LARGE-SCALE DATA ACQUISITION AND SCADA APPLICATIONS OVER POWER LINE NETWORKS

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Abstract: A system that enables narrow band power line communication to be used for data acquisition applications over large areas, such as a district or a town, is presented in its design and architecture. We present the capabilities of the system, which include the possibility to use existing applications and field-level equipment and extend their communication ability to the wide-area power line network. The core of the communication system is designed to employ not only power line communication, but also other communication channels.

Keywords: telecontrol, communication networks, protocols, communication systems, automation, data acquisition

1. INTRODUCTION

The communication systems used for many purposes in contemporary energy management are rather conventional with respect to networking capabilities and complexity. Applications like SCADA (Supervisory Control And Data Acquisition) or Automated Meter Reading (AMR) typically require a designated communication channel that they may use exclusively). Standards like EN 62056 (also known as IEC 1107), IEC 60870, or M-Bus are widely used, but are based on the availability of point-to-point connections and allow – if at all – only a limited number of participants on a bus. Addressing and managing of comprehensive networks comprising an adequate number of devices embedded in a hierarchical structure is not foreseen in the protocols. The simplicity of the communication system is also reflected on the physical level. In practice, this is typically a serial line (RS 232 or RS 485). Hence, the implementation of larger systems requires two essential ingredients: a communication channel to bridge the distance between the utility company (the respective control room, to be precise) and the devices or device clusters; and the massive use of parallel channels to overcome networking limitations of the protocols.

A typical way to connect utility servers and field equipment is to use existing telecommunication channels – either dial-up or mobile – or wireless networks. In most cases, however, such infrastructures are provider-based, which reduces in particular the economical control the utility company can gain over a communication system vital for their business. It is therefore obvious that means are sought to use a different infrastructure, which is under the control of the company: the power distribution grid. Contrary to the highly disputed and not overly successful attempts to provide Internet over the power line, SCADA and AMR systems have lower data rate requirements and can be operated using narrowband power line communication, which is much less problematic in terms of electromagnetic interference. Nevertheless, the power line is a rather hostile communication channel, and if it is to be used with state-of-the-art SCADA and AMR protocols and field devices, special precautions have to be taken.

This paper presents the approach to using power line communication (PLC) for low-level data transmission together with standard protocols developed in the EU project REMPLI (Real-time Energy Management with Power-Lines and Internet, project identifier NNE5-2001-00825). The technology of power line communication is covered in (Dostert, 2001). The goal of REMPLI is to use existing applications or equipment (utility meters, switchgear equipment and the like) as much as possible. Therefore we have to provide a channel that is transparent to the application while at the same time fulfilling all its communication needs. A key issue in the communication system is flexibility: due to its modular design it is possible to not only use power line communication as the data transport channel, but also other kinds of communication networks such as the GSM network, wireless networks or dial-up connections. Therefore we have introduced a communication interface that shields the properties of the underlying medium from higher layer communication services. Another aspect is modularity with respect to the higher-level protocols used on top of PLC. The primary goals are SCADA and AMR, but extensions to other applications like energy management or domotic applications are possible and can easily be adopted.

This paper focuses on the power line related parts of the communication system. The Internet Protocol (IP) network, which is also part of the communication system, is not considered here. This is also true for the security related issues that have to be taken into account when using a public network like the power grid for exchanging sensitive data. The security concept of the REMPLI system is described in (Treytl and Sauter, 2005).

The rest of the paper is organized as follows: in section 2 the applications that benefit from the communications system are presented, section 3 explains the details of power line communication layout, while section 4 takes a look at protocol stack. Section 5 describes how to implement different fieldbus protocols seamlessly into the communication system and section 6 shows the communication services that are available for the applications. In section 7 we examine the issue of a dynamically changing power grid and the implications for PLC and section 8 sums up the paper and gives conclusions.

