ADVANTAGE

Advanced Communications and Information processing in smart grid systems

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ADVanced communicAtions and iNformaTion processing in smArt Grid systems

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WP2 D.2.1

State of the Art in Neighbourhood/Industry Area Networks and Definition of Application Scenarios and Research Problems

Abstract:	This deliverable will explore the initial literature study and research directions for WP2 of the ADVANTAGE project. This WP considers smart grid operation in both neighbourhood communities as well as industrial areas. The first research area considers how communications over powerlines may be used to support smart grid operation in neighbourhood areas. To complement this, the second topic will investigate how emerging device-to-device protocols among wireless devices can support the smart grid. The final topic will study the interaction of signal processing algorithms with the communications network to enable smart grid operation.
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1 INTRODUCTION TO WORK PACKAGE TWO: NEIGHBOURHOOD/INDUSTRY AREA NETWORKS

ADVANTAGE Work Package 2 (WP2) focuses on Neighbourhood Area Networks (NANs) and Industrial Area Networks (IANs) which represent a dynamic and versatile environment for the design of real-time, robust, and reliable smart grid solutions. The Early Stage Researchers (ESRs) involved in WP2 are expected to develop communications solutions to enable large-scale monitoring, ranging from collecting energy consumption data via smart metering infrastructure to Phasor Measurement Units (PMUs). More specifically, the topics covered by each ESR will be:

- Device-to-Device (D2D) communications for fundamental applications in smart grid NANs (Charalampos Kalalas, ESR3),
- Power Line communication technology in NANs (Deep Shrestha, ESR4), and
- M2M Communications in Heterogeneous network deployments for extracting of required information regarding loads clustering in the context of smart grid (Mehdi Zeinali Ghayeshghoorshagh, ESR5).

The present document summarizes findings of a literature review on representative wired and wireless communications technologies which can be utilized in wide-area smart grid applications.

1.1. SMART GRID NEIGHBOURHOOD AREA NETWORK

The smart grid NAN forms the communication facility for the electricity distribution systems. It involves communication between numerous electric devices which are deployed in large and complex geographical areas. Power system applications operating in the distribution domain utilize NAN to share and exchange information. Fundamental grid applications within the NAN, include Distribution Automation (DA) and Advanced Metering Infrastructure (AMI) systems.

Enabled by the need for flexible and efficient forms of communication, energy-automation in the distribution domain involves communication between Intelligent Electronic Devices (IEDs) to support important power system functionalities like grid monitoring and control, fault management, maintenance and analysis [ZHA12], [VYA10]. The envisioned large-scale integration of Distributed Energy Resources (DERs) within the electricity grid results in a two way power flow in contrast to the traditional one way power flow [EIT14]. Thus, distributed control and protection systems need to be introduced which involve time-critical communication exchange between substation Local Area Networks (LANs). DA applications are associated with the most stringent communication network requirements in terms of network latency and reliability [IEC11]. While the communication involves fewer nodes compared to AMI deployments, a very short reaction time – often in the range of milliseconds – is required in order to prevent widespread power system failures. The reliability of the communication network is of paramount importance since the implementation of the control functions is critical for the health of the entire power grid.

Enabling a bidirectional communication system between a smart meter and a power utility data centre, AMI systems provide utilities with real-time information about users' power consumption and power quality. In turn, with the ability to monitor electricity usage in real-time, customers are helped to make educated decisions about their energy consumption, adjusting both the timing and quantity of their electricity use. The architecture of the AMI system entails potentially massive amounts of demand information to be collected from every consumer and price information to be sent to the residential premises. A large number of spatially distributed consumer meters periodically transmit relatively small amounts of information over a long distance to a utility. Hierarchical communication network structures have been proposed [MEN14] to handle the data, where concentrator units aggregate consumer meter information before forwarding them to meter management systems at the utility end for processing. Latency requirements for AMI systems are more lenient compared to other communication within the distribution grid, such as protection or control functions. The bandwidth requirements for individual user are relatively low; however, the overall requirements in a NAN increase considerably due to the large number of customer premises.

Performance requirements for different NAN applications can therefore vary significantly. The design of an efficient communication platform that incorporates the diverse - and often contradictory – requirements for various NAN use cases under a common umbrella, constitutes an interesting challenge as an open field for further research.

