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SURVEY PAPER

A survey on networks for smart-metering systems

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Abstract

Purpose – At present the energy generation and distribution landscape is changing rapidly. The energy grid is becoming increasingly smart, relying on an information network for the purposes of monitoring and optimization. However, because of the particularly stringent regulatory and technical constraints posed by smart grids, it is not possible to use ordinary communication protocols. The purpose of this paper is to revisit such constraints, reviewing the various options available today to realize smart-metering networks.

Design/methodology/approach – After describing the regulatory, technological and stakeholders' constraints, the authors provide a taxonomy of network technologies, discussing their suitability and weaknesses in the context of smart-metering systems. The authors also give a snapshot of the current standardization panorama, identifying key differences among various geographical regions.

Findings – It is found that the field of smart-metering networks still consists of a fragmented set of standards and solutions, leaving open a number of issues relating to the design and deployment of suitable systems.

Originality/value – This paper addresses the need to better understand state-of-the-art and open issues in the fast-evolving area of smart energy grids, with particular attention to the challenges faced by communication engineers.

Keywords Digital technology, Energy technology, Information networks, Smart-metering networks, Mesh networks, Smart-grid regulations

Paper type General review

1. Introduction

Energy, particularly electricity and gas, is something that we have grown accustomed to having around. Nearly every piece of household equipment nowadays needs electricity to function, and modern society would hardly function without it. Energy has become something which is always at our disposal when we need it, so much that we hardly ever stop to think about how it gets to our homes, offices, and factories. However, recently awareness of where our energy is produced is increasing, and topics such as energy efficiency are on every one's mind, either because of monetary reasons, or out of concern for the environment. Electrical companies share these concerns, too, and invest heavily both in green energy as well as in ways to reduce costs. Currently, once it has been generated at a power plant, energy is transported to its destination through the electrical grid and through gas pipelines.

The generation and transportation of energy is a complicated problem. Power generation and consumption are not constant throughout the day and fluctuate with

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the daily rhythm of our lives. Traditionally grid operators try to anticipate when extra power generation capacity is needed by watching for signals such as rapid drops in the voltage levels and by taking into account our daily habits and major events. A certain level of power is always needed and has typically been provided by a power plant which is capable of generating power efficiently at low cost over a longer period. Such a plant has high start-up and shut-down costs, and takes a long time to switch on or off (e.g. coal or nuclear). When more capacity is needed quickly, a second type of plant which can be turned on and off quickly and cheaply such as gas turbines is used. These however are more expensive to operate. Consequently, the price of energy also fluctuates slightly over the course of a day, to account for generation costs. However, many sources of renewable energy such as solar and wind do not fall in either category, and their production capacity at any given moment is beyond the control of the grid operator. To further complicate matters, these forms of energy generation may be installed by individual consumers, and in effect provide electricity back to the supplier.

To solve these problems grid operators are looking towards a smart grid (Massoud Amin and Wollenberg, 2005). The smart grid is an effort to leverage modern communications technologies to solve or alleviate these issues. By closely monitoring the individual users and producers of electrical power it is possible to respond to changes in the amount of electricity being used and generated more quickly, and more intelligently. The smart grid needs to enable two-way communications between suppliers and consumers of energy in order to do so. An example of the kind of advantages that can be obtained in this way is a technique known as peak shaving (Caron and Kesidis, 2010), which has the goal to reduce energy consumption during the most active periods. By taking advantage of the ability to send information to the subscriber, the grid operator can influence daily usage patterns, for example by turning on diverse utilities at a time when the load on the network is lowest (or the amount of energy generated greatest). This technique can spread out energy consumption, and in turn, significantly reduce costs. This is especially relevant during peak-hours, when energy costs are at a premium (Erol-Kantarci and Mouftah, 2010). Peak shaving benefits both the consumer and the grid operator. The latter has to spend less money and effort on short-term energy generation such as via gas turbines. The customer benefits because, although the total amount of energy he has consumed is the same, the price of energy can be lower.

A critical part of a smart-grid infrastructure is the monitoring and communication network (Figure 1). In fact, substantial research and standardisation efforts are well underway to developing communication networks that can meet the stringent requirements of smart grids. The focus is on the exchange of information between parties and devices comprising the smart grid.

Also of particular importance to the success of the smart grid is a new type of electrical meter, the smart meter. Most current meter installations use an electromechanical meter which has to be manually read-out on a regular basis. Newer metering installations may use techniques such as automated meter reading (AMR) or automatic meter management (AMM) to facilitate remote meter reading. However, the next generation of smart electricity meters will need to go beyond the capabilities of current meters, to be able to exert extra control from and to the metering devices (Deconinck, 2008). Besides offering the ability to read the meter remotely, smart meters are able to manage connected devices with short feedback and response times, as well enabling two-way communication between suppliers and consumers – a key requirement for the smart grid.

Many technologies are currently proposed, in use, or being evaluated for use in the smart grid and in smart-metering communication. Such proposals range from technologies which aim to re-use the existing electrical grid infrastructure as a communications medium (so called power-line communications (PLCs)), to installations wherein each metering device is equipped with a mobile telephony based communication module (GPRS or GSM). In this paper we give an overview of the current state-of-the-art in communications technology directed towards smart-metering setups. We start with a brief discussion of the requirements of smart-metering systems using an example. Thereafter we present the common approaches to implementing smart-metering systems, including a number of possible implementations of smart-metering systems based on meshed networks. Finally we discuss relevant on-going standardisation efforts.

2. The stringent requirements of smart-metering networks

2.1 Regulatory constraints

A smart-metering system must take its deployment area into consideration in terms of regulatory constraints. As this system will be deployed in the European Union, it must adhere to European laws and regulations. Generally speaking, European law regarding radio frequency (RF) communications is stricter than other areas such as the USA, to avoid losing generality we emphasise particularly on Europe. In the European Union there are efforts underway (namely Mandate CEN/CENELEC M/441 (European Commission, 2009)) to standardise smart-metering interfaces in order to facilitate a large-scale smart grid. Similar efforts are taking place at national levels in the whole

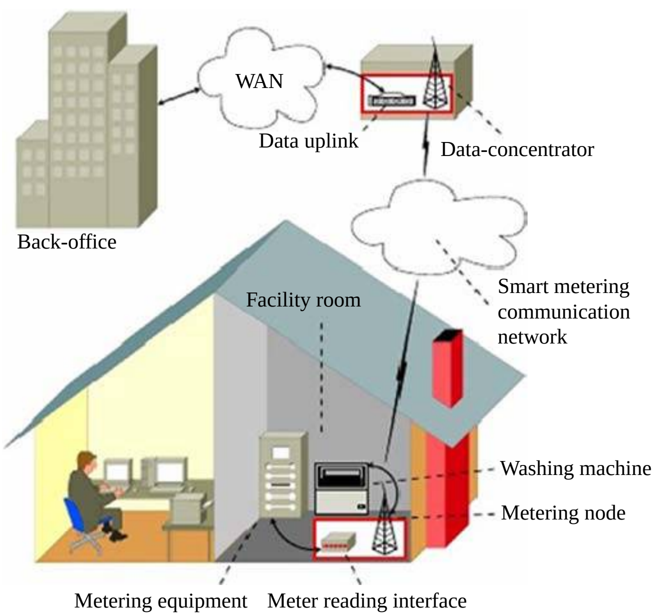

Figure 1. Overview of the smart-grid infrastructure, comprising diverse metering devices (in different households) that together form the smart-metering communication network. Metering data from different households can then be aggregated and, through a data concentrator, will reach the back office via the internet

of the European Union. Particularly in The Netherlands there are efforts to provide standards to which utility meters should adhere, such as for example the Dutch NTA-8130 directive or the Dutch Smart Meter Requirements (DSMR) document (KEMA Consulting, 2008). We discuss there standardisation efforts in greater detail in Section 1.5.

