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Capacity, Bandwidth, and Available Bandwidth in Wireless Ad Hoc Networks: Definitions and Estimations

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1. Introduction

Prasad et al. (2003) offered the most widely accepted definition of the capacity of a path, which has been usefully expressed as:

$$C = \min_{i=1...H} C_i \tag{1}$$

where C_i is the link capacity of the i^{th} hop in an H-hop path. Equation 1 has been the foundation of several clever active probing capacity estimation techniques, such as Pathrate, described by Dovrolis et al. (2004), and CapProbe, described by Kapoor et al. (2004), for example.
Similarly, the link available bandwidth for the i^{th} hop in an interval of time $(t-\tau, t]$, has been defined by Prasad et al. (2003) as:

$$A_i = (1-\bar{u}_i)C_i, \;\; \bar{u}_i = \frac{1}{\tau}\int_{t-\tau}^{t} u_i(s)ds \tag{2}$$

where $u_i(s)$ is the instantaneous utilization of the i^{th} link at time s. The available bandwidth of the path, for the same interval, has been defined as:

$$A = \min_{i=1...H} A_i \tag{3}$$

Definition 3 has also led the way to many active probing available bandwidth estimation techniques and tools, such as Spruce, described by Strauss et al. (2003), IGI/PTR, described by Hu & Steenkiste (2003), Pathload, described by Jain (2002), Pathchirp, described by Ribeiro et al. (2003), TOPP, described by Melander et al. (2000), Delphi, described by Ribeiro et al. (2000), and Traceband, described by Guerrero & Labrador (2009), among others.
Unfortunately, the definitions above do not make any explicit reference to the dependencies that C and A can have on different parameters and network conditions, such as packet length and medium access overhead. This omission suggests that we are dealing with constant parameters of the path, as it is assumed in many cases. Although this simplifying

assumption is highly convenient and approximately correct in wired networks, it does not apply to wireless ad hoc networks (MANETs) due to the shared and unreliable nature of the transmission medium. Nevertheless, many current estimation techniques for MANETs are still based on definitions 1-3, measuring the fraction of time a node senses the channel idle, multiplying this fraction by the physical transmission capacity of the node, and sharing this measurements among the nodes of a path to estimate the available bandwidth (ABW) as the minimum measure among the individual nodes (see, for example, Chen & Heinzelman (2005); Guha et al. (2005); Xu et al. (2003); Ahn et al. (2002); Chen et al. (2004); Lee et al. (2000); Nahrstedt et al. (2005)). This per node estimation is not correct because it does not consider the occupation times of those links that cannot be used simultaneously, nor the additional overhead incurred when trying to use that idle capacity.

In this paper we conduct a theoretical analysis of the capacity (C), the bandwidth (BW), and the available bandwidth (ABW) of a link and a path in a MANET, in order to extend the definitions 1, 2, and 3 to this type of networks. We also develop a procedure to estimate the mean value of these quantities under the particular case of an IEEE 802.11b multi-hop ad hoc network.

Both C and BW are defined as the maximum achievable transmission rate in absence of competing flows, which is the basic notion of capacity used so far. Both of them take into account the shared nature of the transmission medium, but the concept of capacity does not consider the multi-access overhead, while the concept of bandwidth does. The concept of ABW also considers the effect of competing flows to determine the maximum achievable transmission rate.

The fundamental criterion for the extension of these concepts to MANETs is to avoid the elusive idea of a link as a unit of communication resource and to consider the "spatial channel" instead. Here a link is simply a pair of nodes within transmission range of each other, which shares the communication resources of a spatial channel with competing links. Indeed, a spatial channel is just a set of links for which no more than one can be used simultaneously, as defined below. These extensions do not pretend to constitute a detailed theoretical model of the physical phenomena occurring within a MANET, but simply a way to adapt and extend existing definitions. We would like to warn the reader that, during the process, we slightly redefine several well-established concepts in order to adapt them to the conditions we are facing.

After establishing this theoretical framework, we estimate the end-to-end C, BW, and ABW of a path between a pair of nodes in an IEEE 802.11b ad hoc network as a function of the packet length using dispersion traces between probing packet pairs of different lengths. The pairs of packets that suffer the minimum delay are used to estimate C and BW, while the variability of the dispersion trace is fed into a neuro-fuzzy system in order to estimate the practical maximum throughput obtained over the range of input data rates, closely related to the theoretically defined ABW.

In Section 2 we define the spatial channel as a set of links for which only one can be used simultaneously and, based on this simple concept, we develop the new definitions for C, BW, and ABW. In Section 3 we develop a method to estimate C and BW based on the dispersion measures between pairs of probing packets of two different lengths. In Section 4 we use the variability of the dispersion trace in order to estimate the ABW. Section 5 concludes the paper.

2. Capacity, bandwidth, and available bandwidth definitions

Two pioneering works on capacity definitions for wireless networks are those of Bianchi (2000) and Gupta & Kumar (2000). Bianchi computed the saturation throughput of a single IEEE 802.11 cell, defined as the maximum load that the cell can carry in stable conditions. Gupta and Kumar Gupta & Kumar (2000) established some basic limits for the throughput of wireless networks, where the throughput is defined as the time average of the number of bits per second that can be transmitted by every node to its destination. These seminal works have been the basis of additional theoretical models Gamal et al. (2004); Grossglauser & Tse (2002); Neely & Modiano (2005); Kwak et al. (2005); Kumar et al. (2005); Chen et al. (2006) based on similar definitions. More recently, some detailed interference models have shown, analytically, the maximum achievable throughput on a specific link given the offered load on a set of neighbor links Kashyap et al. (2007); Gao et al. (2006); Takai et al. (2001); Sollacher et al. (2006); Koksal et al. (2006). However, these definitions neither extend to the end-to-end throughput nor lead to practical estimation methods.

Several methods have been proposed for the end-to-end capacity and available bandwidth estimation in wireless ad hoc networks based on definitions 1, 2, and 3 Chen & Heinzelman (2005); Xu et al. (2003); Ahn et al. (2002); Sarr et al. (2005); de Renesse et al. (2004); Renesse et al. (2005); Shah et al. (2003). Nonetheless, they are fundamentally inaccurate because, by measuring locally the utilization of the medium, they ignore the self interference of a flow at consecutive links and the simultaneous idle times of neighbor links. The authors of Chen et al. (2009) define the capacity of an end-to-end path as the length of a packet divided by the inter-arrival gap between two successfully back-to-back transmitted packets that do not suffer any retransmission, queuing, or scheduling delay. This definition led to AdHocProbe, but the estimation is only valid for the probing packet length utilized and does not say anything about the available bandwidth. Other authors Chaudet & Lassous (2002); Sarr et al. (2006); Yang & Kravets (2005) consider the interference by estimating the intersection between idle periods of neighbor nodes, so their estimations have better accuracy; but, still, taking the minimum among the individual measurements in the path considering only immediate neighbors, leads to significant inaccuracies. Finally, some estimations of the available bandwidth in a MANET end-to-end path are based on the self congestion principle, under the definition of available bandwidth as the maximum input rate that ensures equality between the input and output rates Johnsson et al. (2005; 2004). This method raises serious intrusiveness concerns in such a resource-scarce environment.

In this section we propose extended definitions for C, BW, and ABW more appropriate for MANETs, where the unit of communication resources is not the link but the spatial channel, so the definitions can take into account the channel sharing characteristic of this type of networks.

2.1 The spatial channel

The concepts of capacity, bandwidth, and available bandwidth are intimately related to the idea of a link between a pair of nodes and a route made of a sequence of links in tandem. However, the main difficulties and challenges with MANETs come, precisely, from the volatility of the concept of a link. While in a wired network every pair of neighbor nodes are connected through a point-to-point link, in a wireless MANET the energy is simply radiated, hoping the intended receiver will get enough of that energy for a clear reception, despite possible interfering signals and noise Ephremides (2002). In this context, a link is simply a pair of nodes within transmission range of each other. In defining bandwidth-related

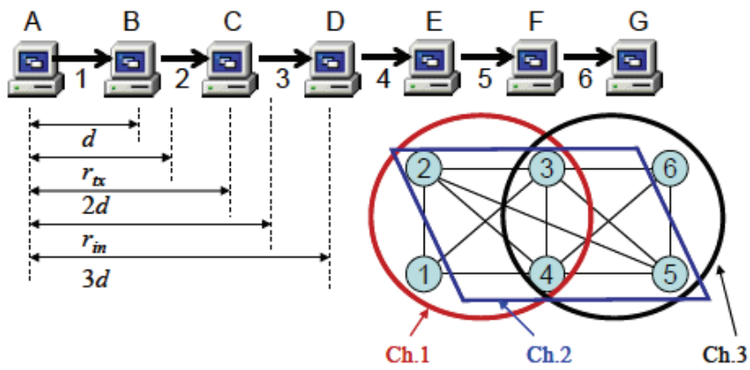


Fig. 1. A six-hop path and the corresponding contention graph showing three spatial channels.

metrics, one of the most important characteristics of MANETs is that two links cannot be used simultaneously if the intended receiver of one of the transmitters is within the interference range of the other transmitter. Accordingly, let us consider a wireless ad hoc network as a contention graph $(\mathcal{L},\mathcal{E})$, where the set of vertices, $\mathcal{L}$, corresponds to the active links of the network, and the set of edges, $\mathcal{E}$, connect pairs of active links that cannot be used simultaneously Chen et al. (2004).