2. REMPLI APPLICATION AND BOUNDARY CONDITIONS

The main goal of the REMPLI project is to design and implement a remote metering and SCADA control network, using power line communication (PLC) as a medium. The use of power line is necessitated by the main target application of the system: it is designed for utilities that automate meter reading in private households and service provider companies, operating in the areas of domotics, in-house security and the like. The only economically-feasible way of providing these applications, especially in those parts of the world, where broadband Internet connectivity in private households is uncommon, is to use the power line, so that any additional wiring is avoided.

Additional to this main goal, the REMPLI system is designed such that it is suitable not only for the aforementioned metering/SCADA tasks, but can also be used for virtually any control and data acquisition application, where power line communication is deemed necessary.

A significant economy-related aspect is that utility companies, service providers and many other control network operators already have some sort of metering and actuator equipment installed. Usually such solutions allow for direct connectivity between the equipment and software (metering or SCADA) using a limited-length physical network, such as RS 232 or RS 485, running some standard or proprietary protocol. Even if this is not the case, the market currently offers a large variety of such field devices and software packages. Thus it makes no sense to develop custom hardware or software for operating over PLC. Instead, REMPLI is thought as a snap-in replacement for the existing physical wire between field devices and control software, as it is shown in Figure 1.

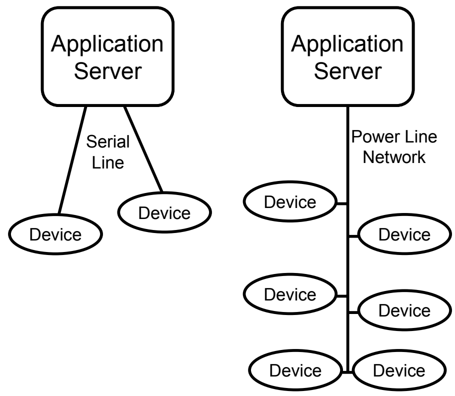

Figure 1: Using PLC network to replace direct serial line communication.

With REMPLI the control application can be substantially increased in scale (meaning the number of attached devices) and distance between them and the control center.

A main boundary condition in energy management applications is to maintain investments in application server software and field devices; the application server is in most cases already installed at the utility side and must be re-used, introducing new software would not be cost effective. Even more, an adaptation of the software to a particular communication system is not feasible either. At best it is possible to do small adaptations to the drivers that transport the metering or SCADA protocol between application server and access point.

Although the protocols used in SCADA and AMR are standardized, there is still a large variety within these protocols, because many of them are specified too loosely (especially at the application layer). For example, IEC 1107 do not ensure interoperability between solutions from different vendors (equipment as well as metering software). If the power line communication system was to be widely adopted without additional adaptations it must exhibit utmost flexibility to serve as a drop-in replacement for the currently dominating direct cabling between application servers and field equipment.

This effectively prohibits the implementation of a gateway solution: if a protocol can be used differently in different implementations (using other semantics at the application layer, as is the case in IEC 1107), it would be necessary to implement a dedicated translator module. Depending on the varieties in semantics this would be necessary for each combination of protocol and vendor. This solution is not reasonable for complexity and software maintenance reasons.

Finally, simple protocol and data translation is the preferred solution, because of national regulations, which impose stringent rules on the communication system: if, for example, metering data are used for automatic billing, the data must not be altered on their way from source (i.e., the meter) to sink (the billing application) or, if there is any equipment in the data path which touches the data as such, it must be certified separately, which is a costly procedure. Therefore it is advisable not to convert the data. Instead we have decided to tunnel all data between the end points of the communication.

3. POWER LINE COMMUNICATION

The layout of the REMPLI power line communication network is based on the requirements set by a number of utility companies – participants of the project. These requirements can be considered as "worst-case": most other foreseen control networks will utilize PLC to a lesser extent or provide a more "friendly" environment to data communication.

The power line network is comprised of two distinct segments. The first one spans from a private household or an apartment, over a low-voltage (LV) power line, to the medium-to-low voltage (MV/LV) transformer station, also called *secondary transformer*. The second segment continues PLC communication further, over medium-voltage lines, to the *primary transformer* (high-to-medium voltage). At this point utilities tend to have some sort of data communication network already installed and running (typically it is based on Internet Protocol (IP) – either via dedicated cables or wireless, such as GSM or GPRS). Thus the last communication segment, between the primary transformer and the utility or service-provider control center, is not PLC-, but rather IP-based. A single installation can encompass several MV segments, each, in turn, attached to several LV grids (the control network can cover a whole district, or even a small town).

