Moving HomePlug to Industrial Applications with Power-Line Communication Network

ZW. Zhao, and I-Ming Chen
Singapore-MIT Alliance program, Nanyang Technological University, Singapore 639798

***Abstract*—Home networking is becoming an attractive application not only for the Internet access but also for home automation. Being a high-speed and dominant standard presently, HomePlug has an important role in home LAN connecting to the Internet. For industrial applications, the Power Line Communication also has significant advances. However, the PHY/MAC technology provided by HomePlug still cannot be employed with some critical features such as real time performance, implications in the event of link and node loss. In this paper, the characteristics of HomePlug PHY/MAC, the property of power line channel, as well as the noise features of power line are analyzed. Based on HomePlug, a model of high level real-time protocol applied to industrial environment is proposed. The protocol simultaneously belongs to layer two and three, and can support real-time implementation with no loss and small delay according to the requirement in PLC networks, for targeting to develop a real time network with high speed power line media and advanced modulation.**

***Index Terms*—HomePlug, Power line, OFDM, Real time, RT-TCP.**

I. Introduction

WITH the improvement of automatic operation in the industrial environment, the traditional low speed control networks such as FFbus, CANbus, ProfiBus, etc. cannot satisfy the requirement of large-scale data transmission particularly some real time data transmission like command messages, interrupt request and data, video stream, etc. So many cost-effective methodologies have been being studied and applied for this demand [1,2,3,6]. The typical approach is to utilize broadband network technology as IP, Wireless LAN for meeting the requirement of industrial environment. In recent years, thanks to ASIC-based signal processing advances, it is possible to refine on the interference and transfer function degradations so as to compromise the power line transmission medium. In this way, the vision of industrial automation with power line communication especially for a smaller local area is possible.

The power line medium is a harsh environment for communication. The channel between any two devices in an application has the transfer function of an extremely complicated transmission line network with many stubs having terminating loads of various impedances. Such a network has an amplitude and phase response that varies widely with frequency. At some frequencies, the transmitted signal may arrive at the receiver with relatively little loss, while at other frequencies it may be driven below the noise floor. Worse, the transfer function can change with time. This may happen because a new device has been plugged into the power line, or if some of the devices plugged into the network have time-varying impedances, which may be the case with switching power supplies or motors. As a result, the nature of the channel between devices may vary over a wide range. In some cases, a broad swath of bandwidth may be suitable for high quality transmission, while in other cases the channel may have a limited capacity to carry data. The most severe interference sources rarely have properties similar to the easily analyzed white Gaussian noise produced by receiver front ends. Instead, the interference can be either impulsive or frequency selective in nature, and sometimes both of them. Due to these frequency variations, efficient use of the medium requires an adaptive approach that compensates for the channel transfer function in some ways. HomePlug technology [10] includes an effective and reliable method of performing adaptation that achieves high rates on typical channels, but which adjusts the bit rate to be against really harsh channels. In addition to the transfer function problem, and equally significant, interference on the power line must be considered. The HomePlug intends for use in home networking, not only for in commercial buildings but also office networking and use encryption utility to ensure network separation between adjacent homes and prevent eavesdropping. When adding a new device to an existing HomePlug network that has a private network password, the new product must have its network password changed to match.

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ZW. Zhao is a Research Fellow of the SMA under IMST (Innovation in Manufacturing Systems & Technology) program and member of technical committee of SMA (corresponding author, e-mail: zwzhao@ntu.edu.sg
phone: +65-67904273; fax: +65-68627215).
I-Ming Chen is a SMA (Singapore-MIT Alliance) Fellow under IMST Program, and also an associate professor of Nanyang Technological University. He is now serving on the editorial board of IEEE/ASME Transactions on Mechatronics, and being member of IEEE and ASME, Chairman of IEEE Robotics and Automation Society, Singapore Chapter (e-mail: michen@ntu.edu.sg).

However, only up to 15 Nodes for safe performance in HomePlug 1.0 standard. Such situation can satisfy most requirements for home networking rather than industrial circumstance. The cause principally originated from the limited bandwidth and MAC protocol. Therefore, an effective RT-TCP protocol is proposed in this paper for industrial applications based on HomePlug standard. The remaining sections are arranged as: Section 2 analyzes and discusses the PHY/MAC technology of HomePlug 1.0, and basic flow for channel access of MAC layer is given. Some characteristics of power line communication are analyzed in section 3. Section 4 investigates the differences between home and industrial automation in order to educe the possibility of moving HomePlug to industrial environment. Furthermore, the prototype of RT-TCP stack and its basic algorithm are introduced and analyzed. Finally, conclude the paper in section 5.

