MAC Design Considerations for Patient Personal Area Networks and an Implementation Approach

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Abstract— **One of the most interesting modern trends in healthcare sector involves the provision of telemedicine services based on medical sensor networks. The relative infrastructure, also referred to as patient Personal Area Network (pPAN), enables a new way for continuous and real-time monitoring of vital biosignals, without discomforting the person in mind. The inherent features and requirements of pPAN constituting nodes, as well as the prospected functionality of patient telemonitoring applications raise the demand for a thorough consideration of the communication protocol that supports the operation of such networks. Having as a compass the main attributes of the most commonly used medical sensors and the typical functionality of pPANs, this paper focuses on some major design considerations of medium access control (MAC), which comprises an essential part of the communication protocol. It also presents pPAN-MAC, an implementation approach especially designed for pPAN applications, and evaluates some aspects of its' functionality.**

I. Introduction

Patient Personal Area Networks is one of the most emerging and powerful means for health monitoring, which shifts healthcare provision environment from traditional facilities, such as hospitals and medical centers to virtually every place the patient is able to go. Normally, they consist of numerous medical sensor nodes, attached to patients' body, and a general purpose node, which supervises the local network and bridges the gap between patient and the pPAN monitoring centre.

From a technical point of view there are two main directions in the deployment of pPANs; the first is concerned with adopting mature and widely available standardized technologies, such as IEEE 802.15.1 [1] (Bluetooth) and IEEE 802.15.4 [2]. These technologies define a fully functional physical and data link layer mechanism and provide varying quality of service (QoS) to the higher network layer (HNL), features which render them an attractive solution for many pPAN applications.

The second direction is concerned with implementing customized, RF based solutions, and intends to accommodate the communication protocol to pPAN application specific requirements. The advantage of such implementations is that the designer has the ability to decide on the balance between qualitative and quantitative parameters and build application specific functionality, instead of facing the pPAN communication infrastructure as a black box.

In the context of this paper we focus on the later pPAN deployment direction; in section II, we investigate the main design considerations of a MAC protocol designated for pPAN applications. Then, in section III, we present the main features of pPAN-MAC, a MAC protocol whose functionality is oriented towards the accomplishment of fundamental requirements of typical pPANs; in section IV we evaluate indicative proposals of the protocol; and, finally, we conclude our paper in section V.

II. pPAN MAC Design Considerations

A. *pPAN topology*

By definition, pPANs are deployed in the area near the body of the patient. Normally, they consist of medical sensor nodes, which are either externally worn or implanted in patient's body, and a supervisor node, which may be embedded on a mobile phone (e.g. [3]), a PDA (e.g. [4]), a wearable computing system (e.g. watch-alike gadget in [5]), or another prototype device.

The functionality these networks aim at, as well as their typical architecture, render star topology the most appropriate for pPAN applications. Two reasons support such a choice; firstly, the nature of information handled by pPANs does not necessitate for the existence of communication links among each pair of nodes. Only the supervisor is actually interested on the information recorded by the sensor nodes and, additionally, it is the only one responsible for initialization, maintenance and control of their operation.

Secondly, it would make no sense to maintain communication links among sensor nodes, unless in order to retrieve efficient communication paths between remotely placed nodes. In most pPAN applications, however, the network consists of a rather limited number of nodes, placed close together and facing almost the same signal propagation conditions. The implementation of complex topologies (e.g. mesh) for such a network architecture and the consequential demand for appropriate routing processes would rather overkill the processing and energy resources of the sensor nodes, with no added value for the network operation.

Having said that, in the following analysis we fix on star topology and we use the nomenclature according to which medical sensor nodes correspond to slave nodes while the

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supervisor node corresponds to the master of the pPAN.

B. pPAN nodes data rates

The data rates produced by pPAN nodes mainly depend on:

- The nature of recorded signal and its' monitoring parameters (frequency range, sampling rate, resolution, number of leads, when considering ECG or EEG, etc.),
- The ability of the nodes to locally process recorded measurements (transmission of raw data, filtered data or of the processing output, only),
- The specific patient monitoring protocol requirements (measurements execution frequency, measurements length, notification of major only alterations in signals, etc.)

The last two criteria are totally subjective and thus, it is unrealistic to be taken into consideration, when quantifying pPAN nodes data rates. For this reason we focus only in the first criterion. Table I summarizes the minimum, typical and maximum values of data rates for the most commonly used medical sensors, based on respective values of each signal's monitoring parameters [6]. Since the communication link in pPANs is rather asymmetric, with most traffic flowing uplink, from patient's side to the pPAN monitoring centre, we make the assumption that the master node produces on average a 10% portion of medical sensors data rates.