Definition 1. Spatial Channel. A spatial channel is a maximal clique (a complete subgraph not contained in another complete subgraph) in the contention graph $(\mathcal{L},\mathcal{E})$ of a network, i.e., a spatial channel is a set of links for which no more than one can be used simultaneously.

Figure 1 shows a six-hop path in which nodes A through G, connected by links 1 through 6, are uniformly placed on a straight line at a distance d between them. Assuming that the transmission range (r_{tx}) and the interference range (r_{in}) of each node satisfies $d < r_{tx} < 2d < r_{in} < 3d$, there would be three spatial channels in this network, as shown on the contention graph in the bottom-right corner of the figure.

In what follows, we consider the spatial channel as the unit of communication resource, similar to the link in a point-to-point wired network, so we can extend the concepts of C, BW, and ABW.

2.2 Link capacity and end-to-end capacity

We keep the concept of the capacity of a link as the physical transmission rate of the node sending packets over it. But, in a wireless ad hoc network, several links share the same transmission medium, so we take this effect into account to define the concept of path capacity, omitting the effects of multi-access protocols. First, we consider a single pair of nodes, for which we simply define the link capacity as follows.

Definition 2. Link Capacity. For a pair of nodes within transmission range of each other, we define the capacity of the link between them as the physical transmission bit rate of the source node.

Now consider a path that traverses h spatial channels, with n_i links in the i^{th} spatial channel. If every resource is available for the source/destination pair of the path, an L-bit long packet will occupy the i^{th} spatial channel n_i times, during a total effective time of $t_i = \sum_{j=1}^{n_i}(L/C_{i,j})$, where $C_{i,j}$ is the link capacity of the j^{th} link in the i^{th} spatial channel in the path. In order not to saturate the path, the time between consecutive packets sent at the source node must be no less than $t_{min} = max_{i=1...h}t_i$. The maximum achievable transmission rate is $C^{path} = L/t_{min}$.

Definition 3. End-to-End Capacity. The end-to-end capacity of a multi-hop path that traverses h channels, where channel i is composed of n_i links with capacities $\left\{C_{i,j}, i = 1 \ldots h, j = 1 \ldots n_i\right\}$, is defined as:

$$C^{path} = \min_{i=1 \ldots h} \frac{1}{\sum_{j=1}^{n_j} \frac{1}{C_{i,j}}} \tag{4}$$

Note that Equation 4 becomes Equation 1 if each channel were a single link, as it is the case of paths composed of point-to-point wired links. However, differently to Equation 1, we cannot interpret Equation 4 as the transmission rate that a source would achieve in absence of competition because, so far, we have ignored completely the overhead introduced by the medium access mechanisms, which lead to the following concept.

2.3 Link bandwidth and end-to-end bandwidth

In absence of competing stations, the time to get and release the medium in a one-hop transmission is a random variable T, distributed as $f_T(t)$. The time required to transmit an L-bit long packet at a link transmission rate of C bps will be $T + L/C$, which means that, if the link is completely available for that packet, the link bandwidth is a random variable:

$$BW^{link}(L) = \frac{C \cdot L}{L + C \cdot T} \tag{5}$$

distributed as Alzate (2008):

$$f_{BW^{link}(L)}(b) = \frac{L}{b^2} f_T \left(L \cdot \left(\frac{1}{b} - \frac{1}{C} \right) \right) \tag{6}$$

Although the exact form of the expected value of $BW^{link}(L)$ depends on $f_T(\cdot)$, we can consider that, since the average time it takes an L-bit long packet to be transmitted is $t = E[T] + L/C$, the link bandwidth would approximately be L/t, suggesting the following definition:

Definition 4. Link Bandwidth. The expected value of the bandwidth of a C-bps link transmitting L-bit packets is defined as:

$$E\left[BW^{link}(L)\right] = \frac{L}{\frac{L}{C} + E[T]} \tag{7}$$

where T is the time required to get and release the transmission medium at that link.

Now consider a path that traverses h spatial channels, with n_i links in the i^{th} channel and link capacities $\left\{C_{i,j}, i = 1 \ldots h, j = 1 \ldots n_i\right\}$. Under perfect scheduling, an L-bit long packet will take an average time T_i^{ch} to traverse the i^{th} channel, given by:

$$T_i^{ch} = \sum_{j=1}^{n_i} \left(\frac{L}{C_{i,j}} + E\left[T_{i,j}\right] \right) \tag{8}$$

In order not to saturate the path, the average time between consecutive packets sent at the source node must be no less than $t_{min} = max_{i=1 \ldots h} T_i^{ch}$. Under these assumptions, the maximum achievable bandwidth is $BW^{path} = L/t_{min}$:

Definition 5. End-to-End Bandwidth. The average end-to-end BW of a multi-hop path using L-bit long packets that traverse h spatial channels, where channel i is composed of n_i links with

capacities $\left\{C_{i,j}, i = 1 \ldots h, j = 1 \ldots n_i\right\}$ and where the 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} channel is a random variable $T_{i,j}$, is defined as:

$$E\left[BW^{path}(L)\right] = \min_{i=1\ldots h} \frac{L}{\sum_{j=1}^{n_i}\left(\frac{L}{C_{i,j}} + E\left[T_{i,j}\right]\right)} \tag{9}$$

2.4 Link available bandwidth and end-to-end available bandwidth

As stated before, the available bandwidth (ABW) is highly dependent on the competing cross-traffic, which could have a complex correlation structure and interfere in many different ways with a given flow. Therefore, we will no longer look for the ABW probability density function, as we did above. Instead, if we assume that the cross-traffic is stationary and mean-ergodic, and that the queueing dynamics within the network nodes have achieved a stochastic steady state, we can find appropriate definitions for the mean value of the ABW on a link and an end-to-end path.

Consider a network composed of n active links, $j = 1 \ldots n$, and h spatial channels, $i = 1 \ldots h$. The i^{th} spatial channel is composed of n_i links $L_i = \left\{l_{i,j}, j = 1 \ldots n_i\right\}$ with $l_{i,j} \in \{1,2,\ldots n\}$. Let V_j be the set of spatial channels to which link j belongs to, $j = 1,2,\ldots,n$. Clearly, $i \in V_j \Longleftrightarrow j \in L_i$. In the interval $(t-\tau, t]$ the j^{th} link transmits $\tau\lambda_{j,k}$ packets of k bits, $j = 1 \ldots n, k \geq 1$ (note that $\tau\lambda_{j,k}$ is not a per-source rate but a per-link rate, i.e., it includes forwarded packets too). Each k-bit packet transmitted over link j occupies each channel in V_j during $k/C_j + T_j$ seconds, where C_j is the j^{th} link capacity and T_j is the time it takes the packet to get and release the transmission medium at link j.

The time a spatial channel $i \in \{1,2,\ldots,h\}$ is occupied during the interval $(t-\tau, t]$ is:

$$E\left[T_i^{occ}\right] = \sum_{j \in L_i} \sum_{k=1}^{\infty} (\tau \cdot \lambda_{j,k}) \left(\frac{k}{C_j} + E\left[T_j\right]\right) \leq \tau \tag{10}$$

If a link x within L_i wants to transmit $\tau \cdot \lambda$ more L-bit long packets during $(t-\tau, t]$, inequality 10 becomes:

$$\lambda\left(\frac{L}{C_x} + E\left[T_x\right]\right) + \sum_{j \in L_i} \sum_{k=1}^{\infty} \lambda_{j,k} \left(\frac{k}{C_j} + E\left[T_j\right]\right) \leq 1 \tag{11}$$

Setting inequality 11 to 1, we can solve it for $\lambda \cdot L$ to obtain the available bandwidth for link x within spatial channel i, for L-bit long packets. Of course, the true available bandwidth for link x would be the minimum of the available bandwidths it has in each of the channels it belongs to, V_x.

Definition 6. Link Available Bandwidth. The mean available bandwidth in link x during the interval $(t-\tau, t]$ is defined as:

$$E\left[ABW^{link_x}(L)\right] = \frac{L}{\frac{L}{C_x} + E\left[T_x\right]} \left(1 - \max_{i \in V_x} \sum_{j \in L_i} \sum_{k=1}^{\infty} \lambda_{j,k} \left(\frac{k}{C_j} + E\left[T_j\right]\right)\right) \tag{12}$$

Using Equation 7, we recognize that Equation 12 is a direct generalization of Equation 2 for the available bandwidth of a link, where the utilization of the link becomes the maximum utilization among the spatial channels the link belongs to.

Now consider a path within this network, composed of a set of m links $X = \{x_1, x_2, \ldots, x_m\}$. If $\tau \cdot \lambda$ additional L-bit long packets were to be sent over the path in the interval $(t-\tau, t]$, then the new flow is to be added in each channel as many times as links in the path are present within the channel. Correspondingly, the first term in the left sum of inequality 11 must include the new flow in each link of the path within L_i. Writing it down for each link x in the path and each spatial channel i the link x belongs to, the set of conditions in Equation 13 must be met.

for *each* $x \in X$ **do**
  for *each* $i \in V_x$ **do**

$$\lambda \sum_{j \in X \cap L_i} \left(\frac{L}{C_i} + E\left[T_j\right] \right) + \sum_{j \in L_i} \sum_{k=1}^{\infty} \lambda_{j,k} \left(\frac{k}{C_j} + E\left[T_j\right] \right) \leq 1 \tag{13}$$

  end
end

Solving for $\lambda \cdot L$ with equality, we can find the available bandwidth for each link of the path within each spatial channel it belongs to. Taking the minimum bandwidth among the channels, we find the available bandwidth for each link, and taking the minimum among the links, we find the available bandwidth for the path.