The length of both segments, depending on the deployment area, can be rather substantial – up to several kilometers. The low-voltage part can also span across several dozen consumers (in Western Europe) or even up to 500 (in Eastern Europe) consumers (Figure 2). Both factors essentially prohibit use of existing broadband power line communication systems, such as HomePlug (Homeplug, 2005). Instead, the REMPLI project has developed its own narrow-band PLC system, suitable for the described harsh environments and distances of several kilometers (Bumiller, 2005). Conventional power line communication systems have data rates between 300 and 9600 bit/s and are designed for reading actual meter values at most once a day. These data rates are too small for transporting load profiles (where data rates between 30 and 100 kbit/s are required) and much too small for real-time energy consumption monitoring or online trading of energy in an open market via power line (which requires calculated data rates between 100 and 300 kbit/s). The REMPLI system aims at providing 500 kbit/s (100-200 kbit/s on currently regulated CENELC bands) raw bandwidth. While this raw bit rate is of course not available as payload bandwidth for the end user of the system (due to protocol overhead, repetitions and the like), it is still an impressive progress compared to existing systems.

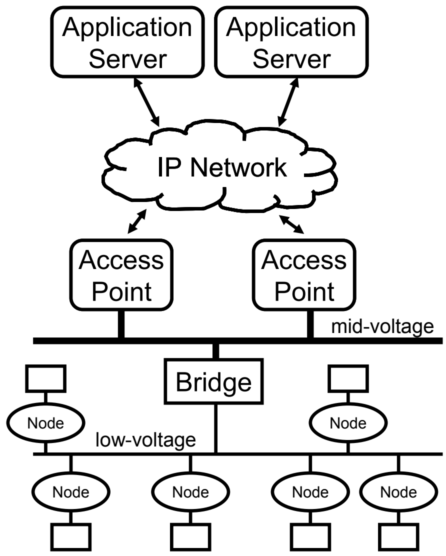

Figure 2. REMPLI communication architecture.

According to the described layout, the PLC system consists of two independent master-slave networks, operating in LV and MV segments respectively. The secondary transformer prohibits transparent data communication between the segments; thus REMPLI introduces a PLC *bridge*, located between the LV and MV parts. The bridge behaves as a slave on the MV side and as a master on the LV side.

For the reasons of reliability and security, a single low-voltage network is usually supplied from two, or even more, secondary transformers. Normally, at a given time only one of these transformers is active (in operation); other are in cold-standby. Since inactive transformers are physically disconnected from the grid, the only way to provide uninterruptible data communication is to install bridges at every secondary transformer, supplying the given LV net. From the upper (MV) side this poses no problem: every bridge acts as a regular slave. However, on the LV side it means that multiple masters are communicating on the same network (under normal conditions it is only one master, installed at the currently active transformer, but under special conditions more than one master can be active). Different masters transmit at different frequencies.

Slaves, upon loosing connection to a current master, perform a frequency scan of the medium and “reattach” themselves to the other master.

Slave devices in the LV network are PLC *nodes*. Every node incorporates a number of interfaces: RS 232/485, pulse inputs, digital outputs, etc., which enable it to communicate with locally attached field devices (such as energy meters and SCADA equipment). The node also has a certain amount of computing power, sufficient to implement communication protocols of the attached devices and installation-specific local control algorithms.

The MV-side master is an *access point*, which routes traffic between the PLC and Internet Protocol (IP) networks. The latter connect access points with application servers (control software, metering systems, SCADA, etc.).

The situation in mid-voltage network is similar to that on the low-voltage side: for redundancy, the same grid is connected to multiple primary transformers, each equipped with an access point.

The dual power supply redundancy, described above, results in a rather awkward situation for data communication:
- in the LV network nodes are uncontrollably roaming between the bridges;
- in turn, in the MV network bridges uncontrollably roam from one access point to another.

