High Bitrate Modem Architecture (WIND-FLEX) wireless LAN: the MAC, the Scheduler and their performance

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ABSTRACT

A novel Wireless Local Area Network (WLAN) currently developed in the WIND-FLEX project(Wireless Indoor Flexible High Bitrate Modem Architecture, European IST Programme, IST-1999-10025, EU Fifth Framework Program, see [4]) and suitable for small-office/home-office environments is described and analysed. The access scheme is TDMA at data rates ranging from 64 Kbps to 100 Mbps over a 50 MHz channel at 17 GHz. Data rate adaptivity requires a feedback channel and ad-hoc procedures. In particular, the MAC (Medium Access Control) drives the physical layer on the basis of link measurements exchanged via a suitable interface. System performance is evaluated via computer simulations by considering different traffic sources and the efficiency of the proposed MAC can be appreciated in terms of the final throughput.

1. INTRODUCTION

WLANs are receiving an increasing interest in the last years, Bluetooth [1], 802.11 [2], Hiperlan2 [3] and HomeRF [4] constituting the main actual proposals.

Compared to them, the WIND-FLEX Local Area Network (WF-LAN) illustrated in this paper adds some important features and provides innovative services. The main target is to allow efficient and fair communications in the so-called small-office/home-office (SOHO) environment, composed of a few rooms: a limited number of devices are then simultaneously active and are typically concentrated in a given area (e.g., the living room or a laboratory). Point-to-point link range varies from 5m (Non Line-of-Sight) up to 20m (Line-of-Sight).

WF-LAN is a meshed network with single-hop architecture: it is then constituted by a group of fully connected devices (DEVs). A common 50 MHz channel is employed to send data at variable bit rate (from 64 Kbps to 100 Mbps, measured at the MAC) according to the actual link state.

WIND-FLEX design encompasses the first two OSI layers, each DEV providing the functionalities to control the radio interface. Layer 2 is further divided into MAC and Dynamic Link Control (DLC) layers. WIND-FLEX also foresees IPv4 and TCP/UDP protocols as upper layers. In order to ensure QoS capabilities, DLC and MAC layers are connection-oriented. Being IP connectionless, DLC maps a TCP connection into DLC and MAC connections.

Any DEV may provide identical services and functions but, according to the current network status (i.e. device positioning, Bit Error Rates affecting the links, etc.), a DEV may assume the following roles:

- *Master*: controls the TDMA frame and synchronises/coordinates active DEVs within the WF-LAN by assigning resources to the other DEVs. It also exchanges data with other DEVs.
- *Slave*: is a generic DEV handling data exchange towards or from other DEVs. A Slave sends to the Master the status of its connections.
- *Gateway*: performs layer 3 translation between WIND-FLEX and another system.

Figure 1 and figure 2 depict a possible scenario and the protocol pile between a Slave and a Gateway. When two Slaves are communicating, each protocol pile reaches the application layer in order to terminate the communication.

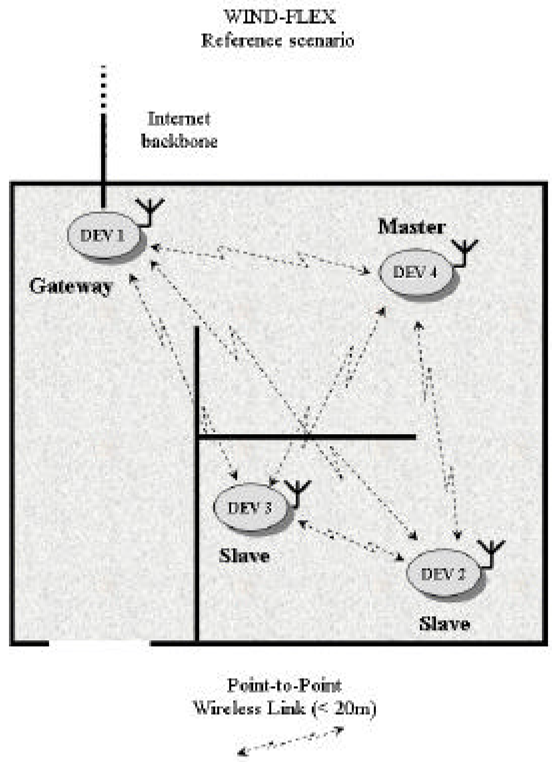

Figure 1: Reference scenario (SOHO environment)

