Estimation of the Effective Throughput in 802.11b WLAN Networks

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Abstract: **Reliable model of the attainable throughput in IEEE 802.11b WLAN is needed to facilitate capacity planning and network deployment. In this paper an approximate analytical formula for calculating effective throughput of 802.11b devices, as a function of a number of competing stations for different sizes of transmitted packets has been proposed. Using this formula WLAN network administrator can estimate the throughput capacity of single access point (AP) shared between multiple wireless stations with sufficient accuracy. The proposed method has been evaluated by experimental results.**

1. INTRUDUCTION

In recent years, IEEE 802.11b Wireless Local Area Networks (WLAN) has emerged as a prevailing technology for the high bandwidth wireless access in limited geographical area for the mobile/portable devices. While allowing for transmission speeds of up to 11Mb/s in the 2.4 GHz ISM band, it has become widely implemented WLAN technology by many manufacturers and customers. The throughput effectively perceived by mobile hosts in WLAN becomes increasingly important as many new emerging applications such as: mobile information access, real-time multimedia communications, networked games, cooperative work, videoconference impose high bandwidth requirements. An approximate model of the attainable throughputs in such WLANs is needed to facilitate capacity planning and network deployment [2] [13] [12] [11].

This paper presents analytical and experimental, characterization of the instantaneous throughput of a station in an IEEE 802.11b WLAN as a function of the number of competing stations sharing an access point (AP). The main contribution of this paper is the proposal of approximate formula for calculating effective throughput of 802.11b devices, as a function of a number of competing stations for different sizes of transmitted packets. Using this formula WLAN network administrator can estimate the throughput capacity of single AP shared between many wireless stations with sufficient accuracy. In this paper we validate the analytical expression with measurement results.

The 802.11b WLAN network physical layer supports multiple transmission rates. Physical layer rate to be used for transmission of particular frame is solely determined by transmitting station (STA). Performance of the WLAN network will be affected by signal strength and degradation in signal quality due to such factors as STA mobility, time - varying interference, and location-dependent errors. In order to maximize the system throughput Adaptive Rate Selection (ARS) may be invoked. Current 802.11b products degrade the bit rate in steps from the nominal 11Mb/s to 5.5Mb/s, 2Mb/s or 1Mb/s when repeated unsuccessful frame transmissions or degradation in received signal strength are detected [1][5]. We study the performance of an 802.11b WLAN BSS (Basic Service Set) in the infrastructure mode, i.e., when a number of stations are associated with a single AP at nominal bit rates of 11Mb/s or 5.5Mb/s.

This paper is organized as follows: Section 2. briefly explains the DCF method of IEEE 802.11b MAC protocol with basic assess mechanism. In Section 3., we propose analytical formula for approximate calculation of effective throughput experienced by host. The network topology used for experiments describes Section 4. Section 5 validates analytical and measurement results. The impact of different sizes of transmitted files on overall throughput is analyzed in Section 6.

2. ACCESS METHODS IN IEEE 802.11b WLAN

The IEEE 802.11b standard defines a fair access to the shared wireless medium through two different access mechanisms: a mandatory contention-based access protocol, called the Distribution Coordination Function (DCF) and an optional polling-based access protocol, called the Point Coordination Function (PCF) providing uncontested access via arbitration by a Point Coordinator, which resides in the AP. The DCF method provides a best effort type of service whereas the PCF guarantees a time-bounded service [1]. Although both methods may coexist, the PCF method may coexist only in parallel with the DCF method and can not exist alone. PCF method would be especially well suited for real-time traffic as it permits to allocate the radio channel according to applications requirements, but the PCF method is very rarely implemented in current 802.11 products. In this paper, we focus on the throughput analysis for an IEEE 802.11b WLAN based on the DCF protocol which is widespread in the market today.