II. PHY AND MAC LAYERS IN HOMEPLUG

The HomePlug technology contains a combination of sophisticated forward error correction (FEC), interleaving, error detection, and automatic repeat request (ARQ) to ensure that the channel appears completely reliable to the network layer protocols. Both a robust physical layer (PHY) and an efficient media access control (MAC) protocol must be included for enabling a reliable communication on the power line medium, where, the modulation involving mixing, coding, the definition of basic packet formats, etc. are specified by the PHY layer, and the MAC protocol controls the sharing of the medium among multiple clients.

A. PHY Layer

Orthogonal frequency division multiplexing (OFDM) is utilized as the basic transmission technique in the HomePlug PHY. OFDM is well known in the literature and in industry. It is currently widely used in DSL technology and also in terrestrial wireless distribution of television signals. In contrast to these technologies, however, HomePlug uses OFDM in a burst mode rather than in continuous mode. HomePlug technology also uses concatenated Viterbi and Reed Solomon FEC with interleaving for payload data, and turbo product coding (TPC) for sensitive control data fields. OFDM divides the high-speed data stream to be transmitted into multiple parallel bit streams, each of which has a relatively low bit rate. Each bit stream then modulates one of a series of closely spaced carriers. The property of orthogonality is a result of choosing the carrier spacing equal to the inverse of the bit rate on each carrier. The practical consequence of orthogonality is this: If we perform a Fast Fourier transform (FFT) of the received waveform over a time span equal to the bit rate on an individual carrier, the value of each point in the FFT output is a function only of the bit (or bits) that modulated the corresponding carrier, and is not impacted by the data modulating any other carrier. When the carrier spacing is low enough that the channel response is relatively constant across the band occupied by the carrier, channel equalization becomes easy. Implemented in the frequency domain, equalization can be achieved by a simple weighting of the symbol recovered from each carrier by a complex valued constant. Many different types of modulation can be used on the individual carriers.

The need for equalization in HomePlug is completely eliminated by using differential quadrature phase shift keying (DQPSK) modulation where the data is encoded as the difference in phase between the present and previous symbol in time on the same subcarrier. Differential modulation improves performance in environments where rapid changes in phase are possible. Unlike DSL, HomePlug does not use higher order quadrature amplitude modulation (QAM). With relatively short packets, the overhead required for channel assessment and for estimation of gain and carrier phase creates a capacity penalty that more than offsets any potential gain from the modulation efficiency. OFDM waveforms are typically generated using an inverse FFT (IFFT) in which the frequency domain points consist of the set of complex symbols that modulate each carrier. The result of the IFFT is called an OFDM symbol. Each symbol has a duration equal to the reciprocal of the subcarrier spacing and generally a long time compared to the data rate. At the receiver, the data can be recovered via a forward FFT, converting back to the frequency domain (Fig.1).

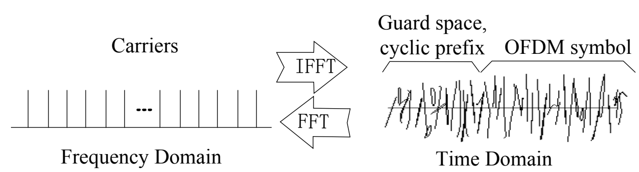

Fig. 1. OFDM waveform generation

Note that the time domain waveform also includes a cyclic prefix, which is essentially a replication of the last few microseconds of the OFDM symbol. The purpose of the cyclic prefix is to absorb the intersymbol interference that results from the fact that the delay presented by the channel is not constant with frequency.

Without the cyclic prefix, some of the samples used in the FFT would contain energy from either the previous or the following OFDM symbol. If the cyclic prefix is as long as the worst case delay variation across the frequency band, then by waiting until the end of the prefix to start taking samples to use in the FFT, we assure that the FFT is not degraded by the neighboring symbols. Formed from a series of OFDM symbols, the HomePlug data-bearing packet consists of a start-of-frame delimiter, a payload, and an end-of-frame delimiter (Fig. 2). For unicast transmissions, the destination station responds by transmitting a response delimiter indicating the status of the reception (ACK, NACK, or FAIL). The delimiter consists of a preamble sequence followed by a TPC encoded frame control field. The preamble sequence is chosen to provide good correlation properties so each receiver can reliably detect the delimiter, even with substantial interference and a lack of knowledge of the transfer function that exists between the receiver and the transmitter interference.

