MAC Protocol Design and Performance Evaluation for Broadband Powerline Communication Networks

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I. INTRODUCTION TO PLC SYSTEMS

A. INTRODUCTION

The unparalleled growth of the Internet in the past ten years, combined with significant technological advancements in the fields of VLSI and digital signal processing and with the telecommunications market deregulation around the world, have made Power Line Communication (PLC) a viable technology for next generation telecommunications. With multiple power outlets in almost every room, everywhere, power lines are already the most pervasive network in the home or small office; therefore, they would be the preferred medium for providing broadband connection to rural or remote areas where telephone and cable connections may not exist. The market for PLC is two-fold: to the home, or "last mile" access, and in the home, or "last inch" access [1, 2]. The PLC access networks consist of a special transmission medium (low-voltage power supply network) providing limited data rates under the presence of an inconvenience noise causing disturbances to data transmissions. The above makes the design of PLC MAC layer protocols an important and challenging task, enabling the PLC to offer a wide palette of telecommunications services with a satisfactory user QoS. The relevant literature on the MAC layer protocols for PLC has focused more on in-home networking [3, 4]. The work presented in this thesis focuses on the "last mile" problem, and introduces novel transmission scheduling schemes which lead to significant improvements on the perceived user Quality of Service (QoS) and on reducing the packet delays in comparison to the Extended Aloha protocol [5, 6], for powerline networks with light and heavy channel disturbances.

B. PLC SYSTEM DESCRIPTION

Independently of the PLC network topology, the communication between the users of a PLC network and a Wide Area Network (WAN) is carried out over a base station, normally placed in the transformer unit. A transmitted signal sent in the downlink direction (from the base station to the users) is transmitted to all network subsections, and hence received by all subscribers. A signal sent in the uplink direction (from a user to the base station) is also transmitted to all other users in the network. Therefore, the PLC access network has a bus structure in spite of the fact that the low-voltage supply networks have physically a tree topology.

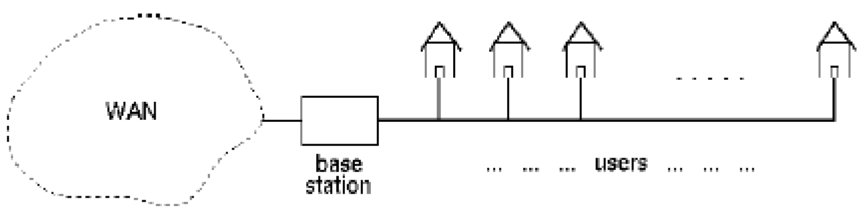

Figure 1. Logical Bus Topology of PLC Network

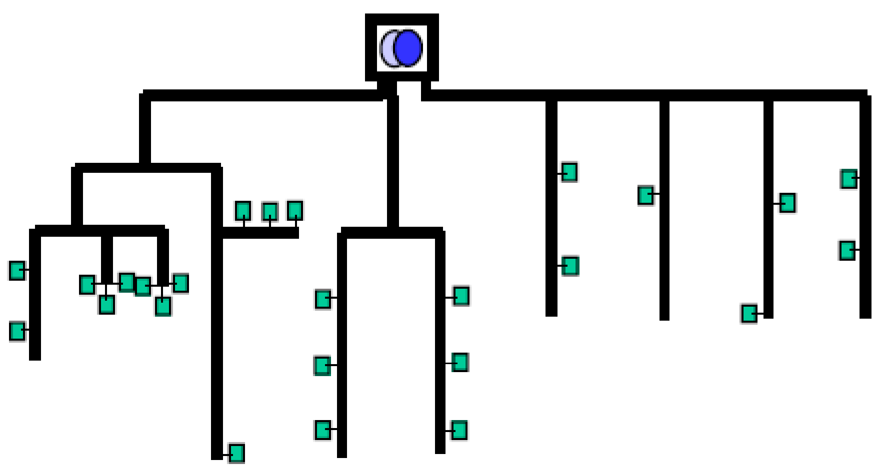

Figure 2. PLC Network Structure

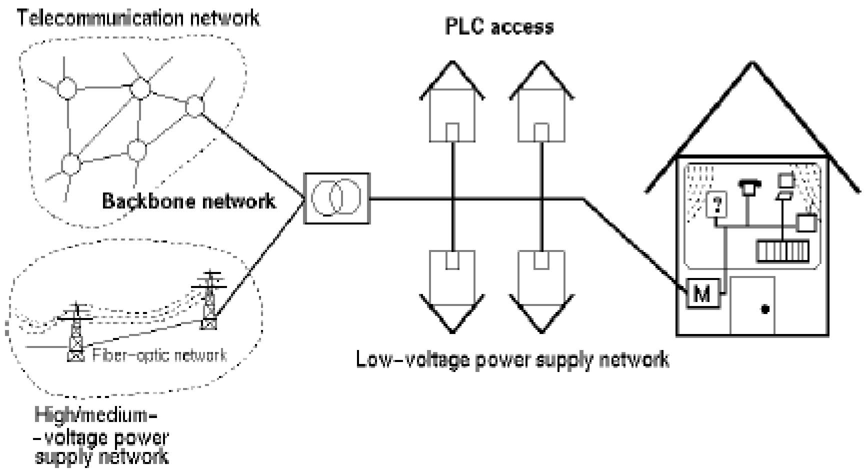

Figure 3. PLC Access Network

Orthogonal Frequency Division Modulation (OFDM) has been outlined as one of the best candidates for application in PLC systems with higher data rates, because of its excellent bandwidth efficiency [5-7]. OFDM provides data transmission over a number of sub-carriers, which makes possible the deviation from critical frequencies (the frequency selectivity degrades the quality of certain sub-carriers, however using OFDM we have the ability to decrease the bit rate in those subcarriers and increase the bit rate in other sub-carriers which are less affected from the frequency selectivity avoiding this way the critical frequencies).

As in [5, 6], we consider an OFDM transmission system which uses a number of sub-carriers distributed in a frequency spectrum as shown in Figure 4. Each sub-carrier (SC) has a transmission capacity and it is possible to form groups of sub-carriers to build up transmission channels (CH) with a higher capacity. In our study we assume that each transmission channel is slotted and has a data rate of 64 kbps and that the network consists of 15 bidirectional transmission channels, one of which is reserved for signaling.

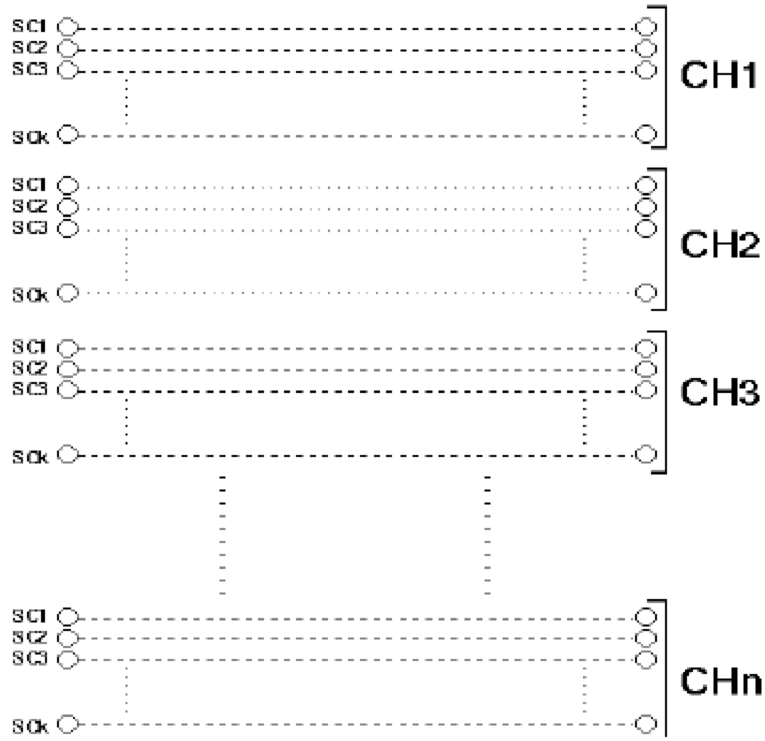

Figure 4. OFDM Channel Structure

The PLC transmission channel is characterized by strong attenuation, changing impedance and fading as well as by a strong noise level caused by various electrical devices connected to the supply networks. Since the asynchronous impulsive noise is the cause of most of the problems related to the correct transmission over the PLC network, it needs to be included in our study. The influence of the channel noise can be modeled by a two-state Markov chain in which one state represents the duration of an impulse, during which the channel is considered as disturbed and correct information transmission is impossible, and the other state represents the absence of noise and hence corresponds to the correct transmission of information. The duration of these two states can be represented by two random variables, each of which follows a negative exponential distribution [8].

As in [5, 6], we have considered in our work two types of channel disturbances in a PLC network (additionally to an ideal, non-disturbed network case): the light disturbances, in which the mean interarrival time of the noise impulses is 200 ms, and the heavy disturbances, in which the mean interarrival time of the noise impulses is 40 ms.

C. THE EXTENDED ALOHA PROTOCOL FOR PLC COMMUNICATION

The work presented in [5, 6] proposes three extensions of the basic ALOHA MAC protocol in order to improve its performance and make it applicable over a PLC network:

a) *piggybacking;* a terminal transmitting the last segment of a packet (message) can also use this segment to request for a transmission of a new packet, if there is one such packet in its queue. In this case the signaling channel is not used for the transmission of the user's request, therefore the request packet collision probability decreases, leading to a decrease in the user signaling delay and to higher network utilization, especially in the case of heavily loaded network. *The signaling delay* is defined as the time needed for the successful completion of the requesting procedure for the transmission of a packet; this procedure includes the transmission of a request message to the base station and the reception of its response regarding the transmission access rights of the requesting user.

b) *use of data channels for signaling;* in order to achieve the reduction of user signaling delay without a simultaneous reduction in network utilization, the authors in [5, 6] adopt the idea presented in [9] that any temporary idle information bandwidth can be used by the reservation procedure without allocating additional network resources for signaling. Hence, in [5, 6] additional data channels are used for signaling, but only if they are currently idle; otherwise, only the signaling channel can be used for the user reservations. Idle data channels are accessed randomly (with an equal probability) for the transmission of the user requests.

c) *application of an Adaptive Backoff Mechanism;* it is known that stabilization of Aloha based random access protocols can be achieved, if appropriate dynamic backoff mechanisms are used, i.e., if the mean retransmission time for a colliding user after an unsuccessful request is not fixed but varies dynamically. In [5, 6] the following backoff algorithm is used for user access to the signaling channel, as well as for user access to the idle data channels which are temporarily used by the network for signaling purposes.

When a new packet arrives at a terminal, a transmission request is sent immediately. In the case that the transmission of the request is not successful, a collision counter (CC) is incremented by one. The request retransmission time is computed from a retransmission interval (RI), the size of which depends on the value of the collision counter and the value of the BRI (Basic Retransmission Interval) constant, according to the following equation:

$$\mathbf{RI}[\text{TimeSlots}] = \mathbf{BRI} \cdot \mathbf{CC} \quad (1)$$

Hence, when the network is heavily loaded, a larger retransmission interval ensures a lower collision probability for the transmission requests. If the request transmission is successful, the collision counter of the corresponding user is decremented by one (as long as $CC > 0$) and the execution of the backoff algorithm for the particular user is finished. The calculated value of the CC during a request procedure is maintained by the user and is used as the beginning value of CC in the subsequent request procedure of the same user.

D. THE EXTENDED ACTIVE POLLING PROTOCOL

The work presented in [5, 6, 15] also proposes various extensions of the basic polling protocol in order to improve its performance over the PLC network. Polling protocols are appropriate when the network is heavily loaded. The polling procedure is realized by the base station which sends the so called polling-messages to each network station according to a round robin procedure. Only the station receiving a polling message has the right to send a transmission request. In such a scheme, collisions do not occur, however the transmission of a request can be disturbed by noise in which case the request packet must be retransmitted in the next dedicated slot.

The most advanced version of the PLC MAC protocol presented in [6] includes the following extensions described in section C:

a) piggybacking

b) use of data channels for signaling

c) application of an Adaptive Backoff Mechanism

Also as in [5, 15] active polling is used to reduce the round trip time of the polling procedure, which increases dramatically as the traffic load gets higher. This way only active users are polled while other stations are temporarily excluded from the polling cycle. The active users are potential data transmitters and the other stations do not currently send any data.

In our work we use only piggybacking and the use of data channels for signaling, but not the adaptive Backoff mechanism.

E. Outline

The outline of the Thesis is as follows. In Chapter II we present algorithmic modifications of the Aloha based MAC protocol for PLC aiming at improving its performance. In the same chapter we present representative simulation results which demonstrate the improved performance of the modified algorithm. Chapters III and IV introduce two new MAC protocols especially designed for PLC networks, based on reservation random access and polling access method, respectively. Through an extensive simulation study our protocols are shown to excel in terms of two key performance metrics (delays experienced by the users and channel utilization), compared to the protocols presented in [5,6]. Finally, Chapter V contains some ideas on how to extend the work in this Thesis.

II. CHAPTER – ENHANCEMENT OF THE ALOHA BASED MAC PROTOCOL

In this chapter we present new algorithmic ideas for the enhancement of the PLC MAC protocol presented in [5,6]. Our proposals affect the channel and slot selection procedures, making feasible for the enhanced PLC MAC protocol to provide improved performance in terms of user QoS, reduced packet delays and better exploitation of the available bandwidth comparing to the PLC MAC protocol presented in [5,6]. Our conclusions are supported by extensive simulation results.

A. PROTOCOL IMPROVEMENT

In our work, we adopt from [5, 6] the idea of piggybacking, and from our earlier work in [9] the idea of using idle data channels for signaling. However, we do not use the adaptive backoff mechanism proposed in [5, 6] for users to select the slot in which they will transmit/retransmit their requests; instead, we propose three new ideas, one of them regarding the channel selection mechanism and the other two of them regarding the slot selection mechanism for a PLC access network.

I. Channel Selection

We will use and compare two mechanisms for channel selection in our study. The first mechanism is similar to the one used in [5, 6] and is referred to in this paper as *Uniform channel selection*. With the use of this mechanism, each terminal which needs to access the medium selects uniformly one of the 15 channels (one for signaling and 14 for data transmissions); the only constraint is that the selection is made among channels which have at least one idle slot in the current channel frame (no transmission is scheduled in that slot from previous channel frames). If the channel is congested, it is not taken under consideration in the channel selection process for the current frame.

Our proposal for a second channel selection mechanism is referred to as *Weighted channel selection*. This mechanism works as follows. At the beginning of each channel frame the base station has full knowledge of the *total number of idle slots in all the data channels and in the signaling channel and conveys it to the terminals* (in the *Uniform channel selection* the number of idle slots of the selected channel is given to the terminal by the base station after the selection is made). Let this total number of idle slots be *S*. The probability for a terminal to choose channel Y, which has, e.g., 3 idle slots in the current channel frame in order to send its request, is *3/S***.** The respective probability for the signaling channel is equal to the total number of slots of the signaling channel divided by S (this happens because the slots of the signaling channel are by nature always idle at the beginning of a channel frame, as no information transmission takes place in them).

The *weighted channel selection* mechanism is designed in such a way as to "push" requesting users to choose, in every channel frame, with greater probability the channels with the larger number of idle slots, in order to decrease the probability of collision.

II. Slot Selection

After selecting a channel, a terminal needs to choose the slot in which it will transmit its request. We propose two different mechanisms for slot selection in our study.

The first mechanism is named *Uniform slot selection* and works as follows. After selecting a channel with M idle slots, the terminal attempts to transmit in the first of these slots with a probability *P*. If M=1, the probability is chosen by default to be equal to 50% (if the probability was set to 100% and more than one terminal chose the specific channel, a collision would be unavoidable). In any other case, the terminal transmits in each idle slot with probability P=1/M. In case of a successful transmission, a terminal acquires the specific slot for transmission in subsequent channel frames, while in the case of a collision the terminal continues to transmit in idle slots with the above-defined probability. If the channel frame ends without the terminal having succeeded in its request transmission, the terminal repeats the processes of channel and slot selection for every new channel frame, for as long as it needs to gain access to medium.

The second proposed mechanism for slot selection is named *Weighted slot selection* and works as follows. After selecting a channel with M idle slots, the terminal creates the following group of M probabilities: {1/M, 1/M, 2/M, 3/M, …, (M-1)/M}, and randomly associates each one of the idle channel slots with one of the probabilities in the group. If M=1, the probability is again chosen by default to be equal to 50%. The *weighted slot selection* mechanism aims at offering the chance to requesting terminals to transmit their requests sooner, by using much higher transmission probabilities than the *Uniform slot selection* mechanism (at the cost of a possibly larger number of collisions).

The results shown in the Figures 1-3 demonstrate the described behavior of the Weighted Uniform selection mechanism. **M** denotes the number of free slots in a certain channel frame and is shown in the horizontal axis. The probability for a terminal to select a particular free slot is shown in the vertical axis. At light to medium traffic (that means more free slots per channel frame, which corresponds to higher values of **M**) the Weighted slot selection technique makes terminals to select slot sooner at the cost of increased collisions. At high traffic load (that means fewer free slots per frame, which corresponds to lower values of **M**) the weighted algorithm behaves like the uniform way of slot selection.

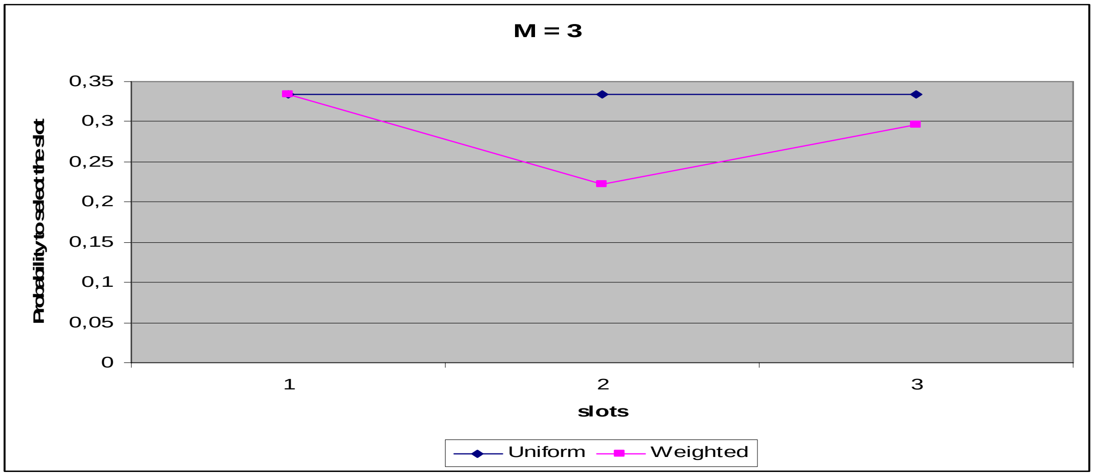

Figure 1. Comparison of the two slot selection schemes with 3 free slots in a channel frame.

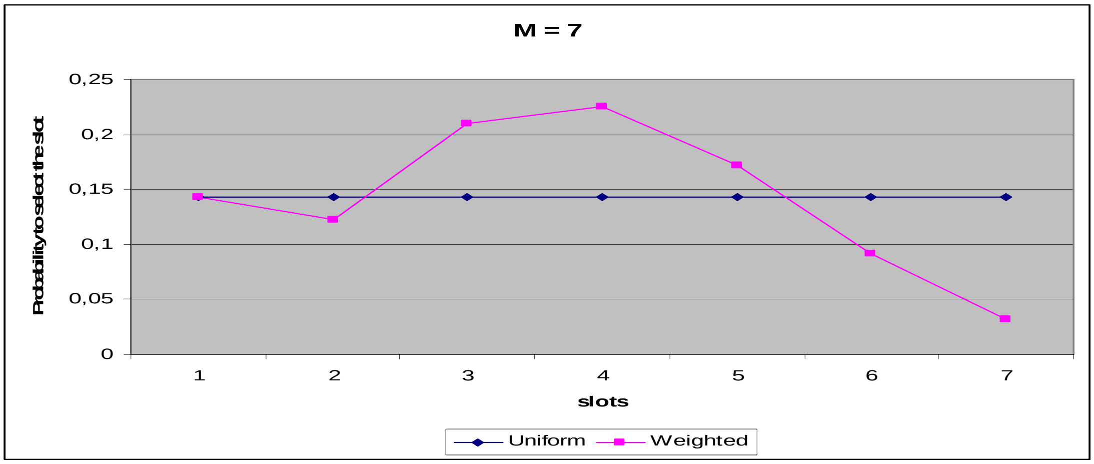

Figure 2. Comparison of the two slot selection schemes with 7 free slots in a channel frame.

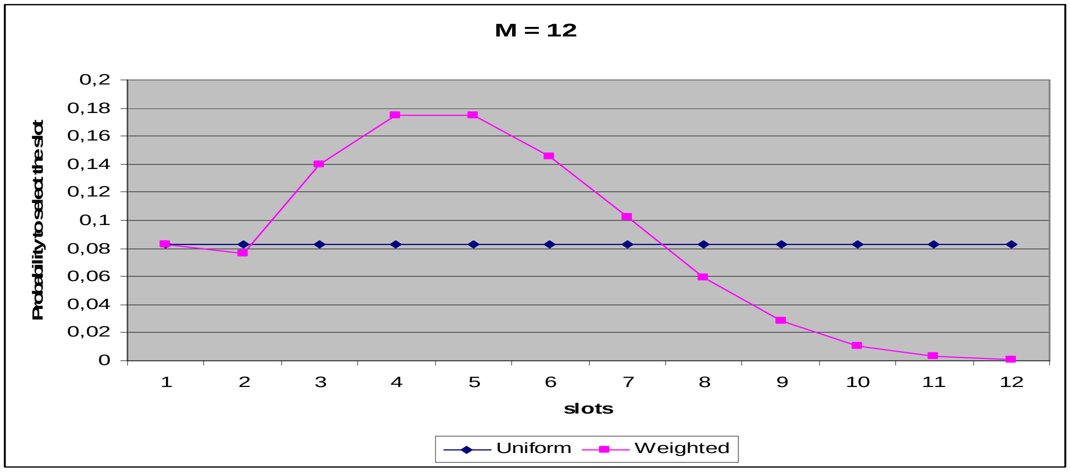

Figure 3. Comparison of the two slot selection schemes with 12 free slots in a channel frame.