Definition 7. End-to-End Available Bandwidth. The mean available bandwidth in a path during the interval $(t-\tau, t]$ is defined as:

$$ABW^{path}(L) = \min_{x \in X} \left\{ \min_{i \in V_x} \left[\frac{L}{\sum_{j \in X \cap L_i} \left(\frac{L}{C_j} + E\left[T_j\right] \right)} \left(1 - \sum_{j \in L_i} \sum_{k=1}^{\infty} \lambda_{j,k} \left(\frac{k}{C_j} + E\left[T_j\right] \right) \right) \right] \right\} \tag{14}$$

Notice again that Equation 14 is a direct generalization of Equation 3. Indeed, in a single spatial channel network, the form it takes is exactly $BW^{path}(L)(1-u^{channel})$.

2.5 IEEE 802.11b example

Consider the case of the IEEE 802.11b DCF multi-access scheme in RTS/CTS mode, in which the time to acquire and release the transmission medium is $T = T_0 + L_0/C + B_o\sigma$, where T_0 is a constant delay (propagation time, control timers, and PLCP transmissions at the basic rate), L_0 is the length of the overhead control information (RTS, CTS, Header, and Acknowledgment), σ is the length of the contention slot, and B_o is a backoff random integer uniformly chosen in the range $[0, W-1]$, where W is the minimum backoff window. If we approximate T as a continuous random variable uniformly distributed in $[T_0 + L_0/C, T_0 + L_0/C + (W-1)\sigma]$, we get from Equation 6 the following distribution for the link bandwidth, $BW^{link}(L)$:

$$f_{BW^{link}(L)}(b) = \begin{cases} \frac{L}{b^2\sigma(W-1)} & if \;\; b \in I_b \\ 0 & \text{otherwise} \end{cases} \tag{15}$$

$$\text{where } \; I_b = \left[\frac{CL}{L + L_0 + C(T_0 + \sigma(W-1))}, \frac{CL}{L + L_0 + CT_0} \right]$$

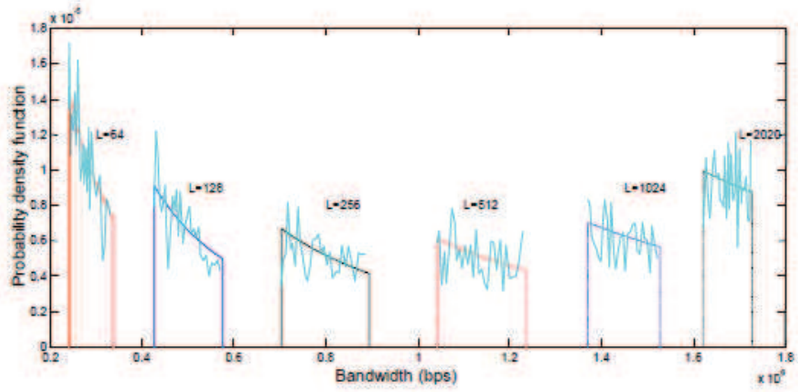


Fig. 2. Bandwidth distribution of a 2 Mbps IEEE 802.11b link.

Figure 2 shows the pdf using a 2 Mbps link as an example with different packet lengths and the corresponding histogram estimations obtained from Qualnet®SNT (2007) simulations.
By direct integration, the average link bandwidth becomes:

$$E\left[BW^{link}(L)\right] = \frac{L}{(W-1)\sigma} log\left(1 + \frac{C(W-1)\sigma}{CT_0 + L + L_0}\right) \tag{16}$$

which can be well approximated as Alzate (2008):

$$E\left[BW^{link}(L)\right] \approx \frac{L}{\frac{L}{C} + \left(\frac{L_0}{C} + T_0 + \frac{W-1}{2}\sigma\right)} \tag{17}$$

as in Equation 7.
Consider now a single channel n-hop path for which the total acquisition and release time will be:

$$T^{ch} = \sum_{j=1}^{n}\left(T_0 + \frac{L_0}{C_j}\right) + \sigma\sum_{j=1}^{n} B_{0_j} \tag{18}$$

where B_{0_j} is the backoff selected by the transmitter of link j, uniformly and independently distributed in the range of integers $[0, W-1]$. Defining X as $\sum_j B_{o_j}$, then T^{ch} becomes:

$$T^{ch} = nT_0 + \frac{L_0}{C^{ch}} + \sigma X \tag{19}$$

where C^{ch} is, according to Definition 3, $1/\sum_{j=1\cdots n} C_j$. Assuming B_o is continuous and uniformly distributed in $[0, W-1]$, for $n > 1$ we can approximate X as a Gaussian random variable with mean $n(W-1)/2$ and variance $n(W-1)^2/12$, in which case the distribution of the spatial channel bandwidth becomes;

$$f_{BW^{ch}(L)}(b) = \frac{L}{\sqrt{2\pi}sb^2} exp\left[-\frac{1}{2}\left(\frac{b - L/m}{sb/m}\right)^2\right] \tag{20}$$

where

$$m = \frac{L + L_0}{C^{ch}} + n\left(T_0 + \sigma\frac{W-1}{2}\right) \tag{21}$$
$$s^2 = n\sigma^2\frac{(W-1)^2}{12}$$

are, respectively, the mean and the variance of $L/C^{ch} + T^{ch}$. Figure 3 shows the probability density functions, given by Equations 15 and 20, that correspond to the bandwidth experienced by a 1024-byte long packet transmitted over a completely available channel of n IEEE 802.11b hops at 2 Mbps, for n in $\{1,2,3,4\}$. The plots are compared with the corresponding normalized histograms obtained through Qualnet®SNT (2007) simulations, and with a Gaussian distribution with mean L/m and variance $(sL/m^2)^2$. Correspondingly, we propose that the bandwidth of an n-hop channel in an IEEE 802.11b path is Gaussian distributed with the following mean and variance, where Equation 22 is to be compared with Equation 9:

$$E\left[BW^{ch}(L)\right] = \frac{L}{\frac{L+L_0}{C^{ch}} + n\left(T_0 + \sigma\frac{W-1}{2}\right)} \tag{22}$$

$$V\left[BW^{ch}(L)\right] = \frac{n}{3}\left[\frac{L\sigma\frac{W-1}{2}}{\left(\frac{L+L_0}{C^{ch}} + n\left(T_0 + \sigma\frac{W-1}{2}\right)\right)^2}\right]^2 \tag{23}$$

Figure 4 shows the mean bandwidth given by Equation 22 for a single channel path composed of several 2 Mbps hops. Although the Gaussian approximation seems to be valid for a multi-hop channel but not for a single hop channel, Equations 22 and 23 seem valid for $n \geq 1$ hops, especially if the interest is in first and second order statistics of BW.

The bandwidth of a multi-hop multichannel path is the minimum of the bandwidths of the constituent spatial channels,

$$E\left[BW(L)\right] \leq \min_i E\left[BW_i(L)\right] = \frac{L}{\max_i\left[\frac{L+L_0}{C_i'} + n_i\left(T_0 + \frac{W-1}{2}\sigma\right)\right]} \tag{24}$$

where C_i' is the capacity of the i^{th} spatial channel in the path and n_i is the number of spatial channels.

Finally, as an illustration of the ABW concept, consider the two 2-hop ad hoc paths made of 2 Mbps IEEE 802.11b nodes, as shown in Figure 5. Node 5 routes data traffic between nodes 3 and 4 consisting of L_3-bit long packets at λ_3 packets per second. In order for nodes 1 and 2 to communicate, they must use node 5 as an intermediate router. Figure 6(a) plots the bandwidth of the 1-5-2 path, $E[BW(L_1)]$, as a function of the packet length used by node 1, $L_1/8$ bytes, and Figure 6(b) shows the fraction of available bandwidth, $E[ABW(L_1)]/E[BW(L_1)]$ (which, according to Equation 14 does not depend on L_1), as a function of the cross-traffic data rate, $\lambda_3 L_3$, and the cross traffic packet length, $L_3/8$ bytes.

For example, if node 1 transmits $L_1 = 4096$-bit long packets, Figure 6(a) says that the path could carry up to $\lambda_1 L_1 = 565.2$ kbps if there were no competition. However, if node 3 is generating packets of $L_3 = 8192$ bits at $\lambda_3 L_3 = 400$ kbps, Figure 6(b) says that only 44.6% of the bandwidth would be available for other users, in which case the available bandwidth for the 512-byte packets on the path 1-5-2 would only be 252 kbps.