Further, due to switching processes in the power line grid, it is also possible, that during some periods of time the same LV node is reachable via multiple different paths (via different bridges and/or access points).

Neither application software, nor field devices can, or should, implement special handling for the switched and meshed PLC medium. This is done internally by the PLC communication stack, as described below. Each field device is connected to only one node; every application server also communicates to only one of the access points (any of them).

In order to cover a wider range of potential applications, the REMPLI system also supports installations with only one power line segment (either LV, or MV). In this case PLC bridges are unnecessary, since direct communication between access points and nodes is possible.

4. PLC COMMUNICATION STACK

The communication protocol stack, implemented by all devices in the REMPLI network (access points, bridges and nodes) is comprised of the following layers (Figure 3).

- **PLC physical and link layers**, which implement the actual power line coupling. An in-depth description of these two layers is beyond the scope of this article; for more details refer to (Bumiller, 2002) and (Bumiller, 2005).

- **PLC network layer**, responsible for providing datagram-oriented communication in a master/slave fashion with reliable delivery. The network layer communication runs between devices in the same PLC segment; that is, PLC bridges terminate network layer from both sides. At the masters this layer also handles logon/logoff procedures for the slaves (i.e. slaves that "attach" to a master), directly attached to the underlying PLC segment. Upper layers can query the list of slave addresses, which are currently in operation, at any time.

- **PLC transport layer** adds the end-to-end communication capabilities: from an access point, through bridges, to the target nodes and backwards. In a switched/meshed PLC this is the layer that makes a decision, which of the available communication paths should be used to deliver a packet. Information, required for such decisions, is available from the network layer (a special status-of-link table, where all available nodes, along with “link quality” characteristic values, are listed).
  The transport layer also extends network discovery mechanisms such that access points in the MV segment become aware of attached node addresses in the LV segment (information from all bridges is collected together).
  In order to perform packet forwarding between the LV and MV networks, a special transport layer architecture is required at the bridge: both master and slaves sides of the bridge share the same transport layer (unlike the network layer, which exists in two instances: one at the LV side, one at the MV side).
  Similar to the network layer the transport layer communication is reliable and datagram-oriented (connectionless).

- **Communication multiplexer/demultiplexer**. On top of the transport layer, the de/multiplexer merges (and separates on the other side) streams of packets, related to different fieldbus protocols. Another function, performed by this layer only at the access points, is re-routing of packets to nodes, currently unreachable via any of the connected slave-bridges due to PLC switching, through other access points.

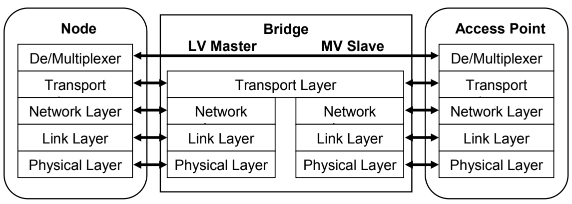

Figure 3. Protocol stack and layer-to-layer communication between different devices in the network.

In some applications the communication de/multiplexer will not be present at the bridge, since this device doesn't need to specifically process application traffic and only forwards packets up and down. However, many utility companies find it useful to install field equipment at the secondary transformers; in this case the de/multiplexer is required at the bridge as well (its architecture and functionalities are then exactly the same as at the nodes).

5. FIELDBUS PROTOCOL HANDLING

A single REMPLI installation can contain different types of field devices at the same time. For instance, one node can be connected to several IEC 1107 (IEC 62056) energy meters, while a second node provides access to M-Bus meters and an IEC 870-5-101 SCADA control box. On the other side of the network every type (group) of devices is typically controlled by a dedicated software application: e.g., all IEC 1107 meters in the network will be polled by a respective metering system.

As described above one of the design criteria for the REMPLI network was to enable transparent transmission of multiple different fieldbus protocols (Lobashov 2003). The number and types of these protocols are not limited to those integrated during system design (currently these are mainly SCADA and metering protocols). Rather, it should be possible that any third party user of the system transmits their application-specific protocols over PLC, using REMPLI as a communication platform.