Various communication technologies have been proposed to support NAN applications in the distribution domain. These technologies include up-to-date wired and wireless communication network technologies. In particular, within the context of WP2, emphasis is given on:

- Power Line Communications (PLC), where data transmission is performed along with electric power transmission through the existing power lines,
- Cellular network-assisted Device-to-Device (D2D) communications, where intelligent grid devices can exchange information utilizing cellular licensed resources over a direct link, rather than transmitting and receiving signals through a cellular base station [FOD12],
- Cellular network-assisted Heterogeneous deployments, where small cells can be used in combination with macro-cells to meet the requirements of smart grid data exchanges,

as key enabling technologies in fundamental operations in smart grid NANs.

2 POWER LINE COMMUNICATION IN NEIGHBOURHOOD AREA NETWORKS

Power Line Communication (PLC) offers a cost-effective solution since it enables data transmission through the existing power lines. The major benefit comes from the use of a single medium for simultaneous data and electric power transmission. The ubiquitous nature and wide availability of PLC networks renders them as an attractive solution for several power applications in customer premises. Electrical wires are omnipresent, from a room in a house to the huge machines and drives in factories. Therefore, a promising opportunity for sophisticated applications arises without requiring investments on additional communication infrastructure. These applications range from home automation, access grid communications or smart metering to the provision of high speed data service to the end users as a solution to the last mile for data service providers.

Since their development, electrical wires were only intended to deliver electricity. Therefore, communication through electrical wire is challenging due to the fact that it is built only to transmit signals which are at 50 or 60 Hz. As a consequence, power lines suffer from [BIG03] [PAV03]:

- Frequency and time varying attenuation,
- Time varying frequency selective channel models depending on location, topology and connected loads,
- Non-white noise,
- Random impulsive noise,

- Limited transmit power due to electromagnetic compatibility issues with other communication systems working in the vicinity,
- Induced noise due to electromagnetic radiations from other wireless communication systems working in the vicinity.

Over the past decades, PLC has been a noble area of research due to its economic advantages. Since there is no requirement of additional physical medium as infrastructure of communication, it appears as an advantageous technology from an economic point of view. Therefore, when developing the concept of PLC to satisfy the demanding requirements of advanced smart grid applications in the distribution grid, adequate knowledge on electrical wires is required and, in particular, on:

- Communication channel,
- Noise (natural and manmade) that it has or induces,
- Technique/technology to overcome these drawbacks.

The following subsection presents the existing research work on modelling power lines as a communication channel in NAN domain.

2.1 Channel Model

The modelling of power lines as a communication channel is basically done following two approaches: *Bottom-Up* and *Top-Down*. A Bottom-Up approach defines the channel model based on the physical parameters of the power lines, such as impedance, wire length etc. In contrast, a Top-Down approach defines power lines as a channel based on the propagation phenomena that it demonstrates.

A measurement campaign for bottom-up modelling of power lines has determined the frequency dependent behaviour of power line impedances. This dependency on frequency causes *impedance mismatch* on coupling a signal in and out of the power line. Apart from the frequency dependency of the impedance, branching in the electrical network also creates impedance mismatch in power lines. These impedance mismatches cause multiple reflection of signals with echoes resulting in a multipath effect [PHI98]. Based on this theory, a path loss model proposed is given by [XIA07]:

$$|S_{21}| = |H(f)|dB + A_{mis1}dB + A_{mis2}dB, \quad (1)$$

where

- $|S_{21}|$ is the transmission gain (voltage gain) of the power line,
- $|H(f)|$ is the attenuation in the power line channel,
- A_{mis1} and A_{mis2} refer to the impedance mismatch at transmitter's and receiver's side respectively.

A similar approach can be also found in [LAZ09], where the effect of multipath propagation due to the number and length of the electrical branches between a transmitter and a receiver is formulated. According to the authors, the multipath effect in power lines can be modelled by three different approaches namely: the Multipath Echo Based method, the Scattering Matrix method and the Hybrid Smith Chart method. Each of these methods has its own tradeoff between complexity and the effectiveness in defining the multipath effect.

An analytic top-down model for the PLC channel is presented in [ZIM02a]. Different propagation effects such as: low pass behaviour, multipath propagation and losses in power line are defined by this model. The mathematical formulation for this approach is given by:

$$H(f) = \sum_{i=1}^{N} g_i \; e^{-(a_0+a_1 f^k)d_i} \; e^{-j2\pi f\left(\frac{d_i}{v_p}\right)}, \quad (2)$$

where

- N is the number of fading paths,
- g_i is the weighting factor related to fading path,
- $e^{-(a_0+a_1 f^k)d_i}$ is the attenuation in the power line with respect to frequency,
- $e^{-j2\pi f\left(\frac{d_i}{v_p}\right)}$ is the delay profile and $\frac{d_i}{v_p}$ defines the delay associated with different fading paths in the power line.