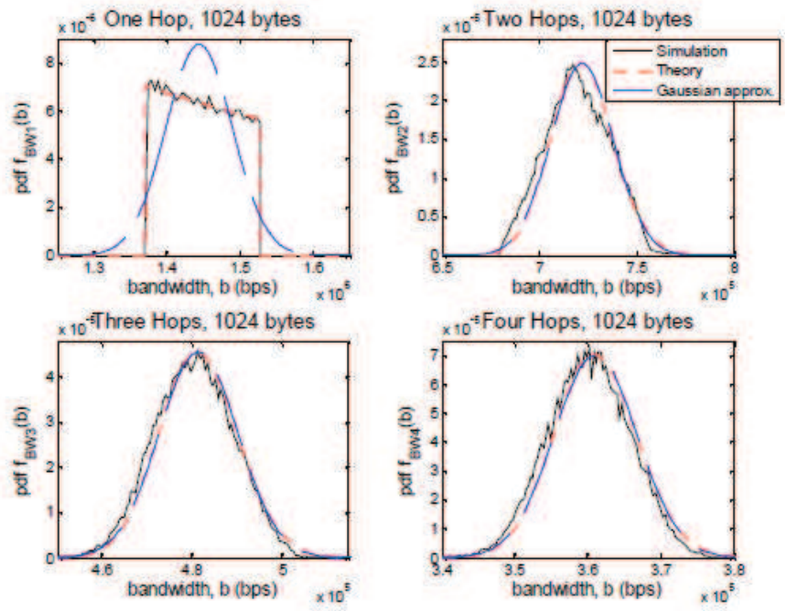


Fig. 3. Comparison of Equations 15 and 20 with QualNet®simulations and the proposed Gaussian approxin

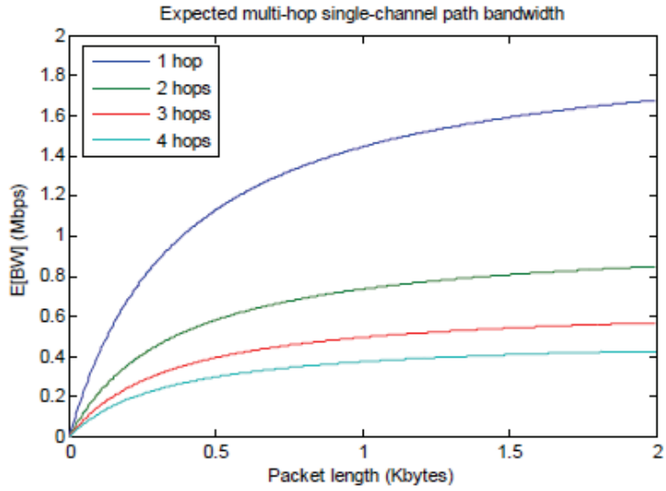


Fig. 4. Expected BW of a multi-hop channel path.

3. End-to-end mean bandwidth estimation as a function of packet length in multi-hop IEEE 802.11b ad hoc networks

It is important to have accurate and timely end-to-end capacity estimations along a multi-hop path for such important applications as source rate adjustment, admission control, traffic engineering, QoS verification, etc. Several methods have been proposed for BW and ABW estimation in wireless ad hoc networks, especially associated with resource constrained routing Chen & Heinzelman (2005); Guha et al. (2005); Xu et al. (2003) and/or QoS architectures Ahn et al. (2002); Chen et al. (2004); Lee et al. (2000); Nahrstedt et al. (2005). However, these methods depend on the particular routing algorithm and use inaccurate estimators. It would be highly convenient to have an end-to-end estimation tool at the

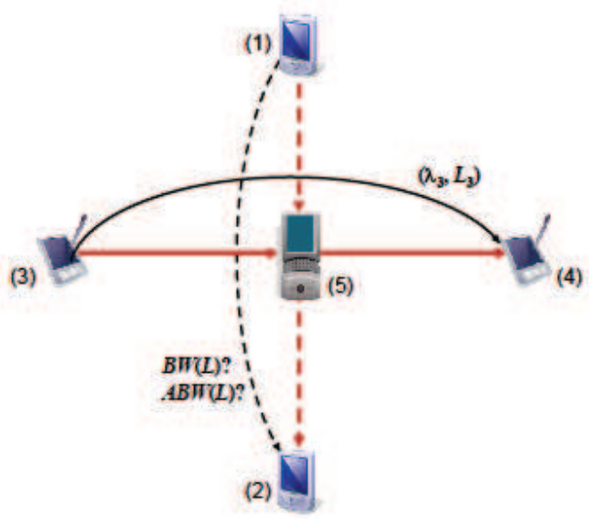
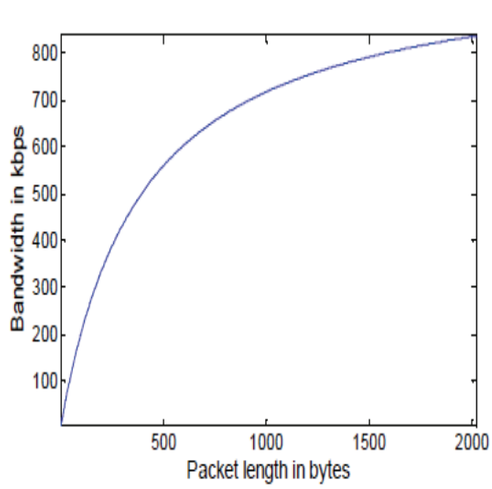
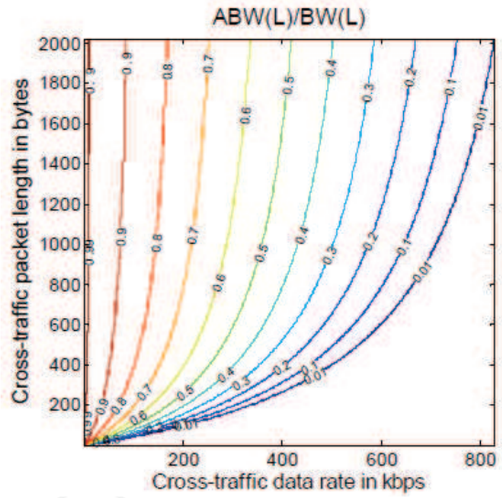


Fig. 5. A simple example to compute BW and ABW.



(a) Bandwidth of a two-hop path.



(b) Fraction of $BW(L)$ still available to the path 1-5-2 when the path 3-5-4 carries a given data rate (horizontal axis) using packets of given length (vertical axis).

Fig. 6. Bandwidth and fraction of available $BW(L)$.

application layer that does not rely on any lower layer assumptions. Ad Hoc Probe Chen et al. (2009), a simple and effective probing method that achieves high accuracy, satisfies these requirements. However, it uses a fixed packet length and returns a sample of the BW associated with that packet length, as if it were constant. In this section we devise a packet pair dispersion method that obtains several samples of BW and use them to estimate the variation range in order to give some confidence intervals for their mean. Our method is fundamentally based on Ad Hoc Probe principles, but we extend it to consider BW as a packet length dependent random variable. We also evaluate the performance of the method in terms of accuracy, convergence speed, and adaptability to changing conditions.

3.1 Measuring procedure

According to Equation 9, the BW experienced by a single packet of length L that finds all path resources completely available, has the form:

$$BW = \frac{L}{\alpha L + \beta} \tag{25}$$

where $\alpha L + \beta$ is the time it takes the packet to traverse the narrowest link in the path. In a single link, for example, $\alpha = 1/C$ is the cost, in seconds, for transmitting a data bit over the link, while $\beta = E[T]$ is the additional cost, in seconds, for transmitting a whole packet, independent of its length. In Equation 9, $\alpha = \sum_{j=1}^{n_i} 1/C_{i,j}$ is the inverse of the capacity of the narrow spatial channel, i, which corresponds to the cost, in seconds, of transmitting one bit over the i^{th} spatial channel, where $C_{i,j}$ is the bit transmission rate of the j^{th} link of the i^{th} spatial channel. Similarly, $\beta = \sum_{j=1}^{n_i} E[T_{i,j}]$ is the sum of the acquisition and release times on each link of the i^{th} spatial channel, the narrow one.

According to Equation 25, if it is possible to estimate $\alpha L + \beta$, the time it takes an L-bit packet to traverse the narrow spatial channel, it would be also possible to estimate the path bandwidth for the given packet length, L. The one way delay (*owd*) would be an appropriate measure of $\alpha L + \beta$ if the path is within a single link channel, but, in any other case, *owd* could be different than $\alpha L + \beta$. Indeed, we can send a pair of back-to-back equal-length packets and measure the interarrival time at the destination as an estimation of $\alpha L + \beta$ but, even in a completely available multi-hop wireless path, there could be scheduling differences that may lead to wrong estimations, as shown in Figure 7 for a two-link channel. The inter-arrival gap at the receiver in the second schedule of Figure 7, corresponding to the minimum *owd* of each individual packet reveals the real value of $\alpha L + \beta$, but the corresponding measure in the first schedule will underestimate $\alpha L + \beta$.

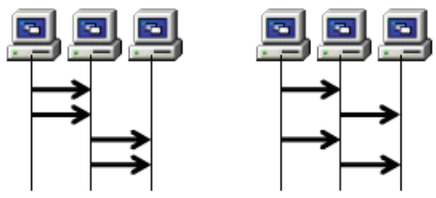


Fig. 7. Two possible schedules for sending two packets on a two-hop path.