Due to this requirement, the application layer of REMPLI devices is designed in a modular way. Every fieldbus protocol is handled by a "triple" of communication protocol drivers:

- At the node side the protocol driver interfaces on the one side with the field equipment (via RS 232/485, digital and analog I/Os, etc.) and on the other side exchanges application Protocol Data Units (PDUs) of the fieldbus protocol over PLC with the access points.

- The access point side driver interfaces with the control software (application server) over the IP network and also communicates with all of its "siblings" (drivers for the same protocol type) at the nodes.

- The application server uses a specific communication driver to exchange data with the respective driver at one of the Access Points over IP.

Depending on the protocols that the connected field equipment support the node can run one or more protocol drivers – each for a single fieldbus protocol (one driver can be, of course, responsible for more than one device of the same type). Every access point always runs a superset of drivers – for all fieldbus protocols, transferred over this PLC network. The application server software typically integrates only one driver, which enables it to transmit application PDUs over IP to the access points. The logical structure of the resulting communication network is shown in Figure 4.

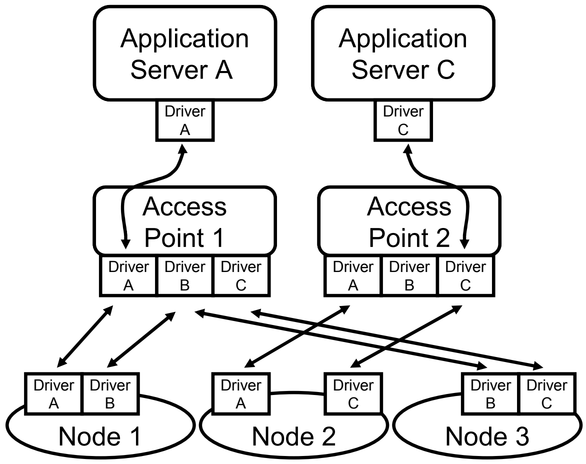

Figure 4. Communication between drivers shown as logical connections between drivers on access points and nodes.

On the PLC side the underlying protocol stack (de/multiplexer and layers below it) fully isolates communication between different types of drivers. Every driver group communicates as if it were the only user of the PLC data transmission services. On the IP side communication is also "isolated": every application server establishes its own TCP connection to one of the access points.

Functionality of the access point and node protocol drivers is not limited to simply tunneling fieldbus protocol PDUs over the PLC. Depending on the protocol, the driver design can include more or less sophisticated parsing and processing of PDUs. The main goal is to reduce bandwidth utilization in the PLC network to a minimum. For instance, an IEC 1107 driver couple will, likely, compress load profile data from meters, while it is transmitted over the power line (decompression will be performed at the access point side, so that the application server receives the original PDU). IEC 870-5-101 drivers, similarly, will suppress transmission of keep-alive polling from SCADA server.

6. COMMUNICATION SERVICES

The modular and open architecture of the application layer (communication protocol drivers) requires "standardizing" the interface, provided to it by the communication system. This interface is located above (or below, in case of a node) the de/multiplexer layer, as shown in Figure 5.

To allow for fieldbus protocol tunneling, the following data transmission services are considered necessary at the access point side, and provided to drivers by the communication system.

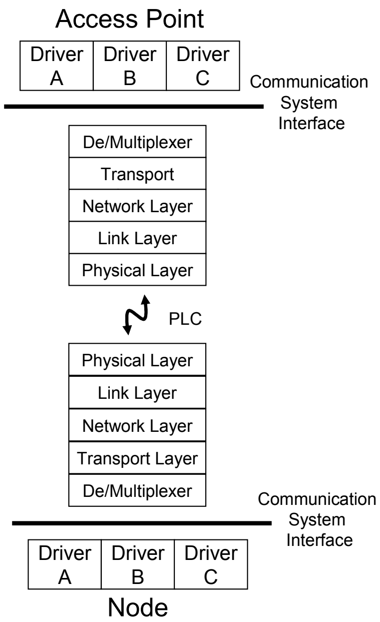

Figure 5. The communication system interface allows using different communication media without changing the system core.