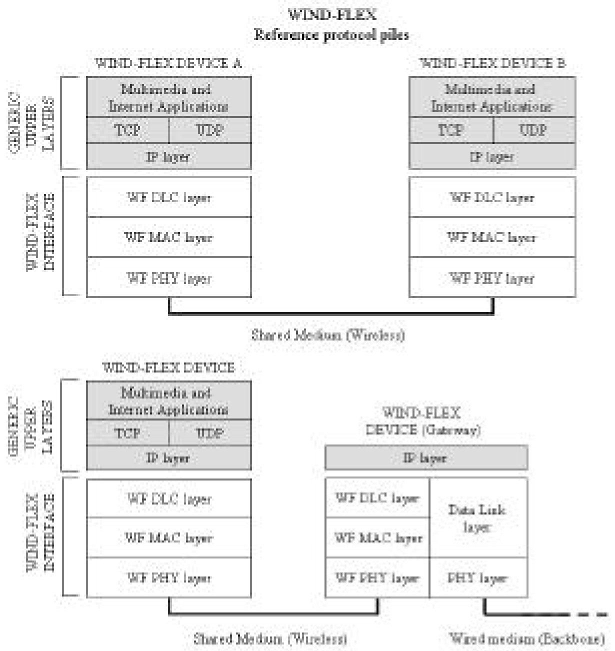

Figure 2: protocol pile of the WIND-FLEX system

Physical (PHY) layer services ensure dynamic adaptivity to time-varying requirements and channel conditions by using A-OFDM [5] and changing the modulations and the gains of the different sub-carriers according to the current link status. An efficient and innovative MAC/PHY interface is then required to support such PHY layer behaviour.

OFDM employs 128 sub-carriers, thus giving frequency non-selective fading for each sub-carrier in the indoor propagation environment at 17 GHz and justifying low-complexity channel estimation and equalization algorithms.

96 sub-carriers transport data and the others contain the cyclic prefix. The useful OFDM symbol part duration is 2.56 µs. Channel code has not been yet decided but a 1/2 convolutional code is assumed here. Flexibility with respect to the channel status is obtained by assigning to each sub-carrier a different number of bits and a different modulation (BPSK, 4-QAM, 16-QAM or 64-QAM), adaptively chosen according to the measured SNR and BER so as to minimise the Average Bit Error Rate.

PHY and MAC layers cooperate to exploit link capabilities and to spread control information over the network.

2. THE MAC LAYER

MAC layer performs all services concerning synchronization and radio capacity sharing among DEVs. This involves the managing of user data and the spreading and handling of the control and signalling information required to perform network coordination and to take decisions regarding, for example, MAC slot assignment.

A User plane (U-plane) and a Control plane (C-plane) are identified. For the U-plane, the main services offered by the MAC are: Transfer of user data, Mapping of logical channels onto transport channel and Spreading and Recovering of control information required by the Scheduler. The main service carried out by the C-Plane is the *Scheduler*. In order to regulate the resource assignment among DEVs, the Master stores some parameters concerning the status of the active connections, which are transmitted through the radio interface, and elaborates them to find the best frame division.

The Scheduler assigns the TDMA slots to the active connections by using their status information. It dynamically manages link capacity according to some parameters exchanged by the DEVs and regarding the status of the active links, with the goal of minimising the number of assigned control slots while ensuring efficient and reliable communications among DEVs.

The DLC receives such parameters from the MAC, associates them to the different connections and employs them for Congestion Admission Control (CAC) purposes, accepting or rejecting an incoming connection according to the actual available system resources. The IP packets of the admitted data flow are encapsulated into a DLC packet and transmitted to the MAC through the pertaining Service Access Point (SAP).

MAC protocol operates in a slotted environment using a dynamic reservation TDMA scheme with asymmetrical TDD. The entire frame is not divided into uplink and downlink. Groups of slots are assigned to the established links whose boundaries moved according to traffic load. The frame has period T_f and is divided into N_s slots having length T_s equal to OFDM symbol interval.