In AdHocProbe Chen et al. (2009), the transmitting node sends several back-to-back L-bit long probing packet pairs in order to select the single pair in which each packet suffered the minimum *owd*, and use the gap between them to estimate $\alpha L + \beta$. If the procedure is repeated for a longer (or smaller) packet length, two points in the curve $BW(L)$ of Equation 25 will be obtained, from which the two unknown parameters, α and β, can be estimated. With these parameters, it is possible to interpolate the whole curve for the total range of allowed packet lengths.

Indeed, if the gaps G_0 and G_1 corresponding to the packet lengths L_0 and L_1 can be measured, it would be easy to find α and β, as follows:

$$\begin{bmatrix} \alpha \\ \beta \end{bmatrix} = \begin{bmatrix} L_0 & 1 \\ L_1 & 1 \end{bmatrix}^{-1} \begin{bmatrix} G_0 \\ G_1 \end{bmatrix} = \begin{bmatrix} \frac{G_1 - G_0}{L_1 - L_0} \\ G_0 - \frac{G_1 - G_0}{L_1 - L_0} L_0 \end{bmatrix} \tag{26}$$

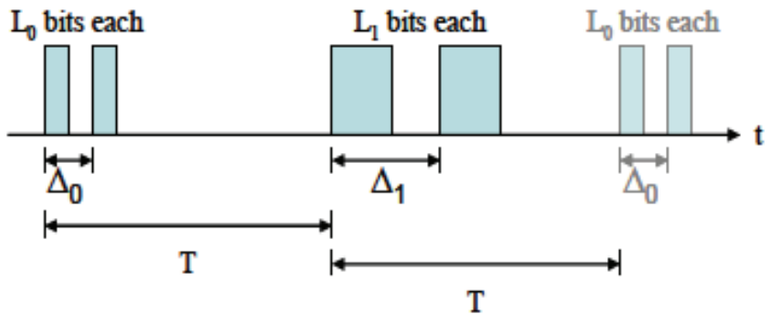


Fig. 8. Probing traffic pattern.

In order to compute Equation 26, the probing traffic will take the form shown in Figure 8. The value of the parameters L_0, L_1, T, Δ_0, and Δ_1 should be selected according to the network environment. In this paper, an IEEE 802.11b network with pedestrian users was used, for which the following parameters were used: $L_0 = 1024$ bits (128 bytes), $L_1 = 11200$ bits (1400 bytes), and $T = 0.25$ seconds. Although Δ_0 and Δ_1 can be adaptively selected to reduce self-interference in an unloaded multi-hop path, in this paper just back-to-back packet pairs were used.

The compromise between adaptability and accuracy is handed by using a window-based analysis. The pairs received during a t-seconds time window will be considered, during which, for each packet length L_0 and L_1, the one way delay of each packet will be measured, and the sum of one way delays of each packet pair, $sowd$, in order to record the minimum $sowd$, $sowd_{min}$. Within the window, those dispersion measurements with $sowd \leq sowd_{min} + (W-1)\sigma$ will be considered as valid realizations of the random variable $\alpha L + \beta$. Clearly, the longer the window length, t, the higher the confidence on the mean BW, and the smaller the window length, the higher the adaptability to changing conditions. Additionally, with several samples, confidence intervals can be found or estimates of the range of BW values, although in this paper only estimates of the mean end-to-end BW will be considered.

An important issue with the mentioned procedure is clock synchronization between transmitter and receiver. Of course, in a simulated environment there is a unique clock system, but in a real implementation, this problem affects dramatically the measurements.

Assume the receiver clock (t_{rx}) and the transmitter clock (t_{tx}) are related as $t_{rx} = (1+a)t_{tx} + b/2$, where there is both a drift term $(1+a)$ and a phase term $(b/2)$, and consider the time diagram of Figure 9, where $td_0^{'}$ and $td_1^{'}$ are the departure times of a pair of packets stamped at the transmitter, ta_0 and ta_1 are the arrival times registered at the receiver, and td_0 and td_1 are the (unknown) departure times according to the receiver's clock.

The correct sum of one way delays would be $sowd_c = (ta_0 - td_0) + (ta_1 - td_1)$, but the measured one would be $sowd_m = (ta_0 - td_0^{'}) + (ta_1 - td_1^{'}) = sowd_c + a(td_0^{'} + td_1^{'}) + b$. This linear tendency can be appreciated by plotting the measured sum of one way delays versus the measuring time, ta_1, as shown in the blue continuous line of Figure 10, corresponding to real measurements on a testbed. Dividing the analysis window in four subwindows, it is possible to compute a least mean square error linear regression on the minimum sowd of those windows, as shown in the diamond marked red dashed line of Figure 10. This linear tendency is subtracted from $sowd_m$ to obtain a new measure, $sowd_m^{'} = sowd_c + c$, where the constant c does not affect the computation of the minimum $sowd$, as shown in the black dotted line.

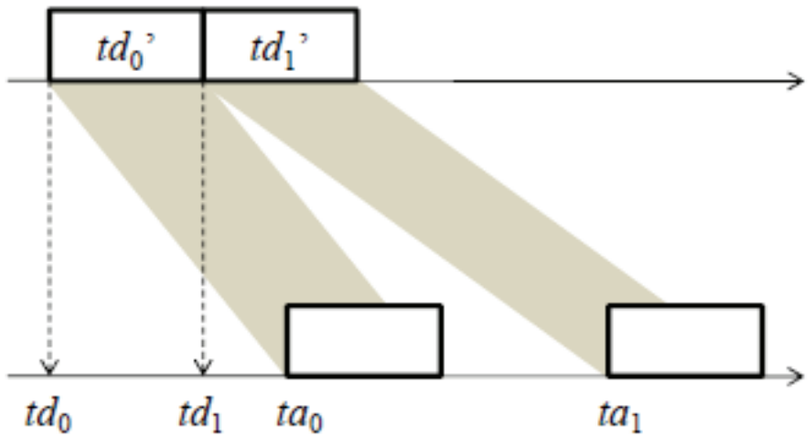


Fig. 9. Time incoherence between transmitter an receiver clocks.

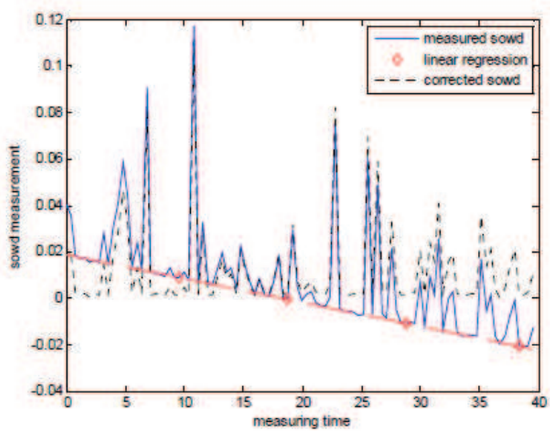


Fig. 10. Correction of clock incoherence through linear regression. Both axis are in seconds.

3.2 Numerical results

QualNet®SNT (2007) was used to evaluate the estimation procedure through simulation experiments using the default physical, MAC, AODV, IP, and UDP parameter values for a 2 Mbps IEEE 802.11b ad hoc network. Figure 11 shows the estimation results using the network shown in Figure 1. The mean BW converges quickly to the theoretical value even for windows of only 5 seconds, while the 99% confidence intervals decrease similarly fast, although with longer windows, since they require several valid samples. The 90 seconds results are identical to the corresponding theoretical values of Equation 22, previously shown in Figure 4.

The above encouraging results are obtained without considering additional traffic or mobility. The effects of these characteristics and, consequently, the adaptability of the protocol, are considered in the scenario shown in Figure 12. This scenario consists of a 5×5-grid of fixed nodes 300 m away from each other and a 26^{th} node moving around on a spiral trajectory at a speed of 2 m/s. There are two VBR flows of 50 kbps each, one from node 6 to node 10 and another one from node 16 to node 20. The bandwidth of the path between nodes 1 and 26 is to be estimated.

Figure 13 shows the estimated mean bandwidth as a function of time for each packet length when the measurement time window is 30 seconds. Notice how easy is it to detect route

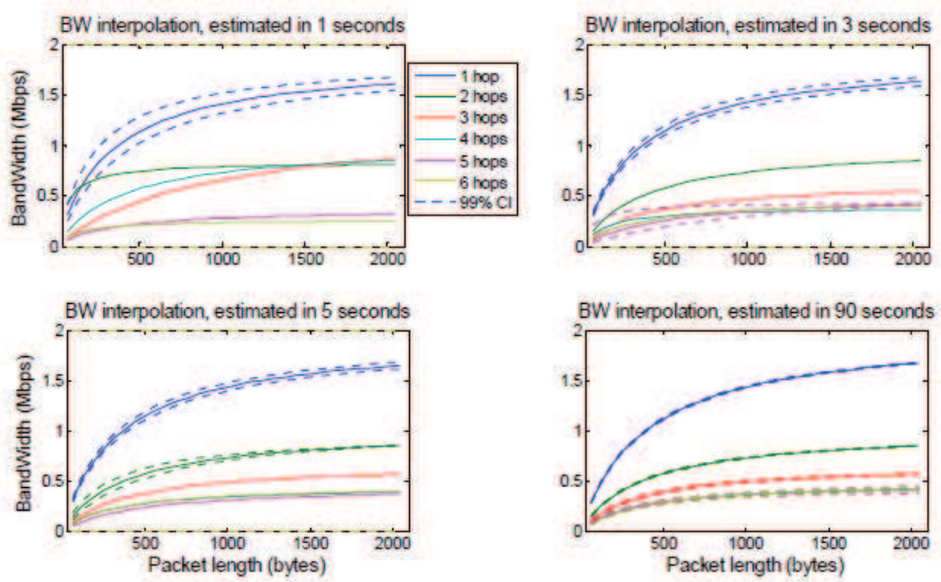


Fig. 11. Convergence speed in absence of cross traffic.