- **Request/response**. Driver can generate a request, which is sent to a certain node. The driver receives a unique transaction ID for the request, after it is submitted, from the de/multiplexer layer. The communication system then waits for a response to be generated by the node. After the response is delivered back to the access point, it is returned to the driver along with the same transaction ID, which was returned upon sending the request (in this way driver can match requests against responses, in case multiple parallel request/response transactions are opened at the same time). If a node does not respond to the request within a certain amount of time, the communication system cancels the request/response transaction and informs the access point side driver about this fact.
  The request/response service is typically used by drivers for handling their respective application protocol transactions. Most metering and SCADA protocols are request/response in their nature, thus they perfectly fit to the master/slave concept of the PLC communication.

- **Request/no-response.** This service is similar to the request/response service, but a node driver does not generate any response to requests when using this service. After transmission of the request is completed, the transaction is considered to be finished, and the requester (driver) is informed about this fact.
  It's worth mentioning that, while no response is generated by the node driver, for reliability reasons the request/no-response service is still internally acknowledged within the communication system. The de/multiplexer layer reports "success" to the driver only after a request message has been successfully delivered to the destination, and this fact has been acknowledged by the node. The request/no-response service can be used by access point drivers to send additional control information to their siblings at the nodes, or to handle some specific application protocol transactions.

- **Multicast and broadcast.** This is an unacknowledged service, used to send messages to a group (or all) nodes, connected to the REMPLI network. The communication system reports that a transaction is completed after the message is transmitted to all specified nodes, but without waiting for any acknowledgement from them. If transmission did not succeed for one (or all nodes) in the multicast group, the driver has no way to learn about this fact. This service can be used, for example, to upgrade software at all nodes in the network: first, access point broadcasts new software images to all nodes and then verifies upload status with each node separately using the request/response service, completing any missing parts of the image.

- **Network discovery.** Depending on the fieldbus protocol and driver functionality, the driver at the access point may need to query information about the list of nodes, currently attached to the network. In particular, this is the case for add-on services, implemented as "virtual protocol drivers" (e.g., system configuration and monitoring "driver"). The communication system offers two such lists: one containing all nodes that are currently reachable directly from this access point and another one, where all nodes in the PLC network (including those that are only reachable via other access points) are included.

Due to master/slave communication in the PLC network, the communication system interface at the node side has to offer a different set of data transmission services:

- **Response.** A counterpart of the request/response service at the access point. When a node driver generates response to a previously received request from the access point, it sends it via the response service. Response messages are always delivered to the same access point where the request was received from (this fact is important in meshed PLC environments, where a single node is "visible" from more than one access point).

- **Alarm.** A node driver can generate an asynchronous alarm message, and send it to the access point driver (without the access point driver issuing a request first). Such messages are delivered to all access points that can currently reach this node. The communication system returns a successful completion result after the

alarm message has been transmitted; i.e., this service is unacknowledged. In a master/slave PLC system implementing acknowledged alarms would require an additional request/response transaction, which is, in most cases, unacceptable.
Since the node has no way of determining, which access point actually receives the alarm message (i.e., where the target application server is connected to), and the message is delivered to all access point protocol drivers within a group, drivers have to coordinate their "efforts" and suppress duplicate alarms. This can require additional driver-to-driver communication over the IP network.

- **Fast status transmission.** Every node driver in the PLC network has a possibility to transmit a few bits of status information to its access point siblings as out-of-band data, included into unused space of the PLC control packets (periodic slave polling, as a part of the internal network management). The transmission is asynchronous: first, the node driver sets the value of its bit field; then, as soon as the polling cycle reaches this node, the bit field is actually transferred to the access point driver. Clearly, if a node driver changes its status bit field faster than the polling cycle period, intermediate bit field values will not reach access points.

The described interface is designed such that it can accommodate different types of protocol drivers (and, respectively, fieldbus protocols) – as long as they fit the master/slave communication principle and do not require too much asynchronous traffic from nodes to access points. Introducing the "standardized" communication interface above and below the de/multiplexer also allows, in principle, to replace PLC network with other communication media (wireless networks, analogue telephone systems, etc.). The latter will not affect communication protocol drivers, field equipment and application software.