However, complying with these standards is not sufficient to build a complete smart-metering system, including the protocol(s) used for inter-device communications. This is because these standardisation efforts are mostly focused on interoperability between different layers in the smart grid. These standards specify the electrical connections and protocols between different components in a smart meter (a single smart-metering unit may consist of multiple components from different vendors and utility companies, see Section 1.2.3). How communications are to be done within a system or layer is left largely unspecified, so these standards have only a limited impact on the routing and communications protocols. These should be sufficiently flexible to ensure that they can (be configured to) accommodate the data that is to be communicated between layers, and provide any guarantees that are required by the standards, e.g. requirements on security or timeliness of data delivery.

Besides these requirements which are specific to smart-metering implementations, other more general restrictions also apply. Both in Europe and USA, and indeed all over the world, there exists regulations which impose certain limitations on the use of radio frequencies. For example, in the European Union there are regulations which affect all union members, as well as the possibility for individual members to amend these global rules. The European EFIS database[1] provides an overview of legislation governing the use of radio frequencies on many levels, ranging from international agreements imposed by the International Telecommunication Union (ITU), down to amendments on the national level. Certain frequency bands are reserved for use by specific applications (e.g. medical usage, amateur radio, etc.), or may require a licensing agreement before they can be used. There are restrictions on the maximum allowed transmission power, or effective radiating power (ERP). There are restrictions on the amount of bandwidth that can be used, or the amount of time a device is allowed to actively transmit (the active duty cycle). The specific regulations and limitations that apply to a specific device thus depend on the frequencies and bandwidth chosen, and on the intended application area. In turn the frequencies and bandwidth requirements are influenced by the application area, and by the capabilities of the hardware that is used.

2.2 Case study: regulation in The Netherlands

To give a specific example, we have developed and trialed a smart-metering network that complies with the Dutch regulations[2], which are among the most stringent in the European Union. Our choice was to operate in 868 MHz band. Section 1.2.3 details the hardware and its requirements, but for this discussion it is relevant that based on decisions made by the hardware development team, the smart-metering device operates in the 868 MHz band. This frequency band belongs to a band allocated for use by "non-specific" short range devices (SRDs), under the following conditions: no use is to be made of channel spacing (however the whole stated frequency band may be used), the device must be limited to a maximum ERP of 25 mW using narrow/wide-band modulation, and the device must operate its transmitter such that it either has a worst-case duty cycle of less than 1 percent or implements some form of listen before talk (LBT). The term "duty cycle" is a measure of the percentage of time that a device is using its transmitter, and can thus potentially interfere with other users of the same frequency band. The duty cycle is measured over a rolling one hour period, and is calculated independently for each device. To calculate the duty cycle one has to measure the total amount of time a device is transmitting using a one hour sliding window. Thus, for any given device, if its transmission behaviour were measured for any period of one full hour, the total time spent transmitting should be strictly less than 1 percent of the time. Concretely this means that, combined with the given transmission characteristics of the transceiver (which does not support LBT), the communication protocol has to ensure that none of the participating metering devices exceeds a 1 percent duty cycle, at a maximum effective radiated power (ERP) of 25 mW.

2.3 Technological constraints

Plate 1 shows a prototype smart-metering device. Internally these metering devices consist mainly of two parts, a measurement station and a meshed transceiver. Often there is also the possibility to connect further measurement stations to the meshed transceiver, e.g. a water- or a gas-metering unit.

Note: The references have been blanked out due to double-blind review

Plate 1.
A prototype device currently trialed in The Netherlands

There are a number of reasons for splitting the measuring and reporting functionality in this manner. The primary reason is practical in nature. The actual measurement devices can be designed such that they provide just the functionality required by the grid operator. However, the reporting functionality needs to operate also outside of the confines of a single house, otherwise it would be impossible to get the measurements to the back office. This does not mean that the actual device needs to operate under varying conditions, but rather that the communication should handle different operating conditions. For example, there may be certain scenarios where the meshed network approach does not work due to environmental circumstances (rural areas are one such example) and a different communication technology is required (such as a GPRS system for example). Rather than designing a completely new meter, the modular approach allows for easily changing to a different communication method when required. This design encourages competition, both among grid operators as well as suppliers of communication modules. Thus, future upgrades to newer technologies can be more cost-efficient because one only needs to upgrade part of the metering device.

Our case study[2] can help to better understand how technical and regulatory constraints influence each other. An important requirement of our system was cost-efficiency, which translates into using cheap, off-the-shelf components available from different suppliers. In turn, this makes it difficult to achieve reliability and resilience. We adopted the Nordic Semiconductor (n.d.) nRF905 transceiver for field testing. This RF transmitter chip is an affordable single-chip solution, capable of transmitting in one of 433, 868 or 915 MHz bands. Not all of these bands are available or well suited for use by smart-metering applications. Although the 915 MHz band could freely be used in the Americas, EU-regulations don't allow it in the European Union, where the 915 MHz band has been reserved for "land mobile" use (i.e. GSM, DECT, emergency services, etc.).

Other reasons lead to disregard the 433 MHz band. In the European Union, and indeed in The Netherlands, regulations governing the 433 MHz band are very liberal, allowing for many applications to make almost unrestricted use of this band. As a result this frequency band is crowded, with some applications transmitting for prolonged periods of time. There were concerns that this would lead to poor performance of the smart-metering system due to interference caused by such external influences. Eventually the 868 MHz was chosen not only because the other two bands were either unavailable or deemed unsuited, but because of the stricter regulations. In this frequency band the Nordic RF transmitter transmits on an approximately 200 kHz wide channel, centred around 868.4 MHz. This allows an effective data rate of at most 50 kbit/s, or just over 6 kB/s.

Another restriction that we always have from the RF chip is that it is required to know in advance the length of the packet that is to be received. This implies that all packets used in the network need to have the same length (i.e., the same number of bytes). In the case of the nRF905 chip, the maximum packet length is fixed at 32 bytes by the hardware. Thus, the protocol has only a very limited amount of space for carrying both protocol headers and data. For example, TCP/Internet Protocol (IP) adds 40 bytes of overhead and thus would not fit in the buffers used by the RF chip for the reception and transmission of packets.

Besides the RF communications chip, the metering device is also equipped with a microcon-troller which is used to perform regular measurements and run the routing protocol, as well as a variety of other tasks (coordination of external devices, controlling the RF communications chip, etc.). The specific microcontroller used in our prototype is the Microchip PIC16F887-I/PT[3], which offers 14 kB of ROM storage, and just 368 bytes of RAM. As discussed in Section 1.5.4, even the smallest IP suites typically require multiple tens of kilobytes of available ROM space, and several kilobytes of RAM. Which makes it impossible to run on typical smart-metering devices. In turn, this demands for lightweight routing protocol.

2.4 Stakeholders' requirements

In addition to the aforementioned requirements, smart-metering networks must also address the needs of a variety of stakeholders:

- The protocol should first and foremost adhere to the legal constraints, in order to be marketable. A critical limit is always placed on the maximum bandwidth consumed and portion of time that the device is allowed to transmit (i.e. the active duty cycle). In our case study, the metering device will attempt to report its own measurements at most four times per hour, thus any single node will only need to perform four short transmission bursts per hour. Therefor the routing protocol is the primary source of transmissions, and thus it is the routing protocol which should ensure that none of the participating metering devices exceed the stated duty cycle.
- The protocol should enable two-way communication with the utility's back office in order to facilitate the reporting of energy and reverse energy[4], as well as gas- and water-readings from the different meters to the utility's back office. Also the protocol should enable the delivery of notifications to the meters, e.g. to inform the meters and other connected devices of changes in prices of the delivered services. This will require the protocol to enable two-way communication between the utility's back office and the metering devices.
- The protocol should be self configuring as much as possible, and should not require expert knowledge to setup. Minimal preparations of the protocol for each device (for example setting an identifier for each device) are allowed, but should be performed beforehand on an off-site location or by the manufacturer. This is in order to facilitate the installation of the metering devices by unskilled labor. After installation of a metering device, the protocol setup should be completely automatic.

3. Smart-metering based on telecommunication networks

A number of possible technologies currently exist, which can be used for the communication between meters and a supplier's control centre. Notably there exist PLC, GPRS access points, GSM, telephone (land) lines, broadband internet access and RF (both licensed and unlicensed radio communications). In this section we briefly describe these various technologies, providing a summary of respective strengths and weaknesses.