The frame control contains MAC layer management information (for example, packet lengths, and response status). The low rate TPC and interleaving used on the frame control provide good immunity to frequency selective impairments as well as broadband interference. All three delimiter types have the same structure, but the data carried in the delimiter varies depending on the delimiter function. Unlike the delimiters, the payload portion of the packet is intended only for the destination receiver. Payload data is carried only on a set of carriers that have been previously agreed upon by the transmitter and intended receiver during a channel adaptation procedure. Because only carriers in the "good" part of the channel transfer function are used, it is not necessary to use such heavy error correcting coding as is required for transmissions intended for all receivers. This combination of channel adaptation and lightening of the coding for unicast payloads allows HomePlug to achieve high data rates over power line. The adaptation has three degrees of freedom:

- De-selection of carriers at badly impaired frequencies
- Selection of modulation on individual carriers (DBPSK (differential binary phase shift keying) or DQPSK)
- Selection of convolutional code rate (1*2 or 3*4).

In addition to these options, the payload can be sent using ROBO mode, a highly robust mode that uses all carriers with DBPSK modulation on each and heavy error correcting code with bit repetition and interleaving. ROBO mode does not use carrier de-selection and thus can generally be received by any receiver. The mode is used for initial communication between devices that have not performed channel adaptation, for multicast transmission, or for unicast transmission in cases where the channel is so poor that ROBO mode provides greater throughput than de-selection of carriers with lighter coding. The HomePlug PHY occupies the band from about 4.5 to 21 MHz. The PHY includes reduced transmitter power spectral density in the amateur radio bands to minimize the risk of radiated energy from the power line interfering with these systems. The raw bit rate using DQPSK modulation with all carriers active is 20 Mbps. The bit rate delivered to the MAC by the PHY layer is about 14 Mbps.

B. MAC Layer

1) MAC frame and analysis: The MAC protocol in the HomePlug technology is a variant of the well-known carrier sense multiple access with collision avoidance (CSMA/CA) protocol. Several features have been added to support priority classes, provide fairness, and allow the control of latency. The use of CSMA/CA means the PHY must support burst transmission and reception; that is, each client enables its transmitter only when it has data to send and, upon finishing, turns off its transmitter and returns to the receive mode. The HomePlug transmission format is shown in Fig. 2. The MAC uses a virtual carrier sense (VCS) mechanism and contention resolution to minimize the number of collisions. Upon receipt of a preamble, the receiver attempts to recover the frame control.

The frame control indicates whether the delimiter is a start of frame, end of frame, or response delimiter. Start of frame delimiters specify the duration of the payload to follow, while the other delimiters implicitly define where the end of transmission lies. Thus, if a receiver can decode the frame control in the delimiter, it can determine the duration for which the channel will be occupied by this transmission, and it sets its VCS until this time ends. If it cannot decode the frame control, the receiver must assume that a maximum-length packet is being transmitted and set the VCS accordingly. In this case it may subsequently receive an end-of-frame delimiter and thus be able to correct its VCS. Fig. 3 displays the basic flow of channel access in MAC layer.

The destination always acknowledges unicast packets at the MAC layer by transmitting the response delimiter. If the source fails to receive an acknowledgment, it assumes that a collision has caused the failure. The destination may also choose to signal FAIL if it has insufficient resources to process the frame, or it can signal NACK to indicate that the packet was received with errors that could not be corrected by the FEC. The contention resolution protocol includes a random back-off algorithm to disperse the transmission times of frames queued (or being retransmitted due to collision) while the channel was busy, and also provides a way to ensure that clients obtain access to the channel in order of their priority. When one node completes a transmission, other nodes with packets queued to transmit signal their priority in a priority resolution inter-val (indicated by PRS0 and PRS1 in Fig. 2). The signals for this purpose use on/off keying and are designed so the priority of the highest priority user can be easily extracted, even when multiple users signal different priorities at the same time.

