Performance of Reliable Intelligent Power Line Communication Network for Digital HPS Ballast Remote Monitor And Control

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Abstract—Power line communication (PLC) plays an important role in such no-new-wiring applications as digital HPS ballast remote management in new public lighting system. PLC data link especially with a large scale of ballast nodes is liable to be destroyed because of the dynamic channel properties. The reasons that lead to the failure of data link, the corresponding methods to enhance the reliability of PLC network are investigated, and the hybrid dynamic topology of the PLC network is studied, which is based on self-organizing algorithm in MAC layer with improved fault-tolerance ability. According to the study results, a low cost TDMA-like MAC protocol suitable for the hybrid PLC network initialized by self-organization algorithm is proposed and the performance is analyzed by M/D/1 model compared with polling. The general round robin cycle duration of PLC networks with hybrid structure that interested to remote monitor and control system is also presented.

Index Terms—fault tolerance, power line communication, reliability, self-organizing control

1. INTRODUCTION

POWER line communication (PLC) over low voltage grid, is an attractive no-new-wiring technology for many researchers and utilities, and the application fields extended from home automation, last mile-access to industrial remote monitor and control. In [1], we present new digital ballast, which is able to dim HPS lamps from 100% till 50% power by changing the switching frequency of the inverter. This enables energy saving as well as lamp life prolonging. PLC is the unique effective way to connect all digital ballasts to communication network over the secondary of the distribution transformer without any new wiring. As a result, even single HPS lamp can be monitored and controlled remotely, which reduces manpower and the cost of maintenance, as is shown in Fig. 1.

In practical, PLC network with a large scale of nodes like remote meter reading and public lighting management system has very low fault-tolerance ability and is always found to be vulnerable in robustness, which lead to the destroy of data link and greatly affects the reliability and the performance of whole

Fig. 1. Monitor and control digital HPS ballast remotely by PLC.

system. The main reason that affects the reliability of connectivity is the dynamic and special power line channel properties [2]-[6], and how to improve the reliability of PLC network especially under such industrial environment as public lighting received very little attention in previous literature.

In [7] we proposed a novel low cost self-organizing algorithm in MAC protocol that upgrades common PLC network to a robust self-adaptive network. When data link fails, PLC system with self-organizing algorithm will automatically search for the possibly connecting nodes and re-establish the logical topology. A part of this work is a continuation of [7], the topology after self-organization is analyzed, a TDMA-like protocol is proposed for monitor and control (steady stream) in the possible hybrid PLC network, and the performance is analyzed experimentally and comparably. Another part of this work is the round robin cycle for PLC network with hybrid topology after self-organization, which will be interested to practical engineering.

This paper is organized as follows. Section 2 investigates the main factors that affect the connectivity of PLC linkage, the usually adopted method to improve reliability, and briefly introduces the self-organization algorithm in [7]. The PLC topology after self-organization is studied, and the development

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process of TDMA-like protocol are detailed in section 3. In section 4, performance of polling and the proposed protocol is compared, and the packet delay useful for evaluating the system is presented. Conclusions and references complete the paper.

II. RELATED KNOWLEDGE AND OVERVIEW

A. Reasons lead to the failure of PLC data link

Different from conventional channels, PLC channel have special properties with noise and attenuation^{[3][5]}, which are the function of time and frequency, and have been addressed by many researchers^[6].

For the new public lighting system, digital HPS ballast, that leads to both signal attenuation and distortion, is the main load connected to power line and affects the reliability of PLC network, though other factors, such as communication distance, cable type, and structure of power grid are also have influence on the robustness of data link. For example, the forehead PFC (Power Factor Correction) components in digital ballast generates 20KHz~150KHz noise in different time, which greatly reduce the performance of the FSK PLC modem (such as ST7536) with the carrier frequency in the noise range.

Generally, increasing the transmission power or the sensitivity at the receiver is a good idea to improve the reliability of the PLC network. But signal power is ruled in limited level especially in radio frequency band^[8] and cost increases at the same time. For the latter, the receiver is more sensitive to useful signal as well as noise in the same frequency range, which has been found in practical public lighting system.

