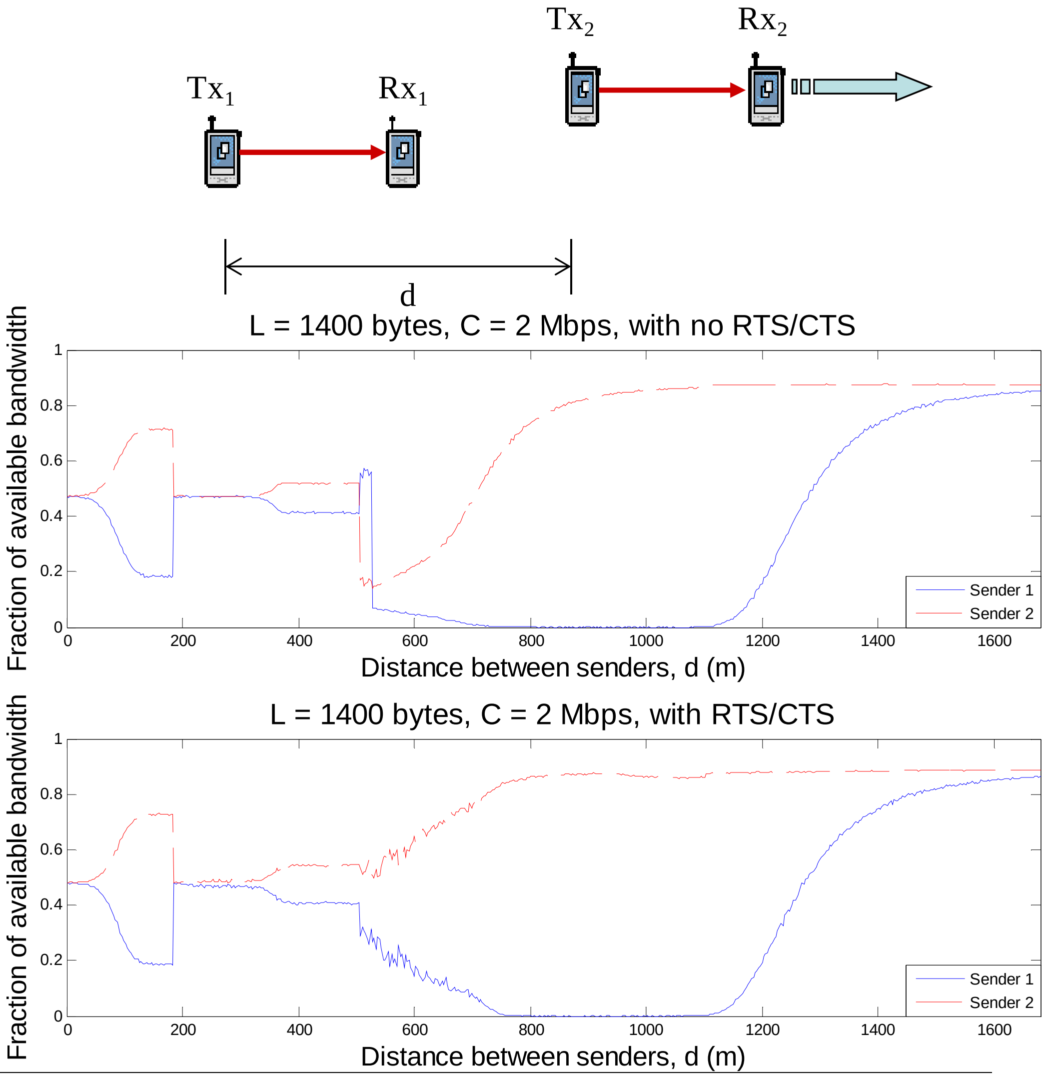
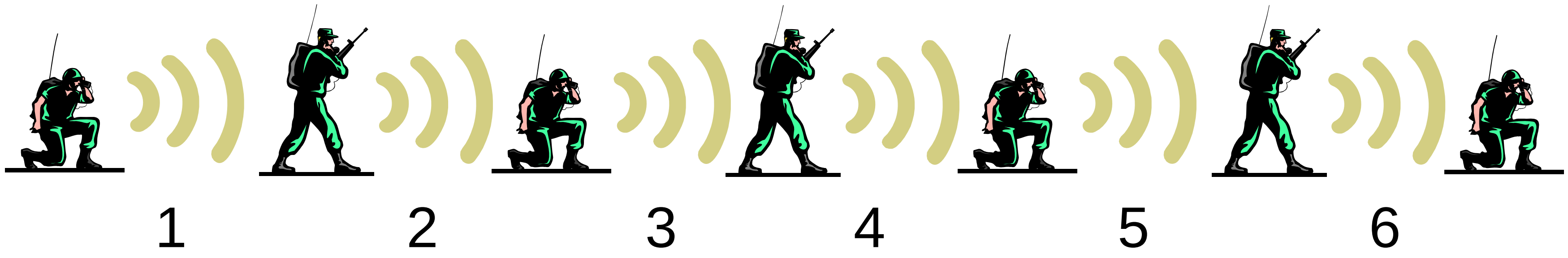
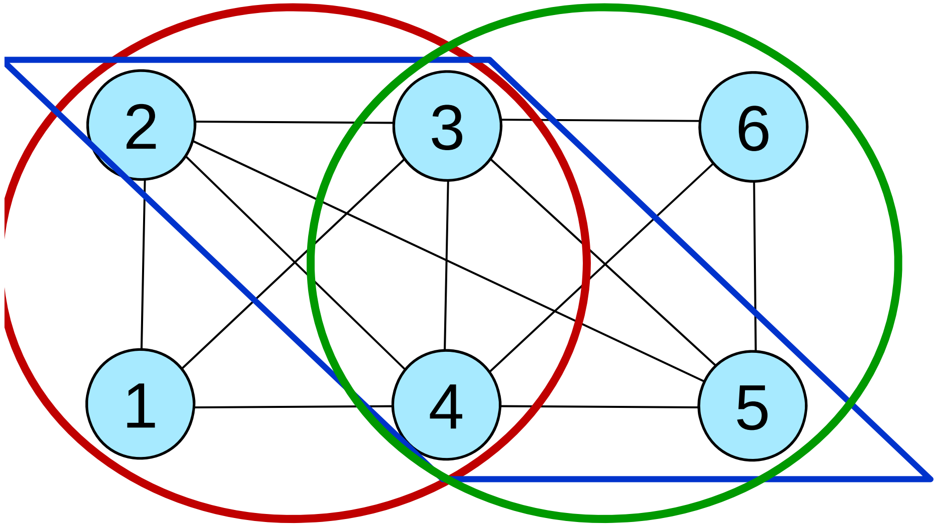
What is a link in an Ad Hoc network?