2) Slot choices: Nodes with queued frames having priority equal to the highest priority signaled choose a slot in a contention resolution window in which they will initiate transmission if no other node begins transmission

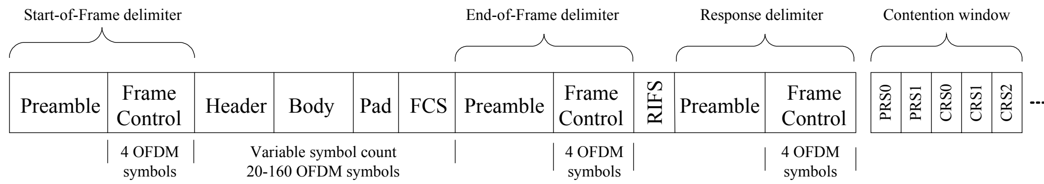

Fig. 2. MAC frame

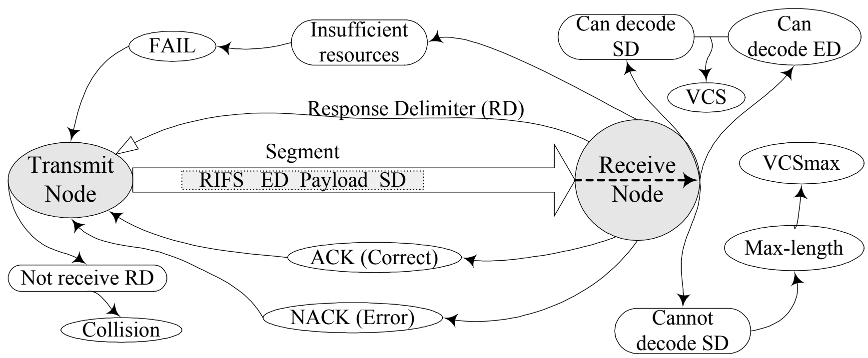

Fig. 3. Channel access of MAC layer

in an earlier slot. Each node chooses its slot at random over an interval that grows with increasing numbers of unsuccessful attempts to access the channel. If a node was preempted in a previous contention resolution window, it continues counting slots from where it left off rather than choosing a new random value. This approach improves the fairness of the access scheme.

Collision can occur if a node wishing to transmit fails to recognize a preamble from another node, or if the earliest chosen slot in the contention resolution window is selected by more than one node. The preamble design is robust enough to ensure that the missed preamble rate is so low that this source of collisions has only minor impact, so the latter cause produces the majority of collisions. Segmentation and reassembly is provided to improve fairness and reliability, and to reduce latency. The MAC also includes features that allow the transmission of multiple segments with minimal delay in cases where there are no higher priority frames queued with other nodes, and it provides a capability for contentionless access in which access to the channel may be passed from node to node.

A common misconception is that contention-based access schemes have potentially unbounded latency. In the HomePlug MAC, the latency is bounded by the expedient of discarding packets that cannot be delivered in the time required by the application. It has been shown that the percentage of HomePlug packets discarded through this approach is low enough to be encompassed by the tolerated missed packet rate for low latency applications such as VoIP or streaming media. The combination of this feature and priority classes makes HomePlug well suited to applications requiring QoS. Channel adaptation occurs when clients first join a logical network and occasionally thereafter, based on either a timeout or detected variation in the channel transfer function (which might be either an improving or degrading condition). Any node can initiate a channel adaptation session with any other node in its logical network. The adaptation is a bi-directional process that causes either node to specify to the other the set of tones, modulation, and FEC coding to use in subsequent payload transmissions.

Privacy is provided through the use of 56-bit data encryption standard (DES) applied at the MAC layer. All nodes on a given logical network share a common encryption key. The key management system includes features that enable the distribution of keys to nodes that lack an I/O capability.

3) Collision: With PHY/MAC protocol above, collisions are inferred under several circumstances. First, if no response is detected when one is expected, then a collision is assumed, although this could be due to a bad channel. Even if a delimiter is detected, if the DC (Deferral Counter) field of the delimiter is bad, or if the FC (Frame Control) does not indicate that it is an ACK, NACK, or FAIL when a response is expected, then a collision is inferred. Finally, FAIL and ACK responses contain a Response FCS (Frame Check Sequence) field that echoes the 10 or 11 (respectively) LSBs of the FCS from frame they acknowledge. If the RFCS field does not match the one sent, then the sender assumes a collision has occurred. Hence, a collision is induced normally by some typical causes, which possible are noise interference to the power line leading to fail to recognize preambles, delimiters and some other messages, or the earliest contention solution slot selected by more than one node.

III. Modeling Power Line Communication

Here, several models for power line communication are formed in order to analyze the characteristics of power line networking. Fig. 4 is a generic random power line channel model and Fig. 5 impulse model. Fig. 6 is for building a power line noise model, which can indicate the features of power line noise. Whereby, we can get a specific power line channel capacities in a frequency band of between 1 MHz and 30 MHz at different conditions based on the random channel model and the power line noise model. It is shown in TABLE I.

