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QUALITY OF SERVICE SUPPORT IN POWERLINE COMMUNICATION NETWORKS

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Abstract: PLC (PowerLine Communication) is becoming an interesting last mile solution for both in-home and access applications, this mainly due to its ubiquity and continually growing bit rate. However what is its capability to provide QoS guarantees for real-time applications is still an open problem. In this paper, we first analyse the real-time QoS supporting of the two main PLC MAC protocols, then address the performance problem of TCP Westwood over PLC by simulation. This simulation study revealed the impact of the packet loss rate on TCP performance. We also discuss the importance of coordinating TCP's RTT estimation with the ARQ of the underlying PLC MAC protocol. *Copyright © 2003 IFAC*

Keywords: Powerline communication, In-home PLC network, QoS, MAC protocol, TCP, Performance analysis.

1. INTRODUCTION

The use of electrical power distribution grids for data transmission is called Powerline communication network (PLC). Powerline has the advantage of ubiquity: available in almost every place and denser than today's existing telephony networks and other dedicated data networks. The same electric outlets that provide power will also serve as access points for the network devices. This forms a multiple access local area network (LAN). In comparison, the phone line suffers from too few connection points. With the deregulation of the telecommunication market, PLC presents a cost-effective, easy-to-adopt home networking solution for new network operators (Hrasnica and Lehnert, 2002; Dostert, 2001). In fact other last mile solutions such as using xDSL and CATV falls to the former monopolistic companies; whilst building new wired or wireless communication systems leads to higher costs and takes longer installation time, and wireless-specific problems of congestion at 2.4 Ghz as well as interference (Azzam and Ransom, 1999).

For competing against other communication technologies in-home PLC networks should be able to support a variety of services for home automation and for multimedia applications. The PLC networks must attach importance to guarantee the QoS requirements (bandwidth, latency, reliability).

Powerline grid is a hostile environment for data communication. As the PLC nodes should work with a low signal power to meet the very strict regulating limit on EMC (e.g. European standard specified in CENELEC EN 50065, using frequency spectrum from 9 to 140 kHz, is the most strict one), disturbances like coloured background noise, narrowband noise and impulsive noise causing by switching on/off of connected electrical equipments are omnipresent (Zimmerman and Dostert, 2000). Two modulation techniques, the single-carrier CDMA (Code Division Multiple Access) and multi-carrier OFDM (Orthogonal Frequency Division Multiplexing)¹, seem to be the suitable ones (Dostert,

¹ Note that OFDM is also used by xDSL and IEEE802.11g

2001) for efficiently fighting against those disturbances while maintaining low EMC emission. This is why most of today's PLC technologies have focused on the design of suitable MAC sub-layer taking into account the specific underlying modulation technique (Hrasnica and Lehnert, 2002). Nowadays, higher data rates have been achieved (see <http://www.homeplug.org>, <http://www.plcforum.com>) to ensure the high reliability and the short response time. In PLC MAC protocols such as Homeplug and Inari (www.easyplug.com/inari_en.htm), real-time QoS features are addressed.

Most of real-time applications run above standard Internet protocol. So it is obvious that MAC protocol alone is not sufficient to guarantee end-to-end QoS and it is important to evaluate the performance of TCP/IP over the PLC MAC layer. However addressing TCP performance with PLC as underlying network is a difficult task. The highly variable and unpredictable levels of impedance, signal attenuation and noise, lead to high bit error rate. To achieve more reliable data transmission, sophisticated modulation, error detection/correction, ARQ (Automatic Repeat reQuest), channel redundancy techniques are often used, but the effective data rate is considerably decreased. Moreover, a PLC system implements dynamic channel management to auto-adapt the time-varying PLC channel's quality, leading to time-variable data rates. This makes it difficult to estimate the message response time, which can be required by real-time applications. At the same time, the packet loss rate and the inaccurately retransmission time out setting of TCP (called RTO) decrease the TCP performance.

In this paper, we study the QoS guarantee of PLC serviced as in-home network. In section 2 we analyse the real-time QoS support of the two main PLC MAC protocols: Centralized token-passing of Inari and CSMA/CA of Homeplug, both use multi-carrier modulation. In section 3 we analyse the performance of TCP sessions over the PLC. The work and its possible extensions are summarized in section 4.