The Contention Graph and the Spatial Channel



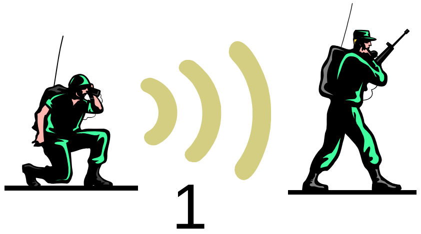


Contention graph: The vertices are the links within the network and the edges represent the impossibility of simultaneous use

Spatial Channel: A maximal clique (a completely interconnected subgraph not contained within another completely interconnected subgraph

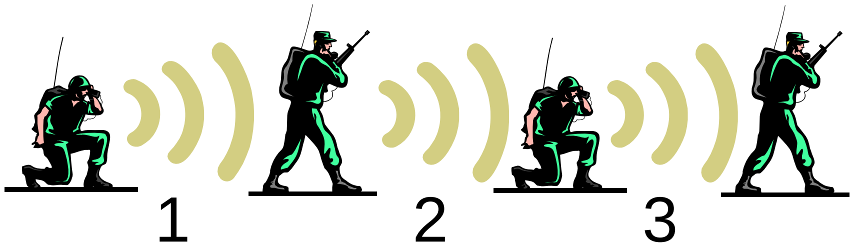
The Resource Unit is not the Link, but the Spatial Channel

Capacity of a Link, a Spatial Channel and a Path



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 path 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 Link

T : Time to acquire and release the medium
L : Packet length
C : Physical data transmission rate