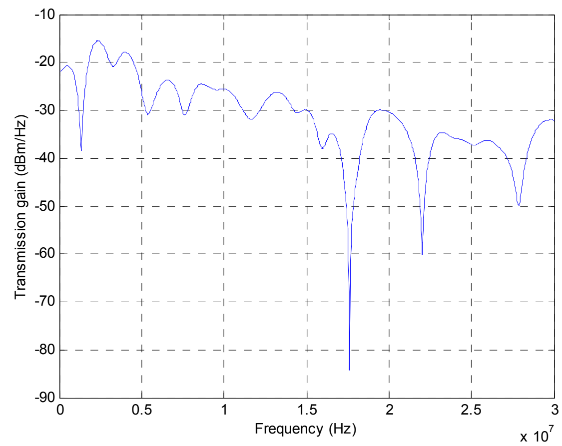

Fig. 4. Power Line Channel Model

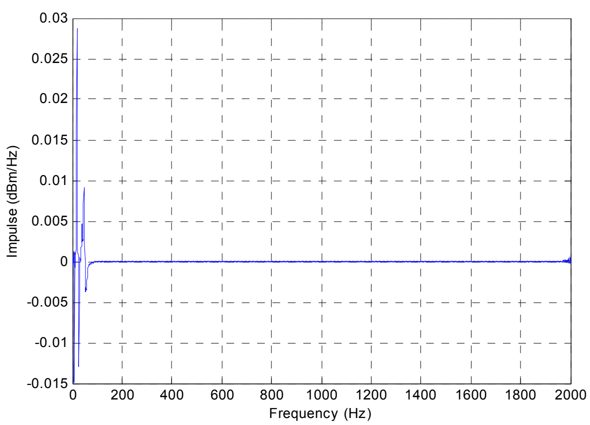

Fig. 5. Impulse model

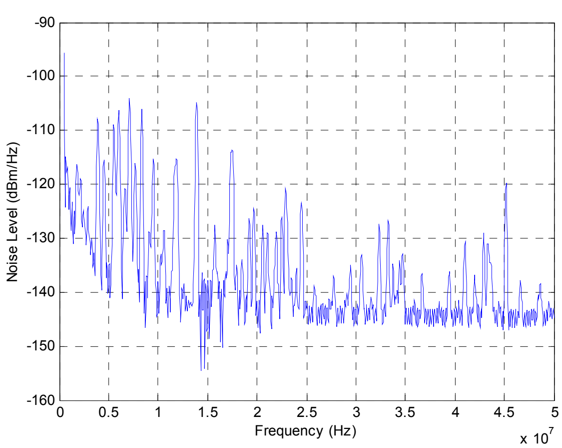

Fig. 6. Power line noise model

TABLE I
AN EXAMPLE OF POWER LINE CHANNEL CAPACITY

Transmit PSD* of -52 dBm/Hz against the noise model	Transmit PSD of -72 dBm/Hz against the noise model	Transmit PSD of -52 dBm/Hz against a background noise	Transmit PSD of -72 dBm/Hz against a background noise
5.3262e+008	3.4066e+008	5.9083e+008	3.9825e+008

*PSD (Power Spectral Density)

IV. RT-TCP INVESTIGATION FOR REAL TIME COMMUNICATION

A. *Comparison of industrial control and home automation*

Generally, there are some necessary features for a control system as follows:

- *Extent*: An indication of the likely physical area to be covered by the communication network.
- *Response time*: how quickly can a transmission be sent from node to node in the network. This will depend on such factors as transmission speed, the number of nodes in service, and the protocol involved, plus of course the response requirements of the application. Normally, the response time includes worst case response time and best case response time and average response time.
- *Robustness*: How should the network behave if there is a breakdown of the communication link itself, which is so-called the event of link loss, and how should the network behave if one of the nodes is lost so-called the event of node loss, which is possible disconnected or faulty.
- *Data security*: is it necessary for the link to be secure (e.g. incapable of being monitored by third parties), and how necessary is it to avoid data corruption form interference, either caused deliberately, (due to malicious tampering), or as a result of such factors as line noise.