2. PLC MAC PROTOCOLS FOR QoS SUPPORT

There exist two possibilities of medium access organisation: static and dynamic. The static access reservation is suitable for continuous traffic (like most of fieldbuses), but not for bursty traffic which is typical for data transfer in in-home networks. So dynamic access schemes are adopted for data transmission and in some cases it should provide QoS other than best-effort to ensure a satisfactory transmission quality for delay-critical traffic. In general, there are two groups of dynamic access protocols: arbitration protocols without collisions (e.g. Centralized Token-Passing of Inari) and

contention-based protocols (e.g. CSMA/CA of Homeplug). In what follows we present briefly the Centralized Token Passing protocol and the CSMA/CA protocol and then analyse their QoS features.

2.1 Centralized Token Passing

Because of the high noisy character of the powerline, the possibility of losing token is very high. So the solution of the Centralized Token Passing (CTP) (Easyplug-Inari, 2001) is more reliable than a distributed token passing.

In the CTP, there is an Active MAC server, which is a kind of master station for token distribution and has the responsibility for arbitrating requests for the Token. It systematically polls all the active stations on the network and gives a Token to the appropriate station wishing to transmit.

To increase the network efficiency, the system allows inactive stations to drop out of the token passing scheme. In addition, if there is no transmission in the system for a period of time, the system can become totally silent, eliminating token passing entirely. And the current MAC server will be eliminated, too. When one station wishing to transmit at the other time, it detects no active MAC server in the system. It need firstly assign itself as MAC server before the transmission. So the system becomes active. Then it transmits the information. To the other stations, when they detects the exited active MAC server, they need to send the insert request to the active MAC Server and get the Server response. After those, if the server accepts its request, the station can transmit the packet when it gets the Token. The Inari CTP protocol event timing is shown in Fig. 1.

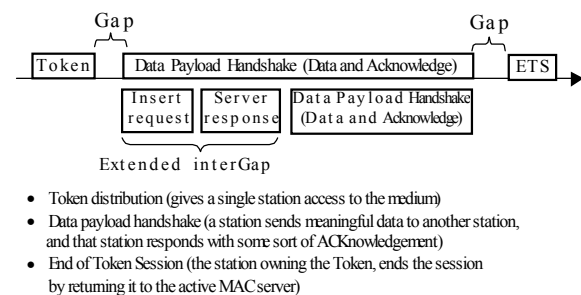


Fig. 1. CTP Event timing

The centralized token passing as an arbitration protocol provides contention-free environment, so it has deterministic delay properties. The client station brings forward QoS requirements, when it sends the insert request command. It provides its own source address, plus desired QoS requirements: the value of Time to Live, Duration, priority and a profile. The active MAC server makes a prioritized scheme according to those parameters.

Priority CTP protocol offers different levels of priorities for data. Prioritization is determined by the application hosted by a particular station. Priority is used strictly by the active MAC server to determine which client stations (higher priority stations) are included on the ring scheme and which (lower priority stations) are "bumped" off the ring scheme. So once the maximum bandwidth has been allocated, the system should deny further admission, rather than dilute the bandwidth of each existing station.

System throttling mechanism Time to Live indicates the longest amount of time that the station would like to stay on the active MAC server's ring scheme, without using Token. It is the initial value that is used to "age" this particular station off the ring scheme. It reduces the overhead allocated to idle users. The active MAC server should minimise unnecessary token passing. The valuable system resource and bandwidth are made to allocate to active users. It increases the capacity and performance of the overall system.

Token Holding Time The duration is defined the time that the client station could use the token after receiving it. It provides the capability for users to request a specified number of back-to-back transmissions per granted token. The higher value allows more information to pass to the user's destination and better throughput potential can be achieved.

Low latency guarantees The profile is a critical QoS value, as it represents three important attributes: latency, concurrent entries, and bandwidth. The active MAC server is assigned a token passing scheme which provides all low-latency users with guaranteed service for their real-time applications. If the profile is ever reached which means that all system resources are occupied, new users with equal or lower priority settings will be denied access to the system. When the requests of a higher priority user are received, the active MAC server can remain guaranteeing the high priority service by cancelling other lower priority service.