Furthermore it is important that in all of the above cases the **LmP**

(Lost mass Probability, Uniform – Weighted mass probabilities),

$$\underbrace{\sum_{i=1}^{n} p_{Ui}}_{\text{Uniform Slot Selection}} - \underbrace{\sum_{i=1}^{n} p_{Wi}}_{\text{Weighted Slot Selection}}$$

has always very low value, as shown in Table 1, indicating that weighted selection algorithm ensures that a terminal will select one of the available slots with high probability.

The value 0.148149 for M = 3, means that if a terminal uses the Weighted Slot selection technique to select a slot within the current channel frame which has 3 unallocated slots, there is almost 15% chance that this terminal at the end of the particular channel frame will not have chose one from those three slots, in which case it will have to repeat the slot selection procedure in the subsequent channel frame.

M	LmP
3	0,148149
5	0,03072
7	0,005246
9	0,000832
11	0,000128
12	0,000049

Table 1.

With the use of our above-detailed ideas, four versions of our proposed MAC protocol will be examined: the Uniform-Weighted selection (U-W), referring to a *Uniform channel* and *Weighted slot* selection, the Uniform-Uniform selection (U-U), the Weighted-Uniform selection (W-U) and the Weighted-Weighted (W-W).

B. RESULTS AND DISCUSSION

The system parameters used in our work are taken from [5, 6], in order to make a direct comparison with that work, which focused only on data (Internet) traffic. The number of data terminals varies between 50 and 500. In [5], two average sizes of user packets are used; 300 bytes and 1500 bytes. Both cases are examined in our study as well. The case of 300-byte packets is important, since packet transmission in PLC should be made in very short frames so that the receiver can adapt to the rapid (< 1 ms) changes in the PLC channel conditions [10] (the mean interarrival time in this case is chosen equal to 0.96 seconds); this is the case defined in [5, 6] as the "frequent request case", which enables us to test our scheme under heavy traffic conditions, since the number of packet transmissions and, therefore, collisions in the PLC network can be significantly higher than in the case of 1500- byte packets. On the other hand, the case of 1500-byte packets is equally important, as when a message reception is not correct, the whole message (all packets in which it is segmented) has to be retransmitted; hence, the transmission of data in large messages under heavy network disturbances can be less advantageous (more packets' retransmission) than the case of transmitting data in small messages.

The offered traffic load per network station (terminal) is 2.5 kbps in both cases (the mean interarrival time in the case of 1500-byte packets is 4.8 seconds). The packet sizes and the interarrival times are geometrically distributed random variables.

As already mentioned, the number of transmission channels is equal to 15 (one of the channels is reserved for signaling), each with a data rate of 64 kbps. It should be noted that currently used PLC systems provide data rates around 2 Mbps; therefore, in this work we assume that in such a PLC system half of the network capacity is used by data connections.

The frame duration is 47 msecs, the slot duration is equal to 4 ms, the slot capacity is 32 bytes and the payload in each slot is 28 bytes. The frame duration divided by the slot duration results in 47/4 = 11.75 slots per frame which is not feasible. That is the reason that every four frames the frame duration is smaller, it has 11 slots and not 12 as normally in all other cases. We simulated one hour of network operation. Each simulation point is the result of an average of 10 independent runs (Monte-Carlo method).

I. Enhanced PLC MAC protocol Vs Extended Aloha based MAC protocol in a disturbance free environment

Figure 4 presents the comparison of our results (with the use of all four versions of our protocol) with the Extended Aloha protocol of [5, 6], in a disturbance-free PLC network with 300-byte packets. It is clear from the Figure that at low traffic loads the signaling delay (i.e., the time from the instance of message arrival at the terminal until the successful reception of the acknowledgement packet sent from the base station to the particular terminal, indicating that the base station has been informed that the terminal has data to transmit) achieved by all versions of our protocol is remarkably lower than the one achieved by the Extended Aloha protocol. It should be mentioned here that throughout the Thesis the delay results presented in Figures correspond to average delays. As the traffic load increases, the signaling delay naturally increases as well, due to the increase in the number of collisions in the network. Still, as shown in Figure 4, the signaling delay achieved by all versions of our protocol remains much smaller than that of the Extended Aloha protocol, by several hundreds of ms. When comparing the results of the four versions of our protocols, W-U selection achieves the lowest signaling delay for low-to-medium traffic loads and U-W selection achieves the lowest signaling delay for medium-to-high traffic loads.

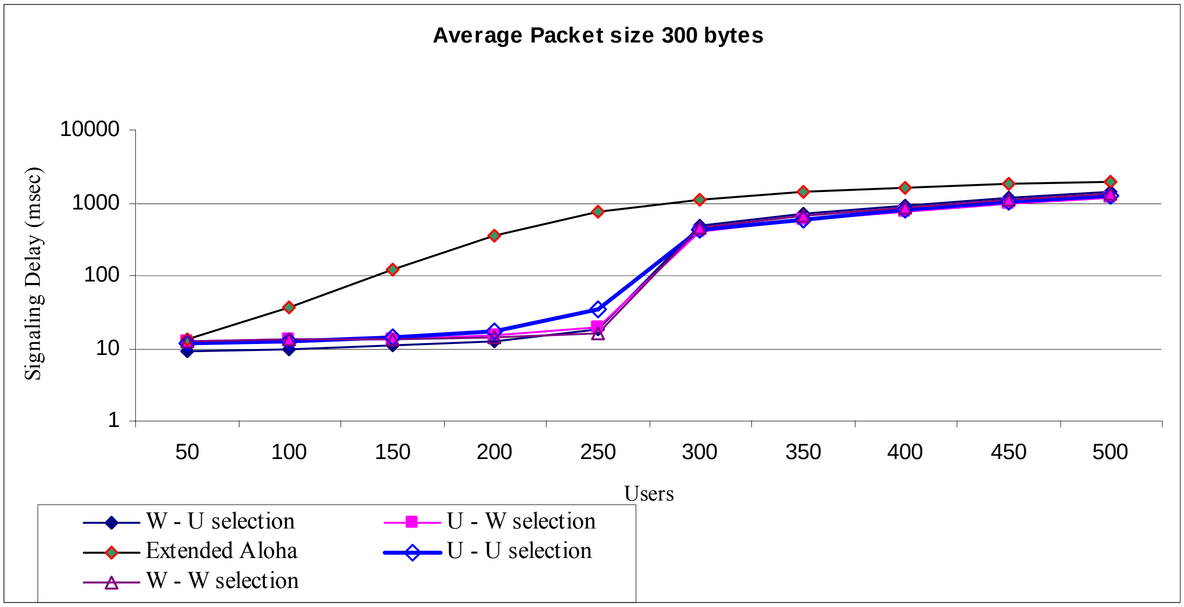

Figure 4. Comparison of the five schemes in terms of signaling delay, for a disturbance-free PLC network (300-byte packets).

Similarly to the work in [5, 6], we define network utilization as the ratio of the used network capacity for data transmission to the total capacity. As shown in Figure 5, for up to 150 users the use of the Extended Aloha protocol provides almost identical performance with the four versions of our protocol (but at the cost of much higher signaling delay, as shown in Figure 4). However, as the traffic load increases, the network utilization achieved by the Extended Aloha protocol becomes significantly smaller than the one achieved by our protocol; more specifically, the difference between the four versions of our protocol and Extended Aloha exceeds 20% when the number of users ranges between 300 and 400. At high traffic loads (>300 users present in the system) the network utilization achieved by our scheme decreases for all four versions, as the number of collisions increases; still, in all the examined cases it remains significantly higher (more than 10%, on average for all four versions) than the one achieved by Extended Aloha (the only exception is the W-U selection version of the protocol, which for more than 500 users is only slightly more efficient than the Extended Aloha protocol).

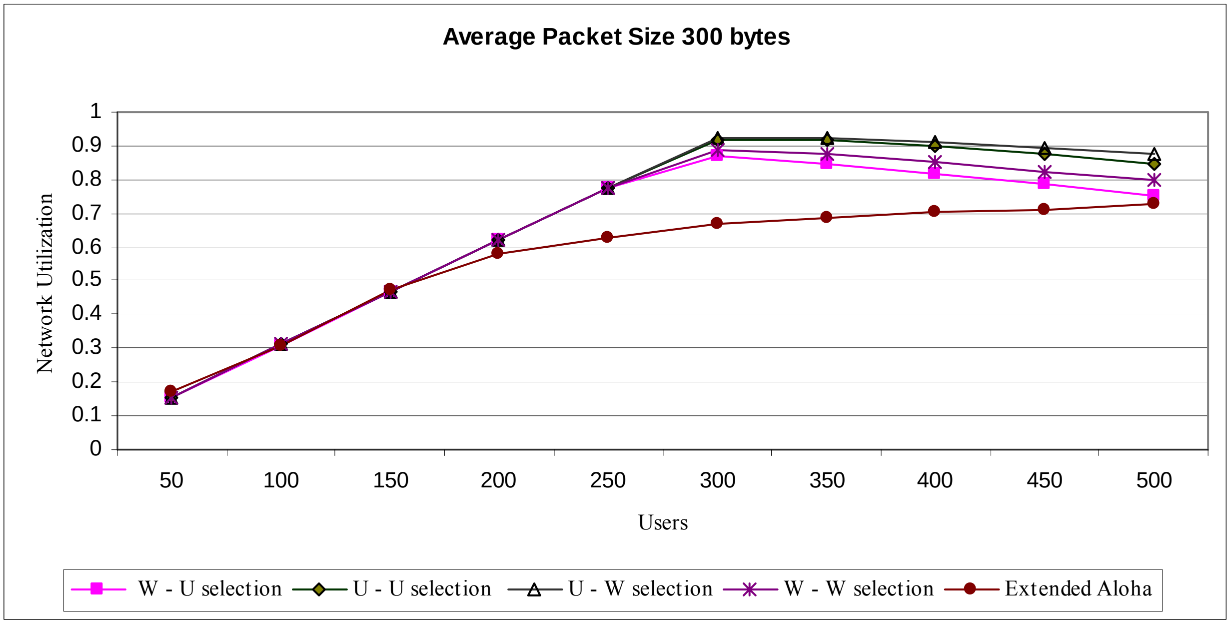

Figure 5. Comparison of the five schemes in terms of network utilization, for a disturbance-free PLC network (300-byte packets).

Since the difference between the Extended Aloha protocol and all versions of our protocol exists in the transmission/retransmission algorithms used, it is clear that our proposed algorithms are the reason for which our schemes excel. More specifically, the adaptive backoff mechanism used in [5, 6] has the inherent disadvantages that: a) after the calculation of the retransmission interval, the terminal will attempt to retransmit in the newly calculated (by Equation 1) slot, disregarding any idle slots which may exist before the calculated one; on the contrary, in all versions of our scheme, a terminal which fails to transmit its request attempts to retransmit (with various probabilities) in each of the immediately following idle slots, therefore our scheme achieves a much better utilization of the available bandwidth; b) as explained in Section C of chapter I, after the end of a request procedure, a calculated value of the CC is kept as a start value of CC for the next request procedure. Therefore, once again, valuable slots are lost with the use of the adaptive backoff scheme in [5, 6] as the terminal does not even attempt to exploit them. Our more "aggressive" policy is the reason for the decrease in network utilization for high traffic loads, which however does not affect our scheme's superiority, as shown in Figures 4 and 5.

A careful observation of the results presented in Figures 4, 5 reveals that our conclusion regarding Figure 4 stands as a common characteristic for all the results of our study on a disturbance-free PLC network; i.e., when comparing the results achieved by the four versions of our MAC scheme, in all cases the W-U selection achieves the best results for low-to-medium traffic loads (number of users less than or equal to 250) and the U-W selection achieves the best results for medium-to-high traffic loads (number of users larger than 300). We conducted extensive simulations in order to define the number of users for which the two protocols achieve the same performance in terms of signaling delay and network utilization (i.e., the "turning point" in which one selection replaces the other in giving the best performance metric results). This number was found to vary between 268 and 270 in all of our simulations.

The reasons for each version's excellence in handling different traffic loads can be found in the inherent logic of each version of our protocol:

a) the *weighted channel selection* "pushes" requesting users to choose, in every channel frame, with greater probability the channels with the larger number of idle slots; however, for medium-to-high traffic loads the weighted channel selection performs less efficiently than the uniform channel selection mechanism. The reason for this result is that in the case of a high traffic load, idle slots are few; therefore, the probability with which the channel with the largest number of idle slots is chosen by requesting users is often quite high, leading to an immediate increase of the collision probability in that channel.

b) the *weighted slot selection* offers to requesting terminals the chance to transmit their requests sooner, by using higher transmission probabilities; however, this choice leads to a higher collision probability. Hence, in the case of low-to-medium traffic loads, where the weighted channel selection is more effective as explained above, the weighted slot selection performs worse than the uniform slot selection, because the combination of the weighted mechanisms for both the channel and slot selection is a "too aggressive" policy (as clearly shown from our performance metrics' results). On the contrary, in the case of medium-to-high traffic loads, where the uniform channel selection is more effective as explained above, the combination of the "less aggressive" channel selection mechanism with the "more aggressive" slot selection mechanism leads to the best performance metric results among all versions of our scheme.

Since the difference between the U-W and W-U versions of our protocol in terms of signaling delay and network utilization for low traffic loads is quite small, as seen from Figures 4-5, it could be argued that the use of the U-W version of our protocol, which clearly excels in terms of network utilization for high traffic loads, should suffice for *all* traffic loads (i.e., a compromise should be made on the protocol's performance for low traffic loads). However, we propose that for a disturbance-free PLC network the most efficient use of our protocol would be a "two-mode" one, in which W-U selection is activated for low traffic loads and U-W selection is activated for high traffic loads (i.e., the best protocol's version should be used for each type of traffic load). The implementation of this "two-mode" protocol is very feasible, since the base station can easily make a rough estimation of the number of users in the system based on the following simple calculations: Since the average packet size is 300 bytes and the slot payload is 28 bytes, a packet needs on average 10.7 slots to be transmitted. The mean packet interarrival time is 960 msecs, i.e., 20.4 channel frames. By comparing the above, we conclude that an active terminal is transmitting for 10.7/20.4=52.5% of the time, and is silent for the rest of the time (i.e., the activity factor is 0.525); the same result can be found by using 1500 bytes packet size and 4.8 seconds mean packet interarrival time. Therefore, the number of users in the system (transmitting and silent) can be estimated by multiplying the number of users currently transmitting in a frame with (1/activity factor). Even if the above estimation is not perfectly accurate (the utilization of the signaling channel in the current frame should also be taken into consideration for a more accurate estimation), it is still adequate as both versions of our protocol have high efficiency, therefore even if the better of the two modes is activated with delay, this will have a very small impact in the user QoS metrics.

A comment needs to be made regarding the significant increase in the signaling delay (Figure 4) when the number of users increases from 250 to 300. In order to explain this increase we will use again the estimation method proposed in the previous paragraph. If we suppose that all data channels are full in a specific channel frame, this translates into 164 users on average being active and transmitting in their allocated slots. If the signaling channel has also been perfectly "exploited", another 12 users have transmitted successfully their requests and are awaiting to enter the system in the next channel frame. In the case of an ideal system, in which user transmissions could perfectly coincide with the "silence" (packet interarrival time) of other users in the network, the total number of users which could be serviced by the network with zero access delay would therefore be equal to (12+164)*(1/activity factor)] = 176*1.904 = 335 users, on average. However, since such a perfect arrangement of user transmissions is not possible, and the existence of collisions creates a significant burden to the network, the number of users for which the system is able to cope without significant delay increase is much lower than 335 and lies between 250 and 300 (it is actually close to 272, slightly varying around that value depending on our MAC protocol version).

II. Enhanced PLC MAC protocol Vs Extended Aloha based MAC protocol in a lightly disturbed environment

The conclusions derived from our results for a disturbance-free PLC network are further confirmed by the results presented in Figures 6-9, where the two versions of our protocol which have been shown to excel (W-U and U-W) are once again compared to the Extended Aloha protocol in a lightly disturbed and a heavily disturbed PLC network, with 300-byte packets. The only qualitative difference of these results with the ones referring to an ideal, disturbance-free PLC network is that our proposed "two-mode" protocol achieves even better results in the realistic case of a PLC network with disturbances, when compared to Extended Aloha. More specifically, in both the cases of light and heavy disturbances the difference in network utilization between our protocol and Extended Aloha reaches up to 26% and is on average close to 13% in favor of our protocol for all traffic loads used in our study (Figures 8, 9). Also, the comparison of the two protocols in terms of signaling delay (Figures 6, 7) shows that our protocol achieves a much smaller delay (by 1.1 seconds on average for all traffic loads used in our study, and by more than 2 seconds when the number of users is equal or larger than 400). The reason for the further improvement of the results achieved by our protocol is that the existence of disturbances in the PLC network further aggravates the efficiency of the Extended Aloha protocol, due to the aforementioned disadvantages of its transmission/retransmission algorithm.

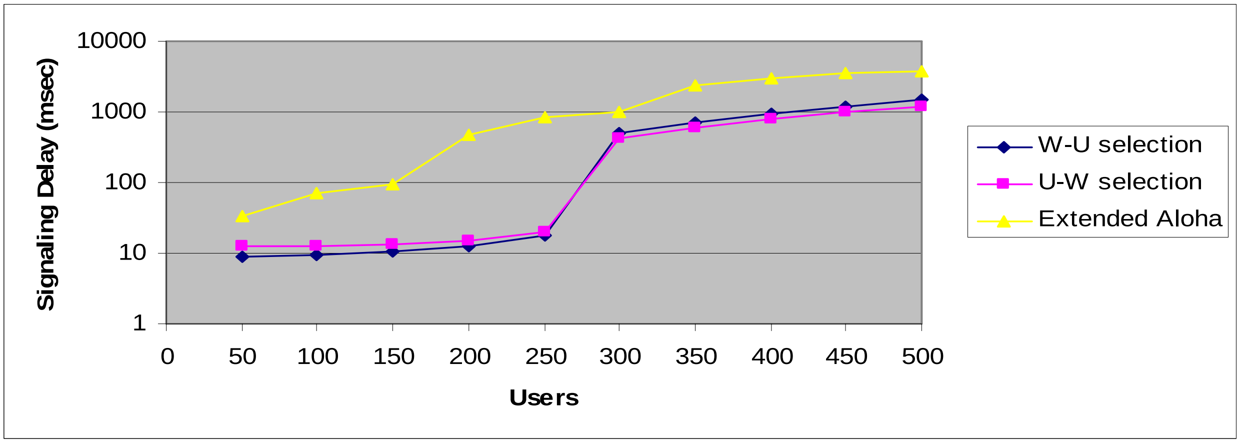

Figure 6 . Comparison of the three schemes in terms of signaling delay, under light disturbances (300-byte packets).

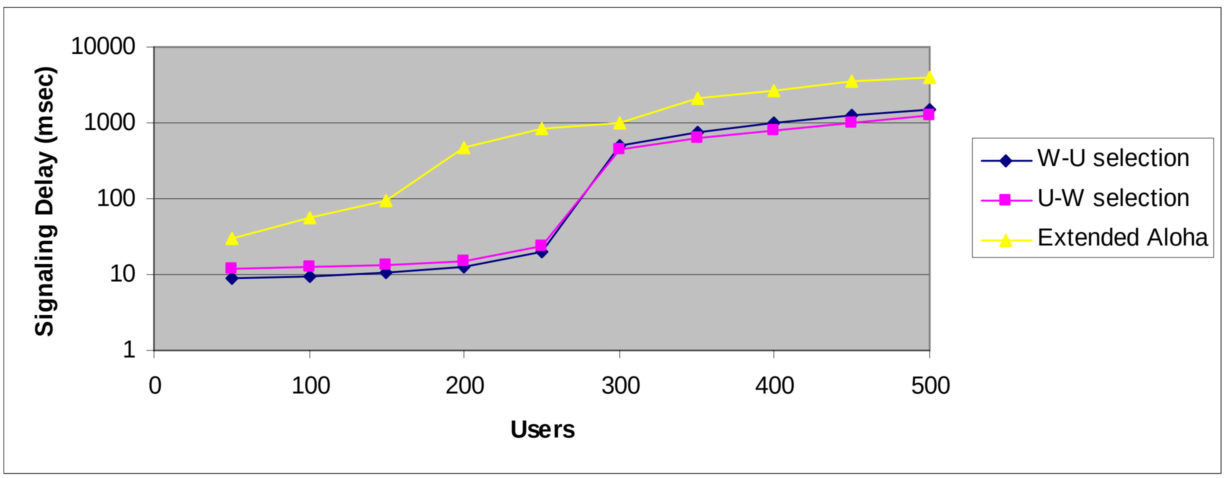

Figure 7. Comparison of the three schemes in terms of signaling delay, under heavy disturbances (300-byte packets).

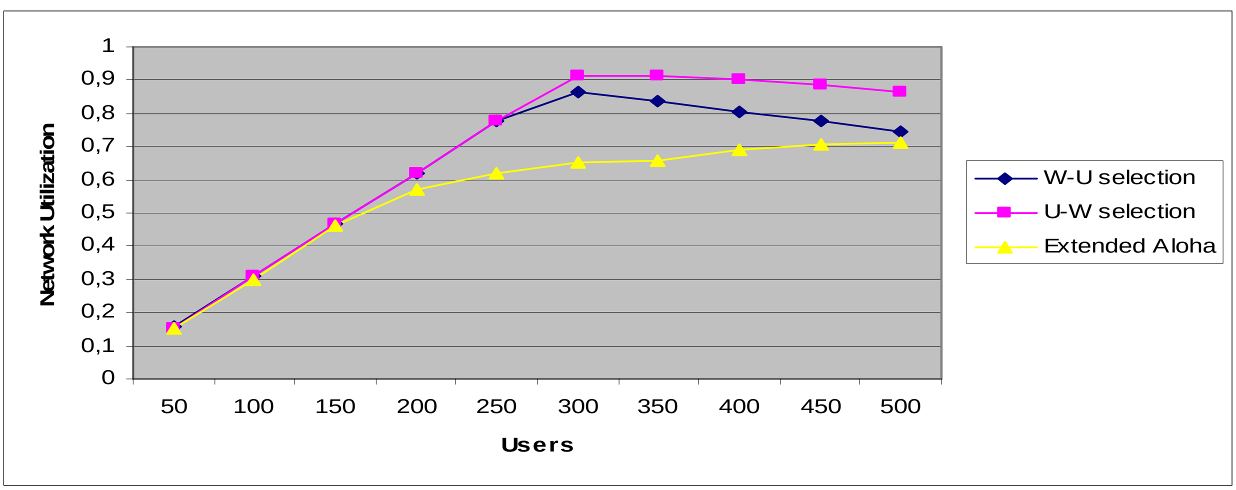

Figure 8. Comparison of the three schemes in terms of network utilization, under light disturbances (300-byte packets).