1) *Home automation*

- *Extent*: Decided by definition, local within a home or building, normally decades or one hundred or so.
- Response time: A response time within 1-2 seconds can be acceptable in most cases. Some types of device can tolerate longer response time e.g. heater, air-condition, etc.
- *Robustness*: It is inconvenient as the event of link loss and the event of node loss, but on serious implication in most cases.
- *Data security*: If the system permitted access to the home/building or incorporated a security system, then susceptibility to external monitoring/tampering would be most unacceptable. Otherwise, it is no serious impact for users.

2) Industrial control

- *Extent*: It may involve a self-contained section of a plant, or may involve several items of plant sharing a network. The transfer of information over a larger area is likely to be handled by an alternative system such as a formal field-bus. So the extent is relatively localized.
- *Response time*: Normally a response time within 1-2 seconds maximum would be essential for real-time control. However, a longer time cannot be acceptable.
- *Robustness*: If the event of node/link loss existed for longer than a certain period, or occurred at the wrong point within an operational sequence of a process, it is potentially serious. Ideally, each node should have the ability to perform automatically in a safe distributed manner when the link/node is lost in networks.
- *Data security*: Unless specified request that may be a risk of malicious disruption to the process under control, it is less important.

B. Prototype of RT-TCP stack based on HomePlug

Future industry control may involve many sorts of medias, e.g. real-time control command, real-time feedback message, possible video and audio streams, so the network needs to adapt to such medium requirements. TCP/IP protocols have been utilized widely and deeply and show better robust performance for applications in the Internet, Nonetheless, for industrial circumstance, TCP/IP cannot be employed completely with a good characteristic, no matter its reliability and robustness. In HomePlug, both MAC and PHY need length information, and the MAC also needs contention control and priority information. The compromise used in the HomePlug 1.0 standard is to violate strict layering for the sake of efficiency, and allow the universally readable FC field to hold information needed by both layers. For this reason, the delimiter FC fields appear in the PDUs (Protocol Data Unit) of both layers. Here, the PHY frame is called PPDUs (PHY PDU), and the MAC frames MPDUs (MAC PDU), and not worry that the FC appears in both.

Hereby, a prototype of RT-TCP stack is proposed. The essential conception is as: Every device with no data transmission in RT-TCP networks should receive the response signals coming from other devices and configure the RT-TCP control parameters according to these signals. The one device that transmits data needs to cope with the transmission subjecting to its RT-TCP algorithm. The prototype of RT-TCP stack is shown in Fig. 7. The shadow in the protocol stack indicate that some messages of a lower layer can be collected by the relative higher layer, so that great benefit for an effective control is easier achieved with more information produced in lower layers.

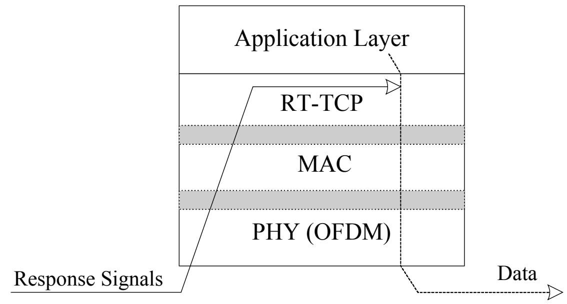

Fig. 7. Prototype of RT-TCP stack

C. RT-TCP protocol and its algorithm

1) TCP summary: The aim of running TCP protocol in networks is for network flow control by means of to avoid overloading network, and Infer available network capacity. The source rate can be indicted as

$$\text{Source rate} = W \times MSS / RTT \ \text{(bps)} \qquad (1)$$

where, MSS is Maximum Segment Size. Limit the number of packets in the network to window W. W = min (cwnd, awnd), cwnd and awnd represent congestion window and receiver (advertised) window respectively. Furthermore, source calculates cwnd from indication of network congestion indicated by losses, delay and marks. The corresponding algorithms to calculate cwnd include Tahoe, Reno, Vegas, RED, REM, etc. Receiver advertises awnd with each ACK, and the size of awnd can be the performance limit (e.g. sensible default 16kB on a LAN).