2.2 CSMA/CA

CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance) is firstly used in IEEE802.11. It has been enhanced and now used by many PLC protocols (Gardner *et al.*, 2000; Intellon).

PLC uses both physical carrier sense (PCS) and virtual carrier sense (VCS) to infer whether another station is transmitting. PCS is provided by the Physical layer upon detection of the Preamble. When frame control field of a packet is detected, VCS is asserted by the MAC. VCS tracks the expected duration of channel occupancy as expressed in the

Frame control fields. VCS expires at the next opportunity to contend for the channel.

Media access is based on a randomized contention window with exponential backoff, similar to Ethernet. For a station to transmit, it shall sense the medium to determine if another station is transmitting. If the medium is considered idle, the frame can be transmitted immediately. If the medium is not idle, media access is determined by the contention window using the random backoff time. All stations shall invoke the backoff procedure when a packet is queued for transmission and the medium is busy as determined by the carrier sense mechanism. Followed the priority resolution period, each station randomly selects a transmission slot (set Backoff Timer) in the contention window. The Backoff Timer shall be decremented by one for each SlotTime that both the physical and virtual carrier senses are determined to be idle. When the backoff timer is zero, the station can transmit.

Unlike conventionally wired Ethernet stations, a station cannot detect a collision while transmitting. When the transmitting station don't receive an acknowledge packet (ACK) from the intended receive station, a collision occurs.

For meeting the demand of QoS, the protocol uses a several level priority scheme controls delay for data types requiring better than best effort delivery. Moreover, it also uses "segment bursting" and "contention free" access to provide low latency and jitters. Homeplug CSAM/CA protocol principle is shown in Fig. 2.

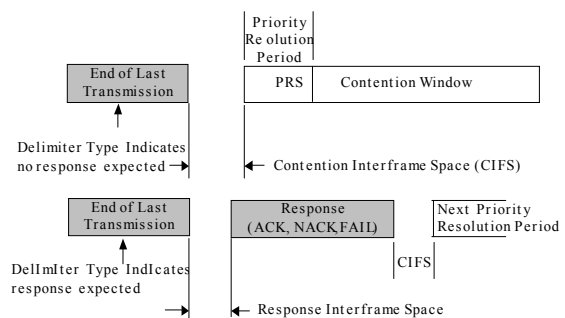


Fig. 2 the principle of CSMA/CA

Priority The contention window is preceded by a priority resolution period that narrows the field of contending stations to those with the highest priority frames queued. And the priority resolution period may contain some bits for priorities. When one node completes a transmission, other nodes with packets queued to transmit, signal their priority in the priority resolution period. High priority has the shorter capture duration. Lower priority has longer capture duration. It means different priorities have the different the maximum value of backoff time. Only the node, which wins during the priority period, can enter the contention window and then access to the medium.

Low latency guarantees CSMA/CA is a contention protocol, so it has non-deterministic latency. PLC protocol uses segment bursting mode and contention-free (or centralized token passing or polling) mode to make best efforts to guarantee the low latency.

Because of the time-varying characteristics of the noise and attenuation in the powerline, PLC uses short packets. Segment bursting mode allows all packets of a block to be transmitted back-to-back unless interrupted by a higher priority. It allows higher priority frames to jump in between the slower transmission's segments.

An extension to the segment bursting mechanism provides Contention-free access to the medium. To gain control of the medium for contention-free access, a node shall contend at the highest priority, using the normal channel access mechanism. Once the node has gained control of the medium, it shall maintain control of the medium. The Contention-free Control entry contains a list of MAC addresses and the count of the number of addresses in the list. There may be zero or more addresses in the list. If sending a Contention-free Control entry with only its own MAC address in the list, the node can implement a simple poll and response access mechanism. If including a list of several other MAC addresses in the Contention-free Control entry, a token passing access mechanism may be provided.

By combining the polling and token passing mechanisms, a node can implement an access mechanism that has the advantages of both polling and token passing. Finally, this method for controlling contention-free access to the medium allows multiple logical networks to cooperate, apportioning and sharing the available network bandwidth in a controlled fashion.

