On Improving the Extended Aloha Protocol for Broadband Powerline Communications Networks with Light and Heavy Disturbances

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Abstract — **Powerline Communications (PLC) are currently being considered as an alternative for high-speed data communications and Internet access. With multiple outlets in almost every room, power lines are already the most pervasive network in the home or small office. This work presents a new Medium Access Control (MAC) protocol for the "last mile" access PLC networks. Via an extensive simulation study, our protocol is compared to a well-known protocol from the literature in terms of the efficiency of the transmission of short messages; our protocol is shown to excel both in network utilization and in the average signaling delay required for the completion of the transmission request procedure, in both the cases of a lightly and heavily disturbed PLC network.**

I. INTRODUCTION

The utilization of the power grid for communication purposes is not a new idea. In fact, utility companies have been using the medium and high voltage distribution lines for operation and maintenance, metering and load management since long ago. However, the data rate for protection and telemetering purposes is at most a few kbps and is not comparable to the Mbps data rates needed for the support of multimedia applications. Still, the unparalleled growth of the Internet in the past ten years, combined with the significant technological advancements of VLSI and digital signal processing, and with the telecommunications market deregulation around the world, have made PLC a viable technology for next generation telecommunications. The major attraction for PLC is obviously the fact that power lines already exist, everywhere; 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 [1-3]. The relevant literature on the MAC layer for PLC has focused more on in-home networking [4-6]. The work presented in this paper focuses on the "last mile" problem.

We consider a PLC access system using the low voltage power supply network for the connection of end-users/subscribers to a wide area network. Since a number of subscribers in a low voltage electrical power supply network need to share the transmission capacity of a PLC access network, a high gross data rate on the medium is necessary *to ensure the required Quality-of-Service (QoS) to subscribers* and to make PLC systems competitive to the other access technologies (xDSL, WLL, etc.). PLC systems applied to the telecommunication access networks use a frequency spectrum of up to 30 MHz and act as antennae producing electromagnetic radiation, which causes disturbances to other telecommunication services working in this frequency range. Because of that, PLC networks have to work with a limited signal power which makes PLC systems more sensitive to disturbances from the electrical power supply network and from the PLC network environment [8]. Well-known error handling mechanisms can be applied to PLC systems to solve the problem of transmission errors caused by the disturbances (e.g., Forward Error Correction (FEC) and Automatic Repeat request (ARQ) mechanisms). However, the use of these mechanisms consumes a part of the transmission capacity (due to the required overhead, and the need for retransmissions) and therefore decreases the already limited data rate of the PLC systems; *this fact creates the need for high network utilization in PLC networks*.

The above-mentioned goals can be realized with the use of efficient methods for network capacity sharing, i.e., with efficient MAC protocols. Our work focuses on the proposal of a new MAC protocol, which is compared with a well-known work from the literature, the extended Aloha protocol from [7, 8]. Our protocol is shown to provide significantly improved results in respect to the above-mentioned goals.

II. PLC SYSTEM DESCRIPTION

A. PLC Network Topology and Structure

PLC access networks are connected to the backbone communication networks via a base station. Many utilities supplying electrical power also form their own telecommunication networks which can be used as PLC backbone. The low-voltage supply systems build various network topologies. The topology of a low-voltage power supply network depends on several factors, such as the location of the PLC network, user/subscriber density, network length and network design [8]. Generally, several network sections exist between the transformer station and the users. Sections can have different structures (their common characteristic is that they generally have a tree structure). Users can be distributed in a symmetric or in an asymmetric way. Some characteristic values describing an average structure of a typical PLC network can be found in [8, 9], which note that the number of users in the network can reach up to 400, the network length between transmitter and receiver

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is less than 500 meters and the number of network sections can reach up to 5.

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 holds a bus structure in spite of the fact that the low-voltage supply networks have physically a tree topology.

B. Transmission System

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 [7, 8, 11-13]. OFDM provides data transmission over a number of sub-carriers, which makes possible the deviation from critical frequencies.

As in [7, 8], we consider an OFDM transmission system which uses a number of sub-carriers distributed in a frequency spectrum. Each sub-carrier (SC) has a transmission capacity and it is possible to make groups of the sub-carriers to build up transmission channels (CH) with a higher capacity. In our simulations we assume that a transmission channel offers a fixed data rate of 64 kbps.