The time it takes an L-bit long packet to be sent is

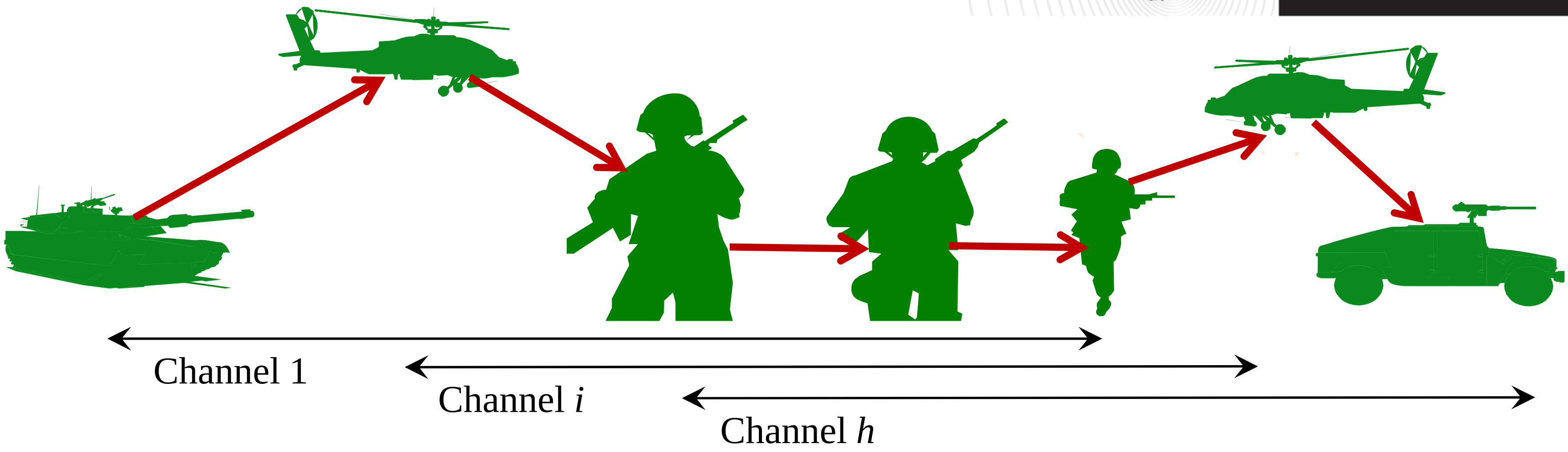
$$T_{tx} = T + \frac{L}{C}$$

$$BW^{link}(L) = \frac{L}{T_{tx}} = \frac{C \cdot L}{L + C \cdot T}$$

$$f_{BW^{link}(L)}(b) = \frac{L}{b^2} f_T\left(L \cdot \left(\frac{1}{b} - \frac{1}{C} \right) \right)$$

$$E\left[BW^{link}(L) \right] \approx \frac{C \cdot L}{L + C \cdot E[T]}$$

Bandwidth of an *h*-channel multi-hop Path



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

h = Number of spatial channels in the path

n_i = Number of links in the i^{th} spatial channel

$C_{i,j}$ = Capacity of the j^{th} link of the i^{th} spatial channel

$T_{i,j}$ = time it takes a packet to get and release the medium in order to be transmitted at the j^{th} link of the i^{th} spatial channel

Available Bandwidth of a Link

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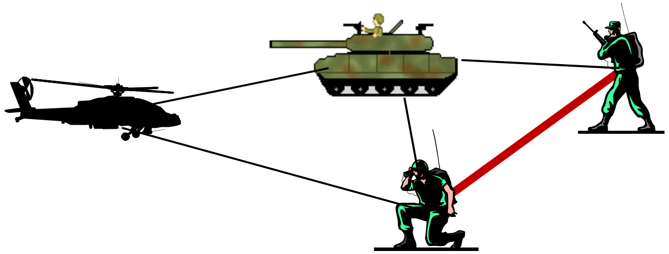

$$E\left[T_i^{occ}\right] = \sum_{j \in L_i} \sum_{k=1}^{\infty} \left(\tau \cdot \lambda_{j,k}\right) \left(\frac{k}{C_j} + E\left[T_j\right]\right) \leq \tau$$

T_i^{occ}=Occupation time of channel i during an interval of length τ

L_i =Set of links in chanel i

$\tau \cdot \lambda_{j,k}$ = Number of k-bit long packets sent through link j during τ

C_j = Physical transmission rate of source node of link j

T_j = Time to acquire and release the chanel at link j

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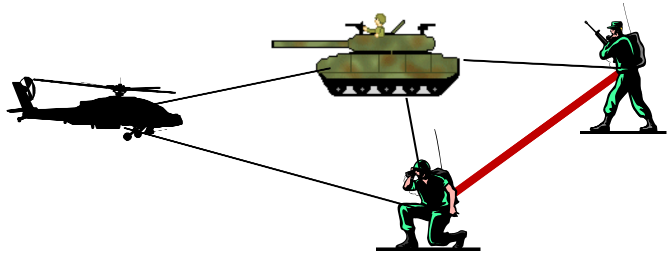
Available Bandwidth of a Link