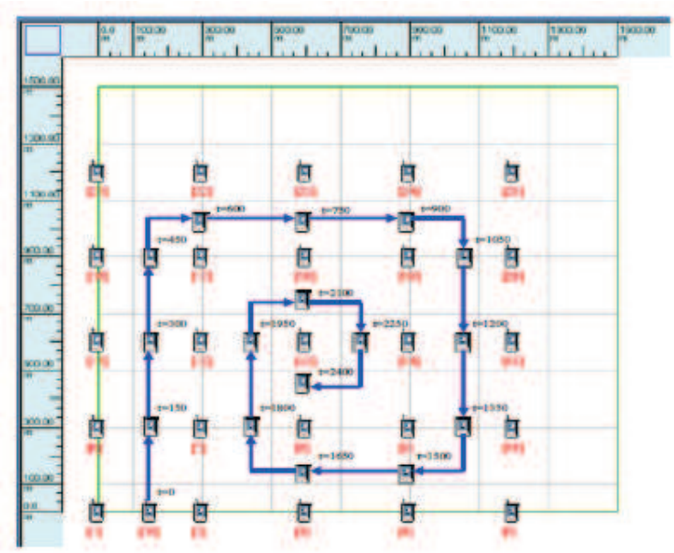


Fig. 12. Mobility scenario for adaptability test.

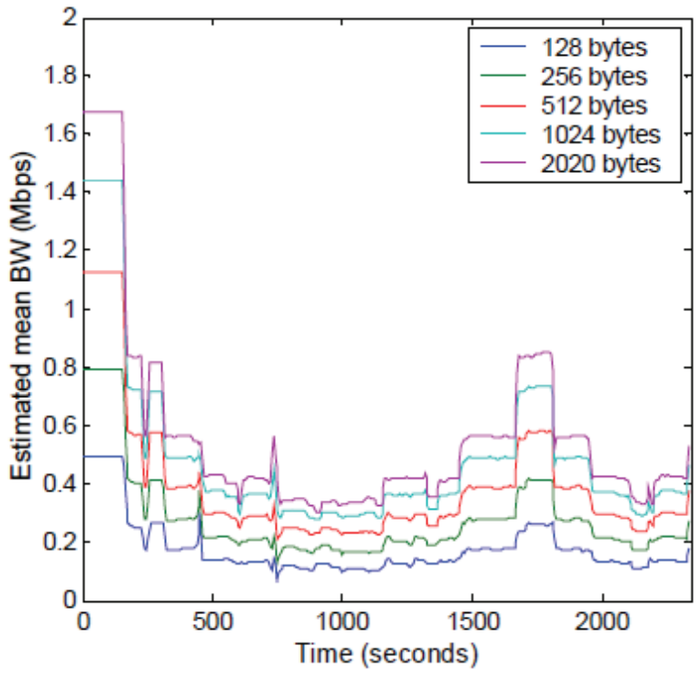


Fig. 13. Mean BW estimation under mobility.

breakdown and reestablishment epochs by inspecting Figure 13. These results show that, as long as the durations of the routes are in the order of several tens of seconds and the network is not highly loaded, the estimation scheme can offer high precision and good adaptability.

4. End-to-end available bandwidth estimation in multi-hop IEEE 802.11b ad hoc networks

In this section, the active probing technique that estimates the bandwidth (BW) of an end-to-end path in an IEEE 802.11b ad hoc network, shown in Section 3, is incorporated into a new neuro-fuzzy estimator to find the end-to-end available bandwidth, for which the theoretical definition of Equation 14 is an upper bound. The gaps between those pairs of packets that suffer the minimum sum of one-way delays are used to estimate the maximum achievable transmission rate (BW) as a function of the packet length, for any packet length, and then the variability of the dispersions is used to estimate the fraction of that bandwidth that is effectively available for data transmission, also as a function of packet length. However, instead of the perfect-scheduling and no-errors approximation of Equation 14, we consider implicitly all the phenomena that jointly affect the truly available bandwidth and the dispersion measures, using a neuro-fuzzy identification system to model their dependence. For example, even in the absence of competing flows, there can be self interference when consecutive packets of the same flow compete among them on different links of the same spatial channel within the path. Furthermore, cross-traffic can do more than taking away some BW of the path by interacting through MAC arbitration, as it can also reduce the signal-to-noise ratio at some parts of the path, or can even share some common queues along the path. Another largely ignored aspect that is indirectly captured by the neuro-fuzzy system is the fact that, once the unused BW is to be occupied, the arrival of the new flow can re-accommodate the occupation pattern along the neighborhood of its path.

In order to consider all these interacting aspects, the neuro-fuzzy estimator is trained on data collected from a large set of simulated scenarios, for which Qualnet®SNT (2007) is used. The scenarios were carefully selected to have enough samples of each of the effects mentioned above, and combinations of them, over a wide range of configuration parameters, so as to get a representative set of data for training, testing, and validation purposes. With all these data, the estimator learns how to infer the available bandwidth from the variability of the dispersion traces. The system is designed so as to have good generalization properties and to be computationally efficient. As a result, an accurate, efficient, and timely end-to-end available bandwidth estimator is obtained.

4.1 Practical ABW

The definition of ABW above (Equation 14) is an extended version of the widely accepted concept of unused capacity of the tight link. But in wireless multi-hop ad hoc networks this unused bandwidth can differ from the additional achievable transmission rate because, due to interference, the unused capacity may not be completely available. Indeed, once a new flow is established in the given path to occupy some of that unused capacity, the interfering cross-traffic can re-accommodate itself in response to the new flow, changing the perception of the new flow about its available bandwidth. So, it is tempting to define a practical ABW as the throughput achieved by a saturated source. However, due to self interference, a saturated node could reduce its throughput far below of what a less impatient source might obtain. Another practical ABW could also be defined as the maximum achievable transmission rate that does not disturb current flows, but this is a very elusive definition because, due to the interactions in the shared medium, even a very low rate new data flow could affect current flows.

Accordingly, an additional reasonable practical definition of ABW is the maximum throughput achievable by a CBR flow in the path, where the maximization is performed over the range of input data rates. Although, intuitively, this definition makes better sense, it is the most unfriendly for estimation purposes, because it requires the estimator to explore different transmission rates in order to find the one that maximizes the throughput. However, instead of doing this process on-line, it is possible to collect accurate and representative data to feed a machine learning process that would relate the statistics of the packet pair dispersion measures with the true maximum achievable rate in the path. First, an experiment to measure the probing packet dispersions is conducted and, then, the same experiment is replicated to measure the available bandwidth as the maximum achievable throughput. Then the ratio between the maximum achievable throughput and the bandwidth is computed (the "availability", $x = ABW/BW$), in order to relate it to the variability of the dispersion measures. The underlying hypothesis is that, since the probing packet pair dispersions are affected by the same phenomena that determines the current ABW, the costly search of an optimal input rate can be avoided if it can be inferred from the statistics of the dispersion trace. So, our definition of ABW would be given as follows:

$$ABW(L) = \max_{\lambda>0} \left[\lim_{t\to\infty} \frac{n(t;\lambda)L}{t - t_1} \right] \tag{27}$$

where L is the length, in bits, of the transmitted packets, $n(t;\lambda)$ is the number of packets received up to time t when they are sent at a transmission rate of λ packets per second, and t_1 is the reception time of the first received packet. To evaluate Equation 27 experimentally, a large number (1000) of packets is sent at the given rate λ. If the receiver gets less than 25% of the

transmitted packets, the loss probability is considered too high and the available bandwidth is set to zero for that input rate. Otherwise, the throughput for this rate is computed as $\Gamma(L;\lambda) = (n-100)L/(t_n - t_{100})$, where n is the last received packet, which arrived at t_n. The first 100 received packets are considered part of a transient period. Then, through bracketing, the value of λ that maximizes Γ is found, which becomes our practical $ABW(L)$. Since it is possible to keep constant conditions in the experimental scenarios, this procedure gives a very accurate measure of ABW.

It is interesting to notice the relationship between Equations 14 and 27. In a wired network, they are supposed to be the same, where Equation 27 is oriented to a self-congesting estimation procedure while Equation 14 is oriented to a packet pair dispersion measure. Indeed, Equation 28 shows two "equivalent" definitions of ABW in the period $(t-\tau, t]$ for a single link of capacity C bps that serves a total traffic of $\lambda(s)$ bps at instant s, widely accepted as equivalent Prasad et al. (2003).

$$\begin{aligned} ABW(t-\tau,t) &= \frac{1}{\tau}\int_{t-\tau}^{t}(C-\lambda(s))ds \\ &= \arg\max_{R}\left(R \mid R + \frac{1}{\tau}\int_{t-\tau}^{t}\lambda(s)ds < C\right) \end{aligned} \tag{28}$$

However, from previous discussion, it is clear that they can be different in wireless ad hoc networks. In this section, the work is aimed at designing a system capable of learning, from sample data, the intricate relations between ABW, as defined in Equation 27, and dispersion measurements. So, a representative set of data must be collected in order to determine whether the dispersion measurements carry enough information for a significant estimation of ABW or not. If that is the case, that data could be used to train a neuro-fuzzy system.