3.1 Power-line communications

Power-line communications or power-line carrier (PLC) (Götz *et al.*, 2001), is a communication technology which aims to make use of pre-existing electrical infrastructure (i.e. the power grid) to establish a communications network.

The communication is relatively short range, typically only used to bridge the distance from the metering installation within a house to the nearest electrical substation. At each metering station a PLC modem is installed, which communicates with a single "data concentrator" at the substation. At the substation still a different communications technology such as GSM or a GPRS access point is used to finally transport the data to the back office.

The main advantage of PLC is obvious: no additional infrastructure needs to be set up, since it is possible to simply reuse the pre-existing electrical cabling that runs from the substation to each house as the communication medium. However, PLC does suffer from a number of drawbacks which have hindered its widespread adoption. The first problem is that PLC has a relatively short transmission range due to high attenuation caused by transformers and interference from electrical appliances (lowering the signal-to-noise ratio) (Deconinck, 2008; Olsen, 2005). Even very simple electrical equipment such as light dimmers used by consumers may cause significant interference. Another source of interference may come the actual wiring itself, which (especially in old neighbourhoods) may be of such poor quality as to render PLC unusable (Keemink and Roos, 2007). Further complications arise due to the fact that regulatory authorities often allot only very limited bandwidth for PLC applications. In the European Union, for example, the usage of PLC has been standardised, and only a very small spectrum has been reserved for utility communications. The result is that realistic communication bandwidths only reach up to about 4 kbit/s (Deconinck, 2008). The reason for these restrictions is to ensure that the devices communicating over PLC do not exceed electromagnetic interference (EMI) tolerance levels mandated by safety regulations.

One of the first large-scale roll-outs of smart meters using a PLC-based communications system was performed by the Italian Enel SpA (Vasconcelos, 2008). This was one of the first electrical companies in the European Union to completely replace its entire installation base of electricity meters with remotely operable devices. Enel SpA replaced around 30 million metering devices, requiring an update to their information and communication infrastructure (now based on PLC technology), at an estimated cost of €2 billion. The roll-out was expected to be very successful, as it was anticipated that the initial investment would have been earned back within five years. However, it remains unclear how often readouts occur, how much data is used and what level of remote interaction with the meters is possible. Smart-metering requires the ability to quickly communicate with meters in order to achieve good peak shaving. Enel SpA's system is better classified as an AMR or AMM type system.

A PLC type system like the one deployed by Enel SpA can be part of or directly connected to the electricity meter, drawing its power directly from the grid. This means that as long as there is power in the grid, the metering device will keep operating. Other systems would still be able to operate on reserve power and communicate the failure to the back office in the case of a power outage (e.g. using a battery backed or other type of uninterruptible power supply (UPS)). A PLC-based system however might not be able to inform the back office of the power failure. If the outage is caused for example by a physical disruption of the power lines, the PLC modem will not be able to maintain communications with either the back office or the data concentrator. A system which does not rely on any physical connections would be able to report the power outage to the electrical company, allowing for a quick and timely response. Also similar is the use of a dedicated endpoint to which each metering device connects in order to communicate with the back office. In the case of PLC technology this endpoint has a direct, shared, physical connection to the metering devices, similar to a large token-ring network. This means that the total available bandwidth has to be shared by all connected metering devices which are in range of the data concentrator. As mentioned before, the requirements on EMI (limiting the maximum transmission power) and attenuation issues mean that PLC communication bandwidths are very low. RF communications in the unlicensed spectrum suffers no such drawbacks and can communicate at much higher speeds, allowing for an increased throughput volume of data and a more real-time connection between the home and the back office.

3.2 Unlicensed RF communications

RF communications refers to a diverse set of wireless transmission technologies, standards and techniques. RF can operate both on licensed and unlicensed frequencies. The difference between licensed and unlicensed RF is merely a distinction on the regulatory level, with little implications on technical considerations. In licensed RF, frequency ranges are allocated to specific parties, which are granted for the exclusive use of their respective allocated bands. It is possible for frequency ranges to be allotted twice or to overlap for different usage, so long as it can be shown that this does not cause interference between the different applications. This could for example be the case when two applications would only be used in mutually-exclusive geographical locations, with limited broadcasting power.

RF communications in the context of smart metering are mostly applied in combination with some other communication means. This is because while RF communication is an attractive solution for short to medium range communications, it is not well suited to long-range communications, which would be needed to communicate to the back office. In such context, wireless RF communications may be used for communications among metering devices, while technologies such as GPRS or other broadband connections are used to communicate with the back office. RF components can be manufactured far cheaper than typical broadband modems or GSM/GPRS components due to the fact that they can be far simpler in design and do not require strict and extensive verification of operating modes. This because they are not designed to inter-operate with devices (such as mobile phones) and have a far lower radiating power. By using RF communications for local communications (possibly over multiple hops), setting up a small-scale local network, it is possible for many metering devices to share a single (internet) access point. It is this sharing of a single, more expensive, communication device which gives RF communications the possibility to achieve dramatic reductions in deployment and operating costs compared to typical smart-metering solutions. In Deconinck (2008) various technologies such as PLC, GSM, telephone (land) lines and RF are evaluated based on cost per meter. It is shown that, considering the hardware investment, RF is among the cheapest solutions, on par with the use of PLC and the re-use of pre-existing broadband connections.

Another advantage of RF communications is that it allows positioning all components of the smart-metering system out of harm's way. The RF module can be integrated into the metering device itself, whereas the external access point can be securely stored in an off-site enclosure (i.e. not on the subscriber's premises, but for example inside a nearby transformer housing). A RF module itself uses less power than other communication modules, such as those used in PLC or GPRS based systems.

Low power usage is of great importance in the large-scale roll-out of smart meters, as one of the goals of the smart grid is to achieve reduced overall power consumption. The communication latency of RF is lower than PLC, but also lower than that of GPRS when rolled out on a large-scale. Thus, RF communications are able to offer a more real-time connection with the back office, again a key requirement to the smart grid.

Possible disadvantages to RF communications are issues related to the use of certain frequency bands. The preferred solution would be to secure a dedicated frequency band for use in smart-metering applications. However, securing a frequency band for a particular use is a long and tedious process, involving many interested parties (e.g. governments, companies, non-governmental organisations, etc.), and it may not always be possible to secure a license for a particular frequency band. Since at present no such band has been allocated, currently most implementations of RF communications make use of the unlicensed bands.

The unlicensed spectrum is in principle free-for-all. However, there are some rules and regulations set forth by various standards organisations (ITU, European Telecommunications Standards Institute (ETSI), Internet Engineering Task Force (IETF)), which govern the use of these frequency bands. Typical restrictions include: setting limits on the amount of time that may be spent transmitting a signal (i.e. a transmitter has a limited duty cycle); limiting the effective radiated power (ERP) on which the signal may be emitted; and placing limits on the amount of bandwidth that may be used. However, these guidelines may vary greatly between legislative areas, and usually apply only to each individual device. Also, these restrictions do not govern how any two devices should coordinate their efforts to share the medium, and in fact devices are free to send at any time so long as they respect the aforementioned restrictions. This means that there always remains the possibility for interference with other devices, if for example two devices adopt a policy whereby they start transmitting without first performing any carrier sensing.

There are many wireless standards which are designed to operate in the unlicensed transmission bands (IEEE 802.15.4 (IEEE Communication Society, 2003), ZigBee (Alliance, 2005), ISA100.11a (ISA Standard, 2009), WirelessHART (Song *et al.*, 2008), RuBee (IEEE Communication Society, 2006), etc.), of which ZigBee is likely the most well known. The ZigBee standard is designed to operate in the unlicensed 2.4 GHz (world wide), 915 MHz (Americas) and 868 MHz (Europe) industrial, scientific and medical (ISM) bands. The ZigBee standard offers many different features and operating modes, allowing great control over the configuration of a node. It is possible to choose between carrier sensing, multiple access/collision avoidance (CSMA/CA) and guaranteed time slots operating modes; to decide whether or not devices should form a beacon-enabled network (where nodes periodically announce their presence to the network); and what type of network should be constructed. ZigBee supports constructing different network topologies, such as star and tree-like networks, as well as generic mesh networks. However, whichever network topology is constructed it is always required to have a single master device. The routing protocols used in ZigBee are based on the well-known *ad hoc* on-demand distance vector (AODV) routing (Perkins *et al.*, 2003). However, this abundance of features comes at a price. Eventhough the radio modules themselves are (relatively) inexpensive, the ZigBee qualification process involves a full validation of the requirements of the physical layer, driving up costs (Yes and Adopter, n.d.).