2.1. Transmitting techniques in DCF access protocol

There are two techniques used for packet transmitting in DCF. The default one is a two-way handshaking mechanism, also known as basic access mechanism. A positive MAC acknowledgement (ACK) is transmitted by the destination station to confirm the successful packet transmission. The other optional one is a four-way handshaking mechanism,

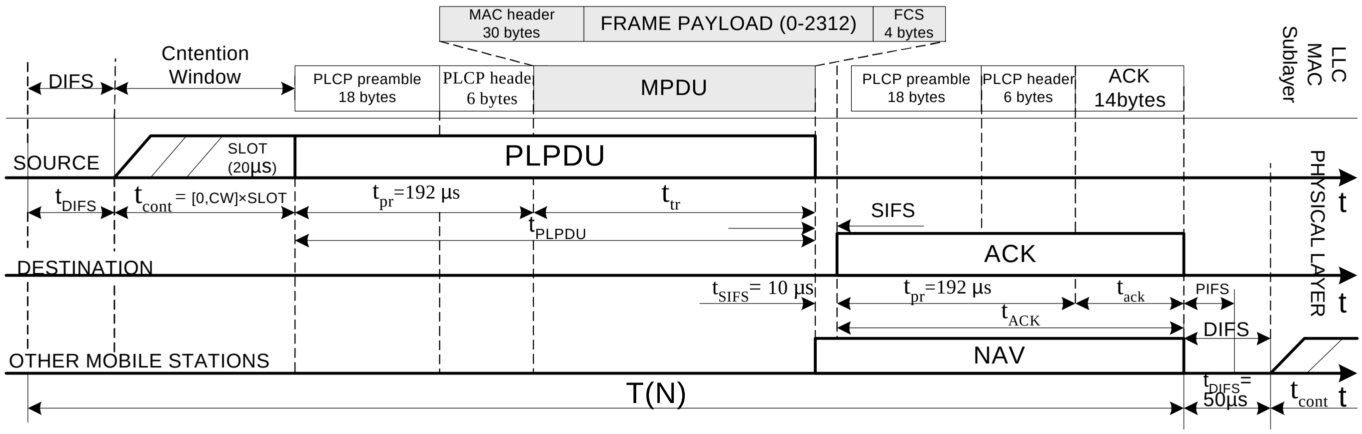

Figure 1. IEEE 802.11b DCF basic access mechanism

which uses request-to-send/clear-to-send (RTS/CTS) technique to reserve the channel before data transmission. This technique has been introduced to reduce the performance degradation due to hidden terminals. However, the drawback of using the RTS/CTS mechanism is increased overhead for short data frames [3].

2.2. Performance of DCF basic access method

The frame format of an IEEE 802.11b frame is shown in Figure 1. When a frame or MAC Service Data Unit (MSDU) arrives at the MAC layer from the higher layer, it is encapsulated in a MAC Protocol Data Unit (MPDU) by adding 30 bytes of the MAC header, and 4 bytes of Frame Control Sequence (FCS) field executing Cyclic Redundancy Check (CRC) principle. The MPDU is then passed to the PHY layer, which will attach 18 bytes long Physical Layer Convergence Protocol (PLCP) preamble used for synchronization of the receiver and 6 bytes long PLCP header.

The DCF access mechanism is a distributed medium access protocol based on Collision Sense Multiple Access with Collision Avoidance (CSMA/CA). CSMA/CD is not used because a station is unable to listen to the channel for collisions while transmitting. Basically, the DCF works as follows: before a station starts a frame transmission, it shall sense the wireless medium to determine if it is busy. If the station detects that the wireless medium has been idle during more than a time interval called Distributed Inter Frame Space (DIFS), the station can transmit the frame immediately (Figure 1.). If the medium is sensed as busy, the station waits until the channel becomes idle, then defers for an extra DIFS interval. If the medium remains idle, the MAC starts the backoff procedure by selecting a random backoff count. While the medium stays idle, the backoff counter is being decremented every slot time, and when the counter reaches zero, the frame is transmitted. To select the random backoff count, each station maintains a contention window (CW) value. The backoff count is determined as a random integer drawn from a uniform distribution over the interval [0; CW-1][1][11][13].

Priority access to the wireless medium is controlled by use of Inter Frame Space (IFS) intervals, i.e., time intervals between the transmissions of consecutive frames. The 802.11b standard defines four different IFS intervals: Short IFS (SIFS), PCF IFS (PIFS), DCF IFS (DIFS), and Extended IFS (EIFS) [7]. A basic medium access method is shown in Figure 1.