4.2 Data collection and preprocessing

With the procedure described above, it is possible to collect a large data set that relates the dispersion measurements of the active probing packet pairs with the corresponding ABW on different scenarios. The data set must reflect the most important features of the underlying characteristics of any IEEE 802.11b ad hoc network, which include the interaction between competing flows by buffer sharing, by MAC arbitrated medium sharing, by capture effects or, simply, by increased noise.

All these aspects of the dynamic behavior of an IEEE 802.11b ad hoc network (and their combinations) are captured using the network configuration shown in Figure 14, where different parameters can be changed in order to explore a wide range of cross-traffic interference conditions. In the experiments, we varied the value of the distance between nodes (from 50 to 300 m), the physical transmission rate (1, 2 and 11 Mbps), the use of RTS/CTS mechanism, the number of cross-traffic flows (from 1 to 8), the origin and destination of each cross-traffic flow (uniformly distributed among the nodes), the transmission rate of each cross-traffic flow (from 50 kbps to 200 kbps), the packet length of each cross-traffic flow (64, 100, 750, 1400 and 2000 bytes), and the buffer size at the IP layer (50, 150 and 500 kbytes).

For each condition, the ABW between each of the 21 pairs of nodes of the second row was found, for four different packet lengths (100, 750, 1400 and 2000 bytes), averaged over 10 independent simulations. Then each experiment was replicated to take a dispersion trace of probing traffic for each measured ABW. This way 6000 samples were obtained, where each sample consisted of a traffic dispersion trace, a

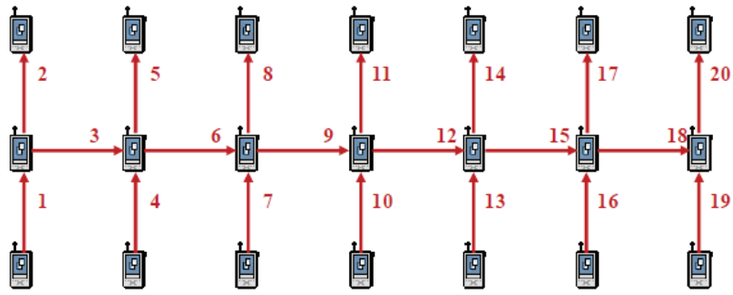


Fig. 14. Test scenario for data collection.

corresponding $BW(L)$ function, and four measured availabilities for four different packet lengths, $\{x(L_i) = ABW(L_i)/BW(L_i), i = 0 \ldots 3\}$.
The traffic dispersion trace represents a huge amount of highly redundant data, from which the set of statistics that brings together most of the information about the availability $x(L)$ contained in the whole trace must be selected.
The traces were grouped in analysis windows of 200 packet pairs, overlapped every 4 pairs and, for each analysis window, the following statistics of the dispersion trace for the two probing-packet lengths, L_0 and L_1 were measured:

$\theta_1(L_i) =$ mean of the gap between packets of a pair of L_i-bit packets
$\theta_2(L_i) =$ standard deviation of the gap between packets of a pair of L_i-bit packets
$\theta_3(L_i) =$ mean of the *sowd* (sum of one way delays) of a pair of L_i-bit packets
$\theta_4(L_i) =$ standard deviation of the *sowd* of a single pair of L_i-bit packets

where, in each analysis window, the gaps and *sowds* are centered and normalized with respect to the gap between the packets that suffered the minimum *sowd*, in order to get comparable magnitudes over different network conditions. The vector of eight input parameters will be denoted as θ, while the vector of four input parameters corresponding to a given packet length L will be denoted a $\theta(L)$.
Figure 15 shows the probability density functions (pdf) of each component of $\theta(L)$ within the collected data for $L_1 = 1400$ bytes, conditioned on a low or high availability, where similar results hold for $L_0 = 100$ bytes. A low availability tends to increase the values of the parameters and disperse them over a wider range, as compared to a high availability. These remarkable differences in the conditional probabilities indicate the existence of important information about the availability $x(L)$ contained in this set of statistics, so the later can be used to classify and regress the former. It is this discrimination property what is to be exploited in the available bandwidth estimator.

4.3 Neuro-fuzzy system design

First, a fuzzy clustering algorithm is used to identify regions in the input space that show strong characteristics or predominant phenomena. Then, the clustered data is used to train simple neural networks, which can easily learn such phenomena. The local training data is selected through alpha-cuts of the corresponding fuzzy sets, and the antecedent membership functions are used to weight the outputs of the locally expert neural networks, according to the following simple rules:

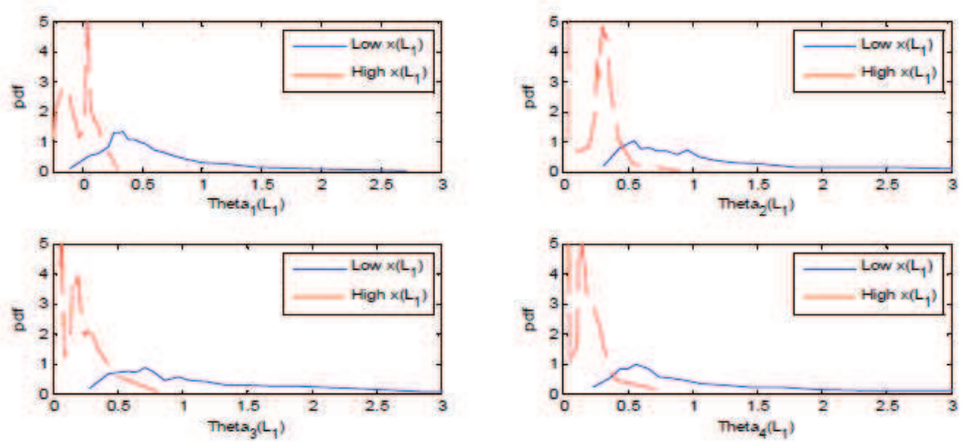


Fig. 15. Probability density functions of the measured statistics conditions on a high or low availability.

if θ *is in cluster* j **then**
| $x(L_i) = \text{neuralnet}(i, j)$
end

A large number of clusters can give a high accuracy at a cost of a high computational complexity. Since the efficient use of computational resources is an important requirement for ad hoc wireless networks, two neural networks were locally trained on two different subsets of the input data. The local data was selected through a fuzzy c-means clustering algorithm on the whole set of input parameters. This choice leads to good regularity and generalization properties and a good compromise between bias and variance errors, while keeps a low computational complexity. The global model takes the following form

$$\hat{x}(L_i) = f_i(\theta \mid r_1)\mu_{r_1}(\theta) + f_i(\theta \mid r_2)\mu_{r_2}(\theta) \tag{29}$$

where $f_i(\theta \mid r_j)$ is the output of the locally expert network for L_i-bit packets in the j^{th} region, and $\mu_{r_j}(\theta)$ is the membership function of the set of input parameters in the j^{th} cluster. The neuro-fuzzy estimator, shown in Figure 16, estimates the availability for four different packet lengths (100, 750, 1400 and 2000 bytes).

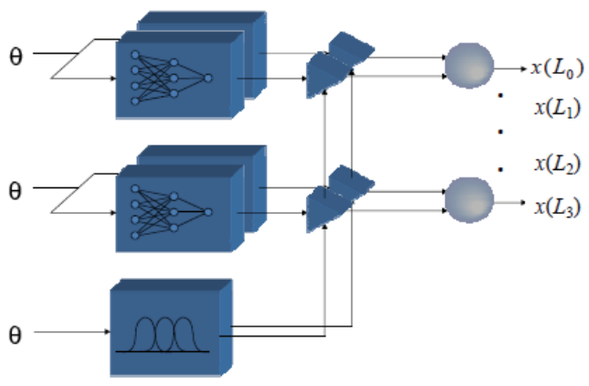


Fig. 16. Structure of the neuro-fuzzy estimator.

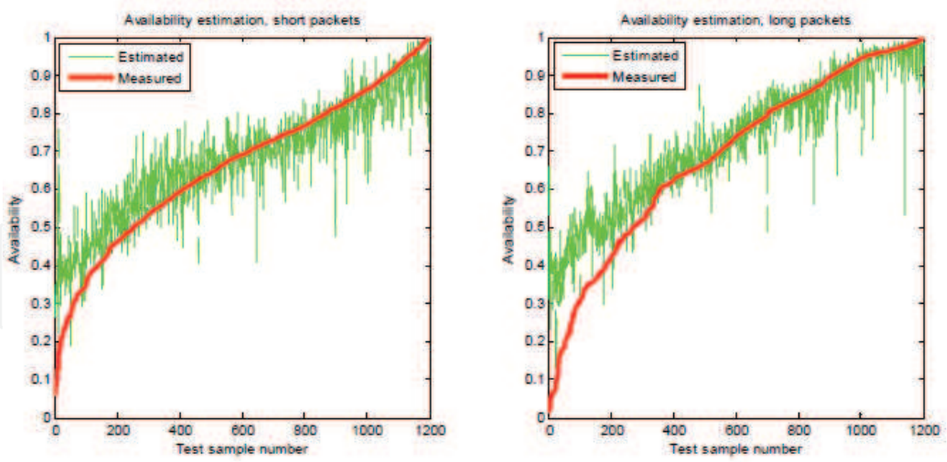


Fig. 17. Availability estimation on the test trace (data not seen by the system during training).