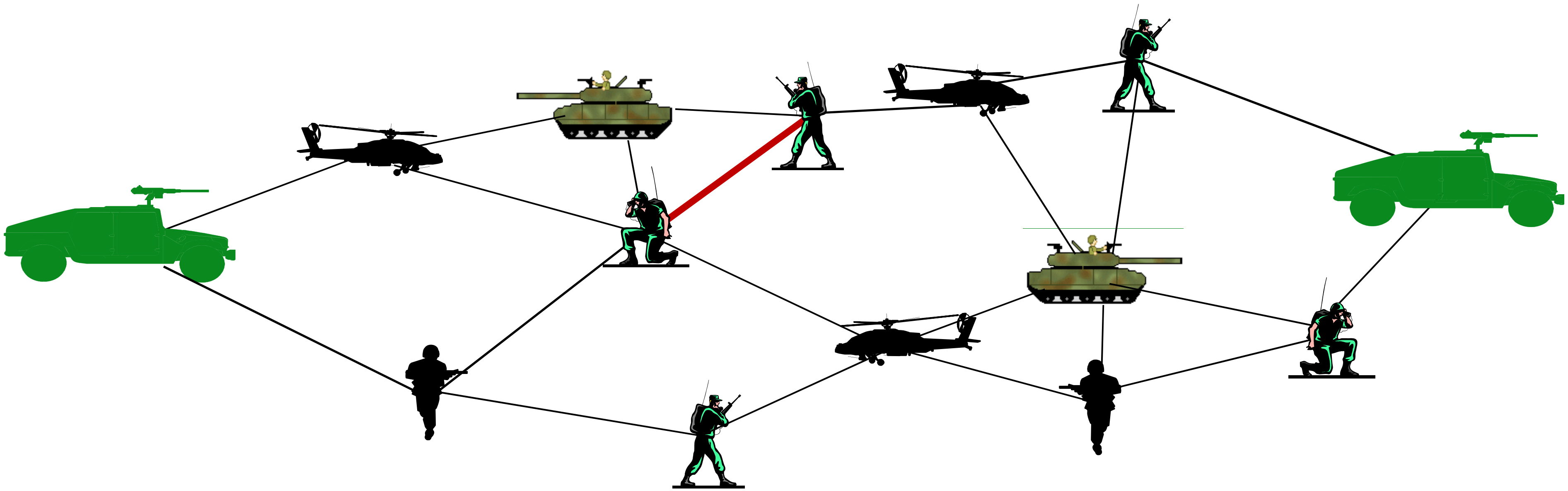


Link x within L_i wants to transmit $\tau\cdot\lambda$ more L-bit long packets during $(t-\tau, t]$

$$\lambda\left(\frac{L}{C_x}+\mathrm{E}\left[T_x\right]\right)+\sum_{j\in L_i}\sum_{k=1}^{\infty}\lambda_{j,k}\left(\frac{k}{C_j}+\mathrm{E}\left[T_j\right]\right)\le 1$$

$$\mathrm{E}\left[ABW^{link_x}_{channel_i}(L)\right]=\frac{L}{\frac{L}{C_x}+\mathrm{E}\left[T_x\right]}\left(1-\sum_{j\in L_i}\sum_{k=1}^{\infty}\lambda_{j,k}\left(\frac{k}{C_j}+\mathrm{E}\left[T_j\right]\right)\right)$$