TABLE I
INDICATIVE DATA RATES OF COMMONLY USED PPAN NODES

pPAN nodes	Data rate (kbps)		
	min	typical	max
ECG	1	12	192
SpO_2	0,24	0,72	1,28
EEG	8	24	48
Gyroscope	0,8	0,8	1,6
Accelerometer	0,8	2,4	4,8
NIBP	2	5	10
Glucose	$5,4 * 10^{-5}$	$5,4 * 10^{-5}$	$5,4 * 10^{-5}$
Temperature	$2,7 * 10^{-5}$	$2,7 * 10^{-5}$	$2,7 * 10^{-5}$
Master node	~1,28	~4,82	~27,7

C. pPAN nodes' transceiver duty cycle

In several applications, the executed patient monitoring protocol does not necessitate for continuous information upload; it is rather oriented towards occasional transmissions, either scheduled or unscheduled, solicited by the pPAN monitoring centre or unsolicited, due to a measurement threshold exception. Such functionality means that the MAC protocol should be possibly designed to handle only sporadic and bursting traffic.

Under this context, the definition of static and extended duty cycle for pPAN nodes' transceiver is a rather inefficient design solution. Contrarily, an elegant pPAN MAC protocol feature would be to have the transceivers operate in stand by mode for the majority of time and wake them up only and exactly when necessary to handle information. The resulting dynamic and limited transceiver duty cycle would affect positively pPAN energy efficiency, given that it would bound the operation of this power-demanding component.

D. pPAN MAC energy efficiency

We have implied in previous section that energy efficiency is an essential prerequisite for a qualitative MAC protocol. This happens because excessive energy demands increase battery capacity requirement, which in turn increases its dimension and therefore the overall system size and weight. Moreover, battery life is shortened and thus, frequent replacement is necessary, resulting on reduced user's acceptance and rapid de-activation of implantable sensors.

Several research studies (e.g. [7], [8]) conclude that the major steps towards the design of an energy-efficient MAC protocol are:

- The avoidance of collisions; the simultaneous transmission from more than one node and the consecutive retransmission need, lead to undesirable energy wastage and reduce the throughput of the system. Therefore, the MAC protocol should be such that it eliminates collisions' occurrence.
- The avoidance of idle listening; the transceiver consumes virtually the same energy while operating in receiving mode, no matter what the channel activity status is. This bears out the importance of designing a medium access technique with very limited idle listening.
- The implementation of transmission power management mechanism; energy outspending due to lack of dynamic determination of transmission power level affects badly energy efficiency. Sophisticated and dynamic selection of this level is necessary to handle information between pPAN nodes without wasting energy.

E. pPAN MAC frames categorization and importance classification

The MAC process which is responsible for MAC frame preparation and transmission, may receive simultaneously numerous requests from either HNL or other MAC processes; each request has varying importance and criticality in terms of sound network operation and efficient patient monitoring. In a typical pPAN use case, the sensor nodes periodically compose and transmit MAC frames, carrying their measurements or just a notification of the condition of the recorded signal (e.g. normal, no alteration). Moreover, the pPAN master node exchanges with sensor nodes MAC frames, related to the establishment and maintenance of communication links and the access to the medium. All these MAC frames are characterized as *typical MAC frames*.

We have already mentioned that in the context of pPAN applications, exceptional transmissions may also occur. For example, a sudden deterioration of patient's health should trigger an alarming notification to the pPAN monitoring centre. We characterize the respective MAC frames as *critical MAC frames*.

The above mentioned categorization is denotative of the varying importance of the transmission requests which are handled by MAC layer and reflects the need for a transmission priority mechanism.

III. Proposed Methodology

A. Medium access policy

pPAN-MAC protocol is based on the assumption that the nodes that constitute a pPAN share a single communication channel. Given this, its' medium access policy combines functional characteristics of TDMA-like and CSMA/CA-like protocols.

In particular, it defines four types of timeslots:

- *Transmission slot* (TX slot); only during such a timeslot transmission can take place,
- *Reception slot* (RX slot); only during such a timeslot reception can take place,
- *Stand by slot* (SB slot); the transceiver operates on stand by mode and no activity takes place in the medium,
- *Receive to synchronize slot* (RXS slot); it is a type of RX slot implemented in slave nodes only, and is used before, and in order for the slave to get synchronized with the master.