B. MAC protocols of PLC network

Though physical topology of low voltage grid is mainly tree-like distribution (residential power distribution) or bus structure (public lighting), the actual topology in data link is decided by MAC protocol. Efficient MAC protocols are very important for the reliability and a good utilization of PLC network.

Conventional matured MAC protocols, such as polling and CSMA/CD, are broadly used in industrial monitor and control system and computer network. The premise of these protocols is the connectivity of network. But actually PLC network is a non-steady network with dynamic topology because of the properties of PLC channel and the nodes. When conventional MAC protocols, which have not any adaptive ability to this dynamic environment, are directly applied to PLC network, the connectivity is liable to be destroyed.

In digital HPS ballast network based on PLC, a node joins in or is removed from the PLC network, it may have very little influence on the channel properties. But, to the whole PLC network, the data link among some nodes and the topology in the logical layer must have been changed. Part of the data link failure will occur only when a repeater for signal regeneration fails. Suppose that in the PLC network for public lighting, a digital ballast node with the ID number 10 (in short form, node 10) fails or the channel environment gets serious, the original

designed relay function of node 10 will not work, and the other nodes 11, 12, 13, etc., which depend on the relay station node 10 to get data stream, will also be lost in logical linkage, then the original data link is destroyed.

To improve the reliability of PLC network, PLC system should have the on-line ability of rapidly recognizing the new changed nodes and re-establish the data link. The re-establishment of PLC data link can be realized through method proposed in [7], finding out the possibly connected nodes and assign the ID number to each of them in data link layer.

C. Dynamic re-establishment of data link for the reliability of PLC network

Fig. 2. Self-organizing for the reliability of PLC network.

When connectivity is failed, re-establishment of data link in PLC network can be realized by the gateway device, which is always in the secondary of the distribution transformer to bridge the data stream over the transformer, by detecting the possibly connecting nodes and automatically assigning to each of the n nodes an integer ID number in the range $[1, n]$ such that no two nodes are assigned the same ID^[7]. This process is self-organizing, as is shown in Fig. 2. When the self-organizing accomplished, the previous destroyed data link has been connected again, and the reliability of PLC network for digital HPS ballast monitor and control is improved.

D. Self-organizing control algorithm overview

Gateway starts up the re-establishment by broadcasting the initialization command, and the number of the nodes that can receive the command is assumed to be m ($1 \leq m \leq n$). We define that the m nodes are located in the same layer (Layer 1). Then the remaining $n-m$ nodes (hidden nodes), which are connected to PLC network physically, are automatically masked logically and cannot compete for ID because of the PLC network properties. The m nodes that received the command compete for the ID number by sending message back to the gateway. Until there is only one node's message on the channel,

the gateway assigns the unique ID number to this node (ID=1), and then this node quit the competition. The remaining $m-1$ nodes continue to compete for ID recursively, until all the m nodes get ID.

As a result, the nodes in Layer 1 have been assigned the m ID numbers in total in the range $[1, m]$, and the node with the minimum ID number has the highest priority.

The nodes in the same layer continue to broadcast the initialization command to search for the possibly connecting

Fig. 3. Initialization of data link for self-organization.

nodes in next layer according to the sequence of priority. The node that receives reply from nodes in next layer becomes the Group Manager of the corresponding nodes. This process is repeated until no answers from the possible next layer. Then the self-organization accomplished (as is shown in Fig.3). The General self-organizing strategy is concluded as **Theorem 1**:

In the power line network that consists of n unknown nodes, if the maximum number of nodes in the same channel is m ($1 \leq m \leq n$), then the method for the re-establishment of data link can be accomplished by x Layers strategy with probability exceeding $1/e$ and with the expected number of time slots less

Fig. 4. The extremum conditions of Theorem 1.

than en , and there must be $1 \leq x \leq m$.

When $x=1$, the power line network topology based on *General self-organizing strategy* in the same channel is a single-hop distributed tree, and when $x=m$, the topology has a bus structure, as is shown in Fig. 4.