C. Disturbances in the PLC Environment

PLC systems are more sensitive to disturbances from the electrical power supply network and from the PLC network environment, since they were not designed originally for information transmission. The PLC transmission channel is characterized by a powerful attenuation, changing impedance and fading as well as a strong influence of noise caused by various electrical devices connected to the supply networks.

As the asynchronous impulsive noise is the source for most of the problems connected with the correct transmission over the PLC network, it needs to be included in our study. The influence of the noise can be modeled by a two-state Markov chain (as in [7, 8]), in which one state represents the duration of an impulse, during which the channel is considered as disturbed and no information transmission is possible, and the other state represents the absence of noise and hence the correct transmission of information. These two states can be represented by two random variables, which follow a negative exponential distribution [10].

As in [7, 8], we have simulated in our work two types of disturbances in a PLC network: 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.

III. THE EXTENDED ALOHA PROTOCOL

The work presented in [7, 8] proposed the following extensions of the basic ALOHA protocol in order to improve its performance on the PLC network.

A. Piggybacking

Piggybacking is the term describing the channel access method in which a terminal transmitting the last segment of a message can also use this segment to request a transmission for a new message, if there is one in its queue. In this case the signaling channel is not used for the request transmission and therefore the collision probability decreases, hence leading to a decrease in the signaling delay, especially if the network is highly loaded, and to higher network utilization. *The signaling delay* is defined in our work as the time needed for the realization of the requesting procedure for the transmission of a message; this procedure includes the transmission of a request message to the base station and the reception of its response regarding the access rights.

B. Use of Data Channels for Signaling

The network model used in [7, 8] consists of 15 bidirectional transmission channels (64 kbps each), one of which is reserved for signaling.

Signaling delays can be reduced with an increase in the number of signaling channels. However, such an increase would cause the loss of valuable network capacity in terms of information transmission, hence leading to a decrease in network utilization. In order to achieve the reduction of signaling delay without a simultaneous reduction in network utilization, the work presented in [7, 8] adopts the idea from [14, 15] that any temporary idle information bandwidth can be used for the reservation procedure without allocation of additional network resources for signaling. Hence, in [7, 8] additional data channels are used for signaling, but only if they are currently idle; otherwise, only the signaling channel can be used for the reservations. Idle data channels are accessed randomly for transmission of the requests with an equal probability. After a successful request transmission, a user transmits freely within its reserved slot, which it keeps until the end of its message.

C. Application of an Adaptive Backoff Mechanism

A stabilization of random access protocols can be achieved, if variable backoff mechanisms are used, i.e., if the mean retransmission time for a user after an unsuccessful request is not fixed but changes dynamically. The retransmission time can be calculated according to current system conditions, e.g., the current network load and current number of active terminals. In [7, 8] the following backoff algorithm is used for user access to the signaling channel, as well as for user access to the data channels for signaling purposes.

If a new message arrives at a terminal, a transmission request is sent immediately. In the case that 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:

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

Hence, the retransmission interval increases each time after a collision occurs. Accordingly, a longer retransmission time is computed if the collisions are frequent, which means that the network is more loaded. In this case, a larger retransmission interval ensures a lower collision probability for the transmission requests. If a request is successful, the collision counter is decremented (if CC > 0) and the backoff algorithm is finished. A calculated value of the CC during a request procedure is kept as a start value of CC for the next request procedure.

IV. OUR MAC PROTOCOL PROPOSAL

In our work, we adopt from [7, 8] the idea of piggybacking, and from [7, 8, 14, 15] the idea of using data channels for signaling. However, we do not use the adaptive backoff mechanism proposed in [7, 8] for users to select the slot in which they will transmit/retransmit their requests; instead, we propose three new ideas, two of them regarding the slot selection mechanism and one of them regarding the channel selection mechanism for a PLC access network.

A. 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 [7, 8] and is named *Uniform channel selection* in this paper. 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 named *Weighted channel selection*. Our 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 the signaling channel*. Let this total number of idle slots be *S*. The probability for a terminal to choose channel Y, which has 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 (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) divided by S.

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 collisions in the system.