Upon having received a packet correctly, the destination station waits for a SIFS interval immediately following the reception of the data frame and transmits a positive ACK back to the source station, indicating that the data packet has been received correctly (Fig. 1). In case the source station does not receive an ACK, the data frame is assumed to be lost and the source station schedules the retransmission with the CW for back-off time doubled. When the data frame is transmitted, all the other stations hearing the data frame adjust their Network Allocation Vector (NAV), which is used for virtual CS at the MAC layer, based on the duration field value in the data frame received correctly, which includes the SIFS and the ACK frame transmission time following the data frame [3].

3. THE THROUGHPUT ANALYSIS

In this section, our objective is to calculate the maximum throughput achievable with only one 802.11b AP, taking into consideration the number of competing stations (N) and size of generated MSDU packets (L). All stations are placed in the RF coverage area of same AP cell with equal peak theoretical rates of 5.5Mb/s or 11Mb/s, thus eliminating performance anomaly described in [4]. We assumed situation in witch multiple hosts working in the DCF mode with disabled RTS/CTS function attempts to transmit at the same time, and host that chooses smallest backoff interval first starts transmitting packet without collision (Fig. 1.). The signal propagation delay is very small (around 0.2µs in our simulation) and can be neglected [11][4]. The overall transmission time may be calculated as follows:

$$T(n) = t_{DIFS} + t_{CONT}(n) + 2t_{pr} + t_{tr} + t_{SIFS} + t_{ACK} \quad (1)$$

To simplify our analysis furthermore, we make the following assumptions: (1) there are no multiple successive collisions on the wireless medium; (2) the network consists of a finite number of contenting stations *n* and every station always has *L*-byte long data frame (or MSDU) available for transmission at an infinite rate; (3) collision probability *p(n)* of a transmitted frame is constant and independent of the number of retransmissions that this frame has experienced in the past [11]; (4) frames are received with error only when they encounter collisions due to other simultaneous transmissions and the effect of frame errors due to bit errors introduced by channel noise will be ignored [11]. With these and previous assumptions, a transmission cycle is composed of the following phases that are repeated over time: (1) IFS deferral phase composed of DIFS and SIFS phases; 2) Backoff/Contention phase; (3) Data (or PLPDU) transmission phase and (4) ACK transmission phase. The overall transmission time of the single packet can now be expressed as follows:

$$T(n) = t_{IFS} + t_{CONT}(n) + t_{PLPDU} + t_{ACK} \qquad (2)$$

where IFS time is given by:

$$t_{IFS} = t_{SIFS} + t_{DIFS} \qquad (3)$$

The IFS time is constant which represents the sum of DIFS time (t_{DIFS} = 50µs) and SIFS time (t_{SIFS} = 10µs) (both defined in IEEE 802.11b standard).

The overall frame transmission time experienced by a single host when competing with N-1 other hosts will be influenced by interval t_{cont} that accounts for the time spent in contention procedures. Since there are multiple hosts attempting to transmit, the channel will be sensed busy and hosts enter a collision avoidance phase: a host executes the exponential backoff algorithm - it waits for a random time interval distributed uniformly between [0;CW-1]×T_{SLOT} called backoff count time or contention time (t_{CONT}) before transmission of the packet starts. The contention window (CW) value varies between CW_{min} = 32 and CW_{max} = 1024 and the value of slot time (T_{SLOT}) is 20µs (these parameters are for 802.11b) [4] [7] [12] [13]. The CW size is initially assigned as CW_{min}, and it is exponentially increased up to CW_{max} when a transmission fails. Once CW reaches the value of CW_{max} (after 6 retransmission attempts), remains at the value of CW_{max} (1024) until it is reset. The CW is reset to CW_{min} after a successful transmission or after reaching the maximum retry limit [1].

At saturation, a transmitting station will always have a queue of packets to send, so every transmission is preceded with backoff algorithm. Since the backoff count is uniformly distributed over 0, 1,…, CW_{min}-1 for the first attempt, the backoff timer is $(CW_{min}-1)/2 \cdot T_{SLOT}$, on average. Each transmission has probability *p(n)* of collisions, and a station retransmits a packet until it receives an acknowledgment, so we can model the number of retransmissions per packet as geometrically distributed with probability of success 1-*p(n).* Furthermore, after any unsuccessful transmission attempt, another calculation of backoff count is performed with a new CW value determined as follows:

$$CW_{backoff} = [1-p(n)]\frac{CW_{min}-1}{2} + p(n)[1-p(n)]\frac{2(CW_{min}-1)}{2} + \dots + p^m(n)[1-p(n)]\frac{2^m(CW_{min}-1)}{2} + p^{m+1}(n)\frac{2^m(CW_{min}-1)}{2} \qquad (4)$$

where *m* (0=*m*=6) is number of consecutive retransmission attempts before CW reaches its maximum value (1024) [11].