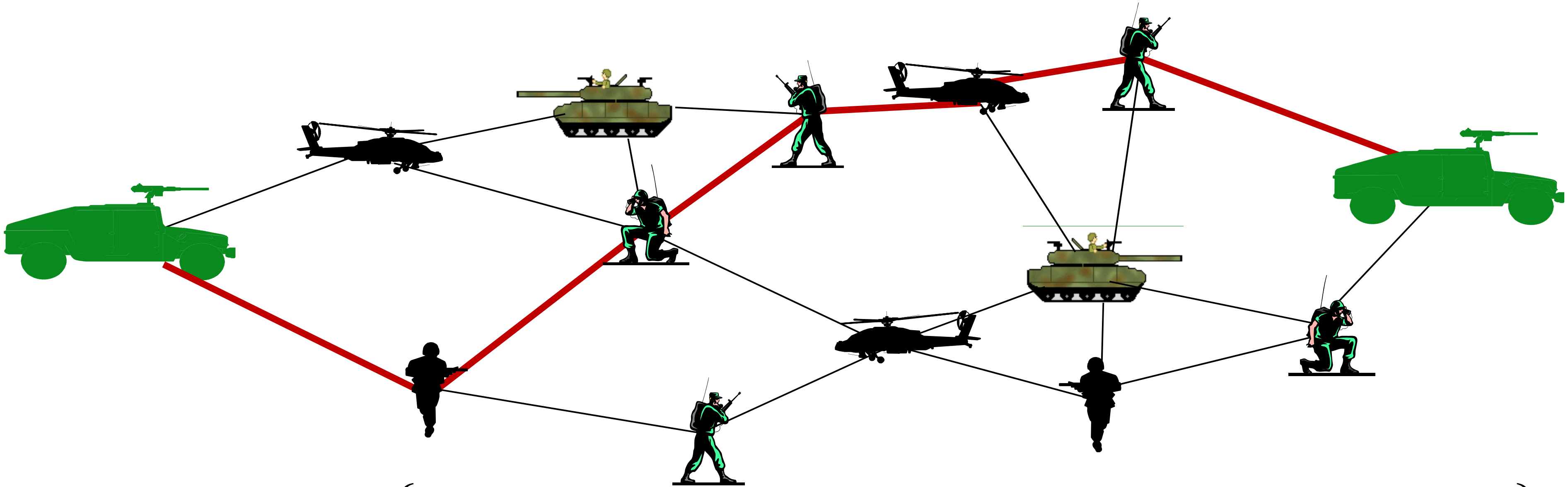
Available Bandwidth of a Link



$$\mathrm{E}\left[ABW^{link_x}(L)\right] = \frac{L}{\frac{L}{C_x} + \mathrm{E}\left[T_x\right]}\left(1 - \max_{i \in V_x} \sum_{j \in L_i} \sum_{k=1}^{\infty} \lambda_{j,k}\left(\frac{k}{C_j} + \mathrm{E}\left[T_j\right]\right)\right)$$

V_x = Set of spatial channels link x belongs to

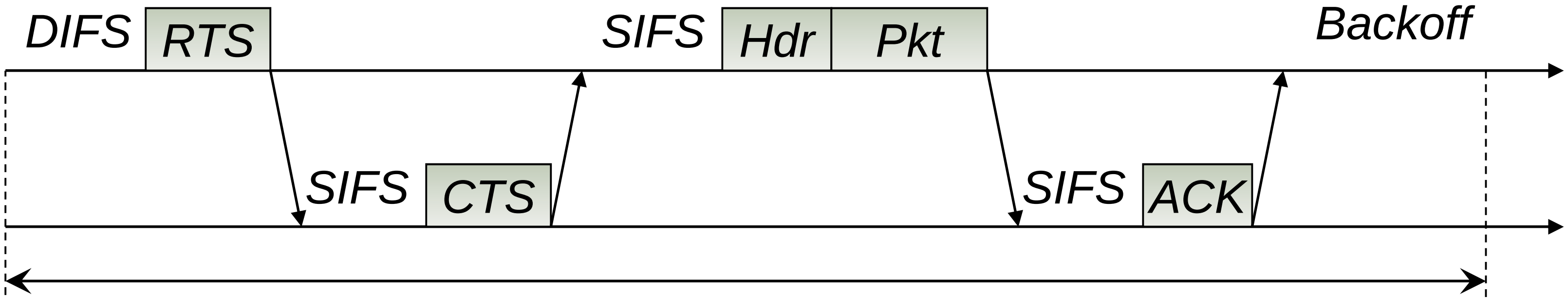
Available Bandwidth of a Path



$$ABW^{Path}(L) = \min_{x \in X} \left\{ \min_{i \in V_x} \left[\frac{L}{\sum_{j \in X \cap L_i} \left(\frac{L}{C_j} + E[T_j] \right)} \left(1 - \sum_{j \in L_i} \sum_{k=1}^{\infty} \lambda_{j,k} \left(\frac{k}{C_j} + E[T_j] \right) \right) \right] \right\}$$