- If W too small, then rate << capacity
- If W too big, then rate > capacity, congestion

The Reno is a successful TCP algorithm, which involves following four operations (Fig. 8 and Fig. 9):

- Slow Start
- Congestion Avoidance
- Fast Retransmit
- Fast Recovery

The basic ideas are

- Gently probe network for spare capacity
- Drastically reduce rate on congestion
- Windowing: self-clocking
- Other functions: round trip time estimation, error recovery
- Fast recovery avoids slow start
- Duplicate ACKs: fast retransmit + fast recovery
- Timeout: fast retransmit + slow start

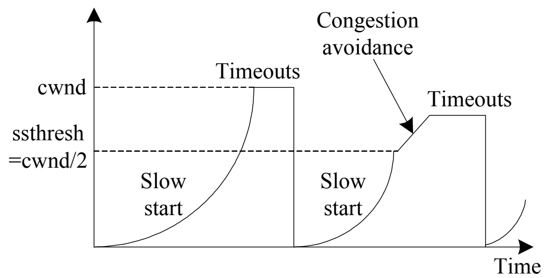

Fig. 8. Slow start and Congestion avoidance

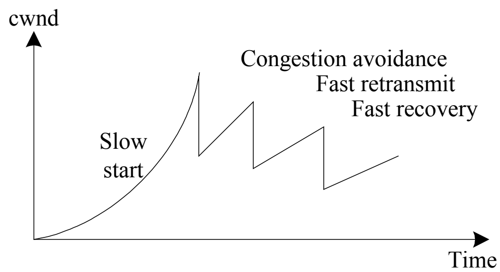

Fig. 9. Fast retransmit and Fast recovery

2) RT-TCP: Different from TCP, loss and bigger delay are sensitive and sometimes not be accepted by RT-TCP. So prohibit loss and longer delay for some sensitive messages in RT-TCP protocol is an essential target. Generally, NACK and FAIL signals act as the response messages for detecting if occurring a collision in power line channel basing on HomePlug communications. We can find out some causes of collision produced according to response signals as

- If a collision is induced by small interference on channel and RFCS bits don't match the sender's FCS bits (11 LSBs), then the corresponding signal is NACK.
- If a collision is produced by busy state of receiver and RFCS bits don't match the sender's FCS bits (10 LSBs), then the corresponding signal is FAIL.
- If a collision is inferred by other reasons such as larger interference, node or link damage, etc. then no response for a transmission.

Where, the conditions of conflict are naturally indicated above, that is, No Response means that there is a serious collision, FAIL an ordinary collision, and NACK also a normal conflict. Accordingly, three collision levels can be classified and coped with in terms of their impact on source rate as follows:

$$\text{Source rate}= MSS \Big/ (\kappa + \alpha N_{NR} + \beta N_F + \gamma N_{NACK}) \text{ (bps)} \quad (2)$$

Where, k is a constant, and $k \geq 1$ (normally $k=1$). N_{NR}, N_F, and N_{NACK} represent the number of No Response, FAIL, and NACK respectively, and their values is either 1 or 0 owing to the mechanism of HomePlug MAC layer. α, β, and γ are the coefficients respectively corresponding to N_{NR}, N_F, and N_{NACK}, and satisfy $1 > \alpha \geq \beta \geq \gamma$. their values are decided by the number of nodes in networks. MSS is also the Maximum Segment Size, and its value equals to 1460 (actual maximum segment size of payload within MAC frame). With this formula, we can get the variations of source rate on different conditions (Fig.10). Here, $\alpha=0.3$, $\beta=0.2$, $\gamma=0.1$, $k=1$. Fig. 11 shows the impact of different parameters like NNR, NF, and NNACK on the resource rate.

The fairness and robustness of every device in a network can be ensured by the contention solution in MAC layer. Whereas, once a device obtain a successful contention, the real time on demand and throughput can be guaranteed by RT-TCP mechanism over the classification and corresponding proposal algorithm for collision types in formula (2).