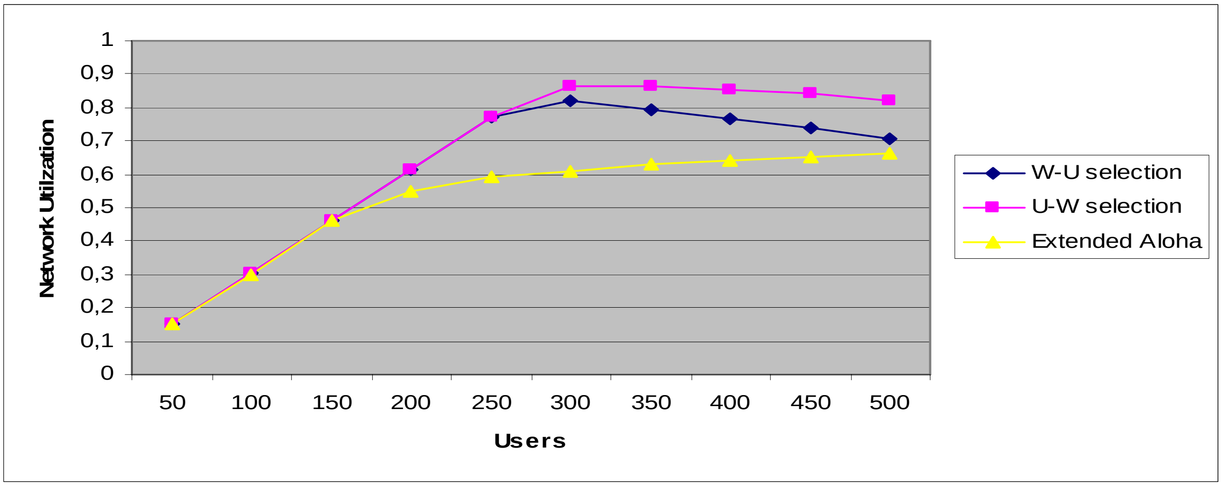

Figure 9. Comparison of the three schemes in terms of network utilization, under heavy disturbances (300-byte packets).

Figures 10-13 present the results for the W-U and U-W versions of our protocol, with 1500-byte packets.

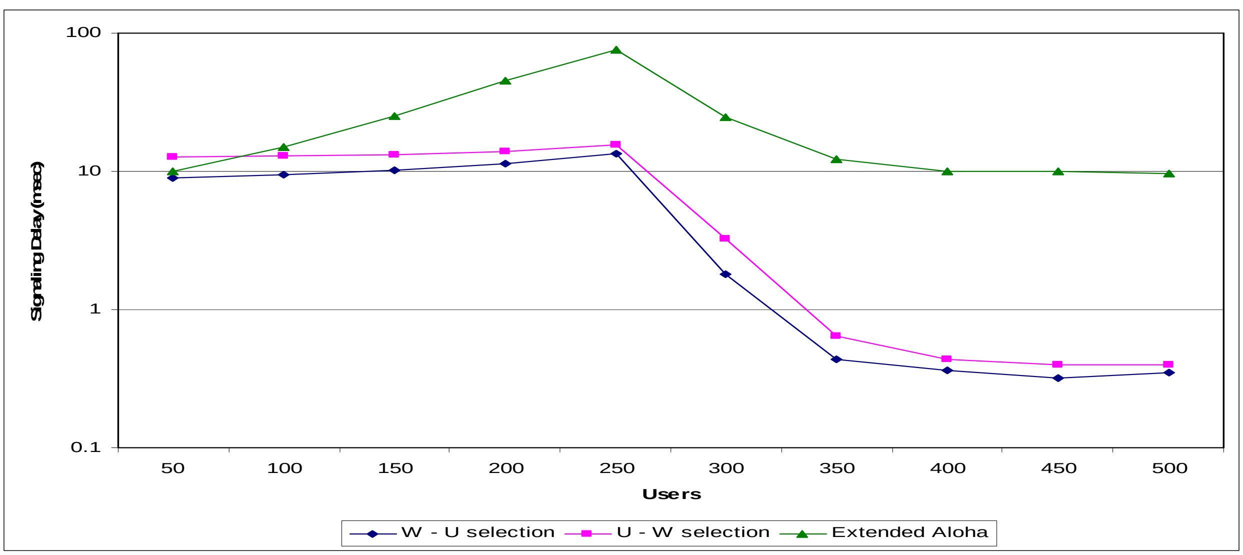

Figure 10. Comparison of the three schemes in terms of signaling delay, under light disturbances (1500-byte packets).

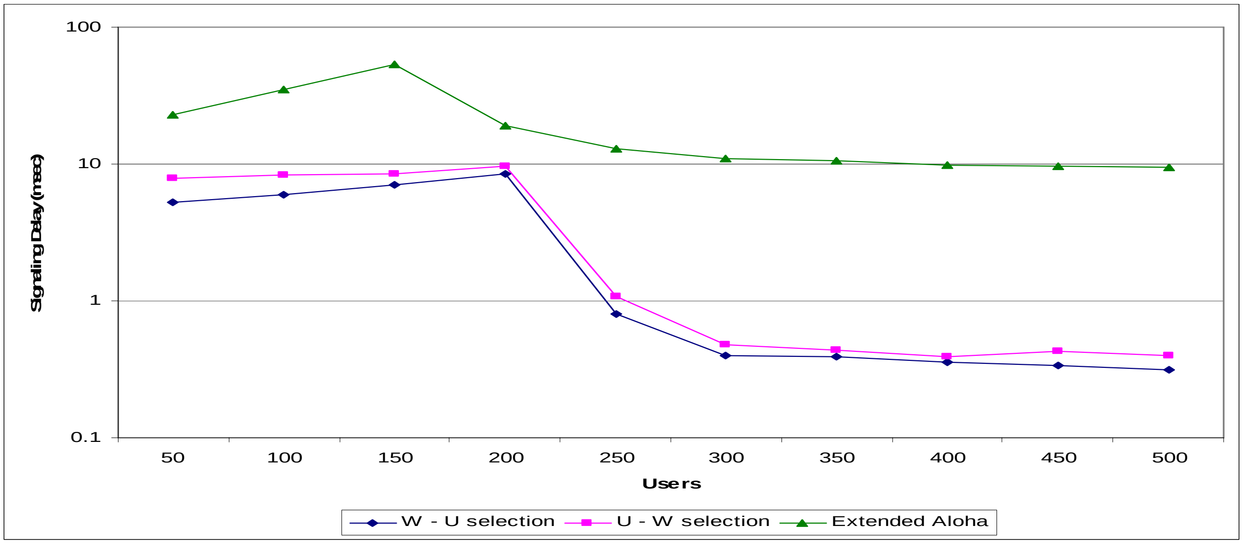

Figure 11. Comparison of the three schemes in terms of signaling delay, under heavy disturbances (1500-byte packets).

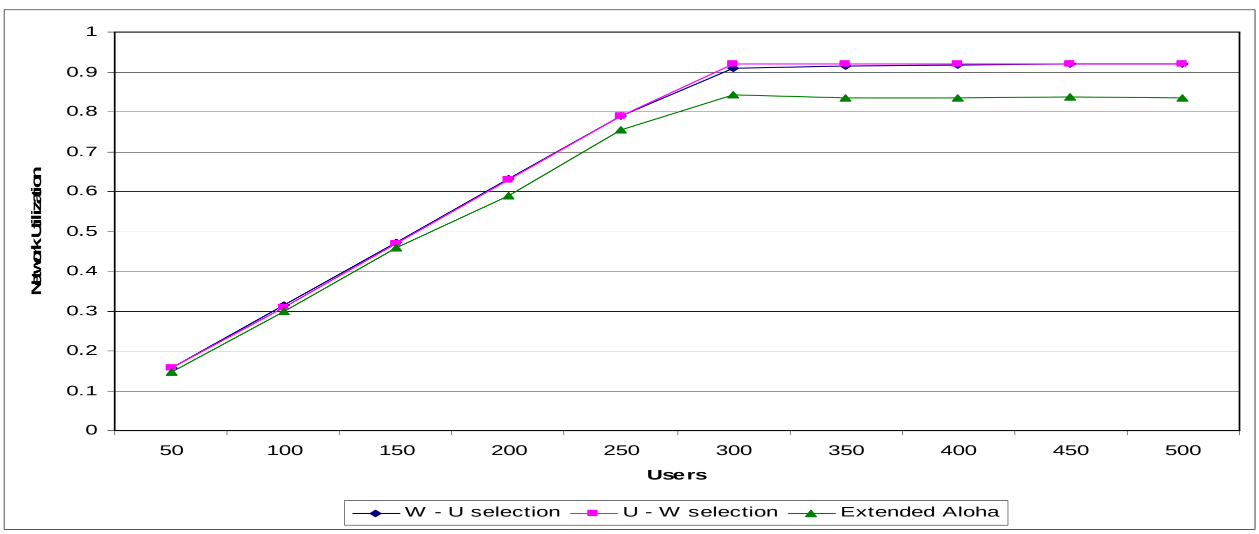

Figure 12. Comparison of the three schemes in terms of network utilization, under light disturbances (1500-byte packets).

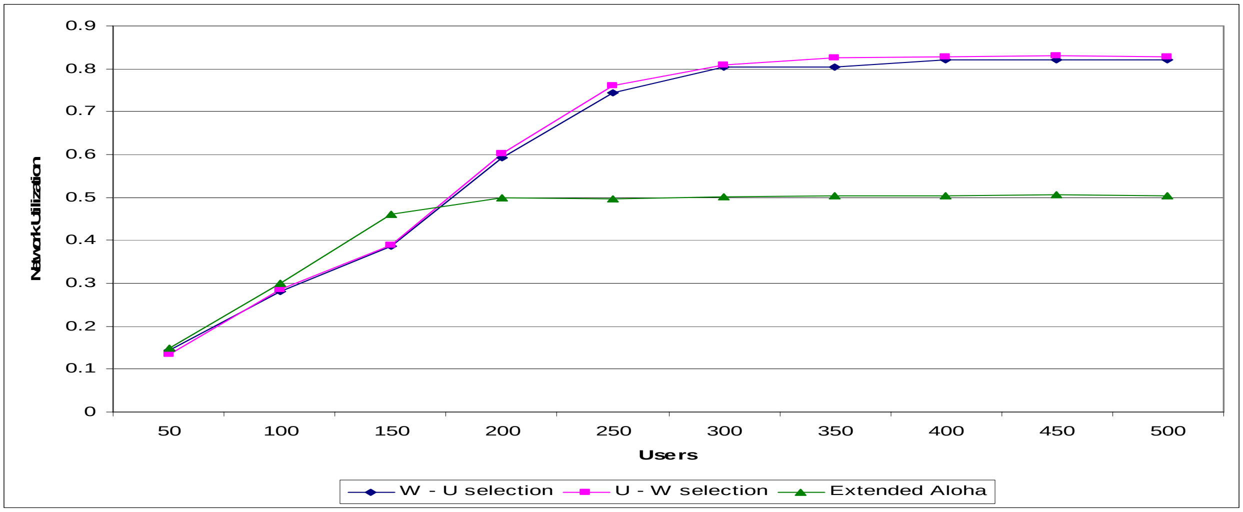

Figure 13. Comparison of the three schemes in terms of network utilization, under heavy disturbances (1500-byte packets).

Figure 10 presents the comparison of our results with the Extended Aloha protocol in a lightly disturbed PLC network. It is clear from the Figure that at all traffic loads the signaling delay achieved by the "W-U selection" version of our protocol is smaller than the one achieved by the Extended Aloha protocol, and the same applies for the "U-W selection" version of the protocol when more than 80 users are present in the system. As the traffic load increases, the signaling delay naturally increases as well, due to the increase in the number of collisions in the network. This increase reaches a peak and is followed by a decrease in the signaling delay for all protocols under study. The reason for the decrease in the signaling delay for higher traffic loads is that the system reaches a saturation point, as is also explained in [5, 6] for the Extended Aloha protocol (i.e., all the available network bandwidth is currently allocated); therefore, the realization of the request procedure is mainly done through piggybacking for the existing users (new users have to "exploit" the message interarrival time of existing users) and the number of collisions is significantly decreased; this is the reason for the decrease in the signaling delay.

As shown in Figure 12 (in which a lightly disturbed PLC network is again considered), the difference in network utilization between the two versions of our protocol and Extended Aloha exceeds 10% when the number of users in the network surpasses 300.

The conclusions derived from Figures 10, 12 are also valid for the results presented in Figures 11 and 13 regarding the performance of our proposed protocol when the network experiences heavy disturbances. However, in this case both versions of our protocol produce significantly improved results when compared to the Extended Aloha protocol (much smaller signaling delay and much larger network utilization, *up to 32% larger than the Extended Aloha protocol network utilization)*.

III. Conclusions

When comparing the results achieved by the two better versions of our protocol, we conclude that they can be used equally well in a PLC network with disturbances and 1500-byte packets. In the case of a lightly disturbed network, the improvement in network utilization provided by the U-W selection is very small, of the order of 0.5%; therefore, the W-U selection seems to be the best choice due to its clear superiority in terms of signaling delay. In the case of a heavily disturbed PLC network, however, the U-W selection provides an improvement in network utilization up to 2% (and steadily more than 1% in comparison to the W-U selection), while again being inferior to the W-U selection in terms of signaling delay. Hence, there is a differentiation in the case of 1500-byte packets, in comparison to the 300-byte case. In the latter, the W-U selection performs better in both network performance metrics for low traffic loads and the U-W selection performs better in both metrics for high traffic loads; in the former, each version of the protocol is dominant in one performance metric: the W-U selection performs better in terms of signaling delay for all traffic loads (the difference is larger in low-to-medium traffic loads) and the U-W selection performs better in terms of network utilization for all traffic loads (the difference is larger in medium-to-high traffic loads). The reason for this result in the case of 1500-byte packets is that, due to the disturbances in the network the whole 1500-byte packet (i.e., all packets in which it is segmented) has to be retransmitted. Hence, the U-W selection leads to a more "aggressive" terminals' behaviour in attempting to acquire a slot (i.e., transmitting with higher probabilities) and therefore to higher network utilization, at the cost of more collisions (higher signaling delay); on the other hand, the W-U selection leads to a more "defensive" terminals' behaviour (smaller transmission probabilities) and therefore to less collisions and lower signaling delays, but also to leaving more slots left unused and therefore lower network utilization. The fact that the W-U selection incorporates a more aggressive policy in channel selection than U-W is of secondary importance here and does not alter the defensive nature of W-U selection, because the number of retransmissions that need to be made due to the effect of network disturbances is so large (5 times larger than the one needed in 300-byte packets); therefore, the significant congestion does not take place when terminals decide on which channel to choose but when they need to find slots to retransmit their data, which is aggravated by the high transmission probabilities used by other terminals in the same channel.

Based on the above observations, it could again be argued that using one version of the protocol would suffice for all traffic loads. However, in the case of 1500-byte packets the preferred version would be the W-U selection, whereas in the case of 300-byte packets was the U-W one. The choice of using a different version of the protocol based on the packet size, while at the same time making compromises on the protocol performance, is clearly not an ideal one. Instead, based on our results (and given the low complexity of its implementation, as it was explained earlier) we propose the use of the "two-mode" protocol (W-U selection for low traffic loads and U-W selection for high traffic loads) *for all traffic loads and packet sizes* in a broadband PLC network with disturbances.

III. A NEW MAC PROTOCOL PROPOSAL

In this chapter we design, evaluate and present a new MAC protocol for PLC networks. The main contribution of the work presented in this chapter in terms of ideas focuses on the request and collision resolution procedures, as it will be described later in detail. We compare the operation of the proposed protocol against the Extended Aloha PLC MAC protocol presented in [5, 6] and we demonstrate the superiority of our protocol through an extensive simulation study. We also compare this new MAC protocol with the enhanced Extended Aloha MAC protocol, presented in chapter II, extracting valuable information for additional protocol improvement towards further reducing the average packet delays and increasing the exploitation of the available bandwidth especially in the case of a noisy environment.

A. The new MAC Protocol

I. Request procedure

In this chapter, we adopt from [5, 6] the idea of piggybacking. We do not use the idea from [5, 6, 9, 11] of using data channels for signaling and the adaptive backoff mechanism from [5, 6] for users to select the slot in which they will transmit/retransmit their requests; instead, we propose a new idea described as follows.

The terminals are divided by the base station, which always has exact knowledge of the number of users in the system, into a number of equal size groups (we use 20 groups in our study). The 1st channel is used only for signaling, each slot of that channel is divided into 20 minislots and each minislot is assigned to one of the 20 groups, i.e. the first group of users uses only the first minislot of each slot of the signaling channel and so on. The number of minislots we can divide a slot, reaches an upper bound when the minislot duration becomes very short and does not suffice for the request packet to be transmitted to the base station and for the base station to send an acknowledgement to the requesting terminals plus guard times and synchronization overheads. Based on the related reasoning in [9], we could have divided each slot into more than 20 minislots, however our simulation results shown later in this chapter indicate that the request bandwidth created through this minislotization is more than adequate. After all, it is clear that we have increased the offered request bandwidth by a factor of 20.

The remaining 14 channels are used only for data transmissions. The Base Station allocates the bandwidth to the terminals which have successfully sent their request and received an acknowledgement.

Based in the above description, it is clear that we have a contention free situation among groups, and that we may face contention among terminals of the same group as they might use the corresponding minislot of the same slot causing this way a collision. To resolve the collisions, we adopt two and three Cell Stack [12], [13] reservation random access algorithms (RRAs).

II. Collision Resolution Procedure : 2,3 Cell Stack Algorithms

When a collision occurs, the base station informs the users within the next slot of the signaling channel on the downlink, that a collision occurred. The users involved in the collision, initiate a counter denoted by r, at the values 0-1 (for 2 Cell Stack), or 0-1-2 (for 3 Cell Stack). A value of zero indicates that this terminal should immediately try to resend its request at the appropriate minislot, defined by the group to which the terminal belongs. In any other case the terminal reduces its counter value by one at each frame, till the counter reaches zero. We adopt the two and three cell stack RRAs due to their operational simplicity and stability.

B. Results and Discussion

The system parameters used in our work are taken from [7, 8], in order to make a direct comparison with that work, which focused only on data (Internet) traffic. The number of data terminals varies between 50 and 500. In [7], two average sizes of user packets are used; 300 bytes and 1500 bytes. Since packet transmission in PLC should be made in very short frames so that the receiver can adapt to the rapid (< 1 ms) changes in the PLC channel conditions [16], we chose to consider in this work only packets with average size equal to 300 bytes and with mean interarrival time 0.96 seconds; this is the case defined in [7, 8] as the “frequent request case”, which enables us to test our scheme under heavy traffic conditions, since the number of collisions in the PLC network will be significantly higher than in the case of 1500 bytes packets. The offered traffic load per network station (terminal) is 2.5 kbps. The packet sizes and the interarrival times are assumed geometrically distributed. As already mentioned, the number of transmission channels is equal to 15 (one of the channels is reserved for signaling), each with a data rate of 64 kbps. It should be noted that currently used PLC systems provide data rates around 2 Mbps; therefore, in this work we assume that in such a PLC system half of the network capacity is used by data connections. The frame duration is 47 msecs, the slot duration is equal to 4 ms, the slot capacity is 32 bytes and the payload in each slot is 28 bytes. We simulated one hour of network operation. Each simulation point is the result of an average of 10 independent runs (Monte-Carlo method).

I. Stack based approach vs Extended Aloha

Figure 1 presents the comparison of the two schemes, with the two and three cell stack algorithms in a disturbance-free PLC network with 300-byte packets. It is clear from Figure 1, that at low traffic loads the signaling delay achieved by the version which uses the two cell stack algorithm is lower than the scheme with the three cell stack algorithm. The situation reverses for medium to high traffic loads, where the three cell stack algorithm handles high complexity collisions slightly better (high complexity collisions means that more terminals participate in the collision). That is why we chose to use the two cell stack algorithm below 300 terminals and the three cell stack algorithm above 300 terminals. As it will be analyzed later, the combined use of the two and three cell stack algorithms is feasible.We conducted extensive simulations in order to define the number of users for which the two protocols achieve the same performance in terms of signaling delay and network utilization (i.e., the “turning point” in which one selection replaces the other in giving the best performance metric results). This number was found to vary between 287 and 290. The reasons for each version’s excellence in handling different traffic loads can be found in the difference between the two versions of the RRAs. For light traffic loads (below 300 users) the collisions rarely involve more than two users. That’s why the two cells of the stack in the two cell stack algorithm are enough to resolve the collision. As traffic load becomes higher, collisions have higher multiplicity and that is why the three cell stack algorithm is more appropriate in this case.

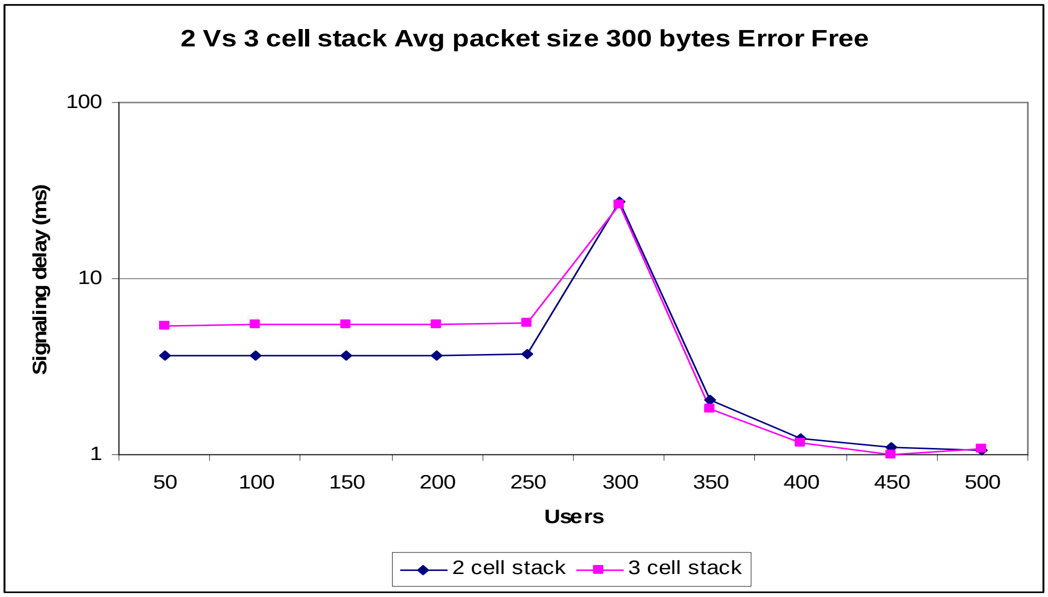

Figure 1. Comparison of the two schemes in terms of signaling delay, for a disturbance-free PLC network (300-byte packets).