III. TOPOLOGY AFTER SELF-ORGANIZING

The self-organizing of PLC system generates new logical topology, though the PLC physical connection is possibly not changed. After the re-establishment, the structure of the PLC network is relatively fixed (until further data link failure occurs), and because of the connectivity various protocol can be performed theoretically. In fact, most industrial PLC applications with a large scale of nodes, such as public lighting system, don't have strict time-delay requirement, which is different from PLC-based last-mile access network that always has burst data and greater capacity requirement of downlink. When self-organizing accomplished, the channel type, connectivity and synchronization method that influence the performance of the network are relatively fixed, and some other factors, such as packet length, buffering capacity, routing method that greatly influence different QoS requirements should be carefully chosen and designed.

After self-organizing, each node has an ID number and can be synchronized by AC220V zero crossing point^[7] without any

Fig. 5. Low cost AC220V zero-crossing point synchronization.

special or expensive hardware for time slot synchronization. As is shown in Fig. 5. Another advantage of using zero crossing point as synchronization is that equally long packet can be utilized by the system, which simplifies the allocation of time slot. As a result it is obviously that collision free protocol with fix-assigned time slot is suitable to this topology.

Most frequently adopted protocol for industry is polling, which is simple and low cost, but the polling delay will increase as the number of digital HPS ballast nodes increases. For the best usage of the tree-like hybrid topology of PLC network, we propose a simple TDMA-like protocol for remote monitor and control as follows.

As Fig. 3 shows that when re-establishment accomplished, gateway has some nodes in Layer1 and each Group Manager has group members in next layer. The gateway or Group Manager allocates time slot to the nodes that it is in charge of.

Suppose that each group of nodes (include gateway or Group Manager) is seen as the single-hop distributed tree, when command from the gateway or Group Manager, the group members will reply in fixed time slot. We define that each group member should send the reply packet in priority sequence (from the minimum ID number to the Maximum ID number). By synchronization of zero-crossing points, each node can calculate the time slot precisely and decide at which time slot to send the reply packet, so without waiting for the channel-free packet (like the polling character in polling system), each node can send reply directly once the time slot that belong to itself arrives. As is shown in Fig. 6.

Fig. 6. Packet transmission in each layer in fixed time-slot like TDMA.

IV. PERFORMANCE ANALYSIS

A. Simplified model of PLC networks with hybrid structure

To compare the performance of the TDMA-like protocol with the one of polling in such distributed tree-like structure, we can see the topology as a single server, n user queuing system. Because each node transmits a packet in every T_c time slot independently, the packet arrival process of different node is independent. Thus the queue at one node is independent the queuing behavior of all others, and the gateway or Group Manager is in continuous service with the deterministic service time T_c . Then we can model the distributed tree structure as $M/D/1$ queuing system, which is helpful for simplifying the analysis of the TDMA-like protocol.

B. Analysis of normalized expected delay

The evaluation of the performance of the proposed TDMA-like protocol for the distributed tree-like structure is relatively complex because actually the PLC network after self-organizing is a hybrid network, which has the feather that each node is possibly in reception range of only a subset of the nodes and similarly the transmitted packet of a node is possibly heard by part of the total nodes, known as multi-hop network in wireless communication field. Another important feather is the dynamic structure, which automatically adapt to the change of the PLC channel when self-organizing for connectivity starts.

Generally, the performance of optimum packet delay as follows can be obtained when the PLC network has only one layer after self-organization. Assume a Poisson arrival process (λ) for each node in each layer, and that the buffering size for packet storage in a queue is not limited (such as very large RAM for short packet), from classical TDMA theory^[9], we have the total expected packet delay of n nodes,

$$D = T \left[1 + \frac{n}{2(1-\rho)} \right] \quad (1)$$

Where $\rho = \lambda T_c$ is the fraction of time the gateway or Group Manager is busy, and $T = T_c/n$ is the packet transmission time.