3.3 Licensed RF communications

The GSM standard was originally developed by the ETSI late in the 1980s. Since first publishing of the standard in 1990 improvements and new standards based on the original GSM specification have been released by different parties. Some such new specifications include standards such as general packet radio service (GPRS), CDMA450 (a CDMA2000 type technology), universal mobile telecommunications system (UMTS) and 3GPP long term evolution (LTE)/advanced LTE. These technologies evolved in order to offer greater bandwidth and lower latencies. This development is predominantly driven by consumer-level applications such as SMS, MMS and mobile internet access. In the context of smart-metering applications there are a number of ways in which these technologies can be employed. The simplest and most straight-forward way is to simply equip each and every metering device with its own dedicated transmitter and receiver. In this way a direct communication between the meter and the central system can be established relatively simply (De Craemer and Deconinck, 2010). Another possibility, which has been brought up previously in our discussion of PLC, is to have only a single GSM-type device, providing a shared connection to which any number of metering devices may connect.

The main advantage of GSM-type connections is ease-of-use and general availability. These types of connections are in common use in the consumer market (e.g. cell phones, smart phones, and various other devices such as internet dongles.). Because of the widespread use of mobile phones, GSM networks have excellent coverage in most parts of the world, with the exception of rural areas (Deconinck, 2008; Keemink and Roos, 2007). Also the components required to connect to GSM networks are readily available and well tested. The downside of this approach when used to set up a direct line of communication is that the communication modules are still relatively expensive compared to alternative communications modules such as those for PLC or RF transmissions. This makes GSM-type connections too expensive to be used in a large-scale roll-out of smart-metering installations. Currently GPRS is the preferred technology, mostly due to the smaller scale deployments of (often) individual connections. Additionally, usage of the service usually requires a subscription to be acquired from a telecommunications company, which adds extra recurring costs (Zhu and Pecen, 2008). It is worth noting that these recurring costs need not be fixed, as the price plan is determined by the telecommunications company. However, this dependency is not very attractive for a grid operator with millions of installed devices. Also, although the reception may be characterised as “excellent”, reception is usually measured in above-ground situations, where people and mobile phones are mostly located. However, the reception in cellars and alike (where the meters are often located) is not guaranteed (Deconinck, 2008).

A further consideration regarding the coverage area of GSM networks is the target technology. As mentioned before there are many newer technologies which are based on GSM such as GPRS, UMTS, LTE, to mention just a few. These technologies offer bandwidths that are in excess of what would be needed by smart grids, but require high-cost components. Moreover, newer technologies take time to adopt and implement, and hence the expected coverage for technologies such as UMTS and LTE can be considerably less than for older technologies such as SMS or GPRS.

Further there may be an issue with the time frame for which any such particular technology will be maintained by telecommunications companies. Although SMS has been in heavy use for a long time already, and presumably will be for many years to come, the longevity of other such technologies is yet to be seen. As new standards are ratified in ever quicker succession it is not unthinkable that some of these standards may be decommissioned after only a few years. Choosing such a standard as the basis for a system designed to last for at least 15 years (Deconinck, 2008) could mean costly replacement equipment, which needs to be issued long before the originally projected end-of-life date of the smart-metering device. It should be noted however that in the case of a large-scale roll-out of smart-metering systems, the large install base may prevent the system from being decommissioned, even if the smart-metering network were to become its sole user. Costs however may increase dramatically in this case, as the electrical company will have to bear the costs for maintaining the network on its own.

Ultimately, each of the different specific technology has its own strengths and weaknesses. For example, SMS is very popular and will in all likelihood remain so for quite some time. However, this same popularity also presents a weakness. Analysis of the reliability of the SMS service showed that under normal circumstances the average latency of SMS messages increased from several minutes (which is already quite high) to an hour during New Year's eve (Meng *et al.*, 2007). The same study also showed the nominal delivery rate for SMS messages to be only about 95 percent. Both high latencies (minutes) and high failure rates (over 5 percent) do not meet the requirements of a smart-metering system, which needs to be able to react and respond quickly to events in the network.

Although nearly a quarter of smart-metering installations in China appear to be based on some form of PLC, those installations only use PLC to construct a form of local communication network, i.e. to construct a local network which communicates with a data concentrator or similar access point. In order to actually communicate the data to the back office ("remote communication") most installations (70 percent of all metering installations) still rely on a GPRS connection (Liu *et al.*, 2009).

However, there are still ample alternative smart-metering installations in use and being designed in China, as well as in other countries. We note a few pure GSM/GPRS based systems independently developed in different countries (Mahmood *et al.*, 2008; Yujin *et al.*, 2010; Al-Omary *et al.*, 2011). These are all quite similar to each other in terms of overall design, although they differ greatly in capabilities and implementation details. Here "pure" means that in these systems each individual metering device is equipped with a dedicated GPRS module for connecting to back office. The GPRS network is then used to directly send and receive data and commands to and from the metering device or data centre. This is arguably a less efficient design than the previously discussed design in which many metering devices share a single GPRS module through a PLC or other type of connection. Because each metering device is equipped with a GPRS module there is a considerable waste of resources, since each (individual) metering device only requires only a small amount of bandwidth to upload the collected data and download any pending commands, usually far less than a typical GPRS connection offers (10-100 kbit/s). Furthermore, there can be some concerns about the number of metering devices that can be expected to use the GPRS network at any one time, leading to congestion of the network (as was observed in Meng *et al.* (2007)), unless some form of coordination is used between the metering devices, or a form of back office initiated polling.

3.4 Telephone (land) lines and (coaxial) cable

Telephone land-lines, or the public switched telephone network (PSTN), refers to the normal telephone line present in most households. There a number of ways to make use of the presence of a land-line such as dial-up internet access, ISDN or a broadband connection provided by one of the various DSL-type technologies. These communication technologies provide a means to establish a two-way, point-to-point (internet) connection between the metering device and the back office. Although the use of a pre-existing communications network for communication in the smart grid might seem natural, a number of shortcomings make them a less than ideal choice.

An initial consideration is the fact that the availability of a telephone line or other suitable communication cable at each meter is a requirement that cannot be always satisfied, especially in developing countries (Khalifa *et al.*, 2010). Even in the developed world more and more people are foregoing a dedicated land-line, favouring a mobile connection as a means to save money. This is made possible thanks to advancements in mobile telephony and mobile internet.

Next, in the case of small-band communication over telephone lines (for example through a dial-up or ISDN type connection) it is not an option to keep the communications line open at all times (the consumer may themselves wish to make a phone call or connect to the internet). Hence it is necessary to only make a connection with the back office at certain pre-set times, either scheduled or when a report is due. There are two major downsides to this. First this means that it will not be possible for the metering company to communicate with the metering devices at any given moment, instead it will be necessary to wait until the metering device initiates communication. Second it means that the device will have to initiate a connection by dialling in. This takes a significant amount of time (again reducing the real-time nature of the system), as well as incurring additional costs associated with the use of the telephone or ISDN connection. Even if this usage is not billed to the subscriber directly, the metering company will need to be billed for the use of the line, which will ultimately be reflected in the pricing plan for the subscriber. Additionally, there is still the issue of interference, with either the metering device or the consumer finding the line in use when access is required.

In the case of a broadband connection, dialling typically has to be done only once, and thereafter the connection can typically remain in an always-on state without issue. This is because these types of connections employ a multiplexing technique which allows them to share the phone line or coaxial cable (frequently used to transmit radio and television signals, too) without interfering with normal operations. However, in spite of this the use of a pre-existing broadband connection, either over a phone land-line using a DSL-type technology or over coaxial cabling, is still impeded by concerns about the sharing of a communication line with the subscriber. Again no such connection may be present.