X = Set of links within the path

IEEE 802.11b example



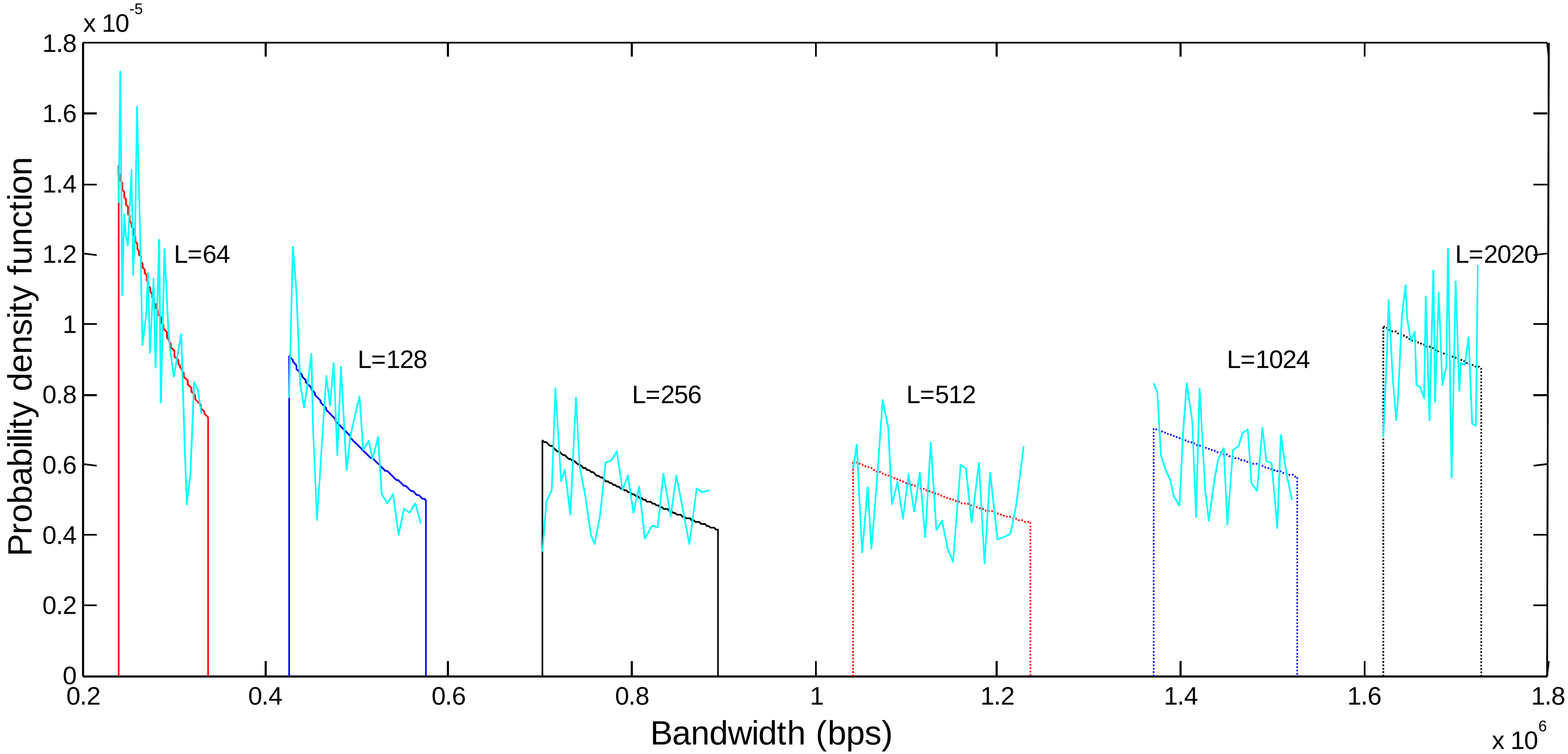
$$t_{Tx} = DIFS + \frac{RTS}{C} + t_p + SIFS + \frac{CTS}{C} + t_p + SIFS + \frac{Hdr}{C} + \frac{L}{C} + t_p + SIFS + \frac{ACK}{C} + t_p + n\sigma$$

$$T_0 = DIFS + 3SIFS + 4t_p \qquad L_0 = RTS + CTS + Hdr + ACK \qquad X = n\sigma, n \sim U(0, W-1)$$

$$t_{Tx} = T_0 + \frac{L_0}{C} + \frac{L}{C} + X \qquad f_{BW}(b) = \frac{L}{b^2} f_X\left(\frac{L}{b} - \left(T_0 + \frac{L_0}{C} + \frac{L}{C}\right)\right)$$