The values of the parameters: $g_{i,}$ a_0, a_1 and d_i can be derived from a measurement campaign done in different power line networks with different branching situations, as shown in [ZIM02a]. The following subsection presents the different statistical and analytical models of noise and interference that are encountered when considering PLC in NAN domain [GOT04], [MUD14].

2.2 Noise Model

Noise in communication system design plays a vital role as it can severely impair the functionality of the communication system. This noise is usually considered (e.g., wireless communication systems) to be Additive White Gaussian Noise (AWGN). However, the noise in the power line cannot be modeled as AWGN; instead they can be defined as a sum of cyclo-stationary Gaussian processes having certain periodic temporal and spectral properties. According to [OHN98], the temporal variance of noise can be modeled as:

$$\sigma^2(t) = \sum_{k=0}^{K-1} A_k |\sin(2\pi f_{AC} t \; + \; \theta_k \;)|^{n_k}. \quad (3)$$

The values of all the parameters in (3) can be obtained by measurements in practical environments. Some referred values of A_k, n_k and θ_k can be found in [OHN98]. This model is further enhanced by a spectral shaping filter, as defined by:

$$\alpha(f) = \frac{a}{2} \exp(-a|f|), \quad (4)$$

and results into a cyclo-stationary Gaussian noise model comprising of both temporal and spectral properties, described by [KAT06]:

$$\sigma^2(t, f) = \sigma^2(t)\alpha(f). \quad (5)$$

The model presented above defines the temporal and spectral behavior of noise which is based on the properties of sinusoids. In many circumstances, it can be noted that resorting to a noise model based on a deterministic approach, as the one presented above, is not always enough. Quite often, noise in power lines shows a random impulsive behavior. The work in [ZIM02b] provides some measurement results for this kind of noise. Therefore, a statistical approach is required in this perspective. Such an approach of identifying and characterizing the impulsive behavior of noise in power line can be found in [SHO14], [AND09].

Apart from the impulsive noise, power lines may also be subject to noise from electromagnetic radiation due to other communication systems operating in the same frequency band [MIL13]. On the other hand, due to unshielded overhead power line transmission of signals might create electromagnetic radiations. These radiations from overhead power lines might induce noise to other communication systems. Therefore, an electromagnetic compatibility (EMC) issue with other communication systems operating in its vicinity arises [MIL13]. This critical problem must also be addressed while designing PLC systems for transmission grids [AMI05]. Apart from this, the crossing over of Medium Voltage (MV) power line by High Voltage (HV) power line in a transmission grid network also induces noise from HV to the MV overhead power lines by space coupling effect. Radiation from HV cable is coupled to the MV cable through air as dielectric material between these two conductors. As a matter of fact the noise in the MV power line is stronger than the noise in low voltage (LV) distribution power line [TAO07].

Different techniques for overcoming noise/interference in power lines can be found in the literature. Coding schemes such as: Generalized Array Codes (GAC) and Row Column Codes (RAC), along with Clipping and Nulling, Iterative and Error correction coding techniques can add robustness against such impairments [SHO14]. It is evident that the periodic and random impulses with induced noise can affect the communication signal drastically in power lines. Hence, a sophisticated communication system should be developed for PLC implementation which can overcome the challenges imposed by power lines [ZIM02b]. The following subsection gives insight on the Multiple-Input-Multiple-Output (MIMO) technology and its enhancements with applicability in PLC.

2.3 MIMO Perspective

The increasing need for massive data transmission through the limited available bandwidth has always been an issue for the development of any communication technology. The available frequency bandwidth has become a scarce asset that needs to be used more efficiently. The use of MIMO on the limited bandwidth can generate capacity gain with respect to traditional power line transmission lines. Multiple parallel channels can be setup between transmitter and receiver in MIMO. These multiple paths in general provide two major enhancements to a communication system: *space diversity* and *spatial multiplexing*. Space diversity provides reliability whereas spatial multiplexing enhances the data rate. Various communication technologies, such as UMTS, LTE and WiMAX, already implement MIMO and it is being considered as a major feature in the upcoming 5G technology [BER14].

There are multiple conductors present in a distribution network, namely Phase/Line (P or L), Neutral (N) and Protective earth (PE). The presence of these multiple conductors can be exploited in order to create multiple paths between a transmitter and a receiver. Hence, exploitation of the MIMO concept for PLC can be performed. A practical approach to perform Single-Input-Multiple-Output (SIMO) in MV power line with one transmitter and three receiver (receiver diversity) is proposed in [HUI04]. A transfer byte rate of 300 bps with error code rate of 10^{-5} was achieved in this implementation.