In the case of a single host that tries to transmit a sustained traffic (the host has always a packet to send), the carrier sense applies also to the host's own transmissions, so that it inserts a random interval between each transmission. This is mandatory, because transmitting frames continuously would prevent any other host from accessing the channel [4]. In that case the analytical formula for t_{cont} as a function of competing hosts is difficult to derive and we propose to use a simple approximation by not taking into account multiple successive collisions. If we neglect multiple successive collisions the throughput can be predicted within error of the order of 3% [4] [14]. Considering that the hosts always sense a busy channel when they attempt to transmit and that the number of transmissions that are subject to multiple successive collisions is negligible (for *m*=0 or 1 in equation (4)) we will take in the account only the first two terms in equation (4).:

$$CW_{backoff} = [1-p(n)]\frac{CW_{min}-1}{2} + p(n)[1-p(n)]\frac{2(CW_{min}-1)}{2} \qquad (5)$$

where *p(n)* is the probability of collisions experienced for each packet successfully acknowledged at the MAC level (0=*p(n)*<1). A simple expression for *p(n)* can be derived by considering that a host attempting to transmit a frame will eventually experience a collision if the value of the chosen backoff interval corresponds to the residual backoff interval of at least one other host [4] [13]. Such an approximation holds if multiple successive collisions are negligible. So we have:

$$p(n) = 1 - (1 - 1/CW_{min})^{n-1} \qquad (6)$$

We will assume that average contention time increases with every new contenting station *(n)* wishing to transmit. So the expression for average contention time (t_{CONT}) as product of contention window value, slot time, constant K and number of competing hosts (*n*) is as follows:

$$t_{CONT}(n) = CW_{backoff} \times T_{SLOT} \times K \times n \qquad (7)$$

where *K*=1 or *K*=2 corresponds to transmission speeds of 11Mb/s and 5.5 Mb/s respectively. Constant *K* is introduced because we assume that average time spent in contention for the same number of stations is two times increased (*K*=2) since theoretical peak throughput is two times decreased

(5.5Mb/s). Finally, average time $t_{CONT}(n)$ spent in contention for each station, expressed as a function of number of competing stations is given by:

$$t_{CONT}(n)=\left[3\left(\frac{31}{32}\right)^{n-1}-2\left(\frac{31}{32}\right)^{2(n-1)}\right]\times\frac{CW_{min}-1}{2}\times T_{SLOT}\times K\times n \quad (8)$$

Transmission time of PLPDU is composed of PLCP preamble and header transmission time (t_{pr}) and MPDU frame transmission time (t_{tr}) [1]:

$$t_{PLPDU}=t_{pr}+t_{tr}=t_{pr}+\frac{(34+L)\cdot 8}{R} \quad (9)$$

where L corresponds to the size of the transmitted packet and R corresponds to the maximum theoretical bandwidth (11Mb/s or 5.5 Mb/s). t_{pr} varies according to the bit rate used by the host. Since the PLCP header is almost always transmitted at 1Mb/s, t_{pr} equals to 192 µs.

An ACK frame is transmitted at the rate equal to data frame rate, and is 14 bytes long, which is usually much shorter than the data frame. Transmission time of ACK frame (t_{ack}) then equals to 10 µs for transmission data rate of 11 Mb/s, or 20 µs for transmission data rate of 5.5 Mb/s. The overall MAC acknowledgment transmission time is composed of PLCP preamble and header transmission time (t_{pr}) and transmission time of ACK frame (t_{ack}) [1]:

$$t_{ACK}=t_{pr}+t_{ack}=t_{pr}+\frac{14\cdot 8}{R} \quad (10)$$

Finally, to compute the effective throughput H we need to divide the overall transmission time of that packet with the number of bits in the transmitted packet [1]:

$$H=\frac{8\cdot L}{\mathrm{T(n)}} \quad (11)$$

According to the last equation, we propose two analytical formulas for calculating instantaneous throughput of a station in an 802.11b WLAN as a function of packet size and number of competing stations sharing an AP. For maximum theoretical bandwidth of 11Mb/s and 5.5 Mb/s instantaneous throughputs is given by next two analytical equations:

$$H_{11}(n,L)=\frac{8\cdot L}{K_1+\frac{(34+L)\cdot 8}{R}+\left[3\left(\frac{31}{32}\right)^{n-1}-2\left(\frac{31}{32}\right)^{2(n-1)}\right]\times K_2\times n} \quad (12)$$

$$H_{5.5}(n,L)=\frac{8\cdot L}{K_3+\frac{(34+L)\cdot 8}{R}+\left[3\left(\frac{31}{32}\right)^{n-1}-2\left(\frac{31}{32}\right)^{2(n-1)}\right]\times K_2\times 2n} \quad (13)$$

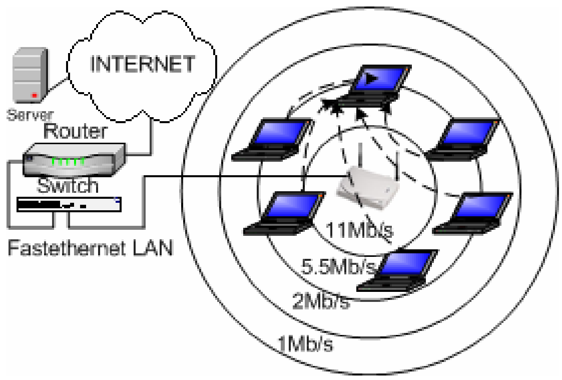

Figure 2. Network topology used for measurements

where constants K are equal to: K_1= 454µs, K_2 = 310µs and K_3 = 464µs. Values of constants K are composed of slot time, CW values and inter frame space parameters defined in IEEE 802.11b standard.

4. MEASUREMENT SETUP

The network topology used for experiments is shown in Figure 2. We study the performance of an 802.11b WLAN BSS (Basic Service Set) working in the infrastructure mode. Up to 11 wireless stations were associated to the same AP on channel 11. The AP is connected to a 100 Mb/s Ethernet access (L2) switch. There were other stations connected to the ports of the switch also. All wireless stations are the traffic sources except one wireless station which receives all the data sent. We used 11 laptops for our experiments with similar processing speed ranging from Pentium-3 1.1 GHz through Pentium-4 1.8 GHz with RAM memory ranging from 128Mb to 512Mb. Network performance of the wireless station is determined more by the wireless card implementation then its processing capacity [2]. The AP used was Symbol Technologies Spectrum24 series 4121 access point [10]. The cards used for sending traffic were Symbol Technologies Spectrum24 PCMCIA wireless LAN adapter. We disabled WEP on the cards and the AP in order to avoid any potential overhead. Since we assumed that problem of hidden station can be neglected, RTS/CTS usage was also disabled on AP, setting RTS threshold to a maximum value (2347).

Our choice for performance testing software was Chariot from NetIQ Corporation [8]. Chariot is an application that allows for several types of end-to-end performance tests (response time, throughput, jitter, delay and lost data for streaming applications) using up to 4 different protocols (TCP, UDP, SPX or IPX). By exactly emulating transaction traffic from real applications, Chariot tests and troubleshoots every segment of WLAN network and provides setup instructions called scripts to endpoint station. These endpoints execute the tests instructions and return the results to the console to be viewed by administrator. On all 10 sending mobile stations programed to send as fast as posible,

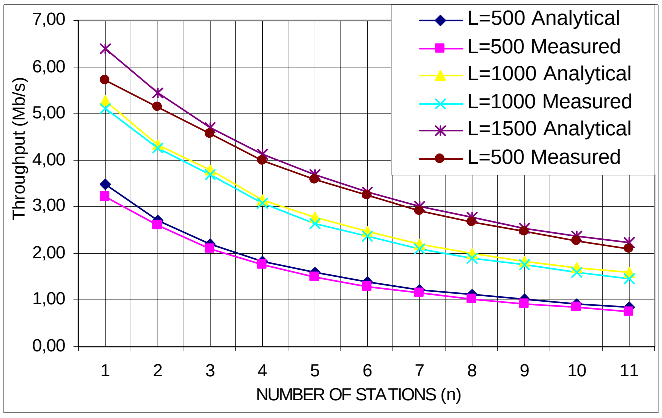

Figure 3.Comparation of the throughput experienced by an 802.11b host when all hosts transmit at 11 Mb/s