B. 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).

With the use of our above-detailed ideas, four versions of our MAC protocol will be examined: the Uniform-Weighted selection (U-U), 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).

V. 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 messages (IP packets) are used; 300 bytes and 1500 bytes. Since messsage 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 messages 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 messages. The offered traffic load per network station (terminal) is 2.5 kbps. The message sizes and the interarrival times are geometrically distributed random variables. In order to make a fair comparison with [7], we also consider in our work that if a message reception is not correct, the whole message (all packets in which it is segmented) has to be retransmitted.

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 performance. Each simulation point is the result of an average of 10 independent runs (Monte-Carlo method).

Similarly to the work in [7, 8], we define network utilization as the ratio of the used network capacity for data transmission to the total capacity. As shown in Fig which a noisyless PLC network is considered), for up to 150 users the use of the Extended Aloha protocol provides almost identical performance with the four versions of our protocol. However, as the traffic load increases, the network utilization achieved by the Extended Aloha protocol is significantly smaller than the ones achieved by the four versions of our protocol, the difference between them exceeding 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 than the one achieved by Extended Aloha (with the only exception of the W-U selection version of the protocol, which for 500 or more users is only slightly more efficient than the Extended Aloha protocol).

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 [7, 8] 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 III.C, 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 [7, 8] 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 Figure 1.

When comparing the results achieved by the four versions of our MAC scheme and shown in Figure 1, it is clear that 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 that the U-W selection achieves the best results for medium-to-high traffic loads (number of users larger than 300). The reasons for this 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, as the combination of the weighted mechanisms for both the channel and slot selection is shown by our results to be a "too aggressive" policy and to lead to inferior 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 W-U selection provides the best results for up to 250 users, while for more than 300 users U-W selection is the most proper choice, 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., to define the "switch point" in which the protocol with the best performance changes between the two). This number was found to vary between 268 and 270 in all of our simulations. In our future work we will use analysis to estimate this number, as well as the other results which are presented here via simulation.

Based on the above (and on similar results on signaling delay which are omitted here for space economy), we proceeded to implement a "two-mode" use of our protocol, in which W-U selection is activated for low traffic loads and U-W selection is activated for high traffic loads. 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 message size is 300 bytes and the slot payload is 28 bytes, a message needs on average 10.7 slots to be transmitted. The mean message 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). 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.

The conclusions derived from our results in Figure 1 are further confirmed by the results presented in Figures 2-5, 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. The only qualitative difference of these results with the ones referring to an ideal, noisyless 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 4, 5). Also, the comparison of the two protocols in terms of signaling delay (Figures 2, 3) 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.

An additional comment needs to be made regarding the significant increase in the signaling delays 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" (message 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).

VI. CONCLUSIONS

This work presents a new MAC scheme for the "last mile" access PLC networks. By comparing our proposed ideas on slot and channel reservation with a well-known MAC protocol for PLC, our scheme is shown to excel both in network utilization and in the average signaling delay required for the completion of the transmission request procedure. Our future work will focus on the combination of the most attractive features of a reservation-type protocol with those of polling mechanisms, which we believe will help to further increase PLC network utilization, especially under heavy disturbances.