The alteration of timeslots is such that, when master operates in transmitting mode all the slaves operate in receiving mode and the opposite. All pPAN nodes operate in stand by simultaneously. The duration of the first three types of timeslots equals to T_{SLOT}, whilst RXS slot lasts $3T_{SLOT}$. This value ensures that, whenever a slave needs to get synchronized with the master and executes RXS-SB slot alteration, it will definitely operate in receiving mode until at least the next TX slot of the master.

The access to the medium by pPAN slave nodes is also ruled by a variant of Request to Send – Clear to Send (RTS-CTS) scheme, used in several CSMA/CA-like protocols (e.g. [9], [10]). The basic idea remains the same: a slave can use the communication channel only when the master grants it the right to do so. For this purpose pPAN-MAC defines the *Token Request* and *Token Grant* MAC frames. These frames also carry information related to the number of requested and assigned TX slots, since slotted timeline renders possible the chance that a slave needs more than a single TX slot to upload its' pending information. By this way pPAN nodes are averted from flooding the medium with RTS-CTS frames and therefore the throughput of the system is not affected significantly by excessive control MAC frames exchange.

It is also worth to be mentioned that, since carrier sensing is not a standard feature in the context of pPAN-MAC, pPAN slaves get aware of *Token Request* frames collision, only after not receiving a *Token Grant* frame in the very next RX slot. In order to avoid collisions due to sequential attempts to acquire the token, pPAN-MAC de-correlates *Token Request* retransmission schemas by forcing slaves to back off for a random number of TX slots after a failed attempt.

Finally, the channel access authority assignment is announced to all the slaves through broadcast transmission by the master, and thus everyone is aware of the channel usage status and does not interfere to token holder's transmissions.

B. pPAN MAC frame format

In the context of pPAN-MAC protocol we define three types of MAC frames; *control frames* which only carry control information related to MAC layer processes, *data frames*, which only carry HNL payload, and *combined frames*, which merge the above types whenever possible in order to eliminate transmissions and increase system's throughput.

All the above MAC frame types have mandatory fields, composing the so called header, whilst the two later types also include payload and footer fields. In its general form pPAN-MAC frame consists of the following fields:

a. *Preamble*; it is a predefined bit sequence, used by the receiver to synchronize its clock with that of sender's and recognize the start of the header of an incoming frame.

b. *Destination pPAN id*; defines a unique pPAN address in order to prevent any two pPAN systems from interfering, if in close proximity.

c. *Destination/Source Node Address*; it carries destination address when transmission from master to a slave takes place, and source address in the contrary case. If broadcast transmission is executed, it carries a predefined value.

d. *MAC frame control*; it carries control information, such as:

- MAC frame type,
- MAC frame command (token request/assignment, poll request/response, link statistics request/response, acknowledgment),
- MAC frame retransmission serial number,
- Transmission power level,
- Acknowledge demand indicator, and others.

e. *MAC frame serial number*; it indicates the serial number of transmitted MAC frame,

f. *MAC frame ACK serial number*; it conveys the serial number of the frame, which is acknowledged,

g. *Data length*; it defines the length of the following field,

h. *Data*; it conveys HNL payload,

i. *CRC*; it conveys the cyclic redundancy check word calculated over the content of the previous field.

The total length of header and footer fields is 15 bytes, whilst the length of data field is variable.

C. Synchronized communication

Synchronization between the nodes of a network is a key demand when TDMA-like access policy is adopted; essentially it means that each node knows exactly when it should transmit or switch its' transceiver on receiving mode, in order to effectively exchange data. The accomplishment of synchronized communication can be based on several approaches: periodic, time-sensitive beacon transmission from master to slave nodes [11]; bidirectional, time-stamped MAC frame exchange to estimate the clock offset among communicating nodes [12], and others. Although very accurate, the disadvantage of many proposed methods is that they aggravate the communication channel with significant

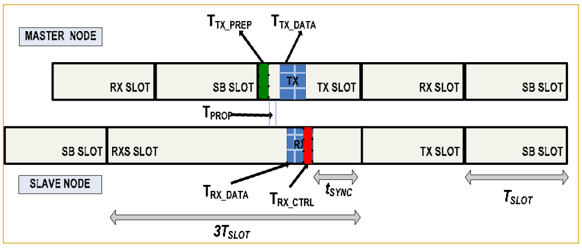

Fig. 1. Offset time calculation for pPAN nodes synchronization

amount of control traffic, generated exclusively in favor of getting and keeping synchronized.