Present PLC implementations are based on SISO technology using only P-N pair for differential transmission and reception. Thus, exploiting the PE cable can result in an additional channel for MIMO

PLC. The signals for MIMO PLC now can be fed and received differentially between P-N, P-PE and N-PE ports. The implementation of 2×2 MIMO where P-N and P-PE ports were used for transmission and reception showed double capacity gain as compared to SISO PLC [HAS10]. This enhancement in capacity can be elaborated with a 2×4 MIMO PLC architecture. One of the additional receiver port in this context can be achieved with use of N-PE pair. Another additional port can be achieved by capturing common mode (CM) signals that are generated due to parasitic effect of components in the electrical network. Therefore, capturing these CM signals will add one logical path at receiver and the resulting 2×4 architecture will be according to Figures 1 and 2.

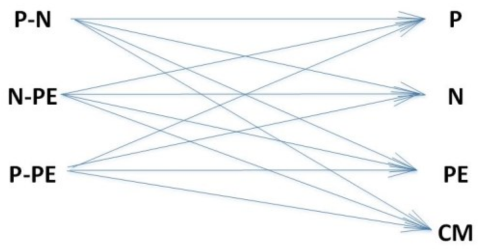

Fig 1. MIMO channels in In-house PLC [SCH11a]

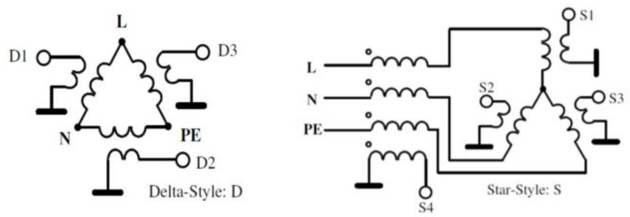

Fig 2. Couplers for signal injection and reception [SCH11a]

The signals in power lines are fed using couplers. The inductive couplers that are useful to inject the signal in and out are delta (transmitter) and star (receiver) respectively, as shown in Figure 2. Among N ports in delta coupler only N-1 simultaneous injections of signal are possible following Kirchhoff's Law. Therefore, any two ports among D1, D2, and D3 can be used for input.

The CM signal being generated along the transmission path adds one more path for reception. The reception of CM signal can be made possible with the use of star coupler at the receiver side. The ports S1, S2, S3 and S4, as illustrated in Figure 2, are the receiver ports and S4 represents the CM reception port. Hence, the final channel matrix for MIMO PLC becomes 2×4, as explained earlier [SCH11a]. In addition, the implementation of beamforming coding, as proposed in [SCH11b], proves the practical feasibility of MIMO PLC enhancement and the capacity gain it can achieve. The HomePlug alliance also provides evidence for this fact by releasing their new standard HomePlug AV2 for in-home applications that provides twice the bit rate with respect to their SISO standard of HomePlug AV [YON13].

The importance of MIMO PLC is also underlined by the activities of European Telecommunication Standards Institute (ETSI). ETSI has conducted one of the largest field survey for the study of power line for PLC. The Special Task Force (STF) 410 was nominated to conduct a massive measurement campaign within 1 MHz to 100 MHz frequency range to access the feasibility of MIMO for in-home scenario. This project was conducted in multiple European Union (EU) countries. The results from this measurement campaign also confirm the results discussed earlier in this section. Thus, it is evident that the electrical power line can be defined as a multipath and frequency fading channel that depends on the network topology and length of the wire [XIA07], [OHN09]. The measurement results show that MIMO power line channels have similar kind of frequency response as SISO channels, with CM being less attenuated but with correlation between them [STF12], [PIT14]. The stationary background noise scenario for all receiving ports has similar spectrum as SISO, with CM having high noise power spectral density. Apart from this, the impulsive noise in MIMO measurement showed very high degree of randomness. Thus, the concluding noise classification for MIMO according to the STF 410 measurement campaign is categorized as [STF12]:

- Impulsive synchronous to AC,
- Impulsive asynchronous to AC,
- Cyclo-stationary,
- Frequency dependent stationary noise.

The noises in all the receiving ports in MIMO are correlated. The noise correlation in PLC, unlike wireless, is due to its similar physical location and exposure to similar noises or interference scenario. In this context, a MIMO transmitter having full knowledge of channel state information (CSI) can enhance the system capacity. A performance study of 2×4 MIMO PLC in the presence of correlated noise is done in [REN11]. The effect of known transmitter and unknown transmitter in presence of correlated noise is evident in the study. It can be concluded that the transmitter with full CSI will boost the system capacity in comparison to transmitter with no CSI knowledge.