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

IEEE 802.11b example



IEEE 802.11b example

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,

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

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

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

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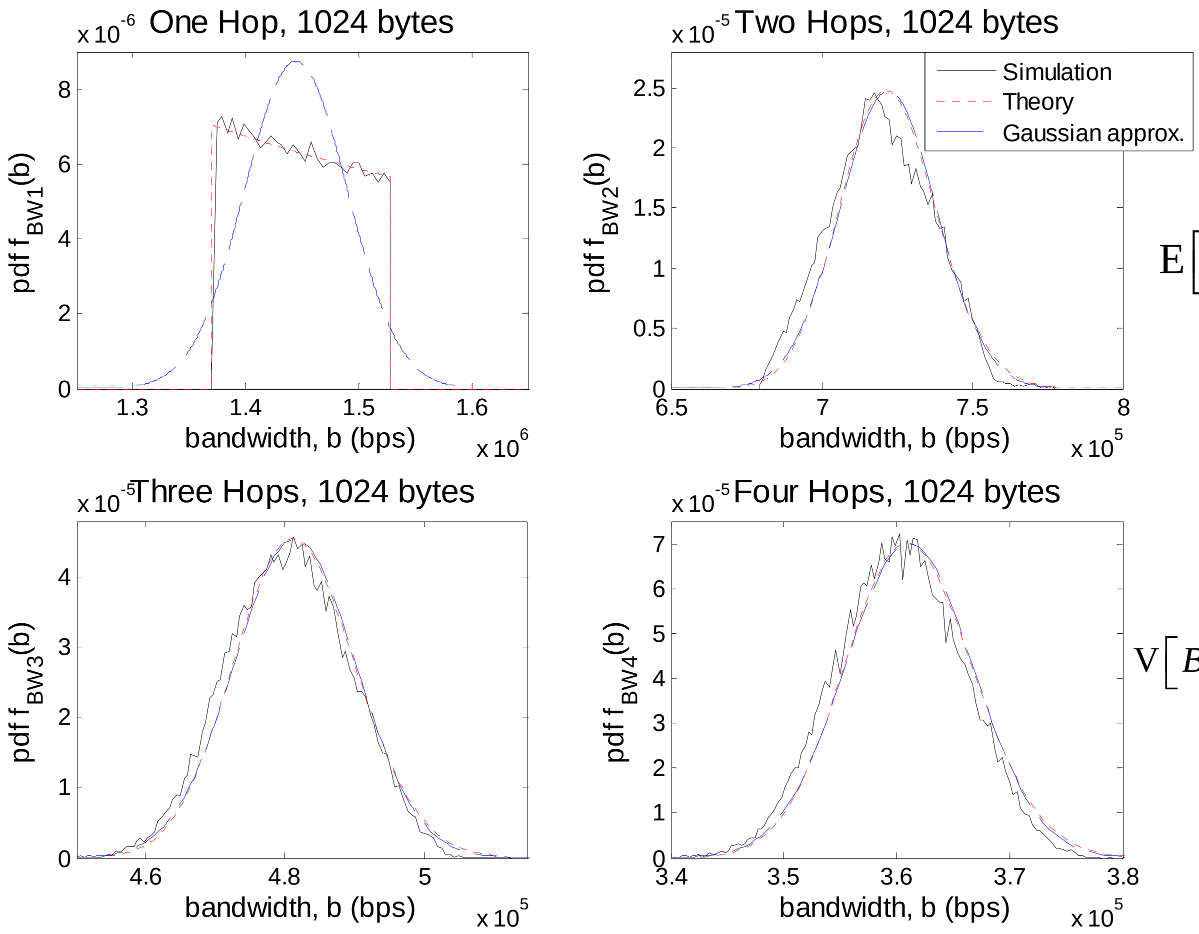
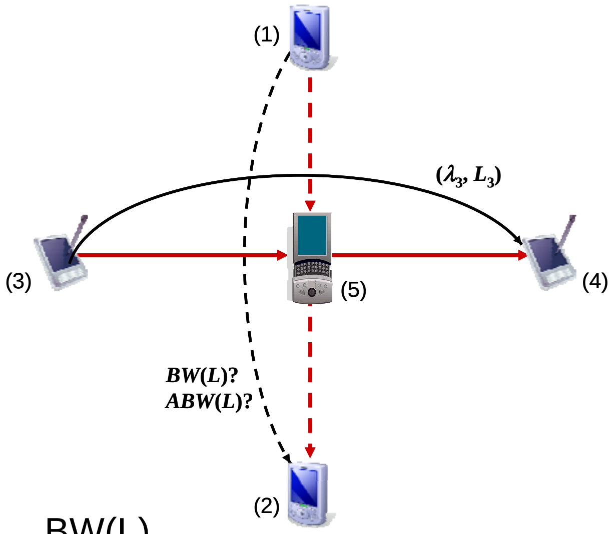
IEEE 802.11b example

