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Abstract *IEEE 802.11 allows for fragmentation tuning and rate selection. Their combined usage is referred sometimes to link adaptation. However, the algorithms of link adaptation are beyond the 802.11 standards. In this paper we investigate the benefits arising from proper use of link adaptation. Particularly, we develop a mathematical model describing the fragmented transmission in 802.11b. We examine potential benefits of it over AWGN and fading channels. More significantly we combine fragmentation tuning with bit-rate selection to yield the highest achievable throughput performance for any given channel conditions. Finally, we propose an algorithm that performs the optimal link adaptation.*

1. Introduction

In recent years the IEEE 802.11 family of WLAN standards has emerged as the dominant technology for broadband wireless access networks. Although it supports relatively low transmission rates compared to the wired technologies the number of WLAN users continues to grow dramatically mostly due to its flexibility and low cost.

The IEEE 802.11b standard approved in 1999 [1], [2] allows for frame fragmentation. Fragmentation is the process by which 802.11 frames are partitioned into smaller fragments that are transmitted separately to the destination. The destination station reassembles the fragments back into the original frame. The WLAN fragmentation and reassembly mechanisms operate at the MAC layer. Only unicast frames are allowed to be fragmented. Each fragmented frame is encapsulated with the usual MAC header and FCS fields and each fragment must be individually acknowledged. For these reasons the fragmentation mechanism decreases the payload-to-overhead ratio. However, fragmentation can enhance the throughput efficiency in cases where channel conditions limit the probability of successfully delivering large frames [3]. Mitigating against the effects of interference and fading is a good example of fragmentation use [4]. Such interference manifests usually in the form of short dense energy impulses or deep fades in SNRs that lead to short failures in communication. By breaking larger frames into smaller fragments fitted to periods of good channel conditions a higher percentage of frames have chances to arrive undamaged. Also if a fragment in a fragmentation burst gets corrupted only that fragment instead of the whole frame is repeated.

Another mechanism widely exploited in a link adaptation scheme is a line-rate selector. Under the 802.11b standard, stations may transmit at one of four predefined line rates, i.e. 1, 2, 5.5, and

11 Mbps. However, the standard doesn't state how to perform multirate switching and that aspect has been left for the manufacturers to implement.

In this paper we investigate the influence of fragmentation on the throughput performance of 802.11b networks. We show that by a proper tuning a fragment size (i.e. the fragmentation threshold parameter) it is possible to optimize the throughput. Moreover, we also demonstrate that by combining fragmentation threshold tuning with line-rate selection further gains are achievable.

In most cases link rate adaptation mechanisms select the appropriate transmission rate on the basis of the packet loss rate or SNRs. In this paper we show that the incorporation of fragmentation into link adaptation can result in significant throughput enhancement.

Other researchers have already employed fragmentation for the purposes of enhancing throughput. For example, Qiao and Choi [5] proposed an optimal link framework that combines tuning of the fragmentation size and the transmission rate. However, their work relates specifically to 802.11a networks, is limited to the use of maximum 10 fragments of equal sizes and more important, doesn't conclude with the proposition of feasible algorithm implementation. In [5] S. Kim investigated the possibility of improving communication at the edges of AP (Access Point) cell coverage through the use of fragmentation.

To conduct this study thoroughly we have examined link adaptation over two channel models: an AWGN (Additive White Gaussian Noise) and flat, slow-fading Rayleigh channel.

This paper is organized as follows: In Section 2 a throughput model is described. Section 3 deals with determining the error probabilities for each of the permitted 802.11b transmission rates. Results of throughput performance are included in Section 4. Section 5 presents a link adaptation algorithm. Section 6 concludes the paper.