The implementation of multicarrier modulation techniques like Orthogonal Frequency Division Multiplexing (OFDM) or Filterbank Based Multicarrier Modulation (FBMC) with MIMO can improve system capacity with reduced effective bit error rate (BER) [ISE04]. The power allocation techniques like: maximization of the harmonic mean SNIR and maximization of the minimum SNIR for OFDM subcarriers can also be used to achieve capacity increment with high reliability in a MIMO PLC systems [ISE04].

As an alternative to wired communications, wireless technologies are considered a promising alternative to support demanding smart grid functions within the distribution domain, enabling communication almost anywhere at relatively low cost. The advantages of lower installation cost, scalable nature and ease of deployment are expected to offer enhanced grid functionalities. The following section emphasizes on cellular technology as the communication enabler in smart grid applications within the NAN domain.

3 Device-to-Device Communications for Smart Grids

Cellular network-assisted D2D communications appears as a promising technology to satisfy the demanding requirements of advanced smart grid applications in the distribution grid. In this scheme, intelligent grid devices in proximity of each other can exchange information utilizing cellular licensed resources over a direct link, rather than transmitting and receiving signals through a cellular base station [FOD12].

Cellular networks appear as a promising technology for wide-area communications within the distribution grid. Their ubiquitous coverage allows smart metering deployments to span over vast areas and be connected into the same management network [HO13]. In addition, the characteristics of cellular networks in terms of offered data rate, low latency and high system reliability, enable critical automation applications within the distribution grid. However, since traditional cellular networks have been primarily designed for human-centric communications, several technical challenges arise for efficient spectrum sharing and radio resource management between conventional cellular users and D2D smart grid pairs.

3.1 Motivation for Cellular - The evolution seen in the distribution grid

Cellular technology facilitates the transformation of the existing aging distribution grid into a modernized and fully automated power distribution system [VYA10]. The future power grid will see an extensive penetration of active elements (which can act as sources of energy) such as DERs, photovoltaic cells, storage batteries and wind energy generators. The distribution system, as the heart of a smart grid, needs to evolve into an active and dynamic system to provide the smart energy infrastructure in the coming years and decades [MAC06]. It is envisioned to be partitioned into smaller, more-manageable, and potentially autonomous operating units that require a flexible and widely adopted communication infrastructure [ZHA12]; thus, cellular technology seems a reliable candidate to support advanced grid applications. Utilities can easily use the existing cellular communication infrastructure to significantly reduce the investment required to implement such services. By enabling connectivity even in remote locations, cellular technology allows for a decentralized structure of the future distribution grid, where active generation/storage units and location-distributed electric power devices are interconnected in the same distribution system.

The expected changes in the distribution domain call for extensive real-time monitoring of the grid. Advanced automation, control and management of distribution networks are needed in order to meet the anticipated increase in distributed energy generation and to tackle the newly raised challenges. The monitoring process involves gathering of information from distribution feeders, transformers equipped with electrical sensors and communication capability, DER sites and customer premises [MAC06]. When data exchanges between smart devices become more frequent to support emerging smart grid applications, cellular communication technologies can be applied to achieve high data rates and low latencies [LIO11]. Operation in licensed frequency bands, increased security and low maintenance costs are also enabling features of present-day cellular networks and highlight their suitability for distribution grid applications.

Long Term Evolution (LTE) communication technology emerges as a promising candidate for satisfying the requirements of advanced smart grid applications including distribution automation, inter-substation communications, outage management, fault detection and restoration. Some of the potential benefits of LTE for supporting communication between devices in the grid include:

- Radio resource management. Unlike the majority of short-range radio network technologies, LTE operates in licensed spectrum and the radio resources are properly managed by the network, to minimize interference and maximize the overall system performance [DAH11]. Communication among smart grid entities can thus benefit of the network control in terms of energy consumption, node synchronization and efficient cellular spectrum utilization.

- Performance. Direct communication between IEDs may be able to achieve even higher throughput and lower latency than communication through an LTE base station. This feature is of utmost importance especially for time-critical protection and control applications in the distribution grid where there is a need to avoid communication through LTE core network which may appear as a bottleneck. The network can still exert control over the radio resources used for these connections, to maximize the range, throughput and overall system capacity.

- Network load. By offloading traffic onto direct communication links, base stations and other LTE network components are relieved of the extensive infrastructure network load. Direct communication avoids routing the traffic through LTE network which leads to efficient and real-time load balancing.
- Energy efficiency. Incorporating smart grid communication into LTE provides the opportunity to achieve energy efficient device discovery. In addition, direct transmission between nearby entities can be achieved with low transmission power.
- Security. Smart grid NAN communication can take advantage of the key generation and distribution mechanisms already available in LTE to achieve high levels of security.