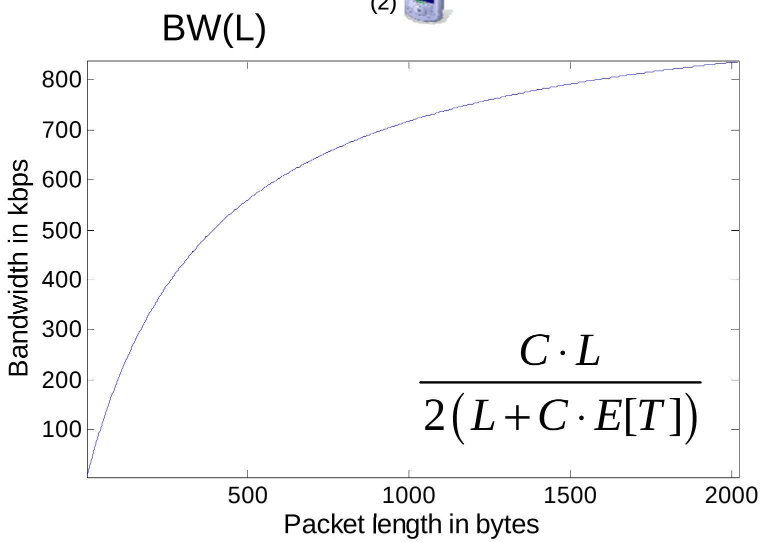


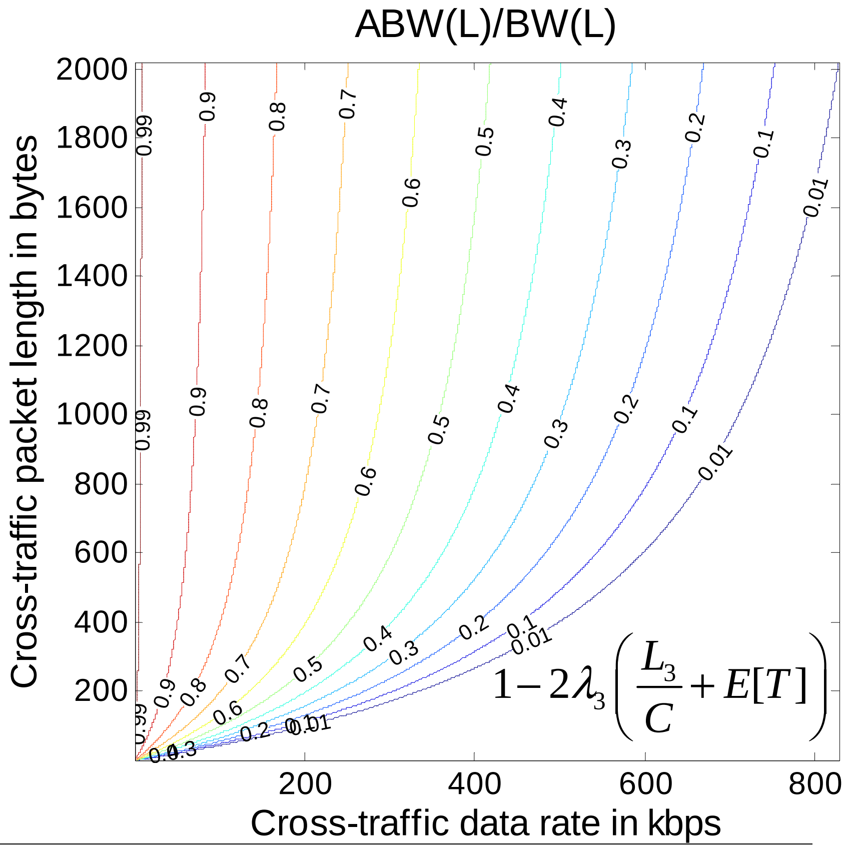
$$\mathrm{E}\left[BW^{ch_i}(L)\right] = \frac{L}{\dfrac{L+L_0}{C_i} + n_i\left(T_0 + \sigma\dfrac{W-1}{2}\right)}$$

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

IEEE 802.11b example







Conclusions

- We have proposed new definitions for capacity, bandwidth, and available bandwidth, which consider the multiple interdependencies in a mobile ad hoc network by replacing the concept of link by that of spatial channel.
- These definitions generalize the widely accepted definitions, in the sense that, if each spatial channel becomes a single point-to-point link, the original definitions are recovered.
- We verified the new concepts in an IEEE 802.11b ad hoc network context.
- We hope these definitions put on solid grounds the search for appropriate estimators, which constitute the future work.