2. Throughput Model for 802.11b

When a MAC frame or MSDU (MAC Service Data Unit) arrives at the MAC layer, it is encapsulated into a MPDU (MAC Protocol Data Unit) by adding a 24 byte MAC header and 4 byte FCS (Frame Check Sequence) field. The MSDU comprises a variable length frame payload whose maximum size is limited to 2304 bytes. The MPDU is then passed to the physical (PHY) layer where the PLCP (Physical Layer Convergence Protocol) preamble and header is attached [1], [2]. This is illustrated in Figure 1. In 802.11b specifies two types of the PLCP preamble: long (mandatory) and short (optional). In this analysis we consider only the short preamble type as it improves efficiency on the network and is currently widely supported by 802.11b STAs. It makes up of 9 byte long PLCP preamble (that is shorter compared to the long preamble by 7 bytes) sent at 1 Mbps and the PLCP header comprising 6 bytes transmitted at 2 Mbps (compared to the long preamble it contains the same number of bytes but it's transmitted at lower 1 Mbps rate). The MPDU may be transmitted at one of four predefined PHY rates of 1, 2, 5.5, and 11 Mbps.
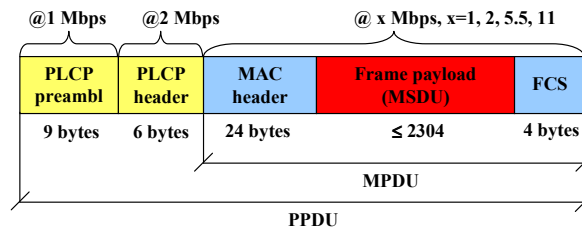

Figure 1. The IEEE 802.11b frame format

IEEE 802.11b supports two modes which allow stations to access the medium: PCF (Point Coordination Function) and DCF (Distributed Coordination Function). The PCF mode is beyond

the scope in this paper as it is widely ignored by vendors. Under the DCF mode all stations start with sensing the medium (Figure 2). If medium is idle they defer for a period of DIFS (DCF Interframe Space) and then execute a backoff procedure. The backoff procedure is based on drawing a random slot from the interval [0, CW_{min}] where CW stands for *Contention Window*. Stations count down from the drawn slot to zero. The first station to reach zero wins access to the medium and may begin transmitting its frame immediately. Each successfully received PPDU must be acknowledged with an acknowledgement (ACK) frame which is transmitted after an interval of SIFS (Short Interframe Space) elapses. Subsequent fragments are transmitted after an interval of SIFS. This procedure continues until all fragments are delivered. However, if the transmission of any fragment fails, the station must contend again for access by deferring for DIFS and executing the backoff procedure.

A frame transmission is considered to have failed if an error is introduced into the PPDU or the ACK. Failure to receive an ACK will also constitute a failed transmission where a timeout for the reception of an ACK frame has been defined as

ACK timeout = SIFS+ ACK+ SlotTime (1)

In order to further simplify the analysis we make the following assumptions:
- There is no competition for access and consequently collisions are ignored;
- Stations operate in the infrastructure mode using the short MAC header which has a length of 24 bytes and a FCS of 4-bytes;
- The sender generates a MSDU of length *L*-bytes which results in a MPDU of *(L+28)* bytes;
- No encryption is used;
- The RTS/CTS mechanism is disabled;
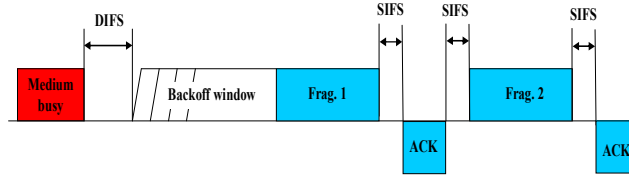- Propagation delays are neglected.

Figure 2. DCF with fragmentation (in general fragments might be more than two)

We now move on to developing a mathematical model for the throughput calculation based upon [5] and [7].

Let us assume that the (*L*+28) byte long MPDU is transmitted using one of the four PHY rates of 1, 2, 5.5 and 11 Mbps. The probability of the successful frame transmission can be expressed in the form

$$P_{succes}^{m}(L) = \left(1 - P_{e\_data}^{m}(L)\right)\cdot\left(1 - P_{e\_ack}^{m}\right)$$ (2)

where $P_{e\_data}^{m}$ and $P_{e\_ack}^{m}$ are the error probabilities for the data and ACK frame transmissions respectively. This expression is valid for channel errors that are statistically independent which is true for channels without memory, e.g. the AWGN channel.

The term $P_{e\_ack}^{m}$ may be dropped as it is several orders of magnitude less than $P_{e\_data}^{m}$. Consequently, $P_{success}^{m}$ can be approximated as:

$$P_{succes}^{m}(L) = \left(1 - P_{e\_data}^{m}(L)\right)$$ (3)

The term $P_{e\_data}^{m}$ may be expressed in the form

$$P_{data}^m(L) = \left(1 - P_e^1(24)\right) \cdot \left(1 - P_e^m(28 + L)\right) \qquad (4)$$

where $P_e^1(24)$ is the error probability for the preamble which is always transmitted at 1 Mbps and $P_e^m(28 + L)$ is the error probability for the MPDU transmission. $P_e^m(L)$ is related to bit error rate (BER) as follows

$$P_e^m(L) = 1 - \left(1 - P_b^m\right)^{8L} \qquad (5)$$

where P_b^m is BER for rate *m*.