2.3 Summary

After having briefly presented the working principle of contention based (CSMA/CA) and contention free (Token passing) protocols, we can conclude that qualitatively spoken, contention based protocols have generally a shorter medium access delay than the token based ones in light traffic load condition (since very low collision probability) and longer medium access delay than the token based ones in heavy load condition. Quantitative evaluation² in (Lu and Song, 2001) for a 4 nodes scenario showed that CSMA/CA gives shorter delay but CTP provides deterministic latency. Both protocols provide different levels of priorities for time-critical applications. The

² Numerical details are not provided because of the confidentiality clause between LORIA and Easyplug

centralized token passing as an arbitration protocol has deterministic delay properties, but it is complex and has higher overheads comparing to CSMA/CA. Unfortunately CSMA/CA has non-deterministic latency. So, a combined CSMA/CA and polling (a kind of CTP) is used in Homeplug. Moreover it proposes to use IETF's SBM and RSVP (at IP level) protocols to handle the latency guarantees, but which in its turn will add the overheads.

In PLC data link layer, effective data rate is impacted by the time-varying disturbances because on-line FEC (Forwarding Error Correction) adaptation and ARQ are often used which add variable overheads.

For protecting user data field against the high bit error rate in PLC, HomePlug uses different FEC codes (specific, Reed-solomon, Convolutional) resulting in a user data payload of between 1/4, 1/2 and 3/4. Combined with the different modulation techniques (e.g. BPSK, QPSK), the effective data rate varies between 14Mbit/s to 1Mbit/s. Inari does not use any FEC code.

In addition to FEC, both of the two protocols use ACK and ARQ when NAK is received by the sender which makes more variable the effective user data rate. HomePlug fixes the maximum authorized retransmission number to 6, while Inari fixes the maximum retransmission number to 256 as it only uses ARQ for improving the reliability.

Noting that for applications requiring a delay guarantee, the use of ARQ can be not suitable as it adds extra delay. To deal with this problem, multi-carrier based MAC protocols implement on-line channel quality estimation for avoiding the high retransmission number of a same packet on a bad sub-channel with ARQ. This allows to decrease the impact of ARQ on the delay variation.

3. TCP/IP OVER PLC

As most of applications run over the standard TCP/IP, the QoS guarantee should therefore be ensured at the TCP level. IP layer is just used for Internet addressing and does not influence neither the reliability nor the delay in in-home network. However the use of TCP could impact the delay as TCP also uses ACK and ARQ as in PLC MAC layer. Unfortunately, TCP is designed and optimised for wired networks in which we assumed that packet losses are mainly because of congestion rather than transmission errors (Jacobson, 1988). So the TCP performance becomes questionable with the underlying PLC networks in which most of packet losses are because of transmission errors and the slow-start mechanism in TCP reduces the throughput. We note that applications running over UDP/IP/PLC has not this problem.

3.1 Packet error rate

In fact, TCP incorrectly interprets the packet loss as a sign of congestion that forces TCP to back off from further transmission, reduce its congestion window and as a result the overall throughput of this connection is drastically reduced. This becomes the predominant shortcoming of TCP over powerline links: the connection suffers long idle periods in which the sender is idle waiting for a timeout, and when the packet is finally retransmitted and recovered, the congestion window is reduced to one segment, thereby reducing throughput until the congestion window again grows to its optimal size.

We find that a new TCP protocol has a better performance against packet loss caused by the error. It is called TCP Westwood (TCPW) with a sender-side modification of the window congestion control scheme (TCPW web site). TCPW is designed for TCP/IP over wireless connections which presents similar problems to TCP/IP over PLC. The key innovative idea is to continuously measure at the TCP sender the packet rate of the connection by monitoring the rate of returning ACKs. The estimate is then used to compute congestion window and slow start threshold after a congestion episode. TCPW differs from TCP Reno in that it adjusts the congestion window after a loss detection by setting it to the measured rate currently experience by the connection, rather than using the conventional multiplicative decrease scheme (i.e. divide the current window by half). The simulation uses ns-2 (ns-2 web site) and the packet size is 1500 bytes. As we assumed the use of multi-carrier based PLC MAC protocol, each sub-channel can then be modelled by an ON/OFF stochastic process with exponentially distributed durations for the ON and OFF periods (Hrasnica and Lehnert, 2002). We thus use a Markov loss model on the link layer (Kumer, 1998). The loss model is a discrete time Markov chain whose transitions are embedded at packet boundaries; thus we express the good state, which means the packet loss rate is zero, and the bad state, which means the packets loss rate is 1, in units of transmission time on the link. Fig. 3 presents simulation results comparing the throughput of TCP Reno and TCPW in a local network with a lossy link showing clearly the gain of TCPW over TCP Reno.