In the context of pPAN-MAC, and aiming at elimination of control traffic, synchronization is not based on particular control frames exchange, but on proper exploitation of timing information extracted from regular frames exchange. In particular, during network setup the slave nodes alternate between SB and RXS slots. After the first successive reception of a MAC frame from the master, each slave calculates an offset time t_{SYNC} (Fig. 1), given by the equation:

$$t_{SYNC}= T_{SLOT}-(T_{TX\_PREP}+T_{TX}+T_{PROP}+T_{RX}+T_{RX\_CTRL}) \quad (1)$$

and switches to RX-TX-SB timeslot alteration. T_{TX} and T_{RX} are the transmission and reception times, respectively, depending on the MAC frame length and the transmission and reception rates, T_{TX_PREP} is the time needed for preparing the transmission, counting from the dawn of the TX slot and T_{RX_CTRL} is the time interceding between a frame reception and the termination of its' processing procedure. For a more thorough estimation of t_{SYNC} the above equation should also include propagation delay; when considering pPAN applications, however this is negligible due to the very limited internodes' distance and for this reason we make do with the above formula.

D. Transceiver low duty cycle operation

Aiming at having the transceiver operate in low duty cycle, pPAN-MAC embodies the following functional characteristics:

- It defines the SB slot which results in an initial reduction of duty cycle by 33%,
- It switches off the transceiver during RX slot, if no activity is detected in the medium at the dawn of the slot. Taking into consideration the synchronization uncertainty due to clock drifts, the above mentioned time interval is set to $1\%T_{SLOT}$; thus, the transceiver operates in stand by mode for $99\%T_{SLOT}$, during RX slot, if no activity occurs in the medium.
- If the physical layer detects activity in the medium during RX slot, the MAC layer executes the so-called packet-sensing: it decodes and analyzes in real-time the incoming bit stream and if it does not track down successively the node's source address or if the MAC frame is not of broadcast type it switches directly to stand by mode.
- During active TX or RX slots, it switches off the transceiver after the completion of transmission or reception, respectively.

The above described pPAN-MAC policy causes that the nodes keep their receiver in stand by mode virtually for the optimum time, resulting in very low duty cycle and respectively low power consumption.

E. Transmission power management

pPAN-MAC incorporates a transmission power management mechanism which is based on the following guidelines:

- For the transmission of MAC frames which are critical or do not claim for acknowledge, or carry acknowledge of critical MAC frames, the maximum power level is used,
- For all the other frames the transmission power level P_{TX} is decided upon the following criteria:

a) The current status of transmission power level $P_{CURRENT\_STATUS}$, concerning the targeted node,

b) The communication link quality, as it is estimated when combining statistics such as the number of correctly received/corrected/rejected MAC frames and the number of correctly transmitted/retransmitted/failed MAC frames, concerning the targeted node. These statistics are projected to the values of the variables $P_{SUCCESS}$ and $P_{FAILURE}$.

c) An offset value, P_{OFFSET}, which determines the difference between $P_{SUCCESS}$ and $P_{FAILURE}$ upon which pPAN-MAC increases or decreases the transmission power level.

Fig. 2 depicts the flow diagram of the proposed algorithm.