Even though the broadband penetration in Western Europe is among the highest in the world, it is still not sufficiently prevalent to assume that a broadband connection will be available in every household or for every metering installation. Eeven in countries with high levels of broadband penetration, adoption is still quite low among the elderly. This is especially true for countries outside of the European Union or in rural areas where it may be difficult to even obtain a broadband subscription. Hence this would entail setting up dedicated broadband connections in the cases where none is present yet. If a broadband connection is already setup, concerns may be raised about the sharing of the connection with the subscriber. For example, since the connection is not owned by the metering company, it can exert no control over it. If the subscriber at any time, for any reason, decides to switch internet service provider (ISP) or even cancel his subscription entirely, the connection to the metering device would be disrupted for an undefined period. This again is unacceptable for a service which must ensure a certain level of reliability. Forcing any particular broadband connection upon subscribers is neither a suitable option, and may even interfere with an existing broadband connection.

A final hurdle is the fact that, regardless of the choice of the above technologies, a connection needs to be established between the metering device and the broadband modem, which is often not in the same place as the metering device (Deconinck, 2008). This would again entail the use of a third means of data transport.

As noted in Khalifa *et al.* (2010), using the PSTN for remote management and smart-metering purposes is an old proposal. A working system is described in Lee *et al.* (1996) as far back as 1996. This system supports reading of up to three utility meters (presumably a gas-, water- and electricity-meter). Even though the idea to make use of the existing telephone connection on a subscriber's premises is a relatively old-fashioned idea, generally associated with various issues and introducing (some) discomfort for the subscriber. However, this has not stopped people from developing new systems based on this technique. We note numerous recent efforts (Kim, 2006; Shen and Dai, 2007; Tian *et al.*, 2007) in China alone. Unfortunately, due to pay-wall restrictions, we could not evaluate these systems. A brief description for one of the new systems is given in Khalifa *et al.* (2010). From this description we can conclude that due to the use of dual-tone multi-frequency (DTMF) signalling for transmission of metering data and commands, the telephone line will still be tied up for the duration of the communication.

3.5 Remarks about infrastructure based approaches

In this section we have presented some of the most common technologies used to implement smart-metering systems, highlighting the strengths and weaknesses for each technology. We have seen that most implementations take a dualistic approach, combining two or more technologies to implement a smart-metering system. This is done in order to improve the quality or reliability of the communications system and to reduce the cost of implementing, installing and operating the communications system. We have seen that most systems tend to use a GSM/GPRS based solution at the data concentrator. This is because this currently seems the most flexible solution. It is possible to use different technologies such as PLC or a broad-band modem at the data concentrator in different metering installations, however it requires the least amount of (testing and development) effort to implement a uniform solution in all deployments.

4. Smart-metering based on mesh networks

Routing protocols can be broadly classified in two categories: precomputed routing vs on-demand routing (Zou and Ramamurthy, 2002). In a precomputed routing protocol (proactive routing), routing tables are constructed before they are needed. That is the nodes in the network are always working to maintain an up-to-date view of the network or their immediate neighbourhood, even when the node would otherwise be idle. Some proactive routing protocols specifically select such idle periods to perform updates to the routing tables, so as not to interfere with the normal operations of the node. In an on-demand routing protocol on the other hand, routing information is not gathered until needed, i.e. when a packet from an upper or, possibly, lower layer is received and needs to be forwarded. The related periodical and event-driven update mechanisms describe at what moment a node publishes routing information to the network. Some protocols are continually communicating routing information in order to keep the view of the network current (and hence are always consuming a portion of the available bandwidth), whereas other protocols attempt to reduce the amount of bandwidth consumed by only announcing detected changes in the network's topology (e.g. links dropping, or new nodes joining the network).

From our literature study we can conclude that this division in proactive and reactive routing protocols holds true in the field of RF communications for smart-metering purposes, too. Routing protocols used in smart metering may range from the very simple ALOHA-like (Abramson, 1970) approaches such as Lichtensteiger *et al.* (2010), to intricately complex solutions such as Hardy and Gafen (2008b), which uses an implementation of collaborative transmission as described in Krohn *et al.* (2007). Next we discuss the most relevant approaches.

4.1 Gridstream

Gridstream™ is a commercial, complete, end-to-end, smart-metering solution developed by Landis + Gyr (n.d.). It is complete in the sense that Gridstream is a full suite of products, including metering hardware, a communications system, a software package, and more. The Gridstream Communications RF communications module was recently evaluated by Lichtensteiger *et al.* (2010), via a simulation based on the OMNeT++ simulator. It was found that the system was a reliable solution, able to achieve a greater than 99.8 percent success rate in obtaining daily meter readings, for a large population of electricity meter endpoints in a utility's service area, at a read-out interval of 7.5 min.

The evaluated Gridstream system uses a time-synchronized slotted ALOHA scheme. This is a well-known extension to the standard ALOHA broadcasting scheme, which yields a substantial improvement to the performance of the protocol. However, the protocol remains based on ALOHA, and the maximum theoretical throughput remains low, at only 36.8 percent of optimal throughput. A clever way to improve the throughput of the network, which is employed by the Gridstream system, is by noting that the throughput is calculated per communications channel. Thus, by increasing the number of available communications channels, the number of collisions on any one channel is reduced, thus yielding a better overall throughput. In this case the system utilises up to 240 discrete channels, each of which has a 100 kHz bandwidth, for a total bandwidth of 2.4 MHz. Each node then uses a frequency hopping sequence which is determined according to the nodes network identity.

Gridstream is targeted for use in the USA, where it can freely use the ISM bands. In the European Union, regulations restrict the available bandwidth, making Gridstream a less suitable solution. Another downside to the frequency hopping approach is that the nodes must coordinate the selected frequency among all nodes participating in a transmission. This complicates the design of the routing protocol considerably, since care must be taken that nodes in a forwarding chain can communicate with both the up stream and down stream nodes. Further this scheme requires more advanced (and hence, more expensive) transmission and reception hardware, capable of rapidly switching between many different communication channels.

The Gridstream system uses a geographical-routing protocol. Although Lichtensteiger *et al.* (2010) states that this ensures that the nodes communicate over the minimum number of hops, in fact no such guarantee can be given. Using a geographical-routing protocol ensures that nodes communicate over the shortest (physical) distance, but there is no guarantee that this indeed causes the nodes to find an optimal route in terms of number of hops, low latency, high throughput, or other criteria. Consider for example the case where in the direction of the data concentrator there is an area of high attenuation, severely limiting the transmission distance. This might be the case for example if there are (one or more) backyards in between the transmitting node and the destination. This means that both the distance that can be covered per hop, as well as the reliability of the link over that hop, is reduced greatly. In this case it might be more advantageous to use a communication path with lower attenuation, which allows covering a greater distance per hop, at a higher level of reliability. In fairness the effect of attenuation is lessened when transmitting with high transmission power, but again this is not always possible (e.g. either due to hardware restrictions, or due to regulations).

Additionally, due to the nature of , each node needs some way to know its own position (geographical coordinates, i.e. latitude and longitude), as well as the position of the target node. This implies either adding a GPS module, which increases the cost of each metering device and seems wasteful in a system which will spend its working life in a static location, or require extra work on the part of the installation personnel during commissioning. Both solutions are more costly, the former requiring additional hardware and the latter requiring more manual labor, with the added possibility for human error and associated rectification costs.

4.2 Routing protocol for low power and lossy networks

The routing protocol for low power and lossy networks (RPL) is a newly developed protocol, destined for use in IPv6-enabled low-power wireless personal-area networks (i.e. 6lowpan (Hui and Culler, 2008) environments). It has been developed by the IETF's routing over low power and lossy networks (ROLL) working group, and is designed to deal with establishing and maintaining connectivity between nodes in low power and lossy networks (LLNs) (Winter *et al.*, 2010). RPL is a gradient-routing protocol, and precomputes the routing information for the network only when necessary (i.e. it is a reactive protocol). RPL builds a special type of tree to capture routing information known as a destination oriented directed acyclic graph (DODAG). The DODAG for the entire network is constructed from a single starting point which is the central node of the network. During the construction of the DODAG each node is assigned a weighting value, which is later used to make routing decisions. When a packet needs to be routed, the node calculates the difference in weighting value between it and each potential next-hop neighbour node, and forwards the packet to the neighbour with the largest gradient. The calculation of weighting values happens according to a weighting function decided upon by the central node.