Based on the above, we conclude that the most efficient use of our protocol is a “two-mode” one, in which the two cell stack algorithm is activated for low traffic loads and the three cell stack one is activated for high traffic loads (over 300 terminals). The implementation of this “two-mode” protocol is feasible, since the base station can easily make a rough estimation of the number of users in the system based on the following simple calculations: Since the average packet size is 300 bytes and the slot payload is 28 bytes, a packet needs on average 10.7 slots to be transmitted. The mean packet interarrival time is 960 msecs, i.e., 20.4 channel frames. By comparing the above, we conclude that an active terminal is transmitting for 10.7/20.4=52.5% of the time, and silent for the rest of the time (i.e., the activity factor is 0.525). Therefore, the number of users in the system (transmitting and silent) can be estimated by multiplying the number of users currently transmitting in a frame with (1/activity factor). We reach the same conclusion even if the average packet size is 1500 bytes, since the average traffic load per terminal is the same in both cases, 2,5kbps. Even if the above estimation is not perfectly accurate (the utilization of the signaling channel in the current frame should be taken into consideration for a more accurate estimation), it is still adequate as all versions of our protocol have been shown from our results to be comparable in their efficiency, therefore even if the better of the two modes is activated with delay, this will have a very small impact in the user QoS metrics.

Another comment needs to be made regarding the significant increase in the signaling delay (Figure 1) when the number of users increases from 250 to 300. In order to explain this increase we will use again the estimation method proposed in the previous paragraph. If we assume that all data channels are full in a specific channel frame, this translates into 164 users on average being active and transmitting in their allocated slots. If the signaling channel has also been perfectly "exploited", another 12 users have successfully transmitted their requests and are awaiting to enter the system in the next channel frame. In the case of an ideal system, in which user transmissions could perfectly coincide with the "silence" (packet interarrival time) of other users in the network, the total number of users which could be serviced by the network with zero access delay would therefore be equal to (12+164)*(1/activity factor)] = 176*1.904 = 335 users, on average. However, since such a perfect arrangement of user transmissions is not possible, and the existence of collisions creates a significant burden to the network, the number of users for which the system is able to cope without significant delay increase is much lower than 335 and lies between 250 and 300 (it is actually close to 272, slightly varying around that value depending on our MAC protocol version).

Figure 2 demonstrates the superiority in terms of network utilization of our protocol against the Extended Aloha protocol. Especially as traffic load gets higher our protocol makes perfect exploitation of all the available data bandwidth, reaching the maximum feasible value of 93% (the remaining 7% is reserved by the signaling channel)

Figure 3 presents the comparison of our results (with the use of our protocol) with the Extended Aloha protocol of [5, 6], in a disturbance-free PLC network with 300-byte packets. It is clear from Figure 3 that at low traffic loads the signaling delay achieved by our protocol is remarkably lower than the one achieved by the Extended Aloha protocol. As the traffic load increases, the signaling delay achieved by our scheme remains unaffected, indicating that the available request bandwidth is enough to cover the needs of the system terminals. The signaling delay with the use of the Extended Aloha increases rapidly as the traffic load becomes higher, due to the increase in the number of collisions in the network. For more than 150 terminals the signaling delay with the two cell stack algorithm is much lower than that with the Extended Aloha protocol (the difference corresponds to several hundreds of msecs).

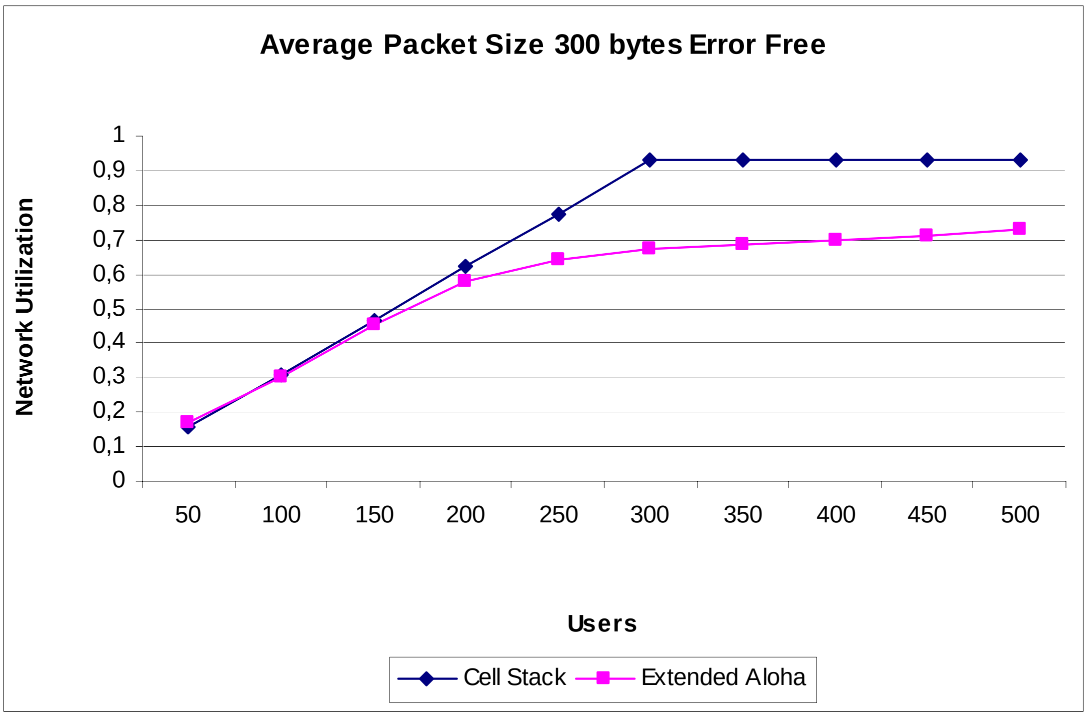

Figure 2. Comparison of the two schemes in terms of Network Utilization, for a disturbance-free PLC network (300-byte packets).

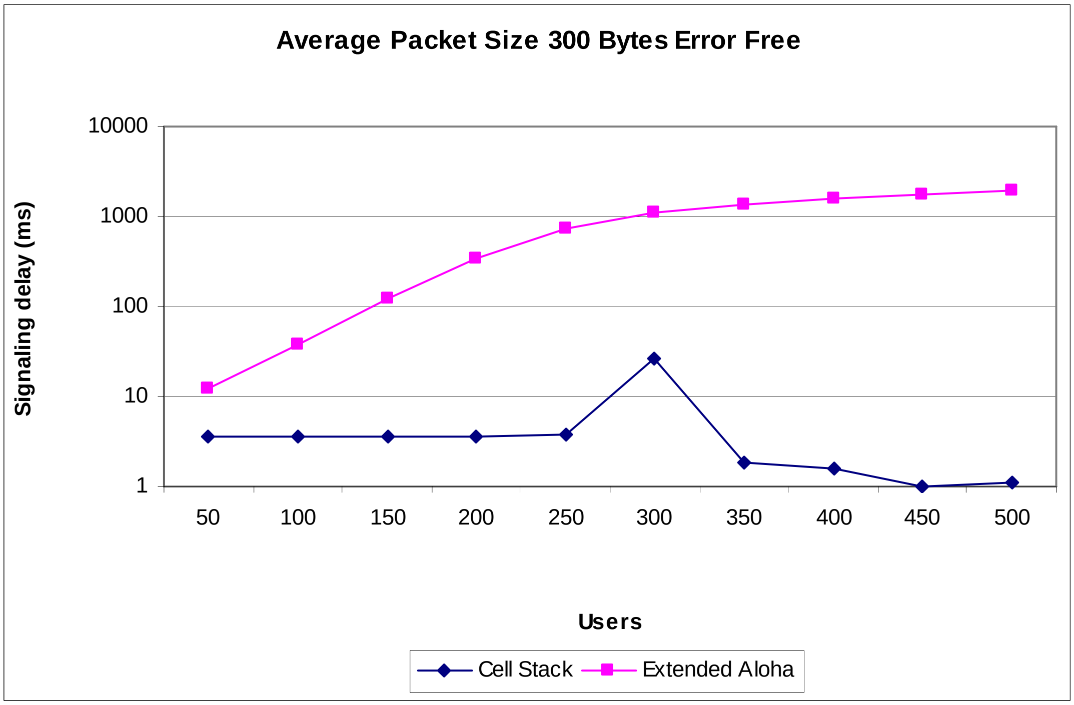

Figure 3. Comparison of the two schemes in terms of signaling delay, for a disturbance-free PLC network (300-byte packets).

A careful observation of the results presented in Figures 3 reveals a rather strange behavior for our protocol over 300 terminals. One would expect that the signaling delay would continue to increase as the traffic load becomes higher. Instead we observe a decrease and at very high traffic loads the signaling delay is lower even from the light traffic load cases. Firstly, one should mention that the scenarios with more than 300 terminals use the three stack algorithm decreasing this way the time needed to resolve the collisions and consequently lowering the signaling delay. However, from the results in Figure 1 we can see that even if we used two cell stack algorithm we would have faced the same situation in terms of signaling delay. The explanation is that for more than 300 terminals the system fails to serve all the terminals. In such case of high traffic load, there are terminals which constantly use the piggybagging mechanism and others who wait for ever for resources allocated by the resource allocation procedure operated by the base station.

The 14 data channels can only serve on average 14*11.75 = 164.5 terminals. The remaining terminals can easily send their requests to the base station on the signaling channel, however there are no resources that the base station can allocate to them. Potential solutions to this problem would be the existence of counter for each terminal which would count the number of continues activations of the piggybacking mechanism by the terminal. After a preselected number the base station should remove the access rights from the terminal and force it to send a new request message if it has more data to send. Such a scheme would be fair between competing terminals but it would increase the signaling delay.

In Figure 3 the superiority of our protocol against Extended Aloha is demonstrated as traffic load gets higher and the network utilization in our protocol reaches the upper bound of 93%. The remaining 7% is used for signaling (the signaling channel). Our protocol uses all the available bandwidth for data transmissions (93% of the channel capacity). The base station allocates slots from the 14 data channels to the terminals which have successfully sent their request without collisions or any other delays.

The conclusions derived from our results for a disturbance-free PLC network are further supported by the results presented in Figures 5-7, where the new version of our protocol is once again compared to the Extended Aloha protocol in a lightly disturbed and a heavily disturbed PLC network, with 300-byte packets. The only qualitative difference of these results with the ones referring to an ideal, disturbance-free PLC network is that our proposed "two-mode" protocol achieves even better results in the realistic case of a PLC network with disturbances, when compared to Extended Aloha. More specifically, in the cases of light disturbances the difference in network utilization between our protocol and Extended Aloha reaches up to 23% for high traffic loads as shown in Figure 4 and almost 24% for a heavy disturbed network, as shown in Figure 6, which is a more realistic scenario for a PLC environment.

A comment needs to be made regarding the behavior in the network utilization (Figures 4, 6) when the number of users increases over 300 which has a steady value for our protocol. In order to explain this, we will use again the estimation method proposed in the previous chapter. Assuming that all data channels are full in a specific channel frame, this translates into 164 users on average being active and transmitting in their allocated slots. In the case of an ideal system, in which user transmissions could perfectly coincide with the "silence" (packet interarrival time) of other users in the network, the total number of users which could be serviced by the network with zero access delay would therefore be equal to (164)*(1/activity factor)] = 164*1.904 = 312 users, on average. That means that as traffic load gets higher the system cannot serve more users as we already have perfect exploitation of the data bandwidth. The only constraint is the noise which causes retransmissions of the affected messages degrading that way the network utilization to 87% in the worst case scenario (heavy disturbed PLC network) as shown in Figure 6.

Also, the comparison of the two protocols in terms of signaling delay (Figure 5) shows that our protocol achieves a much lower delay (by hundreds of ms as traffic load gets higher). The reason for the further improvement of the results achieved by our protocol (comparing to the error free scenario) is that the existence of disturbances in the PLC network causes the terminals to retransmit their messages. As a result the terminals acquire the medium for much longer than the time needed for the transmission of a message and by the time the terminal finishes its transmission or retransmission it has another packet in its buffer which forces the terminal to activate the piggybacking mechanism. This means that there are terminals which keep their access rights almost for ever (especially in very high traffic loads) adding zero values to their signaling and access delays. In the case of the Extended Aloha protocol the increased number of collisions does not allow the terminals to gain access to the channel and the bandwidth is consumed for request transmission by the terminals.

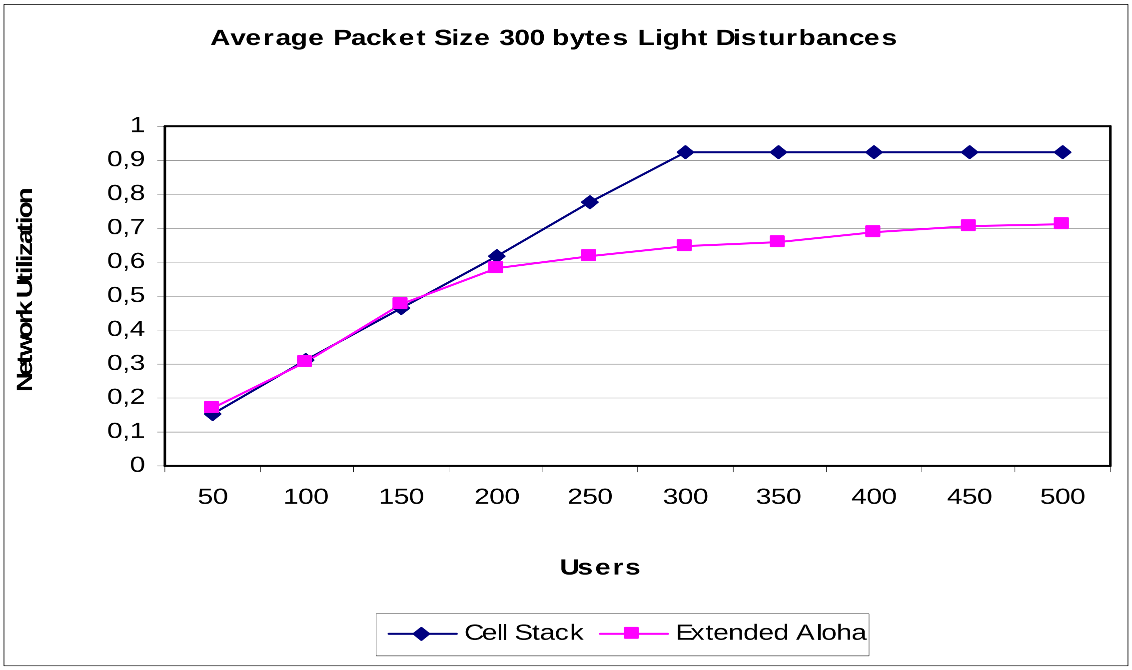

Figure 4. Comparison of the two schemes in terms of network utilization, under light disturbances (300-byte packets).

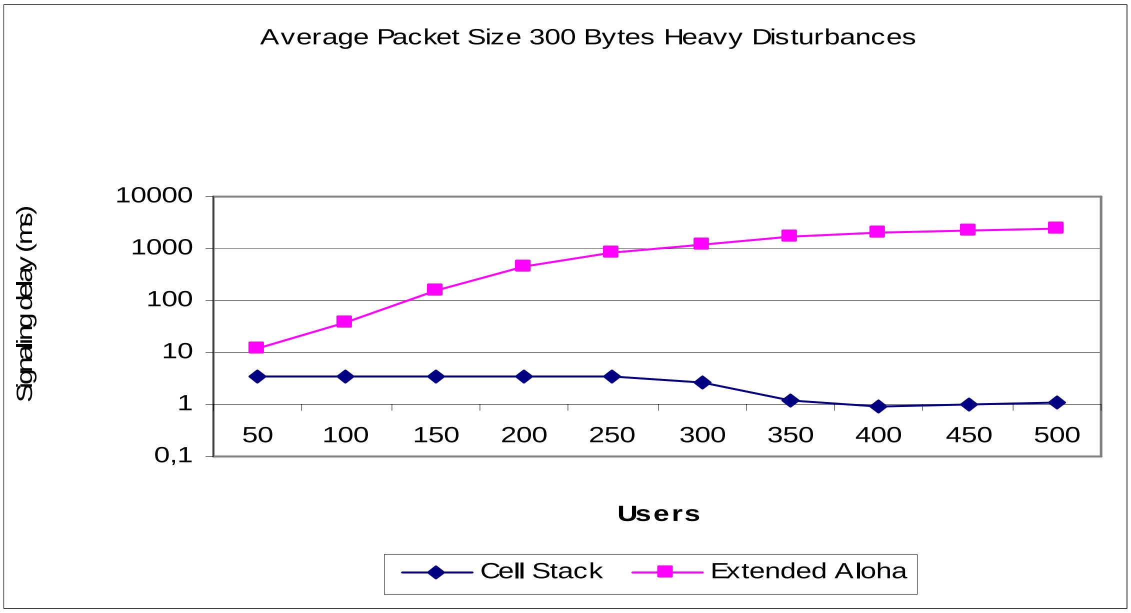

Figure 5. Comparison of the two schemes in terms of signaling delay, under heavy disturbances (300-byte packets).

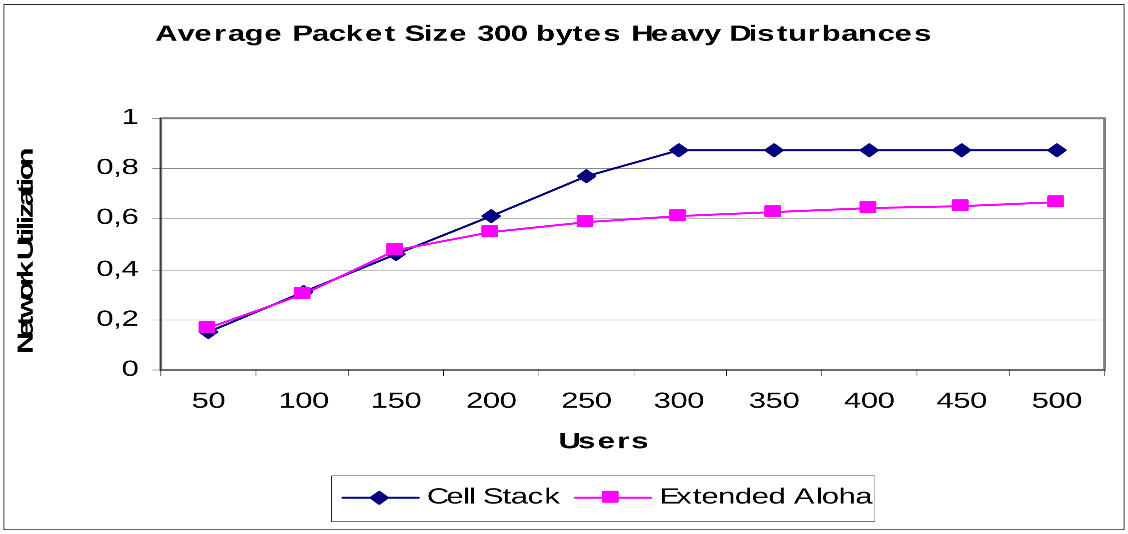

Figure 6. Comparison of the two schemes in terms of network utilization, under heavy disturbances (300-byte packets).

Figures 7 - 9 present the results of the comparison of our protocol with extended Aloha using average packet size of 1500 bytes.

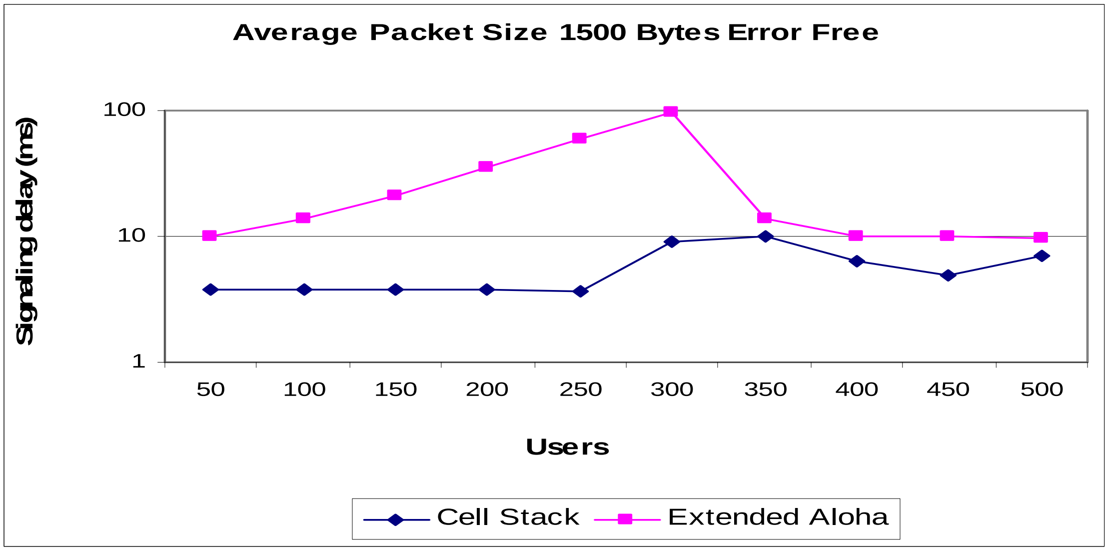

Figure 7. Comparison of the two schemes in terms of signaling delay, with no disturbances (1500-byte packets).