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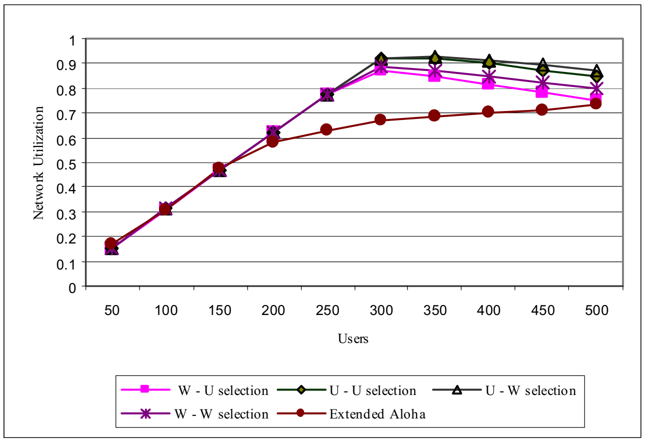
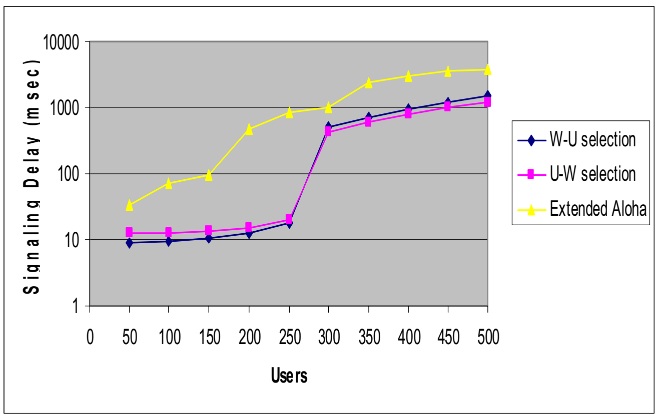
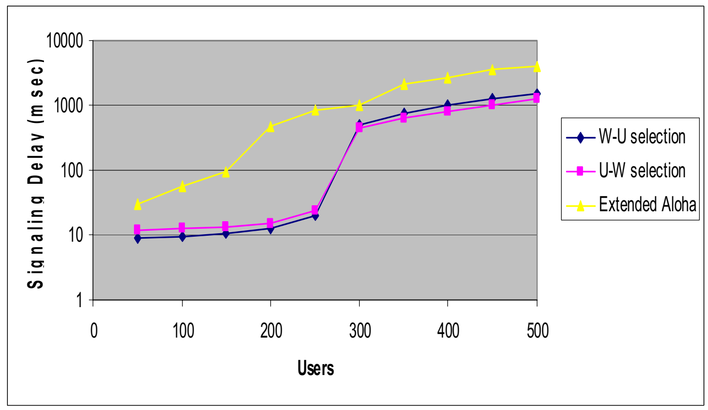
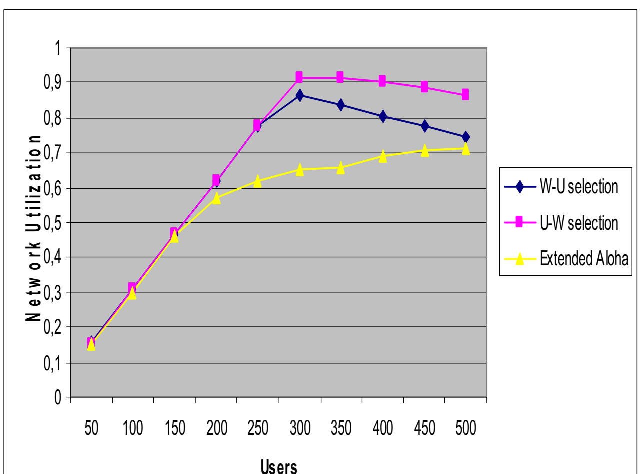


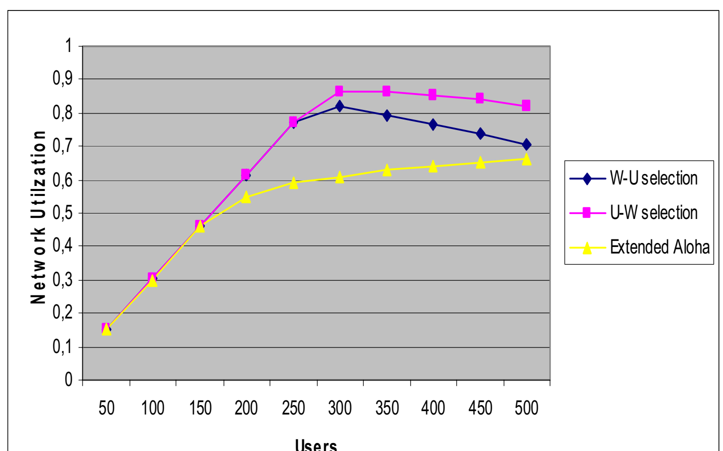
Figure 1. Comparison of the five schemes in terms of network utilization, for a noisyless PLC network.





Figures 2, 3 . Comparison of the three schemes in terms of signaling delay, under light and heavy disturbances, respectively.





Figures 4, 5. Comparison of the three schemes in terms of network utilization, under light and heavy disturbances, respectively.

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