The *propagation delay*, i.e. the round-trip interval between a DEV pair, is about 120 nsec for a maximum DEV distance of 20 m and is small

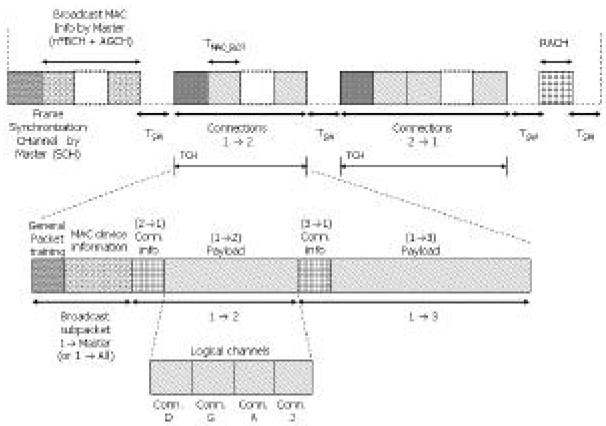

Figure 3: MAC frame structure and transport channel structure

3. THE MAC FRAME

As shown in Figure 3, the frame is composed by different groups of channels described here in the following. The ***Frame Synchronization Channel*** (**SCH**) contains frame synchronisation patterns.

The ***Broadcast Channel*** (**BCH**) reports information about slot usage in the next frame. A *frame division sub-period* informs the Slave(s) about such slot assignment, while an *access grant sub-period* is used by the Master to transmit the reply messages pertaining to the association and to the link and connection set-up procedures, and also to spread some other broadcast information.

The ***Random Access Channel*** (**RACH**) is used by the Slaves to associate to a cluster, following an *association procedure*, and to set-up a connection with another DEV, via the *connection set-up procedure*. A procedure similar to Aloha is adopted to avoid collisions in these slots. All these slots are transmitted at high power level using BPSK modulation with 1/2 turbo coding.

The ***Transport Channel*** (**TCH**) is employed to transmit the data packets. It is constituted by a variable number of slots (as decided by the Scheduler) transmitted by a source DEV and containing connections for *n* different destination DEVs. As shown in Figure 3, the same TCH may carry many link-specific parts, each one having the same structure but pertaining to different connections.

4. THE MAC SCHEDULER

In order to provide a reactive QoS, the Scheduler performs deterministic multiplexing for variable bit rate traffic based on the Earliest-Deadline-First (EDF) technique [7], which is worst-case optimal. It reaches optimal efficiency for guaranteeing the delay to all the active traffic flows, which are managed in the same way by considering only the "packet time left" (difference between the due date of a packet and the current time).

When a large number of connections are served together in the same frame (in particular, if they are transmitted by different source devices) resource wasting is large. In fact, the number of control slots is given by:

$$N_{control} = \sum_{i=1}^{N_{switch}} \left(N_{slot\_synk} + N_{slot\_MAC\_status} + N_{slot\_link} \cdot N_{link,i} + N_{slot\_Tsw} \right) \quad (1)$$

where N_{switch} is the number of transmission/reception switches (not necessary the number of different source devices), N_{slot_synk} is the number of slots carrying packet training symbols, $N_{slot\_MAC\_status}$ is the amount of slots used to transmit broadcast control data, N_{slot_link} is the number of slots that are useful to the receiver physical layer for knowing modulation and power gain patterns, $N_{link,i}$ is the number of different link involved in the ith TCH and, finally, N_{slot_Tsw} is the number of silence slots between two consecutive TCHs.

A first optimisation suggested by Eq.1 is to group the connections the Scheduler allows transmitting, so that there is an unique TCH per each source. This task is carried out by the Scheduler at the end of the algorithm and reduces the wasted slots as:

$$N_{control} = \sum_{i=1}^{N_{senders}} \left(N_{slot\_synk} + N_{slot\_MAC\_status} + N_{slot\_link} \cdot N_{link,i} + N_{slot\_Tsw} \right) \quad (2)$$

where $N_{senders}$ is the number of different source devices which now employs an unique TCH. In comparison with Eq.1, this is indeed an improvement, because $N_{senders} \leq N_{switch}$.

A further improvement can be obtained by changing slightly the Scheduler behaviour to reduce $N_{senders}$ and $N_{link,i}$ by assigning them more slots than before. This makes possible the further reduction of control and silence slots, as deduced by Eq. 2. For this purpose, the Scheduler bases its work on a restricted group of parameters that are used to describe the instantaneous behaviour of the established connections. These attributes do not change during the connection life and are:

$d(i)$: Static Priority associated to the ith connection;

$J(i)$: ith connection lifetime, which can be different among connections.