7. COMMUNICATION IN SWITCHED PLC NETWORKS

The network discovery service at the access point does not provide any information regarding meshed or switched communication paths. The only information that is available to drivers is the list of nodes that can currently be accessed via this access point directly. In case of PLC network, this list is comprised of nodes that have logged in and can be physically reached at the moment. As the network switches and changes its characteristics, this list will change accordingly: new nodes appear, others disappear.

In case of GSM, ISDN or analogue telephone networks this list is more static. It can include, for example, those nodes, for which telephone numbers have been configured into the access point.

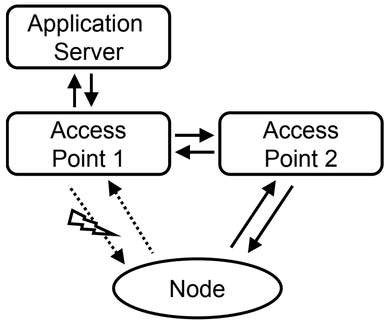

Figure 6. Re-routing of application PDUs through other access points.

Apart from addresses of reachable nodes, the "live-list" also includes connection qualities for each of them (e.g., a relative parameter, expressed in percents). Using this information the de/multiplexer can make decisions on whether a packet, sent by an access point driver has to be re-routed to another access point or not.

As shown in Figure 6 re-routing of messages between access points occurs at the de/multiplexer level and only at the access point side. In fact, each de/multiplexer layer "talks" to de/multiplexers in all other access points over the IP network (communication there is TCP-based and uses point-to-point links).

Horizontal communication between de/multiplexer layers serves three main purposes.

- Every access point periodically informs its siblings about any changes to its live list. Therefore, each de/multiplexer layer knows about current live lists of all other access points in the REMPLI network. Transferred live lists include not only addresses of nodes, but also the connection qualities.

- In case this access point cannot deliver message to a target node (node is currently not on its live list), the de/multiplexer layer can optionally forward the message to a sibling that currently has a link with the node. If none of the access points has the destination node address in their live lists, an error is returned to the driver. Re-routing can also occur in case another access point has a better connection quality to the destination node (more precisely, if connection quality to the node from the other access point is higher by a certain threshold: re-routing of a PDU over the IP network introduces a latency, which can be in some cases higher than that due to retransmissions in the PLC network).

- Responses from nodes, received by a certain access point, are re-routed back to the originating access point, so that its de/multiplexer layer can forward the response to the appropriate driver and close the transaction.

Delivery of multicast/broadcast messages over a switched/meshed network has to be handled in a special way. For instance, in order to cover all nodes in the network, every broadcast message has to be transmitted from, potentially, all access points. This, naturally, causes duplicates appearing at the nodes. Thus every broadcast message needs to be assigned with a system-wide unique ID, transmitted along with it over the PLC. Using these IDs de/multiplexers at nodes maintain a backlog of the recently received broadcasts and, thus, filter out duplicates.

Re-routing of PDUs is optional and always controlled by a communication protocol driver at the access point. Drivers that implement application protocols with integrated link control can prohibit re-routing of messages at the de/multiplexer level, since link management is done by the upper-level software (such an application will then connect to all access points in the IP network).

In order to simplify the design of communication protocol drivers, the communication system interface attempts to "hide" the switched/meshed nature of the PLC network. A typical driver will simply utilize the "automatic" re-routing capabilities, in which case it doesn't need to handle PLC switching at all.

8. CONCLUSIONS

We have presented the design and architecture of a communication system that is on the one hand able to employ narrow band power line communication for SCADA and similar applications, and is on the other hand flexible enough to also support other communication media such as GSM or dial-up lines. The key to this ability is the driver concept, which requires a driver for each application layer protocol to be available at node, access point and application server.

The design of the system reflects requirements by industrial partners in the REMPLI project, namely the possibility to reuse existing investments such as switchgear equipment, utility meters and application software. First tests have shown good results, two upcoming field tests scheduled for the end of this year in Portugal and Bulgaria will show first real-world results of the capabilities of the system.

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