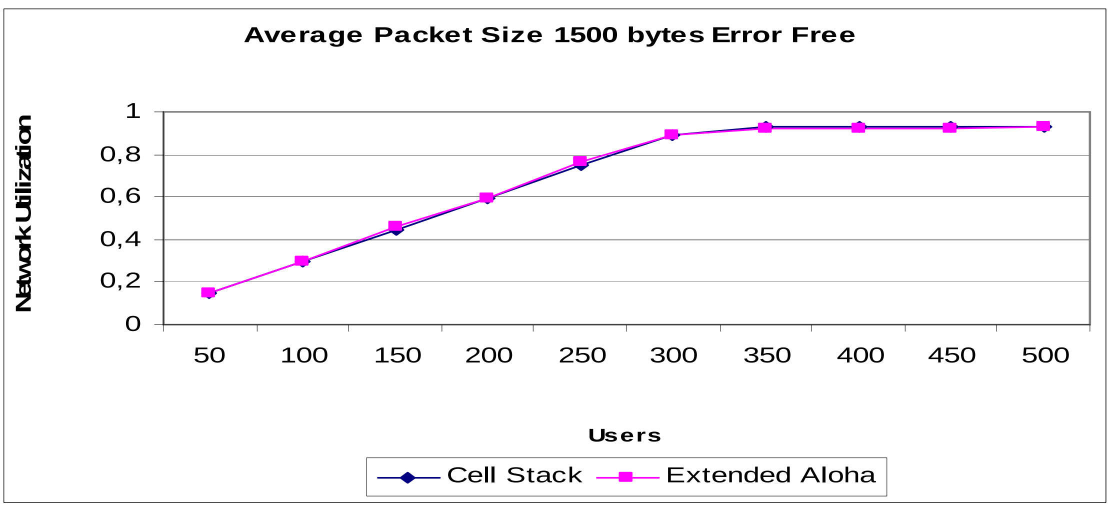

Figure 8. Comparison of the two schemes in terms of network utilization, with no disturbances (1500-byte packets).

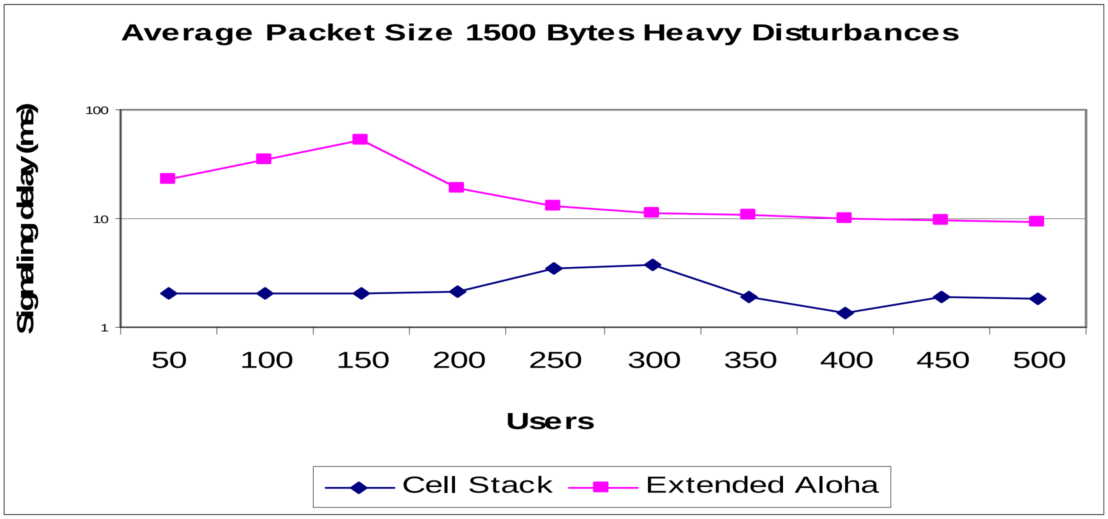

Figure 9. Comparison of the two schemes in terms of network utilization, under heavy disturbances (1500-byte packets).

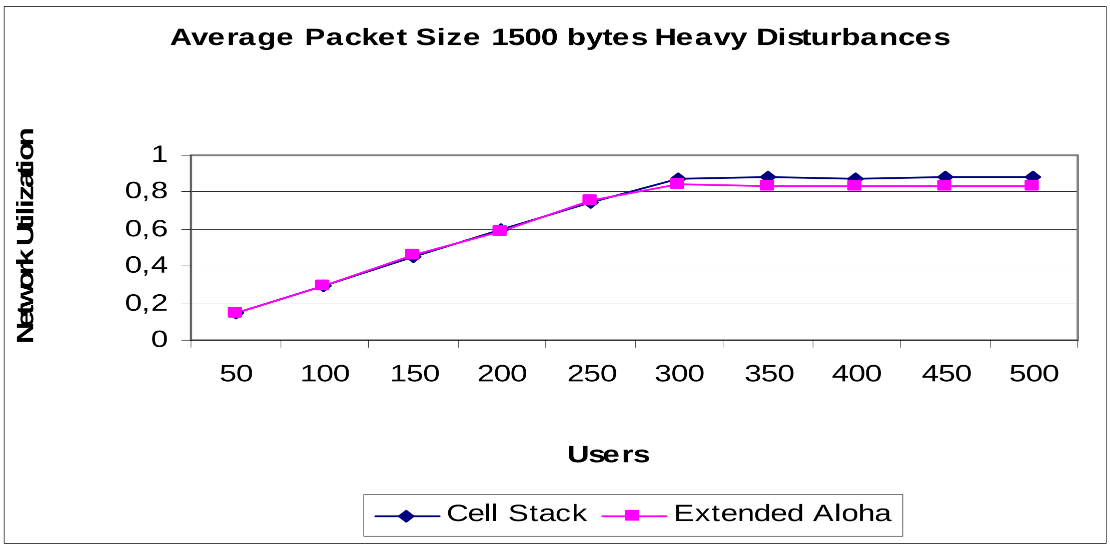

Figure 10. Comparison of the two schemes in terms of network utilization, under heavy disturbances (1500-byte packets).

The reason for the decrement in the signaling delay as traffic loads gets higher, is that the system reaches a saturation point, as is also explained in [5, 6] for the Extended Aloha protocol (i.e., all the available network bandwidth is currently allocated); therefore, the realization of the request procedure is mainly done through piggybacking for the existing users (new users have to "exploit" the message interarrival time of existing users) and the number of collisions is significantly decreased; this is the reason for the decrease in the signaling delay. But in any case, with disturbances or in a disturbance free system, our protocol achieves lower values for signalling delay in any traffic load case compared to the Extended Aloha protocol.

In terms of network utilization we have a slight difference in favor of our protocol especially as traffic load gets heavier. Over 300 terminals, both protocols exploit almost perfectly the data bandwidth with only limitation being due to the disturbances. In the case of a disturbed network and as traffic load gets higher, our protocol manages to use all the available data bandwidth where the Extended Aloha protocol permits, whenever there is a free slot in the data channels, the use of it for sending requests. However, it is almost certain that we will have a collision in such slot because of the large number of terminals waiting to send their requests at high traffic load conditions. This results in decreased network utilization.

II. Stack based approach vs UW-WU algorithm with average packet size equal to 300 bytes

Another important comparison is between our protocol and the protocol solution proposed in the previous chapter, the hybrid U W-W U reservation algorithm, which was proven, under an extensive simulation study, to excel in performance of Extended Aloha protocol in terms of delays and network utilization. In terms of complexity, we cannot say that there are major differences between the two schemes as both protocols use two modes of operation. Two and three cell stack for the algorithm proposed in this chapter and U W and W U for the protocol proposed in the chapter II. The boundary for the change of mode is roughly the number of 300 hundred terminals for both cases. It was explained in detail in the previous chapter that the saturation point of the corresponding PLC network lies just below the number of 300 hundred users. Above this point, more traffic load on the system causes more collisions thus less bandwidth efficiency.

Another important aspect among the two proposed protocols is their different approach towards achieving high bandwidth utilization. The W U-U W uses advanced mechanisms to avoid collisions and utilizes the available data bandwidth (if there is any) for that purpose. The stack protocol approach does not use elaborate tricks to achieve better performance. It simply employs the minislot supported signaling procedure, dramatically increasing this ways the likelihood for the users to successfully send their requests to the base station as soon as these requests are generated.

It is critical therefore to answer the question, which of the two protocols is superior.

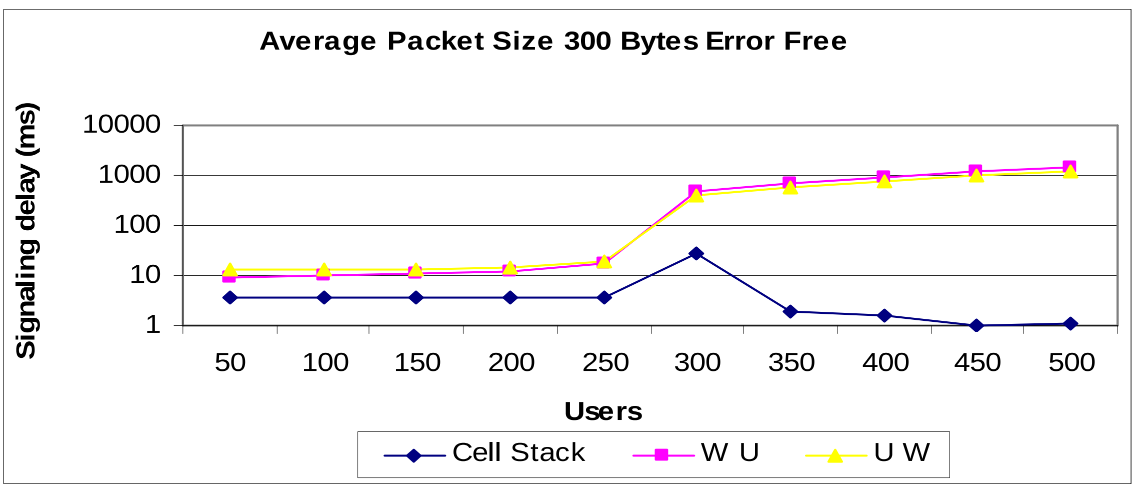

Figure 11. Comparison of our three schemes in terms of signalling delay, with no disturbances (300-byte packets).

Figures 11, 12 provide the results of the comparison among the two proposed protocols in terms of signaling delay and network utilization. For light traffic loads (<300 terminals) the cell stack based approach achieves excellent behavior, indicating that as traffic load gets higher it still manages to offer the terminals excellent chances to successfully send their requests. The W U – U W, incurs higher values of signaling delays, slightly over 10 msec. At 300 terminals, we observe that the W U- U W solution significantly increases its signaling delay as more collisions are happening. At very high traffic load, the signaling delay exceeds 100 msecs. As traffic load increases (250-300 terminals) the cell stack approach increases its signaling delay too, however the latter never exceeds the value of 18 msecs. In this range the 2 cell stack algorithm at this area fails to efficiently resolve collisions. But at 300 terminals the fact that we switch mode to the three cell stack algorithm and the fact that the piggybacking mechanism is constantly activated by the active terminals decrease the signaling delay (it almost reaches 1 msec).

In terms of network utilization we have a full tie for light traffic load. Both protocols can handle the requests and the base station has the resources for allocation. However, as the traffic load gets higher only the three cell stack algorithm can achieve perfect network utilization. The 93% reached by the three cell stack algorithm is the upper bound for this PLC system. The other proposed protocol consumes bandwidth for signaling purposes and as traffic load gets higher we observe that this has a negative impact on network utilization which although not very significant , it is visible only at high traffic loads.

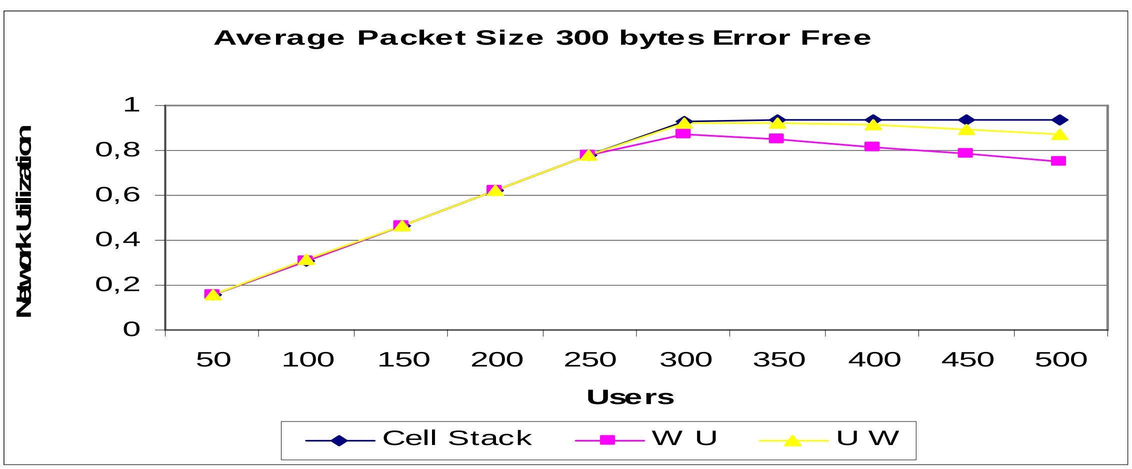

Figure 12. Comparison of our three schemes in terms of network utilization, with no disturbances (300-byte packets).

The existence of heavy channel disturbances always has negative impact on the performance metrics as shown in Figures 13 and 14. However the performance trends of both proposals remains the same with those in the disturbance free case.

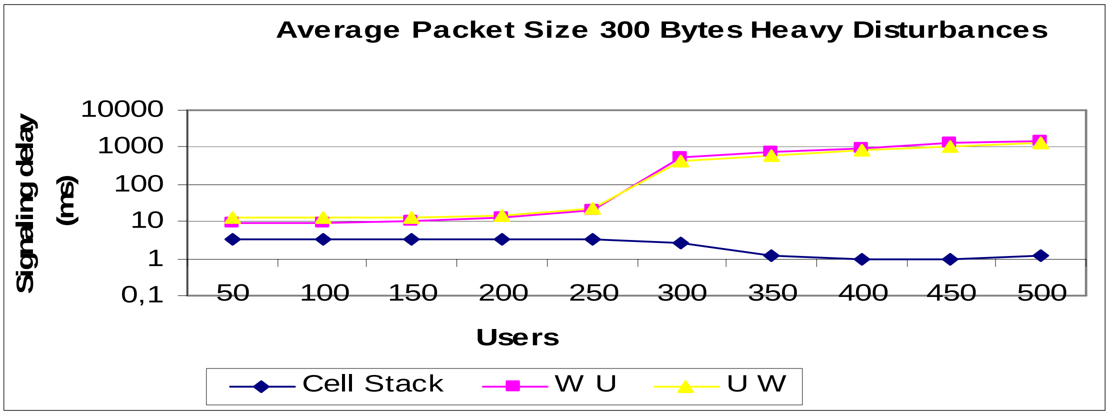

Figure 13. Comparison of our three schemes in terms of signalling delay, under heavy disturbances (300-byte packets).

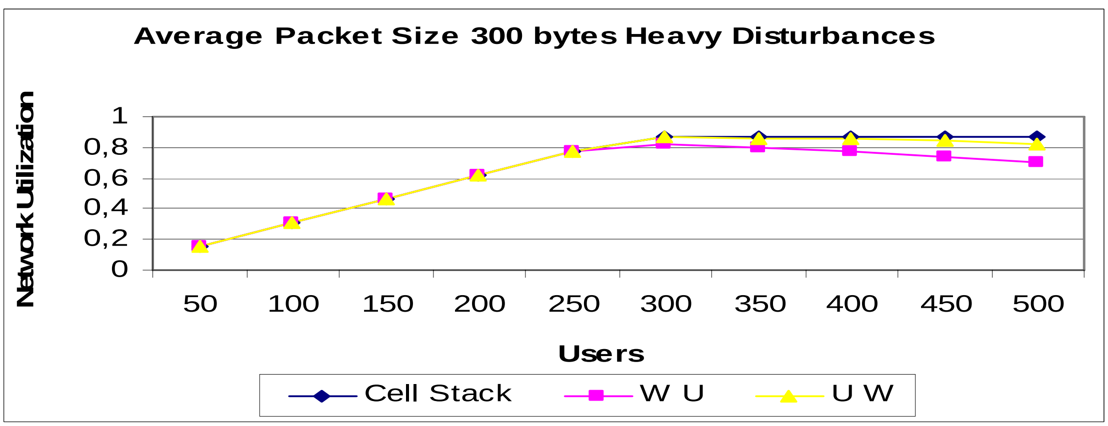

Figure 14. Comparison of our three schemes in terms of network utilization, under heavy disturbances (300-byte packets).

Figure 15 presents the comparison of our two proposed protocols in a disturbed free PLC network when the packet size is equal to 1500 bytes. It is clear from the Figure that at all traffic loads the stack based approach achieves very low values of signalling delay. In high traffic loads we observe that the W U - U W protocol dramatically decreases its signalling delay. This does not imply better behaviour than the cell stack based approach. The explanation has to do with the fact that in the case of average packet size equal to 1500 bytes, the piggybacking mechanism is activated more frequently. This at high traffic load results in users which are always excluded from the resource allocation as they cannot successfully send their requests, and users who use the allocated to them slot for as long as they need it.

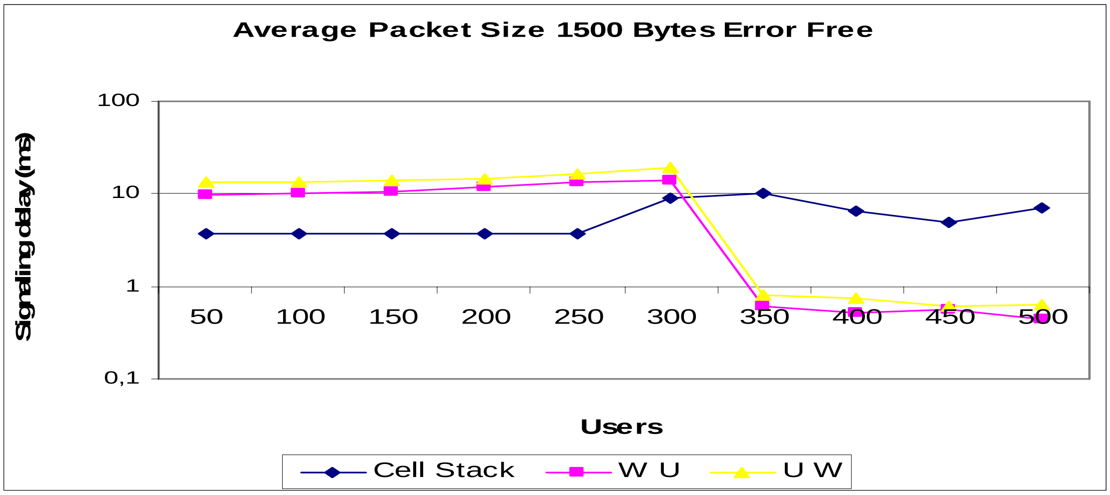

Figure 15. Comparison of our three schemes in terms of signalling delay, with no disturbances (1500-byte packets).

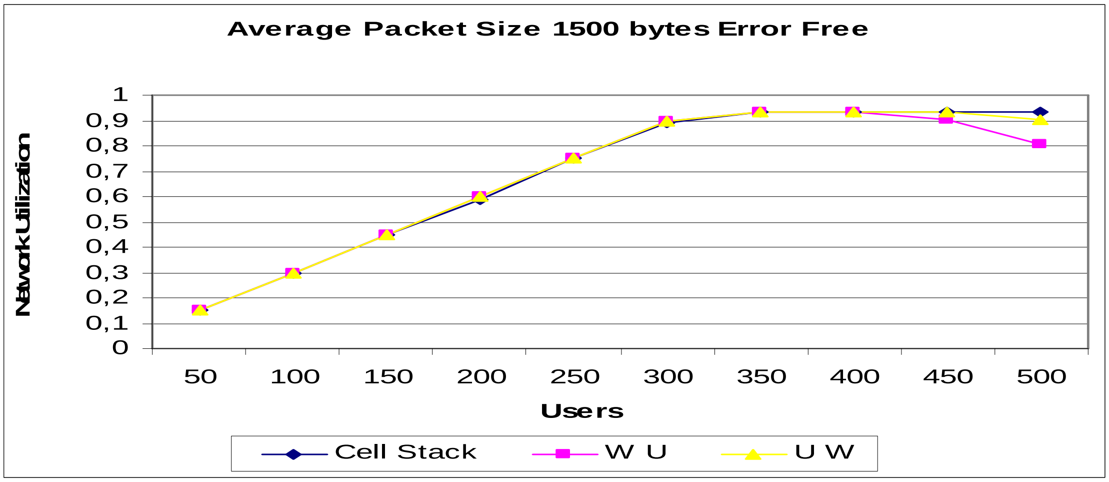

Figure 16. Comparison of our three schemes in terms of network utilization, with no disturbances (1500-byte packets).

III. Stack based approach vs UW-WU algorithm with average packet size equal to 1500 bytes

Figure 16 presents the comparison of our proposed protocols in terms of network utilization with average packet size 1500 bytes in heavy disturbed PLC network. It was mentioned before that when a message reception is incorrect, the entire message (all packets in which it is segmented) has to be retransmitted; hence, the transmission of data in large messages under heavy network disturbances can be less advantageous (resulting in more packets' retransmission) than the case of transmitting data in smaller messages. This characteristic almost eliminates the difference between the protocols in terms of network utilization, but still the cell stack based approach maintains a small advantage, especially at high traffic load against W U-U W. To conclude, the stack based algorithm always achieves better results in terms of network utilization against the W U-U W algorithm, which is expected as only the stack approach uses all the available bandwidth for data transmissions and also it offers almost 20 times more chances to the terminals to transmit their requests.

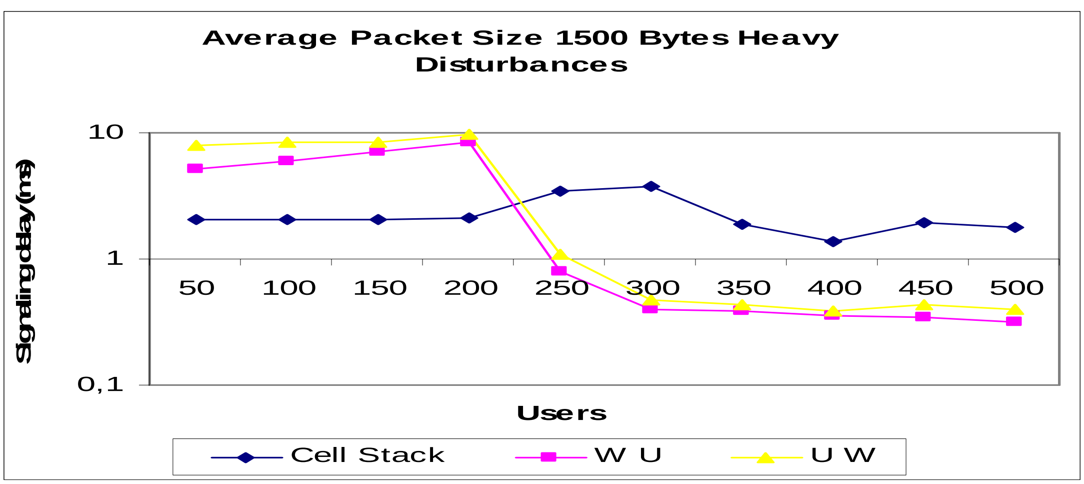

Figure 17. Comparison of our three schemes in terms of signalling delay, under heavy disturbances (1500-byte packets).