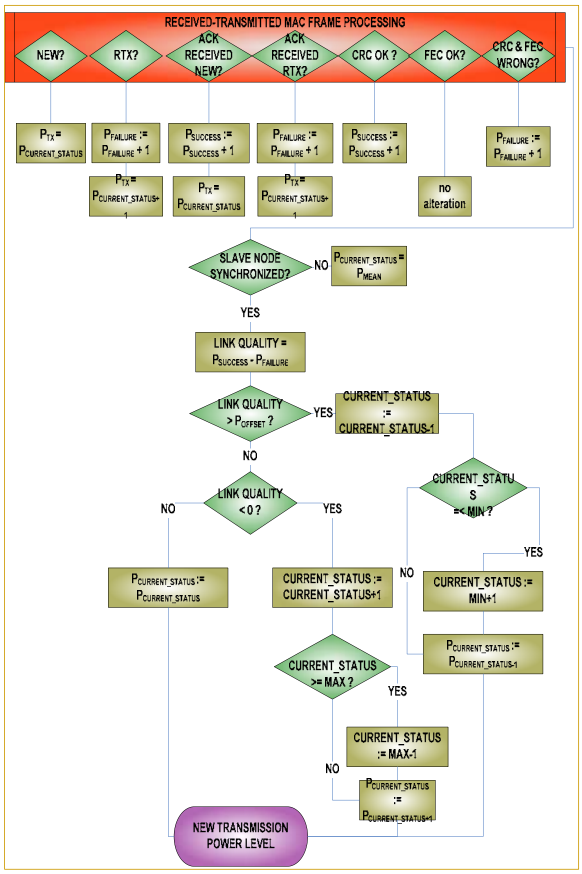

Fig. 2. pPAN-MAC transmission power management

IV. pPAN-MAC EVALUATION

A. Hardware infrastructure

For the evaluation of pPAN-MAC functionality, we set up a testbed network consisting of several slaves and a master node. The processor board of each node contains a microcontroller, the ultra low power Texas Instruments MSP430F149 [13], operating at 4 MHz, and a radio transceiver, the Nordic nRF2401[14], operating in the 2.4 - 2.5 GHz ISM band, and supporting data rates of 250kbps and 1Mbps and programmable transmission power level.

B. Evaluation of collision avoidance

The medium access policy defined by pPAN-MAC ensures that, under regular network operation, the following types of MAC frame transmissions are not subjected to collisions:

- All master nodes' transmissions, since it uses dedicated timeslots for its' transmissions,
- For slave nodes:

a) Typical MAC frames (all types), since for such transmissions the slave must be the token holder,

b) MAC frames which carry acknowledge or response to a request from the master; in such situations the slave is tacitly token holder.

On the other hand, pPAN-MAC does not guarantee collision free medium access in the following cases:

- For slave nodes, when they simultaneously transmit:

a) *Token Request* MAC frames,

b) Critical MAC frames,

c) Combination of the above.

It should be mentioned, however, that the occurrence of collisions does not have persistent character, since a node which suffers from this phenomenon in its first transmission attempt, postpones its first retransmission attempt for a random number of TX slots.

C. Evaluation of transceiver low duty cycle operation

We evaluate the contribution of transceiver low duty cycle operation, accomplished by pPAN-MAC, in protocols' energy efficiency. For this purpose we consider the following use case scenario: the monitoring protocol of a person having heart condition determines that every *f* times/h, the ECG sensor node must upload 30sec of raw data to the monitoring center. We calculate transceiver's energy consumption in a 1 hour interval, when using pPAN-MAC, a TDMA-like protocol (with 15 slaves and timeslot duration T_{SLOT}) and a CSMA/CA-like protocol.

Due to space limitations we omit to give analytical expressions of the energy consumption. We only itemize in Table II the quotas of the evaluation experiment. Interested readers are referred to [15] for further details.

TABLE II
PARAMETERS OF EXPERIMENT FOR THE EVALUATION OF THE CONTRIBUTION OF TRANSCEIVER LOW DUTY CYCLE OPERATION IN ENERGY EFFICIENCY

Parameter	MAC protocol		
	pPAN-MAC	TDMA-like	CSMA-like
T_{SLOT}	0,2 sec		
ECG data rate	12 kbps		
Transmission rate	250 kbps		
Transceiver current consumption			
@ TX	13,0 mA		
@ RX	18 mA		
@ SB	12 μA		
Exchanged MAC frames:	*when TSLOT = 0,2sec, then, for each data upload incident, the slave exploits entirely two TX slots and partially a third one.		
Data	3f	3f	f
Token Request	f	-	f
TokenResponse	f	-	f
ACK	3f	3f	f
Transceiver operation in:			
TX	T_{TX}=3f*T_{DATA} + 5f* $T_{CONTROL}$	T_{TX}=6f*T_{SLOT}	T_{TX}=3f*T_{DATA}+ 5f* $T_{CONTROL}$
RX	T_{RX} =T_{TX}	T_{RX}=225*T_{SLOT}	T_{RX}=3600- T_{TX}
SB	T_{SB}=3600- T_{TX}- T_{RX}	T_{SB}=3600- T_{TX}- T_{RX}	T_{SB}=0

Fig. 3 presents the calculated energy consumption for the three medium access techniques, when f=100; due to the transceiver low duty cycle operation, pPAN-MAC achieves almost an order of magnitude less energy consumption than the other two techniques. Moreover it can be seen that, contrarily to what happens in pPAN-MAC, in pure TDMA and CSMA/CA techniques the required energy funds are virtually independent of data traffic (as expressed by *f*), which denotes that such techniques are rather inefficient with reference to the occasional and bursting data traffic of pPANs.