Now let us define *X* as the length of a fragmented frame. The number of fragments of the length of *X* is equal to $\lfloor L/X \rfloor$ where $\lfloor x \rfloor$ is the floor function. If *X* is not a multiple of *L* then the final fragment size is equal to $L - X \cdot \lfloor L/X \rfloor$.

Each successful fragment transmission consists of a data frame transmission, an ACK frame transmission and two SIFS as shown in Figure 2. Thus the time needed for a successful fragment transmission is

$$T_{frag}(X) = T_{data}^m(X) + SIFS + T_{ACK}^m + SIFS \qquad (6)$$

where $T_{data}^m(X)$ and T_{ACK}^m denote the durations of the data and ACK frames and are given by

$$T_{data}^m(X) = tPLCPpreamble + tPLCPheader + \frac{28 + X}{rate(m)} \qquad (7)$$

$$T_{ACK}^m = tPLCPpreamble + tPLCPheader + \frac{14 + 8}{rate(m)} \qquad (8)$$

However, if the fragment transmission should fail for some reason or others the station has to wait for the ACK timeout before repeating the backoff procedure. The average time required to transmit the fragment may be expressed as

$$T_{frag}(X) = P_s(1) \cdot T_{reg}(X) + P_s(2) \cdot [T_{reg}(X) + T_{def}(1)] + $$
$$P_s(3) \cdot [T_{reg}(X) + T_{def}(1) + T_{def}(2)] + ... \qquad (9)$$

where

$$T_{reg}(X) = T_{data}^m(X) + SIFS + T_{ACK}^m + SIFS \qquad (10)$$

is a cycle time for delivering $T_{data}^m(X)$.

$$T_{def}(k) = ACK\_timeout + T_{back\_off}(k) \qquad (11)$$

is a time that is needed for an STA to defer till commences with another $T_{data}^m(X)$ transmission after *k* unsuccessful transmission attempts.

$$P_s(i) = \left(1 - P_{succes}^m(X)\right)^{i-1} \cdot P_{succes}^m(X) \qquad (12)$$

is the probability of transmitting successfully $T_{data}^m(X)$ at *i*-th transmission attempt.

The average backoff interval associated with a retransmission attempt *i* is $T_{back\_off}(i)$ and may be expressed in the form

$$T_{back\_off}(i) = \begin{cases} \dfrac{2^{i-1} \cdot (CW_{min}+1)-1}{2} \cdot SlotTime & 1 \le i < 7 \\[2mm] \dfrac{CW_{max}}{2} \cdot SlotTime & i \ge 7 \end{cases} \qquad (13)$$

We may rewrite equation (9) in the form

$$T_{frag}(X) = T_{reg}(X) + \sum_{n=2}^{\infty} P_s(n) \cdot \sum_{i=1}^{n-1} T_{def}(i) \qquad (14)$$

The throughput *G* is defined as the number of bits transmitted in a unit of time:

$$G = \frac{L}{\dfrac{L}{X} \cdot T_{frag}(X) + DIFS + T_{back\_off}(0) - SIFS} \qquad (15)$$

where *L/X* is the number of the fragments to be transmitted. We subtract *SIFS* from the denominator term as the first fragment of the *L* long frame is sent after the *DIFS* time. The 802.11b standard states that the *CW* after each successful transmission shall be reset to zero. In our model *CW* will be always zero (i.e. the argument of $T_{back\_off}(0)$) as there is no competition for accessing the channel (there is only one station). Finally, the values for the 802.11b parameters were taken from the standard [1], [2].

3. Error Probabilities for the Four PHY Modes of 802.11b

As indicated in the previous section it is mandatory to obtain the BER for the four transmission rates supported under the 802.11b standard in order to perform throughput calculations described by the model above. These rates correspond to the four different modulation schemes: DBPSK, DQPSK, 16-CCK, and 256-CCK. First we will determine BERs for an AWGN channel, than for a fading one.

BER formulas for the two lowest rates transmission rates, i.e. DBPSK@1Mbps and DQPSK@2Mbps, are given in the literature [8], [9], [10]. The error probability for the 16-CCK@5.5Mbps rate can be computed from the expression for the error probability of 16-biorthogonal signals. However there is no analytical method available for the 256-CCK@11Mbps rate, hence simulations must be employed [11].