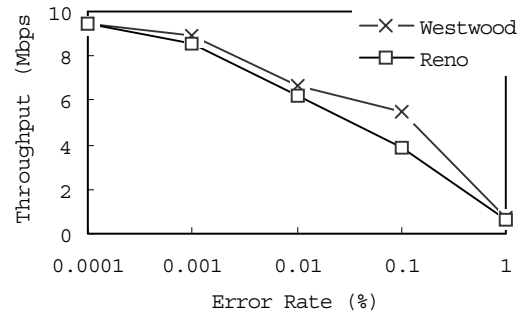


Fig. 3 Impact of error rates for 10 Mbps lossy link

3.2 Adverse interactions between MAC and TCP

TCP implements reliable data delivery by retransmitting segments that are not acknowledged within some retransmission timeout (RTO) interval. To ensure that packets currently in transit do not get retransmitted prematurely, TCP takes into account both the smoothed round-trip time estimate and the linear deviation in its timeout algorithm. Accurate dynamic determination of an appropriate RTO is essential to TCP performance. RTO is determined by estimating the mean and variance of the measured round-trip time (RTT), i.e., the time interval between sending a segment and receiving an acknowledgment for it (Jacobson, 1988). Accurate and current RTT estimates are necessary to adapt to changing traffic conditions and to avoid an instability known as "congestion collapse".

MAC protocol uses ARQ mechanism to fight against the high bit error rate. The number of retransmission is varied. And channel management causes additional rate variation. Channel adaptations occur occasionally, based on either a MAC timeout or on detected variation in the channel transfer function (which might be either an improving or degrading condition). According to the information of real-time channel quality measurement, the transmitter will adjust consequently the bit-time or symbol time, modulation schemes, and error correction codes, channel selection. According to Homeplug and Inari protocols, we calculate the effective MAC layer bit rate variation with the different modulation and FEC rate or channel selection showing in the following tables (Table 1 and Table 2). The bit rate is greatly varied. It leads to highly variable RTT at the TCP sender and arises the problem of configuring the RTO.

Table 1 Effective MAC layer bit rate in Homeplug

| Modulation and FEC rate | Effective MAC layer bit rate | 1500 bytes transmission time (ms) |
|-------------------------|------------------------------|-----------------------------------|
| DQPSK with 3/4 FEC | 13.2 Mbps | 0.91 |

| | | | |
|-------------------------------------|------|----------|-----|
| DQPSK 1/2 FEC | with | 8.7 Mbps | 1.3 |
| DBPSK 1/2 FEC | with | 4.4 Mbps | 2.7 |
| BPSK time&frequency diversity | plus | 1 Mbps | 12 |

Table 2 Effective MAC layer bit rate in Inari

| Condition | Bit rate per channel | Number of channels | Effective MAC layer bit rate |
|--------------------------|----------------------|--------------------|------------------------------|
| Bad (8 channels used) | 56 Kbps | 8 | 0.448 Mbps |
| Good (120 channels used) | 302 Kbps | 120 | 36.24 Mbps |

There are two cases, which may happen in the cooperation of TCP layer and MAC layer.

Small RTO estimation When a packet transmission fails, ACK of MAC layer should demand the sender to retransmit it. The MAC protocol defines a value of MAC retransmission time. If the retransmission timer of the MAC layer does not timeout, RTO expires. The TCP will consider the packet loss due to congestion. It has to restart from a window of one. It may need to retransmit those un-acknowledged packets that are sent before this packet, but are not acknowledged that time. The example in Figure 4 explains the problem. One packet (SEQA=11) is sent, but the transmission is failed. On MAC layer the receiver sends NACK to the sender to ask the sender to retransmit this frame. In the period of MAC retransmission, the RTO expires and the TCP layer of the sender asks the retransmission too. And the sender uses the congestion control mechanism.