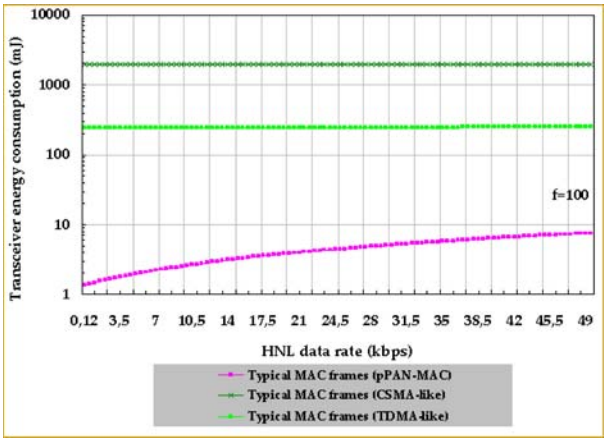

Fig. 3. Impact of transceiver low duty cycle operation in energy consumption, for different medium access techniques

D. Evaluation of transmission power management

In order to evaluate the efficiency of pPAN transmission power management technique ($P_{pPAN-MAC}$) we set up the following experiment: we establish a 10min session between a slave and the pPAN master, during which the former sends

TABLE III
EXPERIMENT PARAMETERS FOR THE EVALUATION OF pPAN TRANSMISSION POWER MANAGEMENT

Parameter	Value
T_{SLOT}	0,2sec
Number of experiment executions	20
Distance between communicating nodes	≤3m
Frequency of change of the relative position between nodes	1 per minute
Maximum number of exchanged MAC frames (optimum interconnection)	• 334 critical data MAC frames • 333 typical data MAC frames • 333 Token Requests • 333 Token Grants • 667 ACKs

to the later typical and critical MAC frames, alternately. Table III summarizes the experiment parameters. For comparison reasons we also run the above scenario using the following transmission power management techniques:

1. Maximum power for all transmissions (P_{ALL_MAX}),
2. Mean power for all transmissions (P_{ALL_MEAN}), and
3. Mean power for all except critical transmissions, for which we use maximum level (P_{MEAN_MAX}).

Fig. 4 presents the mean number of successful transmissions and the mean number of retransmissions for each type of exchanged MAC frame. As expected, the optimum interconnection is best approached by P_{ALL_MAX} technique, whilst the worse alternate is P_{ALL_MEAN}. What is worth to be mentioned is that although P_{MEAN_MAX} proves to support adequately high transfer rate of critical MAC frames -comparable with that of $P_{pPAN\text{-}MAC}$-, it does not succeed to handle as much critical MAC frames as $P_{pPAN\text{-}MAC}$; this happens because acknowledges of critical MAC frames in the context of P_{MEAN_MAX} are subjected to higher probability of damage, compared to $P_{pPAN\text{-}MAC}$.

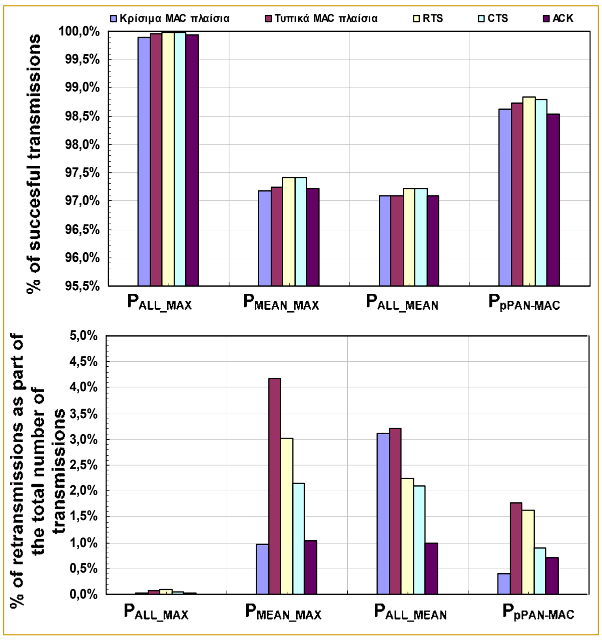

Fig. 4. Impact of transmission power management in quality of communications between a slave and the master

V. CONCLUSIONS

In this paper, we presented some major MAC protocol design considerations, with reference to the prospected functionality of typical patient Personal Area Networks.

Based on these considerations, we have designed and developed pPAN-MAC, the main functionality of which we also presented. Among its special features, and due to space limitations, we only evaluated pPAN transmission power management mechanism and transceiver low duty cycle operation. The results indicate that the proposed protocol bears up the efficient operation of pPANs, in terms of dependable accommodation of critical medical information and thrifty utilization of energy resources.

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