The above comparisons of our two proposed protocols reveal an interesting potential for the stack protocol. As it is mentioned in the previous chapter the user activity factor is 0.525. This means that in the worst scenario (500 terminals) we have 500*0.525 = 262.5 active users. From the results, it is clear that 11.75*20 = 235 minislots per frame are more than enough to ensure that every user will successfully send its request with minimum signaling delay. The next interesting research step is to determine the number of minislots we can sacrifice from the signaling channel in order to increase the available data bandwidth which is proven not to be sufficient at high traffic loads.

Another remark is that stack based protocol provides better results in terms of signaling delay. The difference between the two protocols can reach hundreds of msec as shown in Figures 11 and 13.

In terms of network utilization, the stack approach is always better as it selection provides an improvement in network utilization between 2% and 10% as revealed by the results in Figures 12, 14 and 16. The decrement for both protocols in the case of 1500-byte packets is that in case of an incorrect transmission, due to the disturbances in the network, the entire 1500-byte packet (i.e., all packets in which it is segmented) has to be retransmitted.

The behaviour of the signalling delay presented in the Figures 11, 13, 15 and 17 of our proposed schemes (decrement at high traffic loads) lead us to study the average access delay in order to extract valuable conclusions about the behaviour of our protocols in this area of operation. We define access delay as the time needed for the completion of the requesting procedure plus the time needed for the transmission of the first packet of the message.

As mentioned earlier, signalling delay and network utilization are the metrics affected the most by the reservation protocol used. Access delay, especially at high traffic load, is also affected by the traffic load. When the traffic load is low, the significant part of the access delay is the signalling delay. Above the saturation point at which the maximum network utilization is achieved, the user waiting time amounts to the larger portion of the access delay. We define the waiting time as the time from the moment the base station successfully receives the request packet from the terminal until the start of the corresponding transmission of the data packet by the user. The waiting time does not depend on the applied access method and increases proportionally with the network load (mainly at high traffic loads).

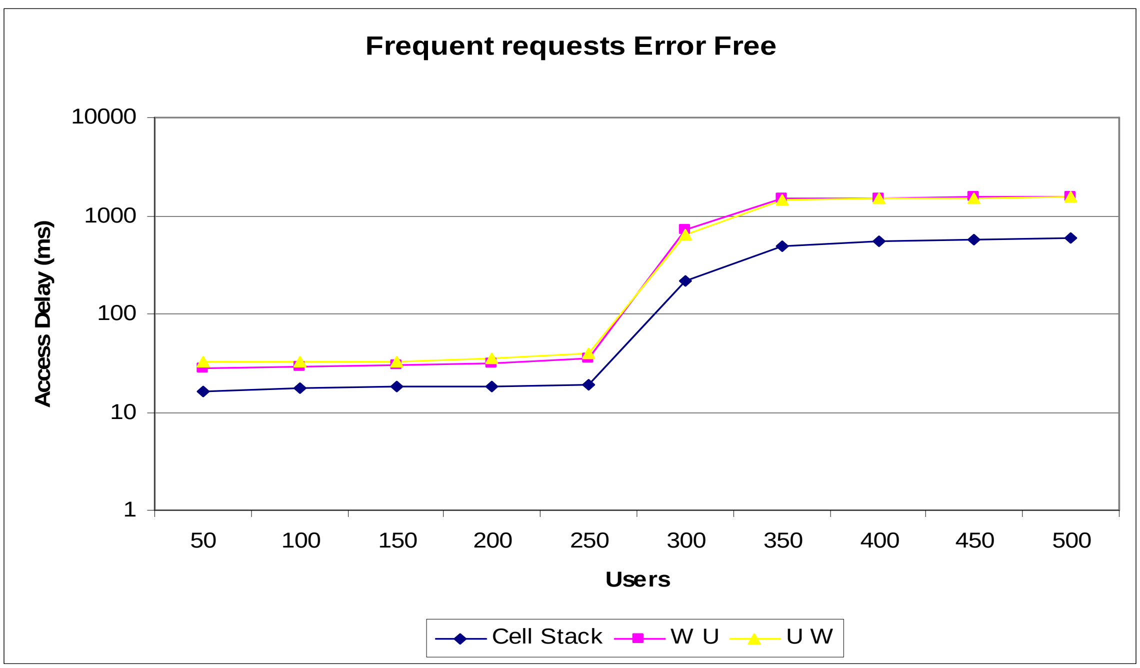

Figure 18. Comparison of our three schemes in terms of access delay, with no disturbances (300-byte packets).

Figure 18 presents the results of the comparison of our three proposed protocols in terms of access delay. The stack based protocol provides better results at low traffic loads (below 300 terminals), almost 50% less than W U, U W. But as we reach the saturation point of the system (around 300 terminals), the frequent piggybacking activation and the fact that there only 168 data slots per frame (14 data channels * 12 slots per frame), cause a major increase of the access delay. Especially for extremely high traffic load, the choice of the reservation mechanism cannot affect the behavior of the system. When there are more than 300 terminals in the system, the three schemes achieve almost the same average access delay due to the fact that there is not enough bandwidth to be allocated to the terminals.

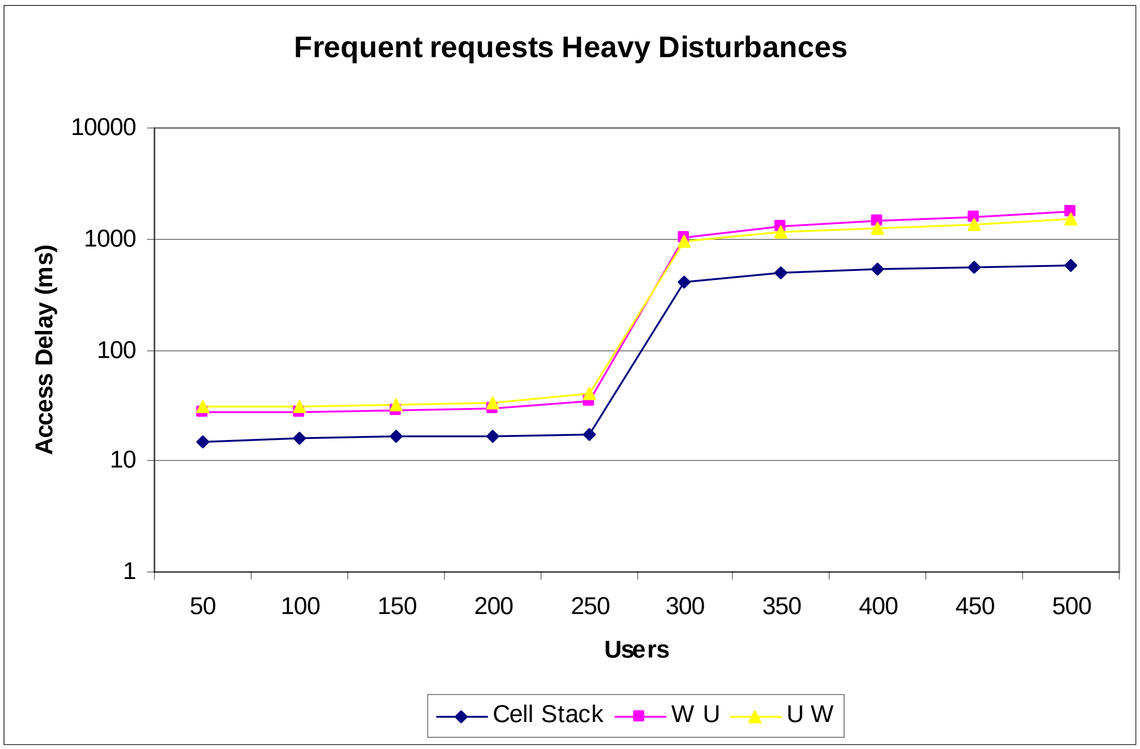

Figure 19. Comparison of our three schemes in terms of access delay, under heavy disturbances (300-byte packets).

IV. Further investigation on the comparison between the stack based approach and the UW-WU algorithm

On the other hand when we have heavy disturbances and high traffic loads, all three schemes have the same performance beyond the moment where the user receives his acknowledgement for his request. In Figure 19 we see the average access delay (the access delay is defined as the signaling delay plus the time needed for the transmission of the first packet of the message).The first part of the access delay is presented in Figure 13. The second "part" of the access delay seems to be the same for the three proposals for a heavily disturbed PLC network with frequent requests. On the contrary when we have rare requests at our system, the use of the stack based protocol seems the only way if we observe the results in Figure 20.

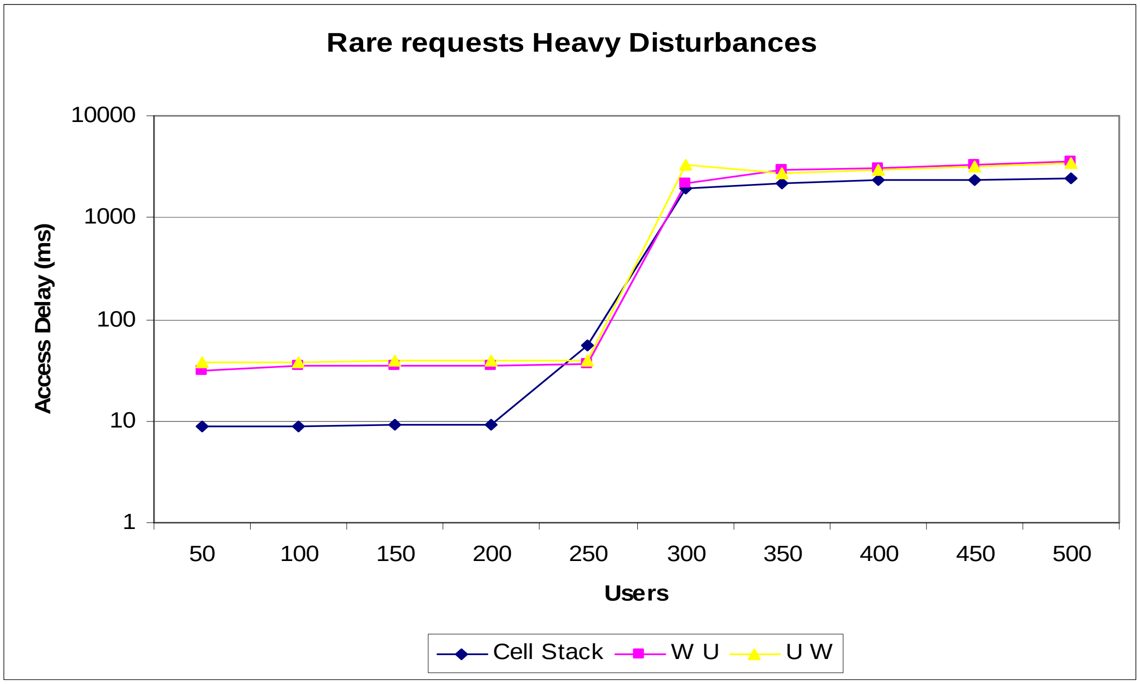

Figure 20. Comparison of our three schemes in terms of access delay, with no disturbances (1500-byte packets).

At low traffic loads the stack based protocol achieves 50% smaller access delays than its other two competitors. As traffic loads gets higher we overpass the saturation point of the system. However, still the stack based approach achieves 33% lower access delays than the W U protocol and 30% lower access delays than the U W protocol.

Based on the above observations, we argue that the stack based protocol achieves the best performance however, only if we use the two cell stack for light traffic load and the three cell stack for high traffic load. The boundary for the mode change should be between 287-290 users for the reasons explained earlier.

IV. CHAPTER – A NEW MAC PROTOCOL PROPOSAL BASED ON THE POLLING ACCESS METHOD

In this chapter we design, evaluate and present a new MAC protocol appropriate for heavily loaded PLC networks. We adopt polling based access, minislots and grouping of users to achieve high performance by minimizing the round trip time (defined as the time between two subsequent polls of a specific user by the base station) and reducing the packet delays. We adopt the polling access procedure in order to enhance the performance of our protocol in the cases where the traffic load becomes heavy. We also compare our experimental simulation results to those presented in [6] corresponding to polling based PLC MAC protocol proposal presented therein. Our protocol is shown to achieve better performance than its counterpart presented in [6].

A. A New MAC Protocol Proposal based on the Polling access method

I. Request procedure

In this chapter, we adopt from [5, 6] the idea of piggybacking and from [5, 6, 9, 11] the idea of using data channels for signaling but not the adaptive backoff mechanism proposed in [5, 6] for the users to select the slot in which they will transmit/retransmit their requests; instead, we propose a new idea described as follows.

The terminals are polled by the Base Station which always has exact knowledge of the number of the users in the system. We use the 1st channel only for signaling, where each slot is divided into 20 minislots and each minislot can be used only to poll one terminal.

The remaining 14 channels are mainly used for data transmissions. The Base Station allocates the bandwidth to the terminals which have successfully been polled and send an acknowledgement. Of course the base station polls only inactive terminals which we do not know if they have data to send.

All the above means that we have a contention free situation among users and we expect to have improved performance at high traffic loads against our former improvements and better results compared to those of the Extended Polling scheme presented in [5,15].

Contrary to our scheme, the Extended Active Polling protocol in [5, 15] adopts a rather complicated algorithm trying to reduce overall network delays. According to this scheme the polling procedure is divided into two phases:

a. Prepolling phase : Estimation of the active users
b. Polling phase : Standard Polling procedure for the active users

For the realization of the above two-step reservation procedure, downlink signaling slots are divided in three fields. The first field is reserved for transmission of a prepolling message, which specifies a group of users that can set a prerequest bit in the next uplink signaling slot. The other two fields in the downlink are used according to the standard polling procedure, for polling messages addressing a user to send a transmission request in the next uplink signaling slot, and for acknowledgments from the base station containing information about the access rights. In the uplink there are the prerequest bits and a request field. Each of the bits is reserved for a user that is a member of a group specified in the prepolling message from the previous time slot in the downlink. The request field is used for the request transmission after a user is polled in the previous downlink slot.

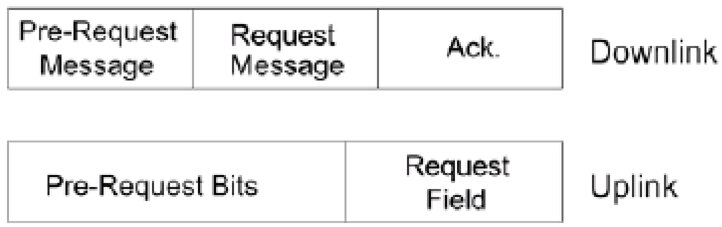

Figure 1. Slot structure for two-step procedure

After a user receives a prerequest polling message that addresses its group, it uses one of the prerequest minislots in the next uplink signaling slot to set a prerequest. Within a group of users there are dedicated prerequest minislots for each of them ensuring that way a contention free transmission of the prerequests. After that, the base station transmits a polling message to the requesting user. Additionally, there is the need for the scheduling of arrived prerequests at the base station, as it can receive multiple requests but it can send only one polling message within a signaling slot. After a user receives a polling message, it transmits a request in the next uplink time slot. After that, an acknowledgment from the base station follows, which defines the access rights.

In the two-step reservation protocol, there exists the possibility that no user will send a prerequest. In this case, and if the base station has already scheduled all previously received prerequests, no user is polled, and the request field in the next uplink signaling slot remains unused. In this case, the base station informs the users that random access to the empty request slots is allowed, making this so-called hybrid-two-step protocol. Of course collisions between randomly realized multiple requests are possible, but only if the request fields are free for random access and if there was no polling message in the previous time slot. If a collision occurs, access to the medium is carried out in accordance with the basic two-step reservation method described in [6].

B. Results and Discussion

I. Mini-slotted polling vs Extended Hybrid Active Polling with frequent requests

The system parameters used in our work are taken from [5, 6], in order to make a direct comparison with that work, which focused only on data (Internet) traffic. The number of data terminals varies between 50 and 500. In [5], two average sizes of user packets are used; 300 bytes and 1500 bytes. Both cases are examined in our study as well. The case of 300-byte packets is important, since packet transmission in PLC should be made in very short frames so that the receiver can adapt to the rapid (< 1 ms) changes in the PLC channel conditions [10] (the mean packet interarrival time in this case is chosen equal to 0.96 seconds); this is the case defined in [5, 6] as the "frequent request case", which enables us to test our scheme under heavy traffic conditions, since the number of packet transmissions and, therefore, collisions in the PLC network can be significantly higher than in the case of 1500- byte packets. On the other hand, the case of 1500-byte packets is equally important, as when a message reception is incorrect, the entire message (i.e., all packets in which it is segmented) has to be retransmitted; hence, the transmission of data in large messages under heavy channel disturbances can be less advantageous (more packet retransmissions) than the case of transmitting data in smaller messages.

The offered traffic load per network station (terminal) is 2.5 kbps in both cases (the mean interarrival time in the case of 1500-byte packets is 4.8 seconds). The packet sizes and the interarrival times are assumed geometrically distributed.

As already mentioned, the number of transmission channels is equal to 15 (one of the channels is reserved for signaling), each with a data rate of 64 kbps. It should be noted that currently used PLC systems provide data rates around 2 Mbps; therefore, in this work we assume that in such a PLC system half of the network capacity is used by data connections.

The frame duration is 47 msecs, the slot duration is equal to 4 ms, the slot capacity is 32 bytes and the payload in each slot is 28 bytes. We simulated one hour of network operation. Each simulation point is the result of an average of 10 independent runs (Monte-Carlo method).

In Figures 2-10 we present the comparison of our proposed scheme against Extended Hybrid Active Polling. In terms of complexity our protocol proposal is much simpler than the Extended Hybrid Active Polling, though they share common elements such as use of data channels for signaling and piggybacking. Of course we also use minislots in a slightly different way, as we can see in Figure 2.

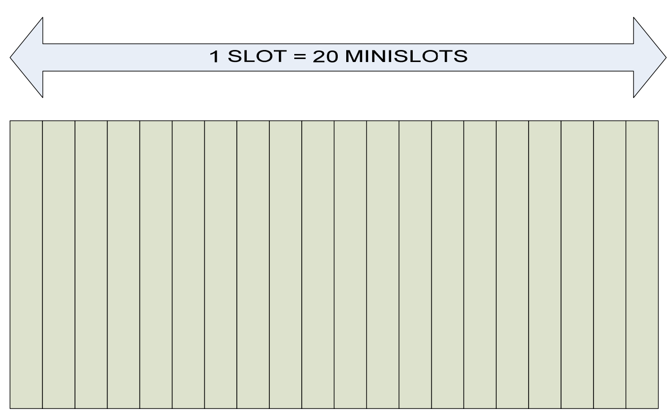

Figure 2. Slot structure for our Polling protocol

From the results in Figure 3, we observe the superiority of our proposed protocol against the Extended Hybrid Active Polling scheme in terms of signaling delay. Our scheme incurs a delay of 37 msecs whereas the delay under the Extended Hybrid Active Polling reaches 400 msecs, at medium traffic loads. At very low traffic loads our scheme provide extremely low signaling delays (1.8 msec) whereas the Extended Hybrid Active Polling incurs signaling delay of around 37 msecs.

Our mechanism minimizes the round trip time much more efficiently as the base station has at its disposed on average 11.75 * 20 = 235 minislots (frame duration = 47 msecs, slot duration = 4 msec and average number of slots per frame : 47 / 4 = 11.75), only from the signaling channel, to poll users. With the use of idle data channels for polling purposes the base station has much more than 235 minislots available in order to poll users. The use of data channels provide plenty of minislots where the base station can send the polling messages, especially at low to medium traffic loads. In a lightly loaded channel there are many unallocated data slots which enable the base station to use the corresponding minislots for the realization of the polling procedure. In our simulations we observed that in such cases the base station has the ability to send polling messages to the same user two or three times in the same channel frame. As traffic load gets higher, the data channels are reserved for data transmissions and the base station uses "only" 11.75*20 = 235 minislots to send its polling messages to the users. That is the main reason for the increment of the signaling delay at light to medium traffic loads. Even with those conditions our protocol incurs 10 times lower signaling delays than the Extended Hybrid Active Polling (37 msecs against 400 msecs in the case of 300 terminals, as shown in Figure 3)

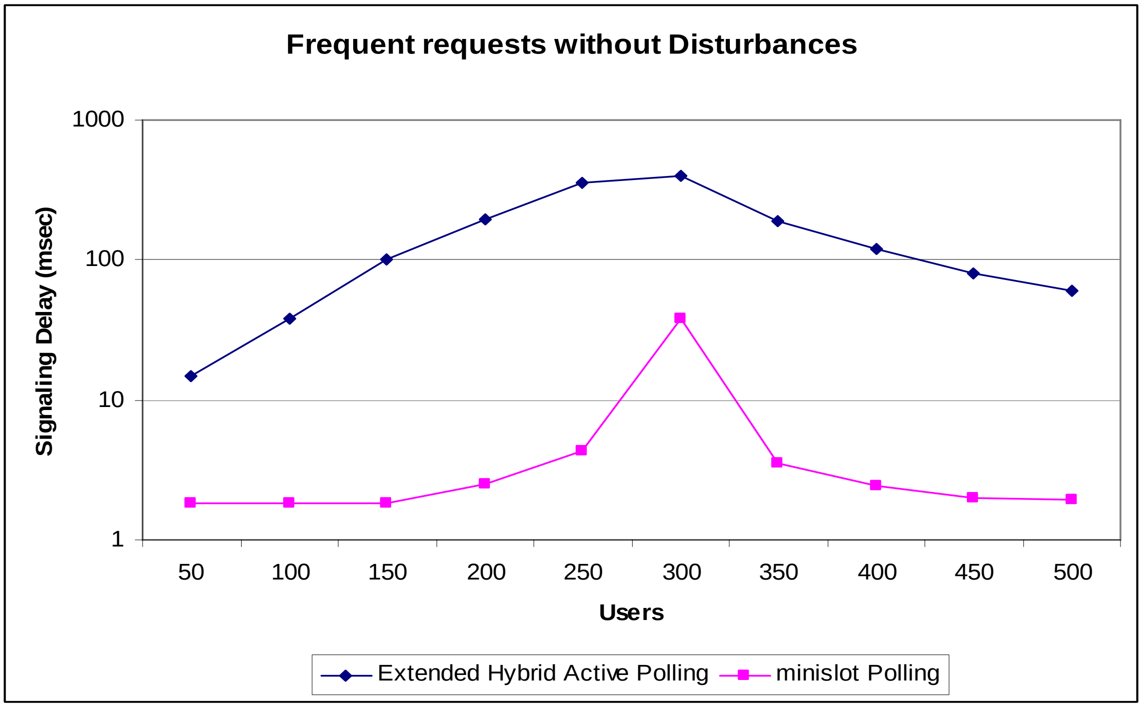

Figure 3. Comparison of the two schemes in terms of signaling delay, with no disturbances (300-byte packets).