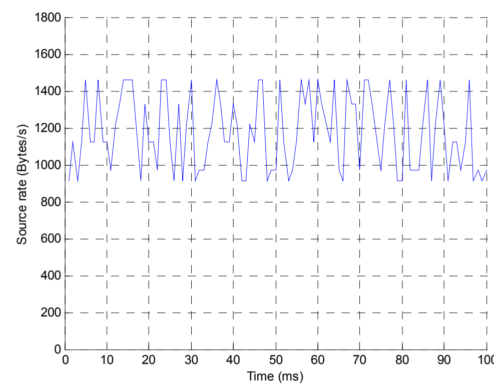

Fig. 10. Source rate variation

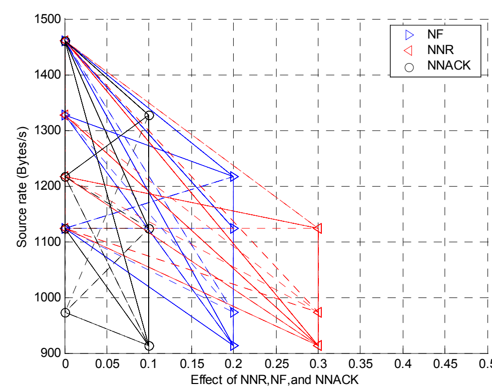

Fig. 11. Effect of NNR, NF, and NNACK to Resource rate

V. Conclusion and Future Work

Although some unsatisfactory features still exist, Power Line Networking is becoming an attractive application not only in Home/Building environment but also in extended applications for industry with a great significance. In the paper, important characteristics of power line communication such as advanced lower layer technologies (OFDM and Extended CSMA/CA), collision investigation, power line channel features, etc. are analyzed and discussed. Regarding the differences between home networking and industrial control, some essential factors are also studied here. The conception of RT-TCP is presented and a prototype of RT-TCP stack is proposed. The methodology of the protocol is discussed. Based on the foundational notation, an algorithm for RT-TCP is presented. The basic performance of the protocol is analyzed. We can find that the algorithm is different from TCP and more suitable for the real time networking with sharing power line bus. The system model will be formed for future simulation, and at the same time improve the actual development.

REFERENCES

[1] Chun-Huan Liu, E. Wade, H. Harry Asada, "Reduced-cable Smart Motors Using DC Power Line Communication," Proceedings of the 2001 IEEE International Conference on Robotics and Automation, pp. 3831-3838, May 2001.

[2] Chun-Huan Liu, and H. Harry Asada, "A Source Coding and Modulation Method for Power Saving and Interference Reduction in DS-CDMA Sensor Netowrks Systems," Proceedings of the American Control Conference, pp. 3003-3008, May 2002.

[3] J. E. Newbury, and K. J. Morris, "Power Line Carrier Systems for Industrial Control Applications," IEEE Transactions on Power Delivery, vol. 14, No. 4, October 1999.

[4] Soo-Young Jung, "A Channel Model for Power Line Communication in Home Network," Proceedings on the 15th CISL Winter Workshop Kushu, Japan, February 2002

[5] J.S.Barnes, "A Physical Multi-path Model for power Distribution Network Propagation," Proceedings, International Symposium on Powerline Communications and its Applications, 1998

[6] T. Bostoen, and Van de Wiel O, "Modeling the low-voltage power distribution network in the frequency band from 0.5 MHz to 30 MHz for broadband powerline communications (PLC)," Broadband Communications, Proceedings, International Zurich Seminar on, pp. 171–178, 2000

[7] C.A. Stutt, W.C. Hughes, R.C. Rustay, and J.T. Gajjar, "Experimental Verification on Distribution Feeder PLC Propagation Model Computations," IEEE transactions on Power Delivery, vol. 9, no. 1, pp. 519–524, Jan. 1994.

[8] M. Ferreiro., M. Cacheda, and C. Mosquera, "A low complexity all-digital DS-SS transceiver for power-line communications," Kyoto, Japan, March, 2003

[9] H. Kanemoto, S. Miyamoto, and N. Morinaga, "Parameter estimation and error rate performance of optimum receiver under Class-A impulsive radio environment," Trans. IEICE B, vol. J82-B, no. 12, pp. 2364–2374, Japan, Dec. 1999.

[10] www.homeplug.com

ZW. Zhao is currently a Research Fellow of Singapore-MIT Alliance. He received the Ph.D. degree from Beijing University of Aero&Astro, PR. China in 2002. His research interests are in space networking, self-organized communication networking, real-time power-line communication and embedded systems. He is now a member of the technical committee of Singapore-MIT Alliance.

I-Ming Chen obtained the Ph.D. degree from California Institute of Technology, Pasadena, U.S.A. in 1994. He was JSPS Visiting Scholar in Kyoto University, Japan in 1999, and currently Fellow of Singapore-MIT Alliance. His research interests are in reconfigurable automation, real-time networking and smart material based actuators. Dr. Chen has published more than 80 technical articles in refereed international journals and conferences. He is now serving on the editorial board of IEEE/ASME Transactions on Mechatronics. He was Program Co-Chairman of IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS) in Hawaii, USA, 2001, and Co-Chairman of Technical Program, 7th International Conference on Control, Automation, Robotics & Vision, Singapore, Dec. 2002. He is member of IEEE and ASME, Chairman of IEEE Robotics and Automation Society, Singapore Chapter, Chairman of Prototyping for Robotics and Automation Technical Committee under IEEE Robotics and Automation Society.