Slaves periodically send to the Master the information regarding the transmission buffer where the Slave stores the incoming packet. Every time a Slave transmits a packet belonging to a particular connection, it builds related MAC packets and then reads the status of that connection sending the following information:

$S(i) = \dfrac{D(i,j) - T_{Current}}{T_{frame}}$: corresponds to the Time-left of the packet at the head of the ith buffer before expiring its due date. It expresses the number of frames before the expiring of the due date of the first queued packet. The Scheduler needs this information, which is sent by each Slave using n_1 bits.

$L_{first-pack}(i)$: is the length of the packet at the head of the ith buffer which corresponds to the ith connection. This information is coded and transmitted using n_2 bits which denote the number of slots which compose the packet according to the particular link status.

$L_{remainig-buffer}(i)$: denotes the length of the ith buffer without considering the first queued packet which corresponds to the ith connection. This information is coded and transmitted using n_3 bits.

A Slave is able to compute the last parameter storing the due date $D(i,j) = t_0(i,j) + J(i)$ of the jth packet of the ith connection, where $t_0(i,j)$ is the arriving time of the jth packet of the ith connection.

The due date is calculated adding the associated lifetime to the arriving time of the incoming packet.

Whenever the Scheduler performs its tasks, it draws up a list of "winners" where, arranged by a "score" (SC), are reported all the connections together with the number of a possible slots assignment.

The SCs are assigned by the Scheduler, having SC_{min} and SC_{max} as lower and upper thresholds respectively. On the basis of the connection class, the SC is assigned using a different expression, i.e.:

$$s_{real-time}(i) = \frac{2^{n_1} - S(i)}{2^{n_1}} p_1 + \frac{L_{first-pack}(i)}{2^{n_2}} p_2 + \frac{L_{remaining-buffer}(i)}{2^{n_3}} p_3 \quad (3)$$

$$AS_{real\_time}(i) = RS(i) \cdot U_{slot} + \left| L_{remaining-buffer}(i) \cdot b \right| \quad (4)$$

where:

$$RS(i) = \begin{cases} L_{first-pack}, if & L_{first-pack} \leq 2^{n_2 - nl} \\ N_{useful\_slot}, & otherwise \end{cases}$$

U_{slot} and b are scalar factors

$P = [\ p_1\ p_2\ p_3\ ]^T$, with the constraint $\sum_{i=1}^{3} p_i = 1$, is the weight vector associated to each factor of the score formula. The Scheduler then assigns to each connection all the needed slots by adding other slots according to the occupancy of their buffers and to the temporal constraints they must respect. The Scheduler finally optimises Eq.2 by reducing the number of connections served in each frame.

5. SIMULATION RESULTS

WIND-FLEX has been simulated using OPNET and the Scheduler has been analysed in detail, with particular emphasis on the dynamic slot allocation. MPEG/2 streams based on UDP/IP protocol and WEB applications based on TCP/IP protocol stack have been considered as suitable test data streams. MPEG/2 is typical of a video source like DVD or Video CD player: the classic AR model [8], [9] has been employed with parameters tuned on the basis of the analysis in [8] and summarised in Table 1.

Figure 4 shows a typical video source behaviour. WEB sources have been modeled as in [10] by a sequence of activity period, as typical of a WEB page download. Sub-sequences are also present due to the transfer of elements like the HTML body or images. The main WEB source parameters are reported in Table 1, whereas a typical traffic behaviour is sketched in figure 5.

The main simulation parameters are listed in Table 2. Error-free transmission, 64-QAM modulation and coding rate ½ are assumed, so that each slot is filled with 288 bits and the resulting bitrate is 112.4 Mbps. A simulation run emulates an activity of 3 minutes.

Different numbers of DEVs and connections have been considered. For a given number of connections, a few slots are expected to be employed for both control information and silence when a few DEVs are active, as also assessed by Eq.2. Similar behaviour is expected when, for a constant number of DEVs, the number of active connections varies. MAC frame occupation due to slots carrying both data and control packets is reported in Figure 6 for three and six active DEVs. From Figure 6, the relationship between the number of served connections in a frame and the amount of control slots reserved by the Scheduler can be stood out. In fact, when many connections are active and each of them is characterised by small bit rate and no stringent delay requirements, then many of them are simultaneously served in the same frame and lots of resources are wasted due to control and silence slots. From Figure 6 it is also observed that, for the same number of connections but larger number of active DEVs, more resources are devoted to transmit control information.