As traffic load gets higher we observe increment at signaling delay. Above 300 terminals in the system, all the data channels are used for data transmissions and this fact combined with the use of the piggybacking mechanism cause the phenomenon where we have users which have successfully sent their request but there are no channel resources available to be allocated by the base station.

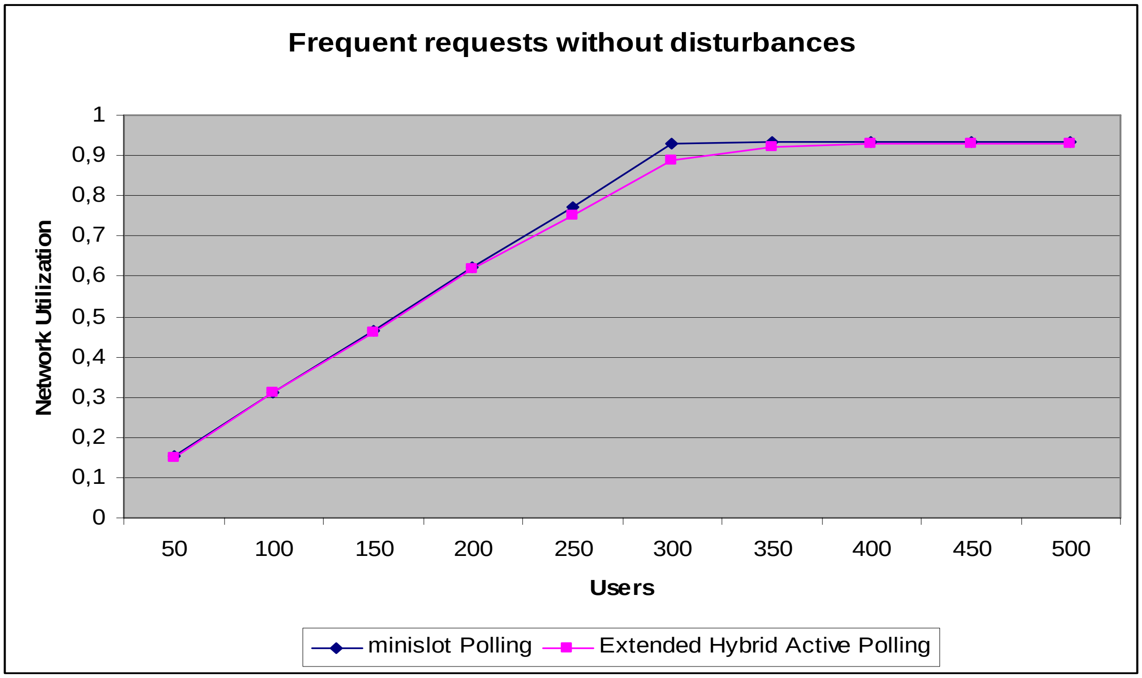

Figure 4. Comparison of the two schemes in terms of network utilization, with no disturbances (300-byte packets).

In terms of network utilization, our protocol is better at medium traffic loads, due to the fact that we always have contention free requesting procedure, while the Extended Hybrid Active Polling not. The saturation point at this PLC system without disturbances is below 335 users, and out protocol makes perfect exploitation of the available data bandwidth which in combination with the smaller round trip times of our polling procedure gives the terminals the chance to minimize not only their signaling delay, but also their access delay.

In an environment with heavy disturbances the conclusions remain the same in terms of signaling delay. Our scheme provides four to ten times lower values of signaling delay compared with the Extended Hybrid Active Polling scheme. If a slot is corrupted, our protocol only loses 20 minislots and the terminals which were supposed to be polled add to their signaling delay counter only 4 msecs (= slot duration). The signaling procedure continues without any further delay in the next slot of the signaling channel or one of the data channels if they currently have free slots.

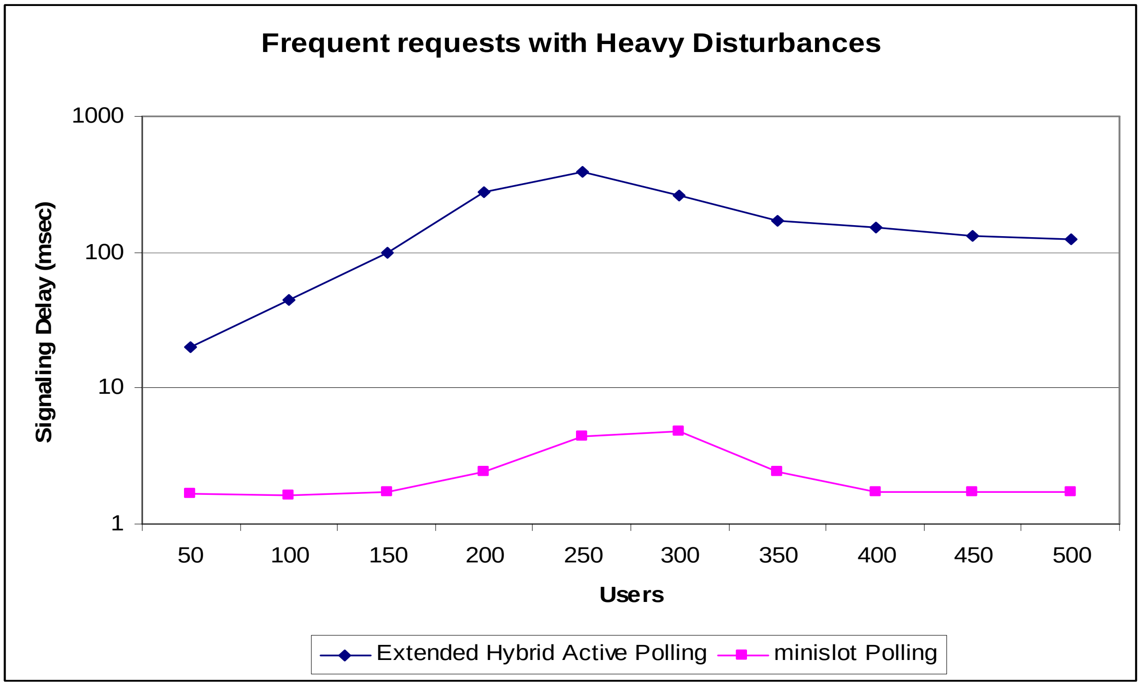

Figure 5. Comparison of the two schemes in terms of signaling delay, under heavy disturbances (300-byte packets).

At high traffic loads our protocol makes perfect exploitation of the available data bandwidth (87%) with only problem being the corrupted slots during transmissions which force terminals to resent the entire message. This situation degrades the maximum network utilization of the Extended Hybrid Active Polling at 83% as shown in Figure 6.

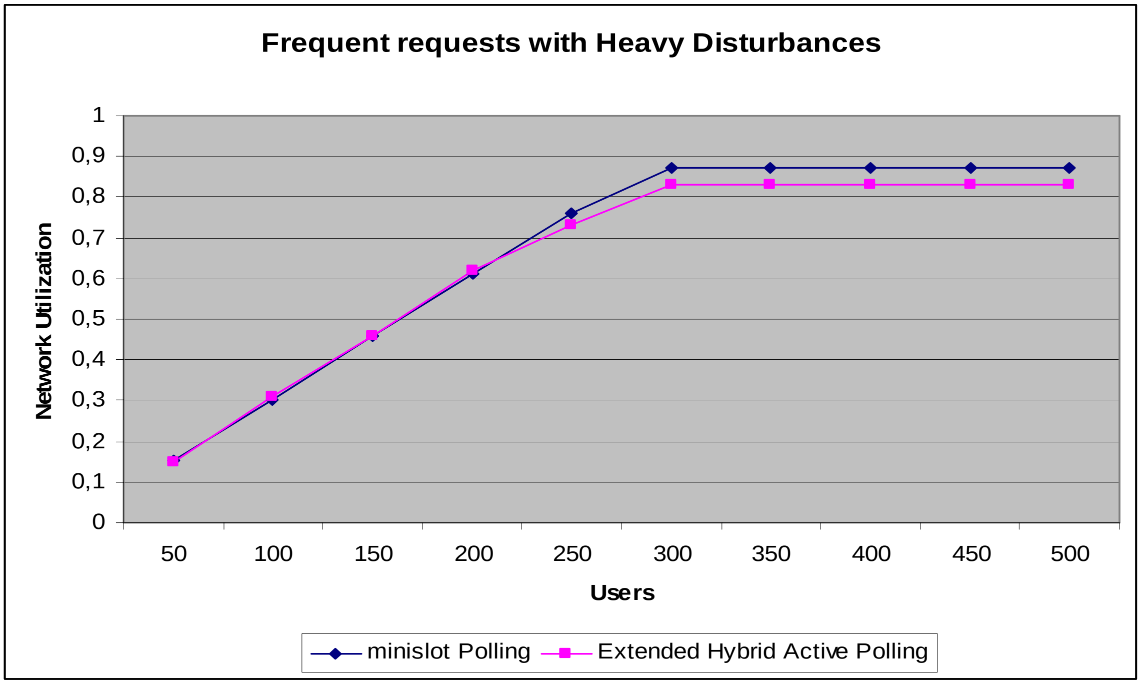

Figure 6. Comparison of the two schemes in terms of network utilization, under heavy disturbances (300-byte packets).

II. Mini-slotted polling vs Extended Hybrid Active Polling with rare requests

Figures 7-10 present the results of the comparison between the two Polling protocols when we have seldom requests at the PLC system. In terms of signaling delay our scheme provides almost 30 times lower values than the Extended Hybrid Active Polling. At the saturation point (the area around 300 terminals for a heavy disturbed PLC system) out protocol achieves signaling delay around 19 msec while the Extended Hybrid Active Polling protocol reaches 500 msecs. Once again it is shown that the available signaling bandwidth which we offer to the users through the polling procedure cover the needs of all the terminals. Especially as traffic load gets higher the combination of the use of the piggybacking (which is activated more frequently when we have seldom requests at the system) with the fact that only 164 users can transmit simultaneously at a frame basis, reduces even more the signaling delay as we can observe from Figure 7. Of course this does not mean that all the users transmit their data, but only that all users can notify the base station in less than 19 msecs on average (maximum value of signaling delay) that they have data to send.

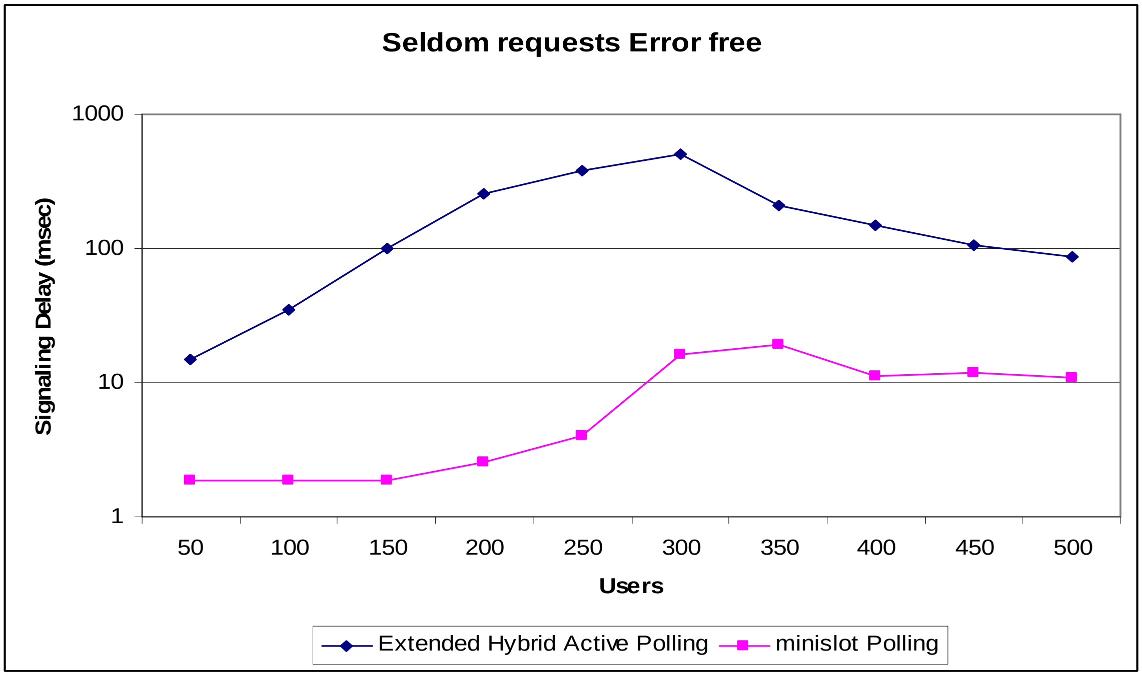

Figure 7. Comparison of the two schemes in terms of signaling delay, with no disturbances (1500-byte packets).

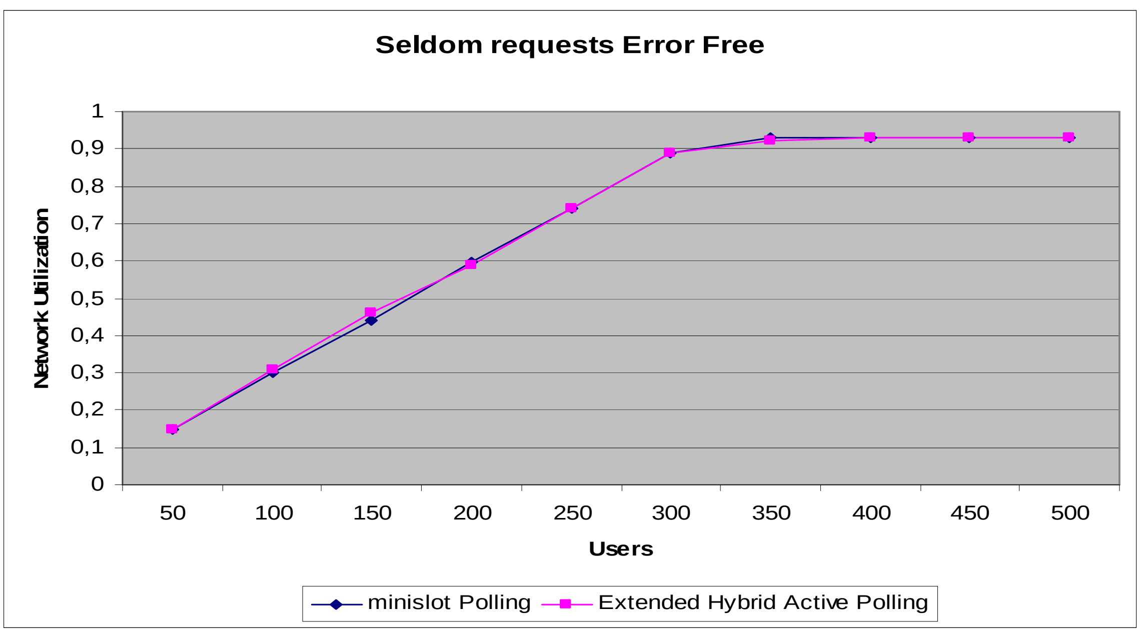

Figure 8. Comparison of the two schemes in terms of network utilization, with no disturbances

(1500-byte packets).

In terms of network utilization we can see from Figure 8 that there are not significant differences, implying that both protocols make perfect exploitation of the available data bandwidth. They both reach the value of 93% (which is the upper bound for this PLC system), the remaining 7% is reserved only for signaling.

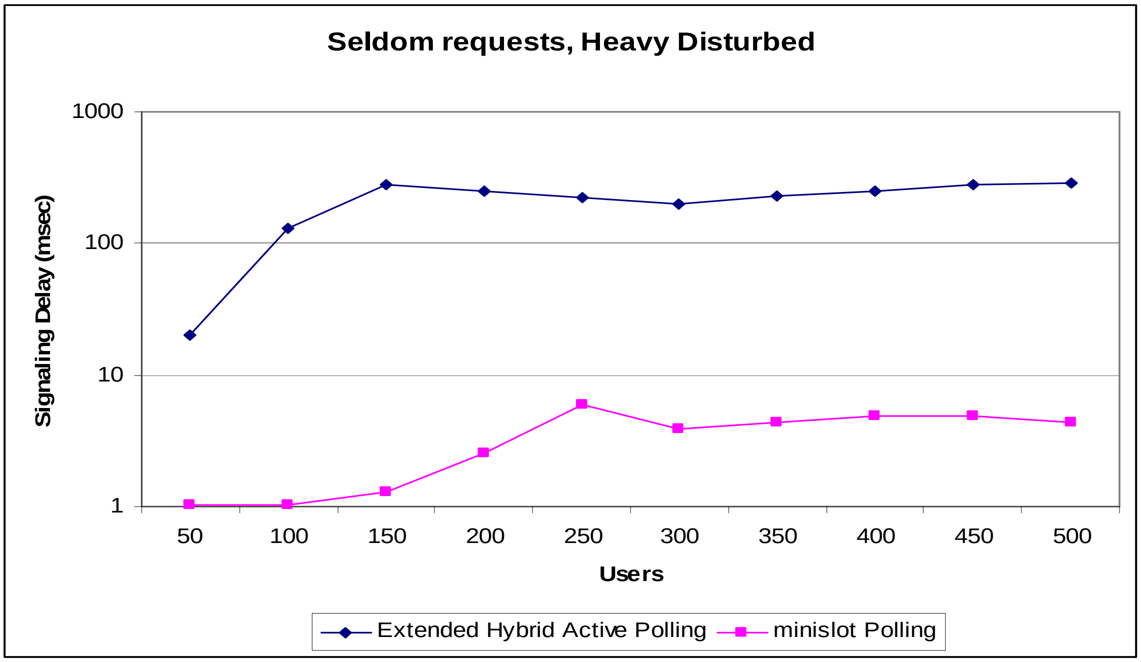

Figure 9. Comparison of the two schemes in terms of signaling delay, under heavy disturbances (1500-byte packets).

The situation remains the same in terms of network utilization when we add heavy disturbances to our system. Our protocol provides always better results as shown in Figure 9. At Figure 10, we observe the superiority of our protocol at medium to high traffic loads. It reaches the value of 57%, while the Extended Hybrid Active Polling reaches 53%. The main reason for the major decrease of network utilization for both protocols, (compare the results in Figures 8 and 10), is the fact that if a slot which is used by a terminal to transmit is corrupted, then the entire message has to be retransmitted. This causes larger delays especially when long messages are used. The best solution to this problem, is to try to reduce the message length while at the same time trying not to increase the signaling delay, considerably as each message requires a successful transmission of a request from the user to the base station.

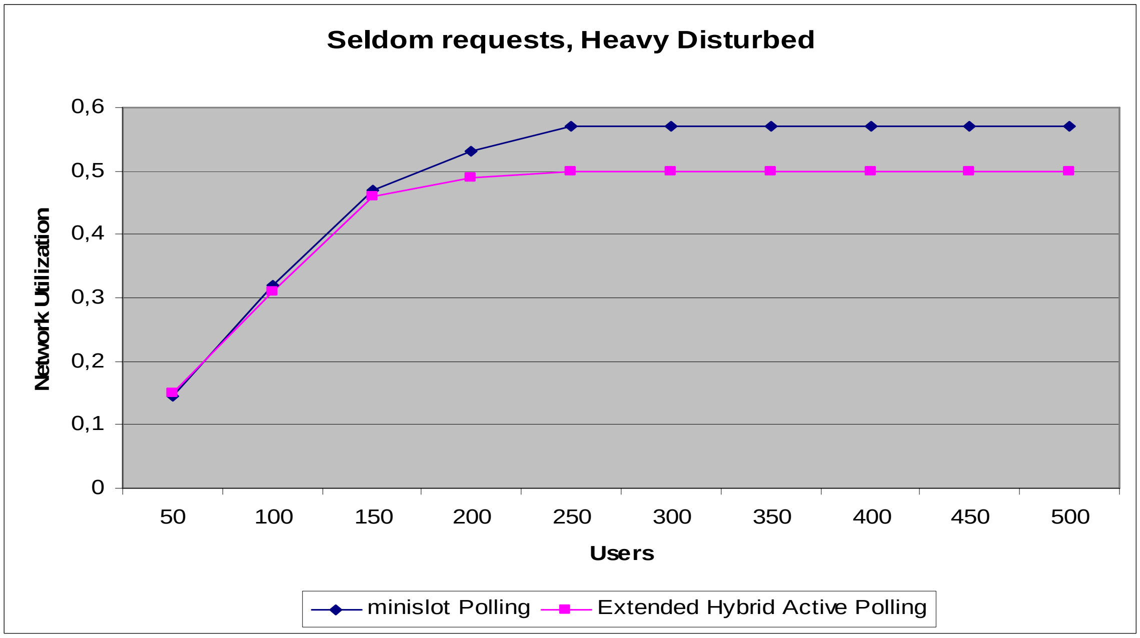

Figure 10. Comparison of the two schemes in terms of network utilization, under heavy disturbances (1500-byte packets).

Another interesting comparison is between our protocol, the so called mini-slotted Polling, and the cell stack protocol which was presented in the previous chapter. Of course these two are totally different protocols, as the one uses polling for the signaling procedure and the other combines reservation random access with two or three cell stack algorithm for collision resolution solution. Our polling protocol also uses data bandwidth, if there is available, while the cell stack protocol uses only the signaling channel for the realization of the requesting procedure. The only common element, is the division of each signaling slot into 20 minislots and this fact makes interesting the comparison of the two protocols in terms of delays and network utilization.