The manufacturer and at the same time a co-founder of 256-CCK modulation Intersil provides empirical BERs for its chip HFA3861B realizing all the rate schemes [13]. In order to overcome the problem of 256-CCK not to being able be mathematically expressed an to be closer to reality we adopted empirical BER curves from Intersil.

Unfortunately Intersil provides only the BERs for the AWGN channel. Therefore we had to compute BERs for a fading channel The BER performance over fading channels is usually obtained though computer simulations due to the complexity involved. However, there is a simple analytical technique to evaluate the BER performance over flat, slow fading channels [8].

Given the BER performance for the AWGN channel, one can evaluate the BER for a flat, slow-fading Rayleigh channel by averaging the BER for the AWGN channel over all possible values of signal strength due to fading.

4. Numerical Results and Discussion

4.1. The AWGN channel

a) Fragmentation adaptation

Figures 3 and 4 present the simulations' results. The figures are grouped in pairs where each pair corresponds to a different transmission rate. Figures 3a, 4a present the throughput as a function of the fragment size where the SNR is the parameter. One can observe from Figures 3a and 4a that the fragmentation process does not influence the throughput performance equally over all SNR values. The curves that show the most promising results arising from fragmentation tuning have been presented separately in Figures 3b and 4b.

Reviewing the performance of the DBPSK modulation scheme presented in Figure 3 one can observe that for all the SNRs (with the exception of SNR = 1dB) the average throughput increases with an increase in the fragment size. The highest achievable throughput is reached for the largest permissible MSDU of 2304 bytes. For a SNR = 1dB the maximum throughput occurs for a fragment size of 1000 bytes.

a) Three dimensional graph combining throughput, fragment size, and SNR

b) Selected throughput curves. Curves from bottom to top correspond to SNR = 1, 2, 3, and 4dB
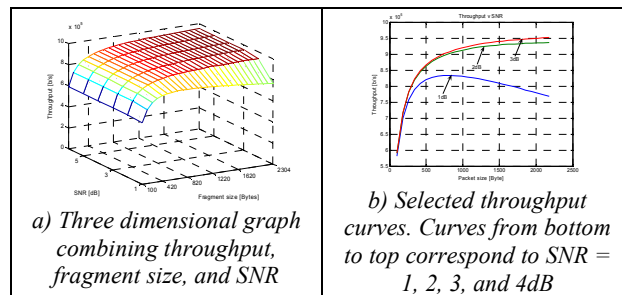
Figure 3. Throughput vs. frame size for DBPSK@1Mbps in an AWGN channel

A different result can be observed for the case of DQPSK modulation (see Figure 4) where for the curves SNR = 3 dB and 4 dB the average throughput decreases with increasing a fragment size.

A similar situation to DQPSK may be observed for 16-CCK and 256-CCK (Figures presenting those haven't been included in the paper for the sake of permitted paper length). 16-CCK can benefit from fragmentation tuning in the SNR range of 6 to 8 dB, while 256-CCK in the range of 9 to 11 dB.

These results show that for certain ranges of SNR, there is an optimal fragment size that can maximize the average throughput. However, in the case of an AWGN channel the size of this SNR is small, typically up to 2 dBs.
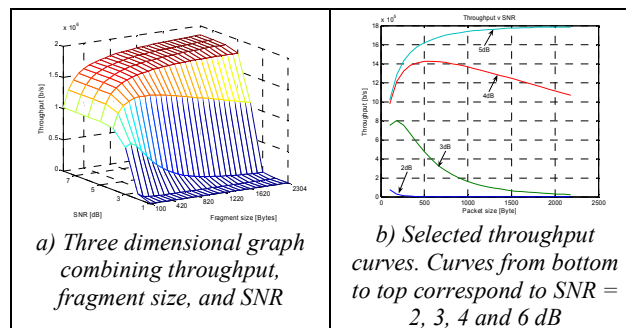

a) Three dimensional graph combining throughput, fragment size, and SNR

b) Selected throughput curves. Curves from bottom to top correspond to SNR = 2, 3, 4 and 6 dB

Figure 4. Throughput vs. frame size for DQPSK @ 2Mbps in an AWGN channel

b) Fragmentation and rate adaptation

To the best knowledge of the authors, none of currently employed link adaptation algorithms takes account of the frame size in the process of selecting the optimal rate. We will show below how this omission can have a negative impact on the average throughput.