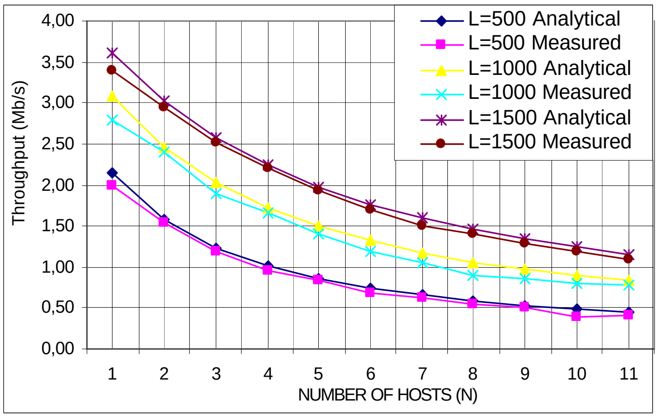

Figure 4. Comparation of the throughput experienced by an 802.11b host when all hosts transmit at 5.5 Mb/s

Chariot console software with the same scripts has been installed. In these setup instrunctions or scripts we defined equal traffic parametars for three different sizes (L= 500, 1000, 1500 bytes) of generated TCP packets. Chariot endpoint software and Ethereal software used to capture and monitor received packets, were installed on wirelass station receiving traffic genrated from all other stations [9].

5. ANALYSIS OF THROUGHPUT RESULTS

Comparison of analytically calculated and measurement - based results of throughput experienced by a 802.11b host when all other hosts transmit at 11Mb/s or 5.5 Mb/s are shown at Figures 3. and 4. respectively. Graphs on Figure 3. and 4. show instantaneous throughput of 802.11b host as a function of number of competing hosts (N) for three different sizes (L) of transmitted packets. We can observe that the measured values correspond fairly well to the analytical expressions. The consequences of neglecting propagation time, multiple successive collisions and frame errors due to bit errors introduced by channel noise are observed in small discrepancy between analytically obtained and measurement-based results.

Analyzing graphs on Figure 3. and 4. we notice that the throughput obtained by the 802.11b WLAN is much smaller than the nominal bit rate of 11 Mb/s or 5.5 Mb/s. For example, if there are no collisions, one host may expect the maximum throughput of approximately half the value of the nominal bit rate. Furthermore, the proportion of the useful throughput strongly depends on the number of competing hosts. The instantaneous throughput decreases as the number of hosts trying to transmit increases. We also observe that the overall throughput of one host (for the same number of hosts wishing to transmit simultaneously) increases when the size of transmitted packet increases. With the larger size of the packet, the larger amount of information is transmitted at the same time resulting in the increased overall throughput. On the other hand, the probability of a packet getting corrupted increases with the packet size, due to the higher Bit Error Rate of a radio link. In the case of packet corruption, the smaller the packet, the less overhead to transmit, thus making smaller packets suitable for real-time applications and longer packets suitable for file transfer and Internet traffic.

6. FTP THROUGHPUT MEASUREMENT

Using the same network topology shown in Figure 2., in our second experiment we measure effective throughput of 802.11b host as a function of number of competing hosts (N) while transmitting three different file sizes. We varied the file size (1Mb, 25Mb, 250Mb, 250Mb and download) with every new measurement to see the effect on the overall throughput. In each of four measurements, the files of the same size are transferred using FTP protocol from all mobile stations to the station acting as FTP server. The throughput has also been measured with NetIQ Chariot console and endpoint software application which was installed on pair of wireless stations. With these measurements we wanted to analyze the throughput behavior of 802.11b devices in realistic circumstances. Such as, the use of the FTP protocol for file transmission as a simple everyday office service. The nominal bit rate of all our throughput experiments was 5.5 Mb/s, with maximum speed of packet transmission.

Figure 5 shows the instantaneous throughput as a function of time for first six hosts starting to transmit file of the same size (25Mb), one by one during the time, with random time period between beginnings of succeeding transmission. As expected, we can observe that instantaneous throughput decreases with every new wireless station starting to transmit.