3.2 Challenges for LTE

However, LTE was not initially intended for smart grid applications but for human-centric broadband applications [LIO11]. In order to support smart grid communications within the distribution grid, LTE needs to be enhanced with a wider range of use case characteristics and adapted to a much more complex range of access requirements. Smart grid services are often associated with stringent requirements which cannot easily be fulfilled by today's cellular technologies [IEC11], [EIT14]. To address this wide range of requirements different technology components are needed, which include techniques that are backwards compatible with LTE, as well as some more radical techniques. In the following, the main design requirements for LTE technology to support the demanding applications in the distribution domain are summarized.

- Smart grid traffic characteristics.
- QoS differentiation for real-time and non-real-time transmissions.
- Network connectivity of a massive number of devices.
- Low latency.
- Data processing.
- Reliability.
- Energy efficiency.
- Spectrum flexibility.
- Security.

3.3 Research Topics in Cellular Networks – State of the Art

Network-assisted D2D communication is expected to provide a significantly better performance as a result of the superior resource allocation and interference management that can be achieved by means of a central entity (i.e., base station) [DOP09]. The above mentioned LTE design challenges give rise to several research initiatives for addressing the problem of integration of smart grid NAN communication traffic in cellular deployments. One of the highlights of 3GPP Release 12 is the introduction of D2D discovery and communication [3GPP12]. Many research efforts are though still required before LTE technology successively supports direct communication between devices in the distribution grid.

In the present research, we are focusing on the problem of efficient radio resource management in D2D-enabled cellular networks. Spectrum sharing between cellular and D2D communications constitutes a fundamental issue in supporting D2D links in LTE networks. D2D can be classified in two categories: in-band and out-of-band [FOD12]. In-band refers to D2D utilizing the cellular spectrum while out-of-band refers to D2D utilizing bands (e.g., 2.4 GHz ISM band) other than cellular band. In the following, the main research topics affiliated to the problem of radio resource allocation are summarized for each category along with ongoing related research works.

3.3.1 In-band

In the case of in-band D2D-LTE networks, D2D links can either share resources with the cellular communications or use orthogonal resources.

3.3.1.1 Shared network

In a network where D2D transmissions reuse cellular resources - called a shared network – resource allocation is simpler and more efficient, at the cost of a denser interference environment which complicates interference management. The concept of radio resource reuse poses new challenges in the context of radio resource management. A key issue in this regard is the minimization of harmful intra-cell interference between cellular users and D2D pairs. The interference can be mitigated by introducing sophisticated resource allocation schemes that increase the computational complexity of the base station and/or D2D devices. Many different approaches to the radio resource management problem in a D2D-enabled cellular network have been proposed in the literature, including interference avoiding resource allocation, interference cancellation and power control.

Several algorithms have been proposed in the literature to deal with interference management between D2D and cellular communication [YE15], [MIN11]. The authors in [KAU08] study the interference mitigation issue through power control schemes where the transmission power of D2D links is properly adjusted to avoid high interference with cellular users. In [PEN09], D2D links use the control channel to estimate the resource blocks that are allocated to cellular users located in their proximity. Similar to the previous approach, D2D links adjust their transmission power after receiving broadcast information about the expected interference from D2D communication on uplink cellular transmissions. In order to ensure reliability of cellular users, the authors in [VAN12] propose a scheme where D2D pairs modify their power level in a way that they do not cause outage for cellular users.

[JAN09] investigated interference-aware resource allocation schemes for D2D links using both downlink and uplink resources. Their approach relies on measurements of the interference levels caused by the active cellular users and base stations at each potential D2D receiver. This data, along with information about the quality of the cellular links, is accumulated at the base stations. The resource allocation for all users in the system in a specific transmission time interval is determined according to the solution of an optimization problem that maximizes the performance of D2D while maintaining a target level of performance in the primary cellular network. This, however, requires global knowledge of the channel state information for every potential link in the network. Currently there are no feasible mechanisms for the timely acquisition of this information in a practical network deployment. Moreover, the exponential complexity of the optimization problem renders it impractical.