Figure 7 shows the mean slots assignment pertaining to data and connection slots, as well as the number of connections served in each frame, as a function of the total number of active connections.

The number of DEVs is fixed (3, 4, 5 and 6 respectively). From the figure the number of wasted slots increase when the system handles many connections. However, the correspondent values are considerably less than the value which can be computed from Eq.2.

Application parameters	***Webs***	***Video***
Average bit rate per connection (Nominal Values)	14500 bps	1.133 Mbps
Average IP datagram length	12000 bits	12000 bits
Statistical distribution which represents the IP datagram length	Exponential	Uniform
Average interarrival time between consecutive IP datagram	0.3 secs	10.6/8.1/5.6 msec (B/P/I frame)
Statistical distribution applied for representing the interarrival time between consecutive IP datagrams	Uniform	Depending on packet length (Exponential) and data rate (Gaussian)

Table 1: Main parameters used to model the applications

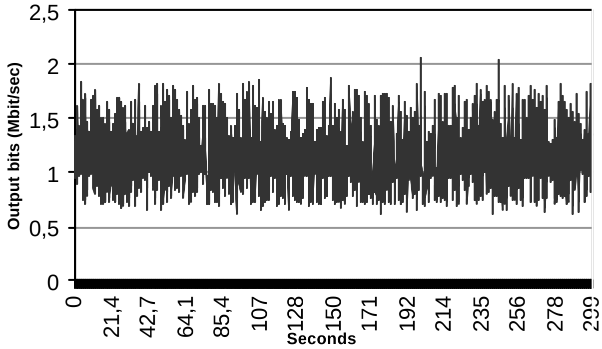

Figure 4: Temporal behaviour of the output bits from a video source

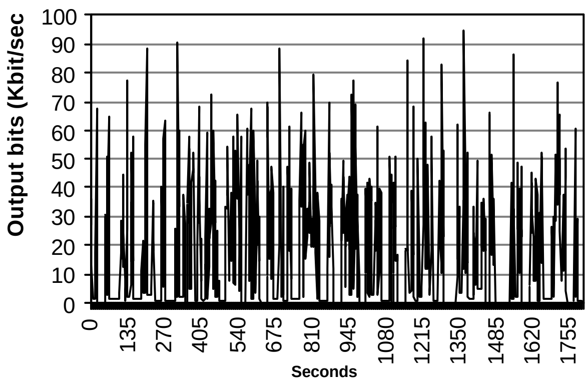

Figure 5: Temporal behaviour of the output bits from a web source

Simulation Parameters	*Value*	*Simulation Parameters*	*Value*
Frame duration	455.7 μs	$N_{slot\_MAC\_status}$	One slot every three served connections in TCH
Slot duration	2.56 μs	N_{slot_link}	1 slot
Bit per slots	288 bits	N_{slot_Tsw}	2 slots
Number of slots per TDMA frame	178 slots	Number of devices	[3,6] devices
Packet lifetime $J(i)$	0.08 s	Number of connections	[6,60] connections
Number of slots used for transmitting TCHs	150 slots	Percentage of MPEG/ WEB connections	60/40 %
N_{slot_synk}	1 slot	Simulation time	3 minutes

Table 2: System parameters used in the performance evaluation

In order to support this point, in Figure 8 the simulated results for the case of three active DEVs are compared with the theoretical values given by Eq.2. The scheduling algorithm does improve global performance: as the theoretical results show, a non-optimised system would have a capacity loss ranging from 14% to 60% while the proposed Scheduler exhibits a loss around 12.5%.

Referring to the case of 3 active devices in Figure 7, the mean MAC frame occupation for control slots exhibits a 'hump', with a maximum when 48 connections are active and then (slightly) decreasing. This reflects the circumstance that the Scheduler attempts to maximize global performance by assigning more slots to each selected connection.

In fact, under high traffic conditions the global buffer occupancy gains more importance and decreases (indirectly) the number of served connections per frame, thus giving better performance.

The same happens when 4,5 or 6 DEVs are active, when the hump corresponds to much less active connections: when the system is loaded with a large number of DEVs and established connections, the Scheduler has more degrees of freedom for obtaining the optimum slots assignment in every frame. From Figure 7 the worse global performance is attained when a larger number of DEVs is active.