All measurement results shown in Figure 7., indicate almost equal overall throughput for the same size of transmitted files. We can conclude that overall throughput does not depend on the size of transmitting files. It depends on number of transmitting stations and moments at which they start to transmit. In last measurement we transferred files of

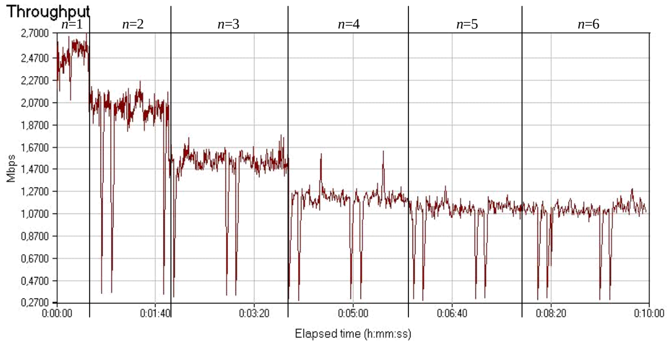

Figure 5. Instantaneous throughput of 802.11b host as a function of time during transmission of 25Mb file

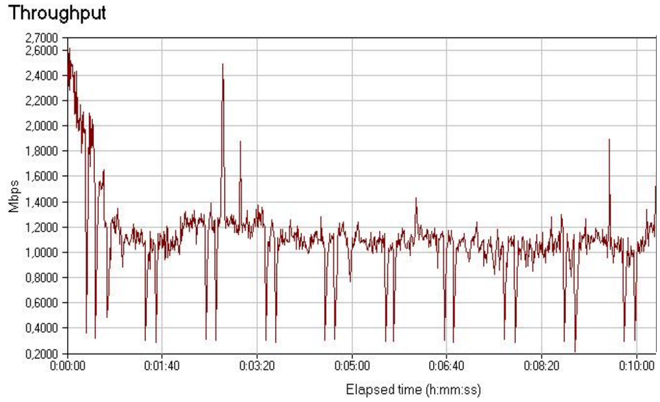

Figure 6. Instantaneous throughput of 802.11b host during transmission of 25Mb file when all stations start transmission simultaneously

25Mb in parallel with downloading file of 25Mb from distant server over the Internet. We can observe considerable throughput degradation caused by two simultaneous transmissions performed by every host.

We also measured instantaneous throughput of 802.11b host when all 10 stations start file transmission process at the some time, downloading identical file of the 25Mb from particular wireless station acting as FTP server (Figure 6.). At the beginning of FTP transmission, we can observe rapid throughput decrease, since all 10 stations placed in the same AP signal coverage area (with equal peak theoretical throughput of 5.5 Mb/s) simultaneously start download of the 25Mb file. When all stations begin FTP transmissions, average instantaneous throughput was 1.15 Mb/s which is almost equal to the result obtained by using equation (13).

7. CONCLUSION

In this paper we have analyzed the throughput performance of the IEEE 802.11b WLAN networks. The measured values correspond fairly well to the analytical expressions we derived for calculating effective throughputs as a function of number of competing stations for different sizes of transmitted packets. This analysis shows that the throughput

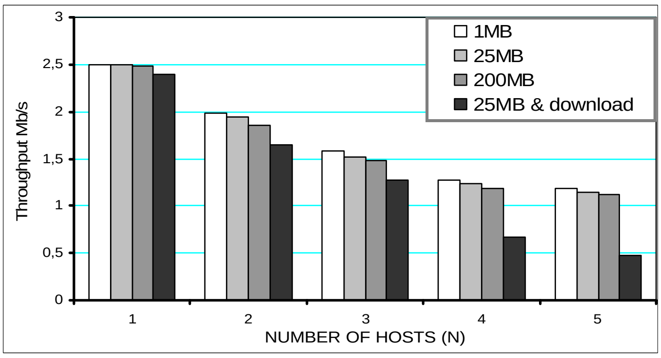

Figure 7. Measured throughput of 802.11b host for different sizes of transmitted files

of the 802.11b WLAN is much smaller than the nominal bit rate. Furthermore, the proportion of the useful throughput strongly depends on the number of competing hosts. The instantaneous throughput decreases as the number of hosts wishing to transmit increases. We also observe that overall throughput of one host (for the same number of hosts wishing to transmit simultaneously) increases when size of transmitted packet increases. Overall throughput does not depend on the size of transmitting files. It depends on number of transmitting stations and moments at which they start to transmit.

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