For the $M/D/1$ system, we know that the fraction of server's busy time equals the throughput, that is $\rho = S$, then we can obtain the normalized expected packet delay by dividing D by packet transmission time T ,

$$\hat{D} = 1 + \frac{n}{2(1-S)} \quad (2)$$

In the PLC network with a large scale of nodes, n is always a big number, so we can simplify (2) as,

$$\hat{D} \approx \frac{n}{2(1-S)} \quad (3)$$

This is the relationship between packet delay and the throughput developed under the $M/D/1$ model. In typical TDMA protocol, each frame needs special hardware (such as synchronized by GPS clock) or some extra bits for synchronization. Different from pure TDMA protocol, the proposed TDMA-like protocol in PLC network need not special synchronization bits in the frame, which gets higher utilization rate of the frames.

Generally, the performance expressed in (3) is optimum can be possibly reached in practical PLC network with self-organizing (when data link has only one layer) algorithm for reliable connectivity. For the hybrid multi-hop topology with the same nodes, system must insert additional packets to control the channel access. As a result, the performance of topology with only one layer expressed by (3) is the upper limit of the hybrid dynamic PLC topology, and the performance in the general hybrid PLC network after self-organization will be lower than or equal to the performance described in (3).

C. Practical cycle delay for Engineering

The round-robin cycle duration is important for PLC based monitor and control system to decide both the cycle delay and code development. From the extremum topology shown in Fig.4 and (3), the shortest cycle delay and longest cycle delay can be reached with the single-hop distributed tree-like topology and the single bus structure, respectively.

Suppose the time slot assigned to each node is T , the uplink packet length as well as bit rate are equal to the ones in downlink, and the number of the same nodes connected to PLC network is n , then in the single-hop distributed tree-like topology, the total time for all the nodes to accomplish transmission is,

$$T_1 = nT \quad (4)$$

In the single bus structure, to calculate the longest cycle duration, we suppose the buffering capacity in each node is just for one packet in industrial environment, so different from conventional high performance token bus, each successor node in PLC network can only forward one packet. In logic layer, gateway sends commands to node1 and node1 answers, the total time is $2T$ (one T is consumed by the packet reaches node1, and another T is used for returning back to gateway), and similarly node2 answers the command from gateway, the total time is $4T$, ..., and the n th node needs $2nT$ time slot to return message back to gateway. Thus the total time slot for all nodes to answer the gateway's command is,

$$T_2 = 2T + 4T + 6T + \dots + 2nT = n(n+1)T \quad (5)$$

Even though other protocols are applied to the proposed hybrid structure, the general cycle duration C of the PLC network with hybrid topology is between the minimum cycle duration and the maximum cycle duration, then from (4) and (5) we have,

$$nT \leq C \leq n(n+1)T \quad (6)$$

that is the general cycle range for hybrid PLC network based on self-organizing algorithm with fix-assigned time-slot.

D. Compare the proposed protocol with polling

For polling protocol, a polling character must insert (by broadcast with address) before any packet transmission, as is shown in Fig. 7. Obviously, the fraction of the time that polling

Fig. 7. Packet transmission in polling.

character consumed in one frame is more smaller, the total cycle duration the polling cost is more approachable to the one the proposed TDMA-like protocol cost. But the time for polling character can never be zero, so it is reasonable that in the hybrid

structure of PLC network after self-organizing for connectivity, the proposed TDMA-like protocol consumes more shorter time to accomplish a round robin cycle than the conventional polling does.

V. CONCLUSIONS

When embedded with self-organizing algorithm, PLC network for digital HPS ballast remote monitor and control has excellent fault-tolerance ability. After self-organization, the topology of the PLC is a hybrid tree-like structure.

The proposed TDMA-like protocol can be applied to each group of nodes in the network, and the upper limit of the performance can be reached by the proposed TDMA-like protocol without any special synchronization bit or hardware. Compared with conventional polling, the proposed protocol has shorter round robin cycle duration. The proposed TDMA-like protocol is suitable for industrial PLC based remote monitor and control system with a large scale of nodes.

Theoretically, the PLC network embedded with self-organizing algorithm can also be applied to access-network to realize automatic connectivity maintenance. But it should be considered that the hybrid topology of the PLC network after self-organizing turns to be more complex for high-speed purpose with high QoS requirement, because the performance of each node (may be a computer, or switch hub) is different. As a result, some problems, such as routing method, packet delay, and channel capacity, should be studied further.

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