[ZUL10] proposed heuristic radio resource management algorithms for downlink or uplink resource reuse in D2D communication, exploiting a similar idea. Radio resources are allocated to cellular users in the conventional fashion according to the respective channel quality and the mobile network operators' preferences. At the same time, the potential D2D transmitter expected to cause the least interference to each cellular link is identified. Reuse of resources allocated for cellular communication in the D2D pairs, is only allowed if the additional interference at the base station, cellular users and D2D receiver, respectively, remains below a certain threshold. Otherwise, D2D communication in the resources allocated to a specific cellular user is prohibited. Despite the reduced computational complexity, this approach still requires full channel state information knowledge. Moreover, the mentioned radio resource management approaches do not consider the QoS requirements of the applications that might be required for D2D. However, they must be taken into account if optimal performance is sought. Some mission-critical applications require such optimization, for instance, in order to lower the end-to-end latency for mobile D2D, as [YIL14] investigated for a human-centric scenario. The acquisition of full channel state information is costly and even infeasible in an environment with fast changing channel conditions, such as the vehicular one.

In an effort to avoid the CSI acquisition, [BOT14] propose a location-based radio resource management approach that relies on network planning instead. The experienced interference by the respective users reusing the same resources is held under certain predefined thresholds by means of sufficient spatial separation. Moreover, (semi-) persistent scheduling for the users contributes to reduction of signaling overhead. Despite the feasibility of this approach from the measurement and signaling point of view, not taking the exact channel conditions into account could lead to suboptimal performance. The proposed network partitioning requires knowledge of the environment and despite not affecting the online operation of the network, the effort spent for the generation of the environment model could be significant.

Interference management schemes based on the definition of interference limited areas –where D2D and cellular users cannot use the same resources - are proposed in [MIN11] and [CHE12]. A mathematical formulation of the optimal resource allocation is proposed by [ZHA13]. The problem falls in the class of NP-hard problems and the authors propose a suboptimal graph-based approach which accounts for interference and network capacity. An iterative combinatorial auction game is proposed by [XU12a] for efficient resource allocation considering sum-rate optimization in a single cell. A similar game theoretic framework is studied in [XU12b] where resource allocation is based on sequential second price auction.

[ZHE12] present the required network architectural enhancements with the introduction of various transmission schemes related to machine-type communication devices. Several radio resource allocation schemes for different transmission links are proposed with the aim of minimizing co-channel interference and maximizing network efficiency. Different aspects of D2D communications in cellular networks –including interference management and mode selection (cellular or D2D) are studied in [LIN14] and [DOP09]. The authors in [XIA11] and [BEL11] propose heuristic schemes to perform power and resource allocation in OFDMA cellular networks, setting as overall objective an enhanced power efficiency.

The authors of [BEL11] propose a resource allocation method which guarantees QoS requirements for both D2D and cellular users. The problem is formulated as a non-linear constraint optimization problem. In [SU13], a system throughput maximization problem is formulated with minimum data rate requirements. The scheduling problem of D2D in OFDMA networks is studied in [HAN12] as a stochastic optimization problem and the objective lies in the maximization of the system mean sum-rate. In [LE12], the optimal resource allocation policy is formulated as an integer programming problem and the authors propose a two-phase suboptimal solution. In the first phase, optimal resource allocation for cellular users is performed based on the technique used in [KIM06]. In the second phase, a heuristic sub-channel allocation scheme for D2D flows is proposed, where resource allocation process starts from the flow with the minimum rate requirements.

3.3.1.2 Dedicated network

On the other hand, in a network with orthogonal allocation - called a dedicated network – part of the available cellular resources is exclusively used by D2D links. The option for dedicated resources for D2D communications has been studied in the literature [ZHO13], [LI12] and [SEP11]. The interference management is simplified but the resource utilization may be less efficient compared to the shared network case. In [GOT13], a class-based analytical model for scheduling machine-type traffic data over LTE networks is presented. A fixed resource allocation scheme is assumed where part of the LTE bandwidth is reserved for human-type traffic and the remaining is allocated to the devices; thus, eventually no contention for network access is taking place. In [YE14] the authors investigate the optimal resource partitions between D2D and cellular networks. Efficient spectrum sharing strategies that allow a relatively fair and interference-aware partition of cellular resources between cellular users and devices have been also proposed [LIN14]. In [CHO14], the authors propose a distributed mechanism for mode selection and spectrum allocation using a carrier sensing threshold for interference control among D2D communication pairs. The objective lies in the maximization of the rate of D2D pairs under target rate constraint for cellular users.

3.3.2 Out-of-band

Heterogeneity in terms of network types and capabilities will be a key characteristic of emerging wireless networks. In order to support the demanding QoS smart grid characteristics, LTE-based systems must be extended, or assisted, by short-range technologies already present in our day-to-day lives. In out-of-band D2D-LTE networks, D2D links utilize unlicensed spectrum in an effort to eliminate interference between D2D and cellular radio connections. However, the use of other frequency bands, non-overlapping with the cellular spectrum, introduces complexity in coordinating the communication over the two different bands. Out-of-band D2D communication may also suffer from the uncontrolled nature of unlicensed spectrum.