Locally trained submodels increased significantly the learning capacity of the whole system, as can be appreciated in Figure 17, which shows the final estimation results on the collected test data using the following settings: small packet size $L_0 = 100$ bytes, large packet size $L_1 = 1400$ bytes, time between pairs $T = 0.25$ seconds, analysis window size $W = 320$ packets. It can be noticed that, unless the network is heavy loaded, the estimation is highly accurate. Indeed, the accuracy is within 15% for more than 80% of the test samples (which were never seen during training) and, within 10% for more than 90% of the samples with availability greater than 0.5.

Having $BW(L)$ and four samples of the availability $x(L)$, $ABW(L)$ can be interpolated as a function of packet length by adjusting some appropriate functional form. In particular, if the ratio of lost packets is low, a form similar to Equation 25 should be selected, but if there is a high ratio of lost packets, it is assumed that longer packets have more chance to become corrupted. Consequently, the functional form of the ABW is assumed to be

$$ABW(L) = \alpha \cdot BW(L) \cdot \exp(-\lambda L) \tag{30}$$

It is possible to fit the function above to minimize the mean square error with the estimated ABW for the four test packet lengths, as obtained from the neuro-fuzzy estimator, which will allow an interpolated estimate for any packet length.

4.4 Numerical evaluation

Many validation experiments were conducted with several scenarios using different network sizes, mobility conditions, data transmission rates, cross traffic intensities and configuration parameters, all of them with very good results. We present here the experiment shown in Figure 18, where the available bandwidth between nodes 1 and 2 is to be found. The nodes are in a 1100×500 m area. All nodes transmit at 2 Mbps and use the RTS/CTS mechanism. Node 1 moves along the dotted trajectory at a constant speed of 2 m/s. Figure 18 shows some intermediate positions of node 1, requiring a path with one, two, three, and four hops. The link between nodes 3 and 4 carries a cross-traffic VBR flow that sends 2000-byte packets at an average rate of 750 Kbps. The results of the probing packet dispersion analysis are shown in Figure 19, where they are compared with the true available bandwidth, obtained by looking

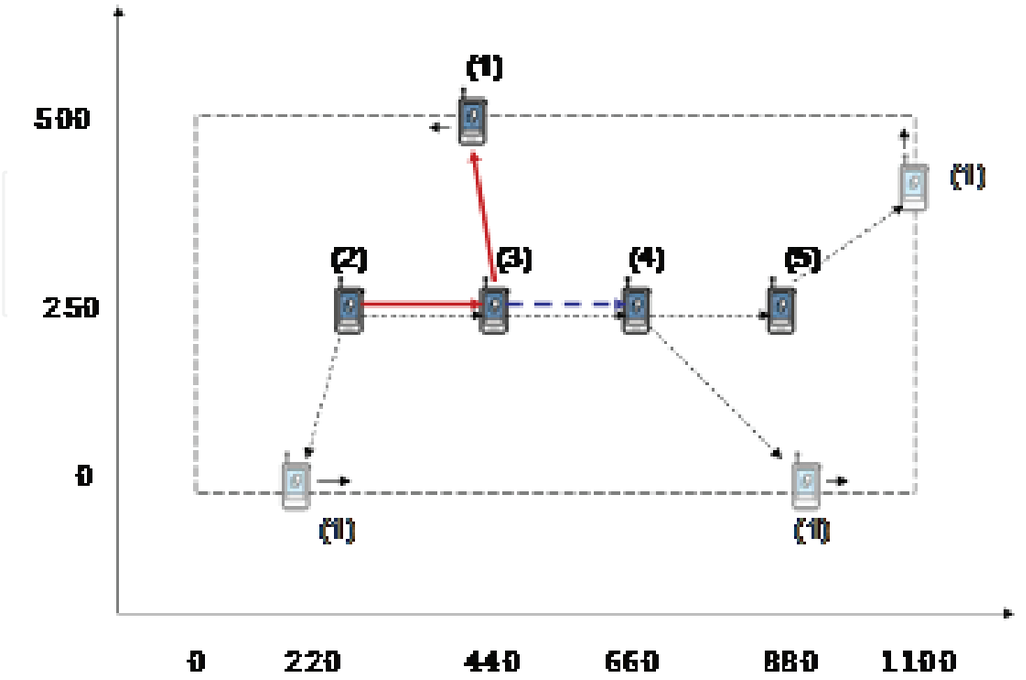


Fig. 18. Mobility scenario for testing the estimation method.

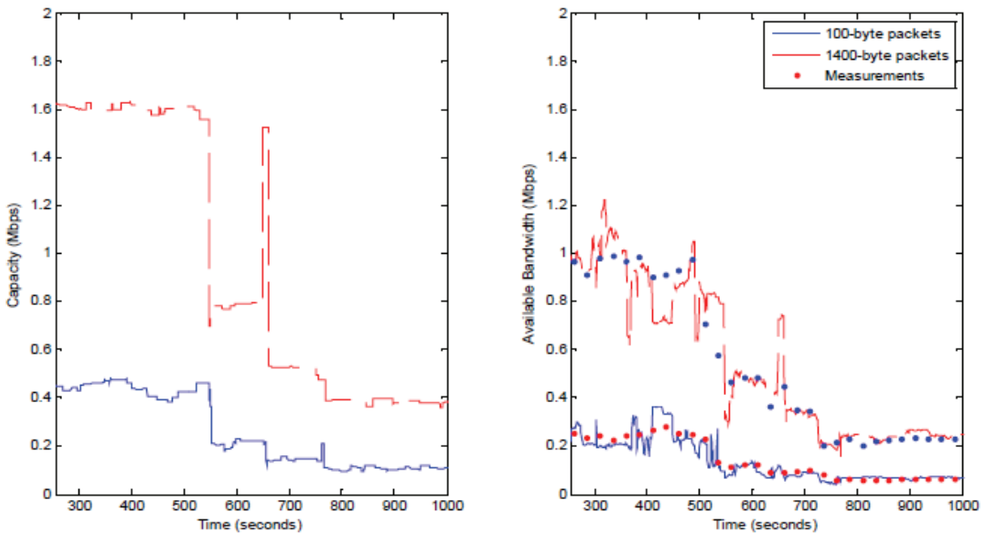


Fig. 19. Bandwidth and available bandwidth in the scenario of Figure 18.

for the maximum achievable throughput at different positions. Notice the high accuracy of the estimation and the detailed resolution of the ABW trace. This resolution is achieved by advancing 320-packet analysis windows every 8 packets. Under no losses, this is equivalent to obtaining, every second, the average ABW on the past 40 seconds.

5. Conclusions

In this paper we present new definitions of capacity (C), bandwidth (BW), and available bandwidth (ABW) for wireless ad hoc networks based on the concept of a spatial channel as the unit of communication resource, instead of the concept of a link, which is not clearly defined in this type of networks. The new definitions are natural extensions of the widely accepted ones in the sense that they become identical if each spatial channel was composed of a single link with no multi-access overhead, as in a point-to-point wired network. We verify the validity of these new definitions in the case of IEEE 802.11b ad hoc wireless networks, where the definitions become close upper bounds of the measured quantities under the assumption of perfect scheduling and no errors.

Then we present and evaluate an estimation procedure for the capacity and the bandwidth of an IEEE 802.11b multi-hop ad hoc path, according to the newly proposed definitions. The procedure is based on an active probing scheme that considers BW as a packet length dependent random variable. The pairs of packets that suffer the minimum delay are used to estimate the BW for two different probing packet lengths, and then the parameters of the functional form of BW are estimated, among which one parameter is the path capacity, C. Finally, the variability of the dispersion trace is fed to a neuro-fuzzy system in order to estimate the practical maximum throughput obtained over the range of input data rates. The theoretically defined ABW is an upper bound of the estimated quantity, obtained under the assumption of no transmission errors and no collisions. However, the estimation takes implicitly into account all the phenomena that jointly affects the variability of the dispersion trace and the maximum achievable transmission rate, including collisions and transmission errors, which are omitted in the theoretical definition of ABW as the unused BW.

We evaluate the performance of the estimation methods in terms of accuracy, convergence time, and adaptability to changing conditions, finding that they provide accurate and timely estimates in an efficient way, in terms of the use of both radio and computational resources.

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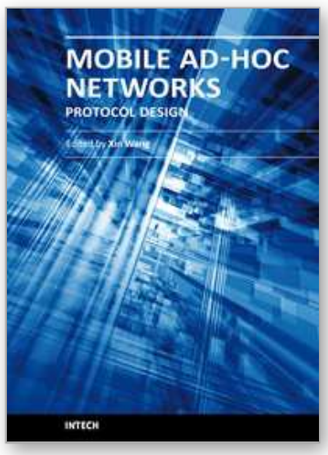
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