Figure 5 shows that average throughput for the two modulation schemes DQPSK@2Mbps and 16-CCK@2 Mbps respectively. Consider a scenario where maximal sized frames (i.e. 2304 bytes) are transmitted over a channel with a SNR = 6 dB. It can be observed here that the DQPSK scheme clearly outperforms 16-CCK with a throughput of ~1.9 Mbps compared to ~0.6 Mbps. Most rate selection mechanisms would probably select the lower transmission rate for this case. However, if we were to employ fragmentation with a maximum fragment size of 750 bytes, then the DQPSK scheme would have the greater average throughput of approximately 1.2 Mbps. The average throughput for DBPSK remains unchanged around 0.9 Mbps. So, by transmitting at the higher rate with fragmentation employed, a larger average throughput can be realized. Similar conclusions can be drawn by comparing the average throughput results for the other modulation schemes.
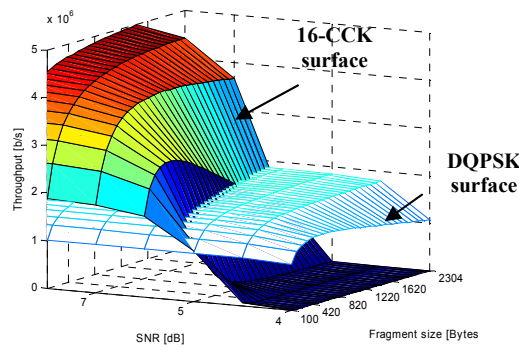

Figure 5. Throughput comparison for 16-CCK@5.5Mbps and DQPSK@2Mbps

Additionally to the above positive impact of fragmentation it has another extremely important aspect in terms of optimizing throughput on the 802.11. The fairness of DCF (contention to the channel) is remained for all stations irrespective of the line-rate STAs use. Due to the reason stations with lower rates occupy longer the channel than stations using higher rates. For example, station using DBPSK@11Mbps will be transmitting data almost 8 times longer then a station using 256-CCK@11Mbps. It such a situation occurs it dramatically reduces throughput for the stations of higher rates. As a result of it the overall throughput performance on a network becomes affected. For that reason it is extremely crucial to keep stations on their higher rates as long they exhibit a satisfactory transmission. As shown above frame size reduction incorporated into line-rate adaptation meets that task fairy.

c) Optimized throughput by proper fragmentation tuning and line-rate selection
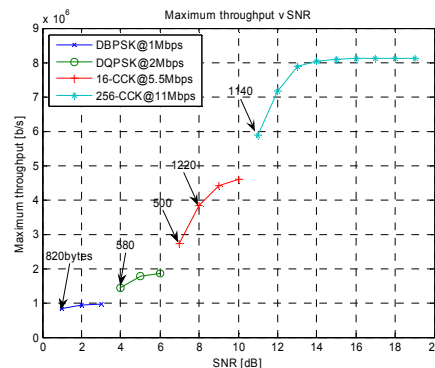

Figure 6. Maximum achievable throughput for the AWGN channel

Figure 6 presents the maximum achievable throughput that is the outcome of appropriate frame size and bit-rate selection. The marked points represent throughput that was soared to maximum by reducing the frame size to the values pointed in the figure. For non-labeled points the longest frame size (2304 bytes) was realizing the biggest throughput. We can see from that figure that up to 3 dB in SNR the best throughput is achievable for DBPSK, between 3 and 5 dB - DQPSK makes the best transmission, for the SNR in the range of 7-10 the modulation that brings the highest throughput is 16-CCK and for the range in 11 up to 19 - 256-CCK.

4.2 Flat slow-fading Rayleigh channel

A similar analysis has been performed for the Rayleigh fading channel and the results obtained are also similar with the one important exception, namely that the SNR range over which fragmentation tuning has a benefit is much larger. For the AWGN channel the range was typically 2 dB, while for the Rayleigh channel it is about 12 dB.

a) Three dimensional graph combining throughput, fragment size, and SNR

b) Selected throughput curves. Curves from bottom to top correspond to SNR from 30 to 46 dB in increments of 2 dB
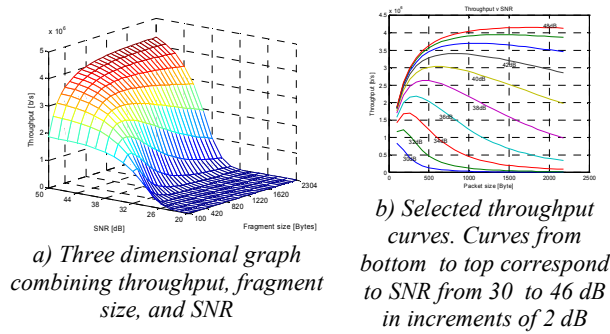
Figure 7. Throughput vs. frame size for 256-CCK @ 11Mbps in a Rayleigh fading channel

As an example consider the case of 16-CCK@5.5Mbps modulation shown in Figure 7. It can be observed here that the SNR values for which throughput improves because of tuning fragmentation lies at least in the range of 30 to 46 dB.