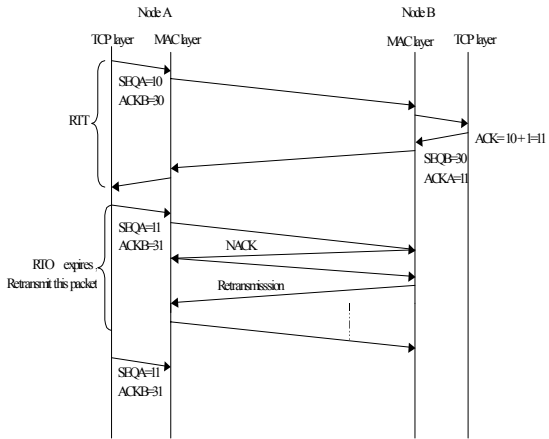


Fig. 4 Problem with small RTO

Large RTO estimation The retransmission timer of the MAC session reaching the maximum time, the retransmission of the MAC session declares failure. MAC session discards this packet, so this packet is lost. But RTO does not expire; the sender is still waiting for ACK of this packet to slide the window size. So it will wait until RTO expires. The network throughput decreases. The example in figure 5 explains the problem. One packet (SEQA=16) is sent after the packet (SEQA=15) was sent, but this transmission is failed. On MAC layer the receiver sends NACK to the sender to ask the sender to retransmit this frame. MAC layer tries to retransmit this frame for several times. After the retransmission timer (MAC layer) expires, the MAC layer gives up the retransmission. But the sender is idle; it is waiting for ACK until the RTO expires. At this interval, the network throughput is zero.

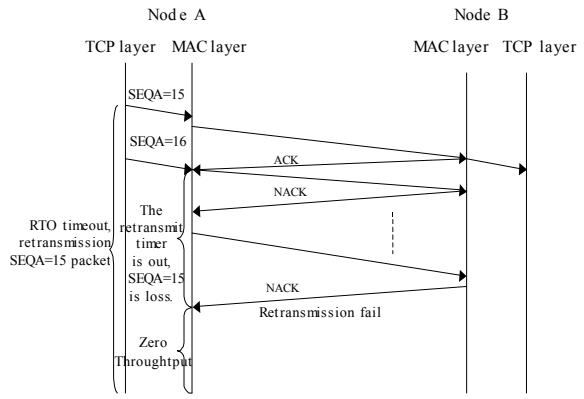


Fig. 5 Problem with large RTO

So how to correctly tune the maximum retransmission times (or time-out value) of PLC MAC protocol taking into account the dynamic behaviour of TCP is a challenging problem. Our on going work aims at establishing a formal relationship between the time-out value of the PLC MAC protocol and TCP's RTO.

4 CONCLUSIONS

Because powerline is a heavily noised transmission medium, mechanisms such as error correction, ARQ and on-line sub-channel adaptation are used in most of PLC MAC protocols to achieve a satisfying low packet error rate. Our analysis of Inari and Homeplug protocols showed that the use of these mechanisms leads to a time-varying data rate, making difficult the delay guarantee. Although both CTP based Inari protocol and CSMA/CA based Homeplug provide basic mechanisms (priority, bandwidth reservation) for QoS guarantees, an end to end QoS guarantee still need much effort from user side. For Internet access applications running over TCP/IP/PLC, TCP

performance is decreased because of packet loss and those mechanisms used by PLC MAC protocol. Now some versions of TCP like TCPW had noticed the impact of packet loss caused by error rate. Simulations we have done showed the notable throughput gain of TCPW comparing to TCP Reno. We also pointed out the importance of coordinating TCP's RTT estimation and the underlying PLC MAC protocol's maximum retransmission number, as it also heavily impacts the TCP performance. Our future work aims at, on the one hand, establishing a formal relationship between TCP's RTT estimation and the underlying PLC MAC protocol's maximum retransmission number, and on the other hand investigating PLC MAC protocols' capacity for handling both hard real-time constrained continuous traffic and (m,k)-firm real-time constrained burst traffic.

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