As the protocol has not (specifically) been designed for use in smart-metering scenarios, it is thus not immediately obvious that RPL is suitable for use in smart-metering deployments. A recent study (Kulkarni *et al.*, 2011) highlights some of the potential issues with using RPL as the routing protocol in smart-metering (mesh) networks, suggests a number of improvements to the protocol in order to adapt to the different circumstances in smart-metering networks, and provides a performance evaluation of these enhancements. The suggested modifications are designed to improve the protocol's reactions to link loss, making it more robust for use in smart-metering networks which require a higher degree of reliability. The modifications extend RPL with a hybrid periodic/event-driven update scheme. Routing information is collected both upon detecting a loss of connectivity, as well as by periodically scanning for nearby data concentrators on alternate channels. This information is then stored so that a node can immediately switch to a secondary data concentrator without going through the process of route construction.

RPL is a fairly complex protocol, relying on large data structures to calculate routing information. The nodes must have sufficient storage capacity and computational power to construct and maintain the DODAGs. RPL performs regular probes for new routes, which could interfere with on-going transmissions of nearby nodes. Scanning for a new data concentrator is only initiated when necessary. RPL does not coordinate node transmissions, each node simply attempts transmission and retries as necessary.

A bigger difference is in the way routing is ultimately performed. RPL is a typical packet-based routing protocol, where routing information for the network is present in all nodes. When a packet is received and needs to be forwarded, each node inspects its own routing table to determine which node the packet should be sent to. In a source-routing protocol the amount of state that is required to be kept in each node is significantly less. With the proposed changes RPL, is capable of handling multiple data concentrators in the same network (thus improving redundancy).

4.3 IEC synchronized wireless mesh network

The Israel Electric Company is also investing in improving its infrastructure, with the goal to deploy an AMR system, as the first step towards setting up a full smart-metering network. A case study was commissioned to investigate the feasibility of using a wireless mesh network based on RF communications (Hardy and Gafen, 2008b). A new routing protocol (referred to hereafter as the synchronized communication protocol (SCP)) was developed and subsequently deployed in a field experiment. This showed that both the protocol and hardware functioned "beyond expectations".

The routing protocol is a time-division multiple access (TDMA) type protocol. Time is divided in slices, sufficiently large to allow any node in the network to communicate with the data concentrator, taking into account the time required to forward each "message" over a pre-specified maximum number hops. For routing itself, SCP relies only on flooding. Normally flooding is not considered as a viable communication technique, or indeed a routing protocol at all. However, in SCP transmissions rely on a special feature of the hardware, which makes flooding practical.

By making use of the principle of collaborative transmission (Krohn *et al.*, 2007; Ringwald and Romer, 2005), multiple nodes can be transmitting (forwarding) the same message simultaneously. This is done by synchronising the transmitters of all nodes on the bit level, so that all nodes are simultaneously sending the same radio wave. This is possible by the assumption that the communication channel has an "OR"-characteristic (Ringwald and Romer, 2005). This synchronisation is done at the physical layer because of the strict requirements on synchronisation. Even a small deviation can cause severe interfere at the receiving nodes, leading to reception failure. Because at any given instance all nodes are cooperating to facilitate the communication between a single node (that node whose turn it is to report to the data concentrator), the protocol in fact lacks routing tables (Hardy and Gafen, 2008a), on the assumption that nodes only need to communicate with a single pre-determined destination (e.g. the data concentrator).

The downside to the approach taken by SCP is that it requires a high degree of cooperation between the hardware and the protocol. In particular the extremely tight synchronisation required by the protocol, coupled with the fact that this synchronisation needs to be implemented at the physical layer in order to be effective, restricts the choice of hardware. Thus, in fact the reliance on the specific capabilities of the physical layer drives up the cost for the hardware.

A final distinction that can be made is the difference in who initiates the communication when a meter reading is to be taken. In SCP, meter readings are initiated by the data concentrator, requiring to poll every metering device in sequence. Because of this, each meter reading requires both more bandwidth and more time than needed. In Hardy and Gafen (2008b) no mention is made of any attempt to limit the number of transmissions. Deploying the SCP system in the European Union could lead to regulatory limitations on the use of bandwidth being exceeded when a large amount of metering devices needs to be read. The protocol requires more messages to be sent for each meter reading, and the whole network participates in the flooding of each message. Although this does rely on specifics of the amount of traffic, number of nodes, meter-readout frequency and other parameters which are not given, this is a scenario that needs to be taken into account before a large-scale international roll-out can be considered.

4.4 Mesh networks based on ZigBee

Besides solutions being developed in-house (Hardy and Gafen, 2008b; Landis + Gyr, n.d.) or modifications to existing systems (Kulkarni *et al.*, 2011), there are also many smart-metering systems which aim to use a well established, standardised platform, such as ZigBee. ZigBee is one of the most popular standards for wireless RF communications, and has a large backing in industry. We have previously discussed ZigBee in Section 1.3.2, and now discuss two example smart-metering implementations based on ZigBee technology, hereafter referred to as system A (Luan *et al.*, 2009) and system B (Zhu and Pecen, 2008), respectively. Both present a fully working system which has been developed and evaluated in the lab, using commercially available off-the-shelf (COTS) components.

Both systems make use of ZigBee's capabilities to form mesh topologies, appointing the ZigBee-coordinator device as the data concentrator. System A splits the metering device into two distinct components. It is assumed that the meter readings which are to be reported to the data concentrator for transmission to the back office are made available by one or more measurement devices. These then communicate with the main module of the metering system, which leverages a ZigBee transceiver-module to transmit data to and from the data concentrator. Each metering device synchronises its internal time to that of the data concentrator when it joins the network. Once synchronized, each metering device periodically transmits its meter readings. It is also possible to request an immediate reading from any meter in the network.

System B also proposes a split between the devices performing the meter readings and the device responsible for establishing network connectivity, but does so for other reasons. It is suggested that converter devices be placed on existing metering installations as an upgrade. This would enable existing metering infrastructure, such as electromechanical electrical meters, to be easily incorporated in an AMR system. Although this does not constitute a smart-metering system, it is however also possible to connect modern meter-reading devices to the networking device, so it can be employed in a true smart-metering system, too. System B uses the Texas Instruments Z-Stack ZigBee (Texas Instruments, n.d.) implementation as its basis. It is not entirely clear whether the routing protocol used in system B is one of those included in the Texas Instruments Z-Stack implementation by default or a modification thereof, although there are indications that the latter is the case. From the condensed protocol description given we can gather that it is similar in spirit to RPL (Section 1.4.2). That is to say the protocol precomputes routing information by periodic updates, and actual routing occurs along a gradient. The updates occur in the form of broadcasts of node information to all neighbours, which include the node's distances in hops to the data concentrator. This is later used during routing to select a next-hop destination. One potential issue with the protocol for use in smart metering is that when a node is reporting a meter reading, it keeps retransmitting this reading until they it receives an acknowledgement. This means that it is easily possible for a single node to exceed the regulatory limits for use of bandwidth, not to mention to interfere with the operation of the rest of the network. This system, like system A, periodically sends meter readings on the node's initiative (i.e. there is no polling done by the data concentrator). It remains unclear if and how this timing is coordinated among nodes.

Both systems demonstrate the ease with which a ZigBee based communications system can be build. However, both systems demonstrate some of the problems that come with relying on ready-built ZigBee technology. System A relies on the default ZigBee routing protocol to perform and scale well when deployed in a large-scale smart-metering roll-out, which does not necessarily hold true. System B does demonstrate that it is possible to change the routing protocol, but this obviously requires using both hardware and software which support replacing the routing layer. Although Texas Instruments Z-Stack appears to offer a ZigBee software stack which allows modifications to the software, this may not be compatible with all ZigBee hardware-modules. Further, system B quotes a $5 (USD) price for the ZigBee module alone, which will drive up the price for a complete metering device by at least that amount.