For the sake of paper length restrictions it will be only mentioned here that the same throughput optimization may be achieved for the fading channel (Figure 6).

5. Adaptation link algorithm

As shown above SNRs can't be treated as an objective measure for selecting a fragmentation and modulation scheme. It is because the same throughput gains are achievable for different SNRs in both channels due to different channel conditions.

An interesting conclusion might be drawn from a more careful observation of BER curves for both channels. Namely, fragmentation tuning benefits measured in SNRs corresponds to the same regions of BER for both channels. Unfortunately WLAN devices don't allow for gaining access to BER unless a specific manufacturer makes it available. Therefore, we think that this measure will be objective.

As stated above it is not feasible to get BERs. But it is possible to monitor PERs (Packet Error Rates) that is closely related to BERs. PER monitoring of different links might be realized by sending custom made broadcast packets over wireless.

From the fragmentation analysis included in this paper we conclude that splitting a frame into more than three equally divided fragments is not of a benefit as it doesn't bring in any significant further improvements (Figure 3 and 4). That's why fragmentation scheme in this paper assumes the transmission of: a) not fragmented frames, b) fragmented into 2 parts, c) fragmented into 3 parts.

The algorithm operations are described below (Figure 8). Each STA periodically broadcasts probe packets of three lengths that would correspond to three fragmentation schemes: a), b), c) at each available bit-rate, and a minimum size packet at the lowest bit-rate. The first type of probe packets emulates the transmission of data frames, the second one - ACK frames. Based on loss rates associated with packets and taking account of time restrictions imposed by the standard (DIFS, SIFS and so forth) a node calculates ETT (Estimated Transmission Time), thoroughly described in [15], for every link to its neighbor. When ETTs for every rate/fragment combination are calculated a rate/fragment combination is selected that goes with the lowest ETT. This algorithm operates in loops. It means in a new cycle different ETTs may be calculated.
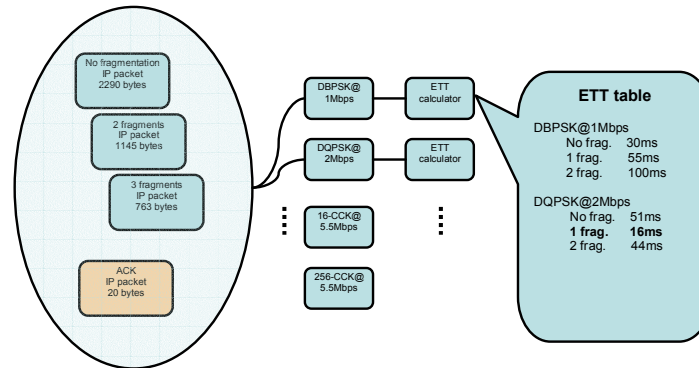

Figure 8. The algorithm of choosing the best fragment/rate combination

This algorithm has been devised for WMN (Wireless Mesh Networks) what means that it may be easily ported over to the infrastructural networks.

5. Conclusions and discussion

In this paper we have examined the benefits for throughput enhancement arising from fragmentation tuning in 802.11b WLANs. We have proposed a mathematical model for the average throughput that includes fragmented transmission over AWGN and flat slow-fading Rayleigh channels. In most applications fragmentation is used primarily to reduce the impact of interference and fading effects on performance. However, in this analysis we have demonstrated that by an appropriate tuning of the fragment threshold it is possible to achieve significant enhancements irrespective of the channel conditions. Those benefits would probably sum up with benefits arising from fragmentation in hostile environments like those with interference. We have also shown that fragmentation adaptation should be included in any link adaptation mechanisms. Rate selection algorithms that omit fragmentation may fail to realize the significant throughput gains that are potentially available.

In spite of the fact that the research we conducted applies for the 802.11b network it may be easily extended to the 802.11g/a networks. More it will be even simpler to perform a similar study for 802.11g/a as keyings used there in contrast to CCK allow itself for a mathematical description.

Further research in this area will involve validation of the theoretical results on an experimental test-bed comprising 17 Soekris boards running under the Linux Pebble distribution [15], [16].

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