In the worst condition simulated (six active DEVs) the capacity loss does not exceed 29% of the total slots used for the TCHs, so that the system can reach the capacity on the basis of the network status, as shown by Figure 9.

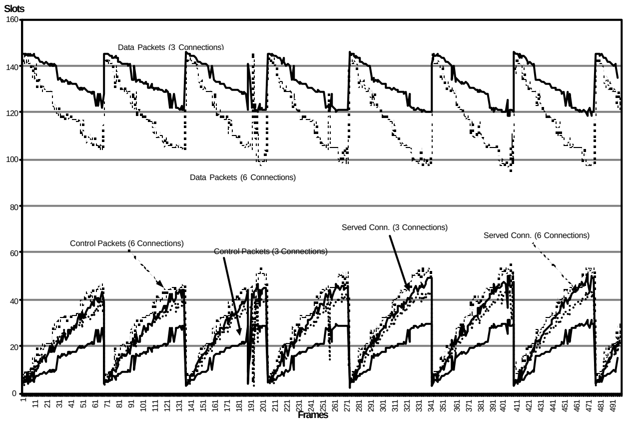

Figure 6: MAC frame occupancy with three and six active devices

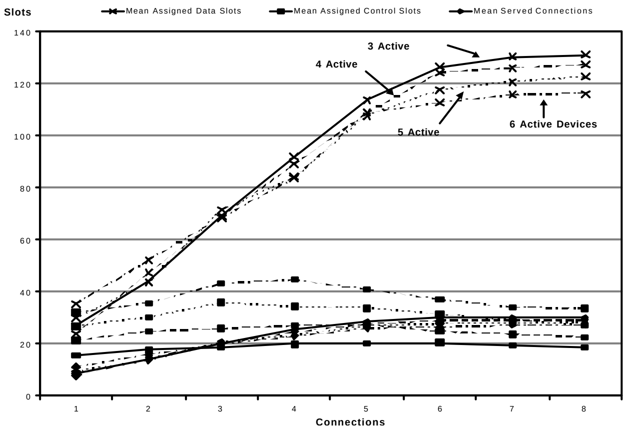

Figure 7: Mean MAC frame occupation with three, four, five and six active devices

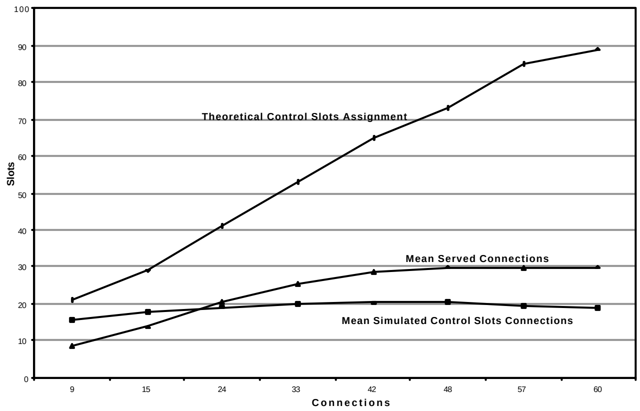

Figure 8: Comparison between theoretical and simulated control slots, with three active devices

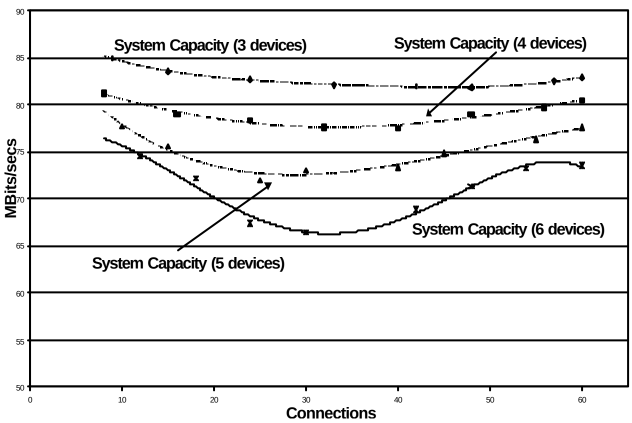

Figure 9: System capacity available for data, with associated best-fitting curves

6. CONCLUSIONS

The WIND-FLEX W-LAN has been described with particular emphasis on MAC and Scheduler. The efficiency of the proposed solution has been evaluated, showing its ability to support high traffic load with reduced performance loss. WIND-FLEX It is then candidate as a viable solution for future fourth-generation WLANs.

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