4.5 Source routing

Resource constrained wireless mesh networks often use a routing protocol belonging to a class of routing protocols known as source-routing protocols. Perhaps the most well known and studied of the source-routing protocols is dynamic source routing (DSR) (Johnson and Maltz, 1996; Johnson *et al.*, 2001). Because DSR is a well-known routing protocol, we will use it to briefly explain the concept of source routing.

The main principle and innovation of source routing is the manner in which the route (or path) which a packet should follow through the network is specified. This method of specifying the route of a packet has long been known, and is even available in the IP as the (optional) strict source and record route (SSRR) or loose source and record route (LSRR) options (Postel, 1981a). DSR adapts this technique by making it the primary means of routing, extending it with mechanisms to discover the ID of the destination node and reactions to loss of connectivity, all operating in an on-demand manner[2].

In DSR (or any source-routing protocol) the sending node needs to have all the routing information required to reach the intended recipient node. There are two basic ways in which a routing protocol can ensure that the sending node has this information. The first is by proactively sharing routing information about the whole network among all nodes. This would effectively mean that each node in the network could reconstruct – or devise an equivalent to – any given route, by looking at the source and destination addresses of a packet, and hence provides no apparent advantage over traditional routing. The second approach is to attempt to gather only that information about the network which is required to reach the target node. This can be done by querying neighbouring nodes for routing information to the destination. If necessary the neighbouring nodes propagate the query up in the network, until eventually the destination node is reached. DSR takes the latter approach, maintaining radio silence until there is data to transmit, at which time a search for the destination is started if no route is yet known.

In order to ensure error-free delivery of packets, some form of acknowledgement is needed in source routing, too. DSR uses a per hop acknowledgement scheme, where each hop is responsible for ensuring that the packet has been forwarded correctly. To prevent having to search for a route every time a packet needs to be transmitted, some way to remember previously discovered routes is required. Both protocols tackle this in a similar way. Instead of maintaining a routing table, nodes maintain a route cache. In this cache the nodes maintain a look-up table of previously used routes. In DSR there many ways specified in which a node can add or remove routes from the cache (e.g. when a node “overhears” a nearby packet transmission, it may include (part of) the route in that packet’s own route cache).

DSR has many more features designed to improve the resilience and performance of the protocol, especially in the later revisions of the protocol (Johnson *et al.*, 2001). Ultimately DSR is a highly complex protocol, capable of providing full internet connectivity to nodes in the mesh network. However, this complexity no doubt comes at significant cost in terms of the amount of work (man-power) involved in implementing and testing the protocol on new wireless devices, the size of the final executable code (requiring more ROM storage) and the amount of RAM required during operation. Although this enables wireless devices to more easily inter-operate with hosts on larger scale networks, in the case of smart metering or even AMR or AMM this additional functionality is neither required nor desired. Smart meters need only to communicate with their controlling station (the data concentrator), which is a single host operated by the utility company, and as we have outlined in Section 1.5.4, these resources are scarce in wireless nodes in general, and in a commercial smart-metering solution especially. In Section 1.2.3 we detailed the very stringent hardware constraints of an example system. In fact, the routing protocol in this system is based on source-routing, and has been optimised to make the most of what limited hardware resources will be available in low-cost smart-metering devices[2].

4.6 Remarks about mesh network approaches

We have discussed a number of smart-metering systems based on mesh networks communicating using RF-technology. We have seen that both very simple and very complex solutions have been deployed successfully, either in field tests, in commercial deployments or both. Given that the complexity of the system seems to have little impact on the effectiveness and reliability of the system, it seems obvious to choose the simplest solution. Complexity often comes at a cost, either as an initial investment in the construction of the system or the cost of its constituent components, or during maintenance or extending the functionality of the system.

There is a great deal of similarity in all of the systems discussed. This is to be expected of course, and the difference is in the details. Many of the presented systems have been designed for a singular purpose, that is to say they have been designed for deployment by a single company or in a single country. This can be a potential impediment to the widespread adoption of a smart-metering products when attempting to market a product on a multinational scale. Great care must be taken on many levels of product development, ranging from ensuring that the selected hardware can operate in the allotted frequency bands, to ensuring that the software observes the rules with respect to the usage of the wireless spectrum.

Finally we have seen that although it is possible to use standardised hardware and software such as IEEE 802.15.4-compliant transceivers and the ZigBee software stack, these too bring with them a set of considerations complicating any design. In fact many solutions in the field or under investigation are derived from the approaches reviewed above (Reid, 2009; Gharavi, 2011; Iwao *et al.*, 2010; Ghassemi and Bavarian, 2010).

5. Standardisation efforts

There is a growing interest in the development and deployment of smart-metering systems in order to realise what is known as the "smart grid". One of the key contributing requirements to the widespread adoption of smart-metering installations and the takeoff of the smart grid is the development of industry-wide standards. This is achieved most effectively when backed by government initiatives. In the following we discuss the on-going standardisation efforts world wide, in the European Union and nationally in The Netherlands. We also discuss some of the other and related standardisation efforts, such as ZigBee and the drive to bring TCP/IP networking and Internet connectivity into all devices, even smart-metering devices.

5.1 Worldwide trends

Worldwide there is a vast difference in the level of on-going and planned standardisation. In the USA for example, until now "few attempts have been made to develop a written specification consummated with standards agreed upon by members of both coteries, due to lack of government support" (Bennett and Highfill, 2008). In contrast in the European Union there is, and has been for some time now, an on-going process of government incited standardisation, both on a Union-wide level as well as on the national level.

In the USA there has recently been a push from the government to explore and develop interoperability standards for smart-grid systems. Currently the US National Institute of Standards and Technology (NIST) is working on a framework of smart-grid standards, with the first phase (a roadmap towards the specifications of a smart-grid interoperability standard) now completed (Rohjans *et al.*, 2010). However, the lack of a comprehensive set of standards has not prevented electrical companies from developing and selling smart-metering systems. Gridstream is but one such example of a commercial offering of a smart-metering system. Interestingly there are also non-utility companies (such as Google, Microsoft and Cisco) which have entered the smart-metering market. The move by industry to develop smart-metering system shows that there is a growing market for these systems. However, the need for standardisation with rigid set of requirements became apparent recently in New Zealand, where a three-year report on the country's smart metering revealed numerous issue with the installed metering devices. The lack of agreed-upon standards was identified as the main cause for the failure of the smart-metering program (Yuan Xu *et al.*, 2010).

The situation in the rest of the Americas is less clear. Brazil participates in the work of the International Electrotechnical Commission (IEC), yet it is not clear whether this has, or ultimately will, lead to the deployment of smart meters in Brazil. We do not know of any current interest in developing a smart grid in the rest of South America. The situation seems similar in much of the developing world, even though there is the possibility to effectively deploy smart-metering systems even in developing countries, with the benefits outweighing the costs of conventional meter installations (Rámila and Rudnick, 2009).

Not only the Americas and European countries are seeking to build a smart grid. In Asia many countries are looking to develop a smart-metering infrastructure. In South Korea for example, authorities have initiated a long term three-phase plan to have a fully operational smart-grid infrastructure by 2030. However, there does not seem to be any form of standardisation being included, with the project focusing instead on developing immediately applicable technologies (Uslar *et al.*, 2010). In China, too, a large-scale effort to develop a next generation electricity distribution system was recently begun, under the "Strengthened Smart Grid" plan. In contrast however to the South Korean approach, the Chinese approach relies on the development of smart-metering standards. This work is being carried out by the State Grid Corporation of China (SGCC), taking into account, and cooperating with, many on-going standardisation efforts, both nationally (NIST in the USA, METI in Japan and several German initiatives) and internationally (IEEE, IEC, ETSI, ITU) (Rohjans *et al.*, 2010; Yuan Xu *et al.*, 2010; Uslar *et al.*, 2010).