III. Mini-slotted polling vs Stack Based Approach

From Figure 11-A we observe that at low traffic loads mini-sloted polling is superior, since it uses all the available data slots to send 20 polling messages in each slot. This minimizes the round trip time reducing that way the signaling delay. On the other hand as traffic load gets higher, the polling procedure is realized only in the signaling channel and this fact combined with the large number of users who have to send their data, increase the signaling delay.

With the use of the stack based approach the signaling delay is lower at high traffic loads than with the use of mini slotted polling protocol as shown in Figure 11-A. The situation reverses for light traffic loads where the mini slotted polling approach deploys large number of minislots for polling purposes from the idle data channels.

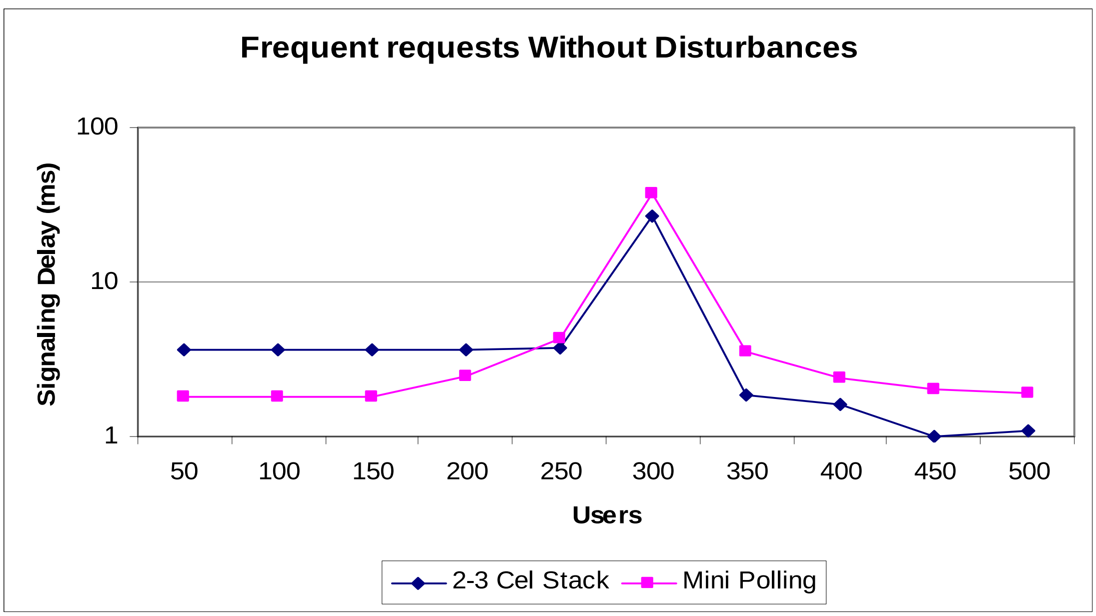

Figure 11-A. Comparison of the two schemes in terms of signaling delay, with no disturbances (300-byte packets).

From the results in Figure 11-B, we observe that as traffic load gets heavier, the access delay increases dramatically. This means that despite the fact that signalling delay decreases at high traffic loads using both protocols, the overall delay increases. The explanation for this is that the base station can "serve" simultaneously only 164 users in each frame. If there are more users which have successfully sent their requests, they are forced to wait for a free slot for a long time. Also the base station for fairness reasons, when there is available data bandwidth schedules the arrived requests in a first come first serve manner.

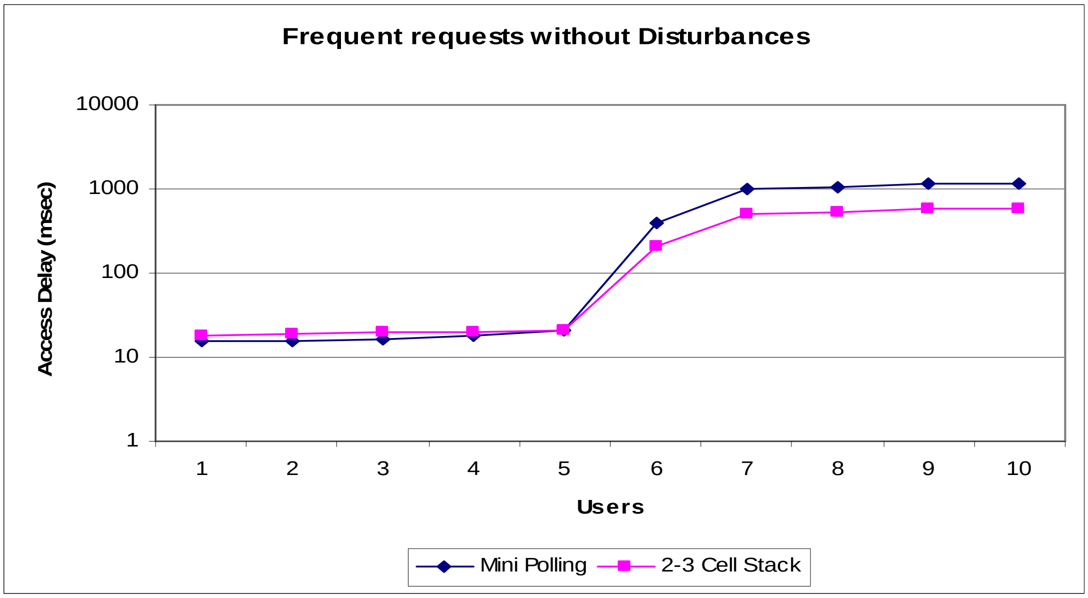

Figure 11-B. Comparison of our two schemes in terms of access delay, with no disturbances (300-byte packets).

In terms of network utilization and for frequent requests we can see from the results in Figures 12 and 14 that both protocols achieve the same performance. This is expected, as they share exactly the same policies in the transmission phase and they use the same 14 data channels for transmissions.

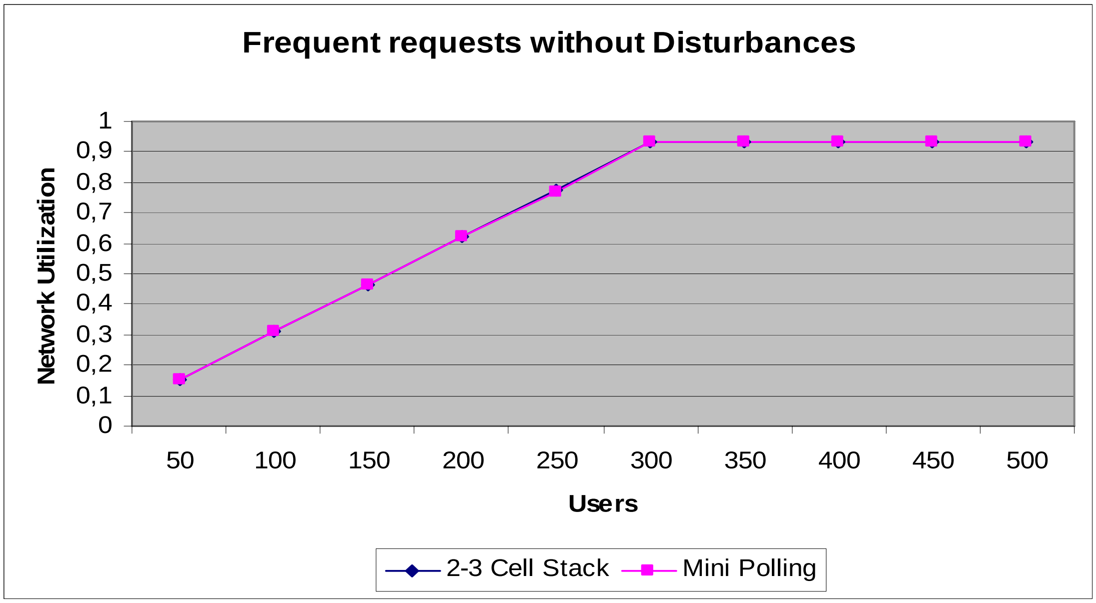

Figure 12. Comparison of the two schemes in terms of network utilization, with no disturbances (300-byte packets).

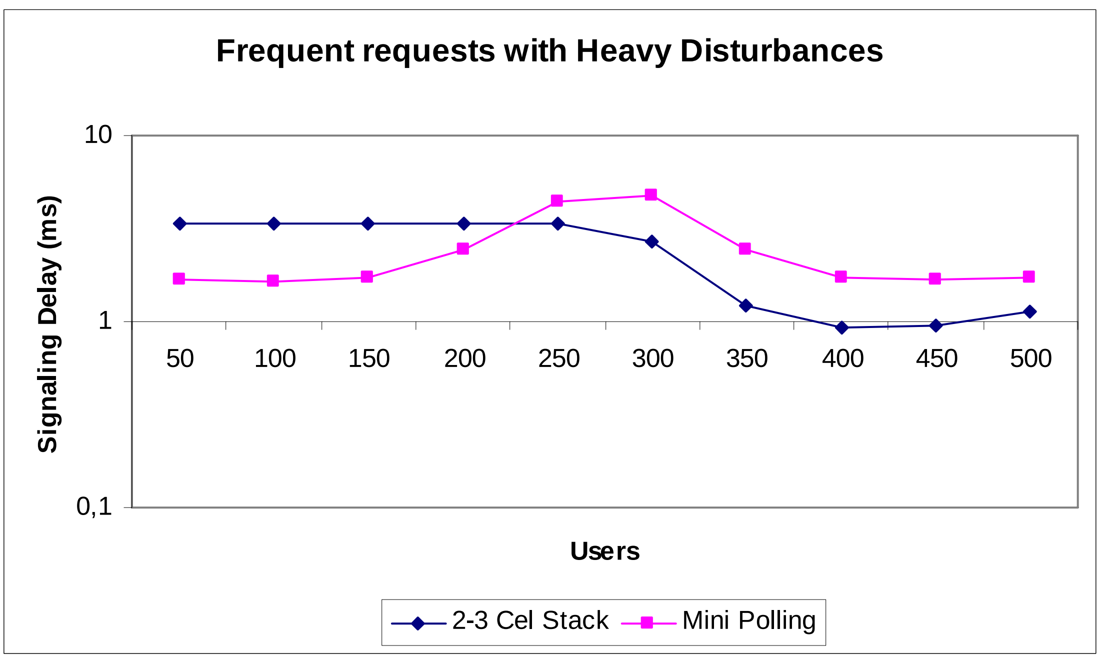

Figure 13. Comparison of the two schemes in terms of signaling delay, under heavy disturbances (300-byte packets).

A further comment that can be made regarding Figure 13 is that the curves are smoother compared to those in Figures 11-A. The reason is that the presence of heavy disturbances degrades the communication between the terminals and the base station, negatively affecting not only the transmission delays (due to the retransmission of corrupted messages), but also the signalling delay.

In Figures 13 we present signalling delays for the two protocols under heavy disturbances. We can see that the two protocols exhibit the same behaviour as in Figure 11-A, where the two protocols were evaluated in an error free environment. Still the two- three cell stack scheme offers better results at high traffic loads, while the mini-slotted polling scheme has lower delays at low traffic loads.

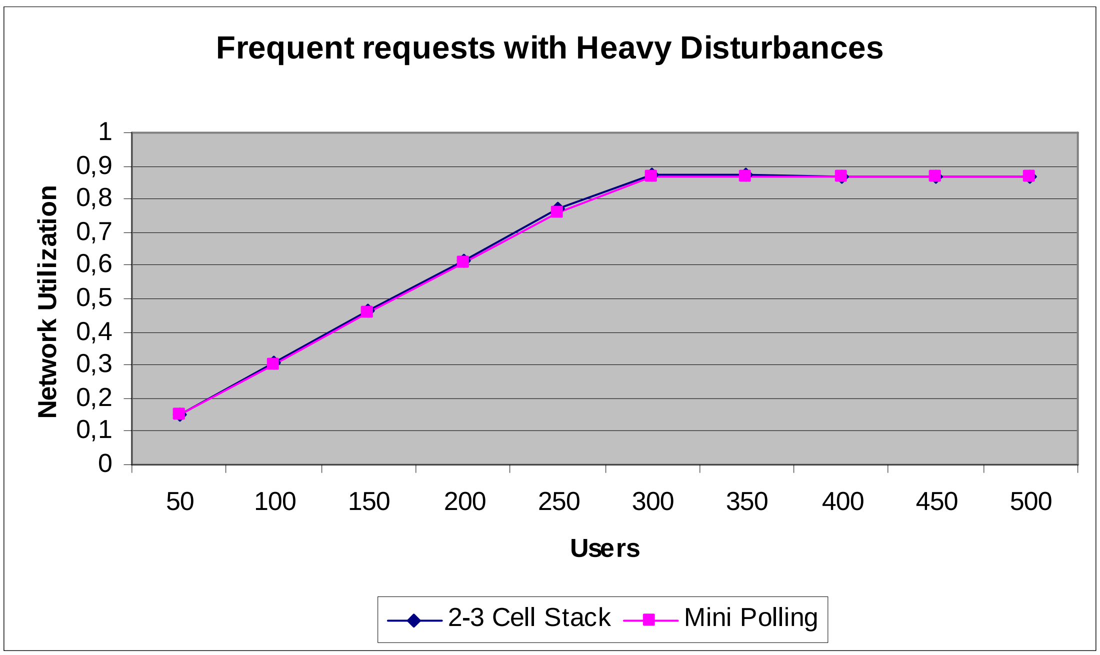

Figure 14. Comparison of the two schemes in terms of signaling delay, under heavy disturbances (300-byte packets).

When we use seldom requests in the system we observe from Figure 16 that both protocols achieve the same performance in terms of network utilization for the reason mentioned earlier.

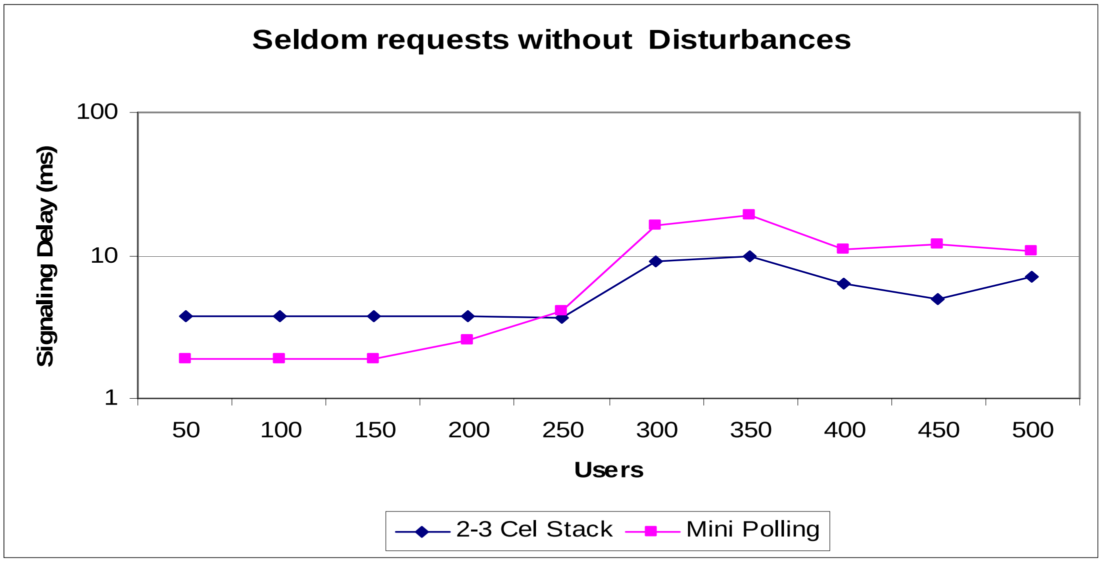

Figure 15. Comparison of the two schemes in terms of signaling delay, without disturbances (1500-byte packets).

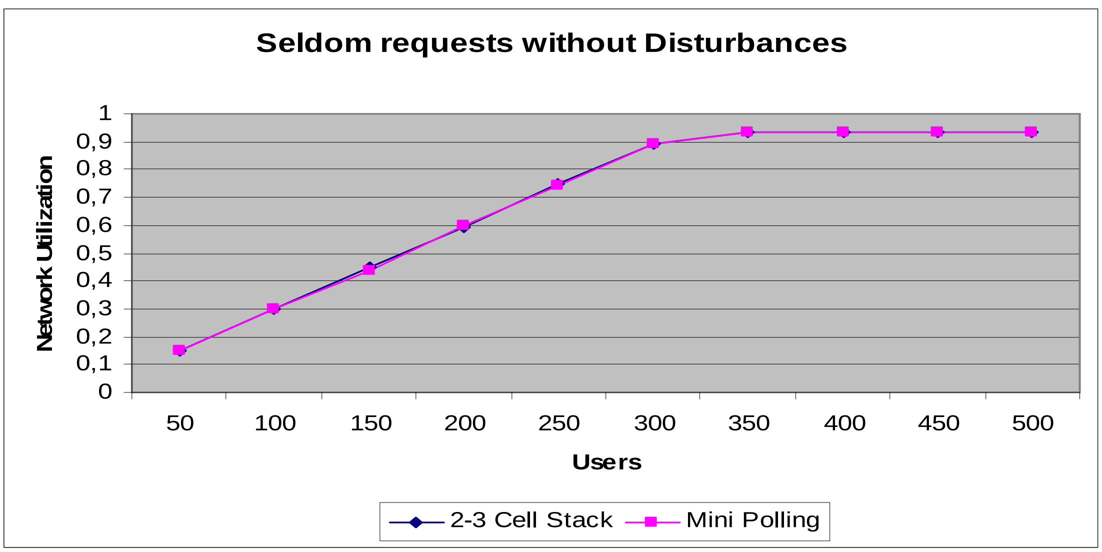

Figure 16. Comparison of the two schemes in terms of network utilization, without disturbances (1500-byte packets).

Figures 15 and 17 present signalling delay results for a disturbed free and a heavily disturbed PLC network, respectively. Still the conclusions remain the same with those we arrived at when we used frequent requests. The mini-slotted polling protocol behaves better than the two-three cell stack protocol at low traffic loads. As traffic load gets heavier the situation is reversed in terms of signalling delay.

If we decide to trace the point where the two protocols achieve the same signalling delay performance, we observe from the Figures, that this point lies between 200 and 250 users. The exact point value depends of course on the presence and the duration of the noise impulses in the PLC network and on the type of requests which we use (seldom or frequent).

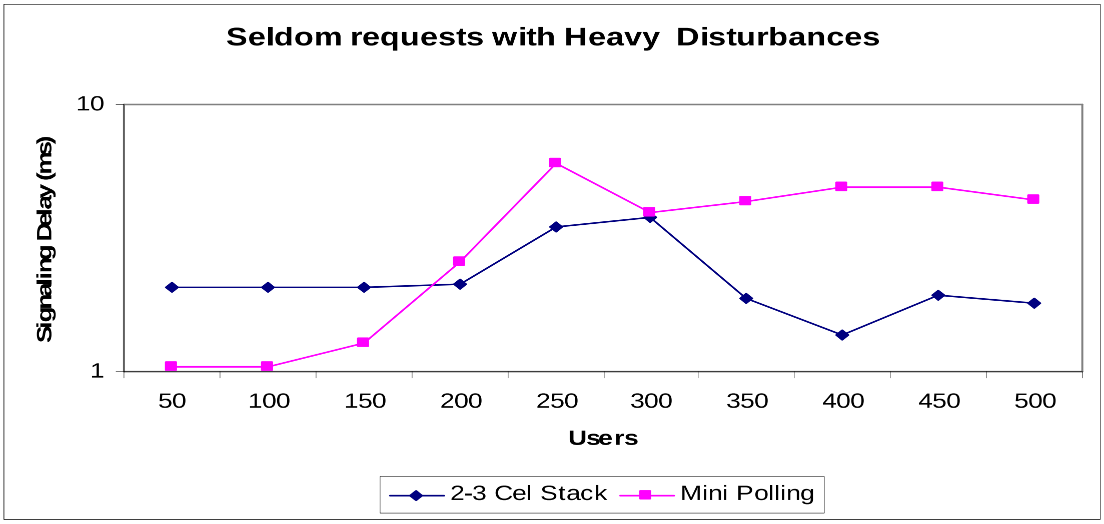

Figure 17. Comparison of the two schemes in terms of signaling delay, under heavy disturbances (1500-byte packets).

Without doubt the 2-3 cell stack and the mini-slotted polling schemes seem to be the most appropriate candidates to be used in a PLC network, each one of them has its own specific area of operation. The combined use of these two protocols can be easily implemented, as we only need knowledge of the following:

- Estimation of the number of users in the system (it was described in chapter II)
- Categorization of the duration and the number of impulses in the system (this is an easy task for the base station, since it is monitoring all the channels in real time)
- The frequency according to which we expect requests by the users (this can be statistically estimated by the base station)

Of course there is still the need to determine how often the base station will recalculate the aforementioned parameters and make sure that the system would not experience oscillations when the traffic load is close to the point of alternation among the two modes of protocol operation.

V. CONCLUSIONS

This work in this Thesis presents new scheduling schemes for the medium access control of the "last mile" access PLC networks; the schemes build on the Extended Aloha protocol or the Extended Polling scheme by adding new ideas for achieving more efficient bandwidth allocation. Our schemes are shown to clearly excel when comparing the pertinent network performance metrics with those of the original Extended Aloha protocol in a lightly and heavily disturbed network, and for both small and large packet sizes. Based on extensive simulation results, we propose a dynamic "two-mode" function for our MAC protocol, in which the protocol alternates its channel and slot selection schemes based on the volume of the network traffic.

A natural extension of our work in this Thesis, involves studying of our MAC protocols performance in the case of integration of voice and data traffic. In addition, there might be room for the further algorithmic improvement in the areas of channel or slot selection and collision resolution which could help us further improve the performance of our MAC PLC protocol.

Our results clearly show that the polling procedure combined with the use of minislots in our protocol, achieve very low signalling delay values indicating that at high traffic loads we could make use of a part of the signalling channel for data transmissions. The potential use of the signalling channel for data transmissions and its application in our protocol should be examined through simulations and evaluated in terms of the performance metrics: average delays and network utilization.

Finally another possible extension of our work involves the performance evaluation of the proposed MAC protocols using noise models which have been found in the literature to closely match the channel conditions of real PLC systems.

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