The standardisation work currently underway by the IEC seems to be the most comprehensive attempt at defining a complete set of standards covering all aspects of the smart grid. The collective work of the IEC on the topic is known as the seamless integration architecture (SIA) and encompasses a large set of standardisation efforts for individual components of the smart grid. This ranges from defining the way in which information on customers and usage is exchanged (IEC 61970/61968: common information model (CIM)) to the actual interfacing standard between different smart-metering devices (IEC 60870: communication and transport protocols). The only current disadvantage is that the SIA is still a work-in-progress, hindering its widespread adoption.

5.2 European Union regulatory efforts

In the European Union the situation is very similar to the global picture. Where the global picture showed that both on a worldwide scale as well as on the international levels different groups are working on standards, the standardisation efforts in the European Union are also on-going on both a national and on a union-wide scale. Therefore, we will restrict to giving just a brief conceptual overview here.

European Union-wide standardisation efforts are initiated by decree of the European Parliament, under advisory of the European Commission. The most important of these is Directive 2006/32/EC of the European Parliament (UNION, 2009). Although this directive does not mandate the deployment of smart-metering systems directly, it is of great influence on the decision process of member states, with most states considering smart metering to be the best suited method to comply with the requirements of the directive (Vasconcelos, 2008). In this way, Directive 2006/32/EC is of direct influence on the behaviour and decision making process of the member states, guiding them into the development of smart-metering solutions. However, it can also be construed as a reaction to already on-going smart-metering deployments (Italy) and standardisation initiatives (Germany). In a similar vein there are efforts underway to standardise smart-metering interfaces in order to facilitate the development of smart grids (Mandate CEN/CENELEC M/441 (European Commission, 2009)). The general objective of this mandate is to create European standards that will enable interoperability of utility meters. However, the vast majority of these standardisation efforts are focusing on PLC and GPRS technologies and protocols.

5.3 National regulatory efforts: The Netherlands

The Netherlands, being a member state to the European Union, has to comply with European laws and mandates. It is however up to each individual member state to determine the best way to fulfil these requirements. Further it is also always possible for member states to strengthen any decision made by the European Parliament. In The Netherlands this has given rise to the Dutch NTA-8130 Directive (Nederlands Normalisatie-instituut, 2007) and to the DSMR document (KEMA Consulting, 2008). These specify the specific functionality which a smart-metering device should provide. This is foremost a practical description of the requirements most smart meters support, such as the ability to report meter readings to the utility company on demand, and without human intervention, the ability to remotely connect or disconnect customers from the electrical grid, etc. How metering devices should interconnect is specified in Mandate CEN/CENELEC M/441 and IEC 60870.

5.4 Smart-metering communications over TCP/IP

There is ever present drive in industry as well as from academia to bring IP technologies (Postel, 1981a) to wireless sensor networks. However, pure IP communications are not often used because of the lack of guarantees this protocol offers. Therefore, in order to make reliable communications the TCP protocol (Postel, 1981b) is used on top of the IP protocol. Yet, typical implementations of the TCP/IP protocol suite tend to be large and complex. Both the size of the executable code as well as the amount of memory required often reaches into the hundreds of kilobytes. These large quantities of memory (both ROM and RAM) are simply not available to small embedded systems. This makes it infeasible to directly make use of existing TCP implementations such as the popular Berkeley BSD TCP/IP implementation (McKusick *et al.*, 1996) or its derivatives (Shelby *et al.*, 2003; Chiang, 2005; Dunkels, 2005). Therefore, a number of solutions and implementations have been proposed to bring IP connectivity to the world of small, embedded, wireless devices and the resource constricted environments in which they operate (Chiang, 2005; Dunkels, 2005; Ploeg, 2006). There even exist proposals to enable full IPv6 accessibility on small embedded devices. However, as indicated in Ploeg (2006) these implementation often still require multiple tens of kilobytes of ROM and, more importantly, RAM. In fact indications are that the commercial offerings of TCP/IP implementations often outweigh their open counterparts in terms of resource utilisation. Further it can be seen that even protocols such as 6LoWPAN (Hui and Culler, 2008), which have been specifically designed for low resource utilisation, still have troubles to fit even on commercial sensor nodes (Cody-Kenny *et al.*, 2009).

The main perceived advantage of the idea of "IP everywhere" is that it becomes easier to interconnect devices and to develop applications to run on these devices, e.g. to cut back on the costs of development. However, we argue that there is a price to pay for ease-of-use. That price is the increase in resources required with increased abstraction, and the reliance on external components (black-box design), wherein one inherits all the flaws and shortcomings of the components, as well as the benefits. The price one has to pay in terms of additional resources and reliability outweighs the potential gains. Cross layer optimisation techniques in particular have the potential to exceed the savings made by using a ready-made TCP/IP solution. Although more expensive to develop initially, the long term savings on hardware and maintenance costs are significantly reduced. Therefore, we concur with the view which is expressed in Shelby *et al.* (2003) that although it is certainly possible to make use of TCP/IP with relatively few resources, a superior alternative may be found in the use of a proxy or translation step in a gateway node, transparently translating between TCP/IP and an optimised protocol.

5.5 Remarks about standardisation

Although there are many standards under development, few are currently complete. Many countries specify a road map towards a smart-metering infrastructure or implementation of the smart grid, but often omit directives specifying specific standards. This holds true not only for the European Union or individual nations. Even though in the European Union there is the Mandate CEN/CENELEC M/441, this mandate still leaves portions of the specification of smart-metering devices open. This is similar to the IEC's SIA standard which, although it goes into great depth specifying all aspects of the smart-grid and smart-metering infrastructure, also intentionally leaves certain aspects undefined. This is done in order to leave enough space for innovations and vendor specific implementations (Rohjans *et al.*, 2010; Uslar *et al.*, 2010). This might be necessary because there can be no single universal technique which is equally well suited to every situation, and even within a certain type of technique there are aspects which can be tweaked to gain optimal performance for the intended application.

In particular there is the issue of how devices within a smart-metering installation are to communicate. This is not standardised, because there are many techniques to choose from, each with its unique strengths and weaknesses, which makes it well suited to a particular situation (we have discussed the most commonly suggested approaches in Section 1.3). Therefore, it is reasonable to assume that smart-metering installations within a particular geographical region (one building, a neighbourhood, or a whole town) will all make use of the same technologies, with all metering devices constructed by the same vendor.

Within the domain of the technique in which we are interested (smart metering over RF communications) there are trade-offs to be made, too. The choice between using standardised hardware and/or software, or creating a proprietary solution is mostly a trade-off between ease-of-construction and costs, both for the hardware, as well as for the software. We have seen that even when standardised hardware is used, it is still required to develop the necessary software (for example the systems discussed in Section 1.4.4). Hence it makes sense, both from a marketing perspective as well as from a performance and efficiency perspective, to design and develop alternative approaches, algorithms, and protocols.

6. Conclusions

We have presented an overview of a diverse set of technologies which can and are used in the deployment of smart-metering systems. We highlighted the strengths and weaknesses of the usage of existing infrastructure (PLCs, land-lines). Although seemingly advantageous, there are significant drawbacks to these technologies. Licensed RF communications networks are a significant improvement, although they can be more expensive. Costs can be reduced by sharing a relatively expensive data uplink among many inexpensive metering devices. We argue that unlicensed RF communication networks, in particular when used in mesh networks, are the most suitable candidate technology to realise such an approach. We have reviewed a number of existing and proposed mesh networks and protocols, showing approaches which result in complicated, expensive designs requiring custom hardware to implement protocol features or using a TCP/IP stack, which consumes large amounts of resources. Existing smart-metering systems make few provisions to comply with on-going with standardisation efforts. We find that, at present, the field of smart-metering networks consists of a fragmented set of standards and solutions, leaving open a number of issues related to the design and deployment of suitable communication networks.

Notes

1. The EFIS database is available online through www.efis.dk/
2. The reference has been blanked out due to double-blind review.
3. www.microchip.com/wwwproducts/Devices.aspx?dDocName = en026561
4. Reverse energy refers to energy generated at the metering site, e.g. energy from solar cells or wind power.

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