In the literature, the use of short-range networks with cellular-based communications has been referred to as the use of capillary networks, where cellular networks act as a connectivity hub to which some machines will connect directly and another significant portion will connect using short-range radio technologies [SAC14]. Beyond that, the aim is to define methods to use them all in a smart, integrated, and seamless manner to ensure permanently available connectivity and reliability.

Through dynamic and efficient network selection, QoS is expected to be further improved and load balancing achieved.

In [SPI09], the authors propose the use of ISM band for D2D communication in LTE. D2D pairs are grouped based on their QoS requirements and only one user per group is allowed to contend for the WiFi channel in order to avoid simultaneous channel contention. Similar cluster-based and game theoretic approaches are proposed in [ASA13a] and [ASA13b] where WiFi communication can be used for entities located in close proximity. The cluster head node communicates directly with the base station and is responsible for forwarding the traffic of the other cluster members to the base station. The improved performance is quantified in terms of spectral and power efficiency and fairness. A seamless offload mechanism in LTE – WiFi networks has been also proposed in [WON13].

[KIM10] present policy-based and multi-criteria decision-making-based seamless vertical handover schemes between LTE and next generation WLAN systems. [NIT12] employ neighbor bandwidth reservation and gateway relocation mechanisms for vertical handover in WLAN-WiMAX-LTE heterogeneous networks. [MIY13] propose fast intelligent inter-layer network selection as a new handover approach to select the best network among the candidate ones, where QoS, handover delay and improved data rates are set to be achieved. Based on IEEE 802.21, [BAE11] proposed a handover triggering mechanism that relies on a time-to-trigger mechanism in order to improve the capacity of both WLAN and LTE networks.

[ROD13] discusses energy-efficient vertical handovers between LTE and WiFi networks. In addition, reliability and availability could be attained if simultaneous random access techniques are used for the same purpose. As an example, consider a critical message that needs to be sent between two substations in a smart grid to avoid a cascade effect and thus a blackout in a given region. The use of simultaneous random access techniques to maximize the probability of delivery could be exploited.

4 M2M Communications in HetNets Deployments for Extracting of Required Information Regarding Loads Clustering in the Context of Smart Grid

The smart grid, which will form the next generation of the power grid, uses two-way flows of electricity and information to construct a distributed and automated energy delivery network. Obtaining energy consumption information is one of the most important goals of the smart grid concept. Understanding energy consumption patterns in real time is extremely important for optimization of energy generation and delivery. Reliable information on electricity generation and consumption patterns through smart metering will be particularly important for improved visibility of network behaviour. Novel applications such as clustering of different generators and loads to simplify energy network management will also emerge [RAM12]. The best candidate technology in order to cover requirements for communications for smart metering and decentralized energy is the Machine-to-Machine (M2M) communication operating as part of a cellular wireless network. M2M communications will involve autonomous data sensing and generation, then the communication, data processing and actuation across smart devices, without the involvement of humans. Low human involvement requires the M2M network to be self-organizing, self-configuring, self-managing, and ideally self-healing. A large number of machines with different functionalities are separately organized to create a M2M network. A M2M network connected to the Internet and deployed for sensing and control purposes refer to one important application of the wider Internet of Things (IoT) [GHA14] [RAJ15].

M2M is expected to be a major growth area for wireless communications in the next decade. M2M communication can cover a very diverse set of applications; thus, there will be very different deployment scenarios and requirements in context of cellular systems. In the smart grid, the M2M applications within the home may include a smart meters, home energy management systems and electric vehicles that must be efficiently charged and controlled via communication links. Although current cellular wireless systems are mainly designed for human voice and data communications, these systems are expected to play an important role in the future roll-out of M2M communications [ZHA14]. Mobile cellular communications has several major advantages, such as global standard infrastructure, cost-effective connectivity, easy installation and maintenance, especially for a short-term and fast deployment of M2M applications. Many papers and research works predict a significant growth for both M2M devices and connectivity devices. For example, over the next few years, large numbers of smart meter devices operating per cell in urban areas is predicted [FRA14].

In order to take full advantages of the opportunities created by growing M2M applications through cellular networks, the third generation project partnership (3GPP) and the Institute of Electrical and Electronics Engineering (IEEE) standardization organizations have started working groups for enabling and simplifying such applications through special releases of their standards.

4.1 Load Clustering Methods

Developing the AMI systems, will ease intelligent management of the power grid in order to improve efficiency and reliability. This will arise mainly due to the ability of extract many features of interest from electricity consumption information. One recognised smart grid application is Demand Response (DR) management. In this application, the utility uses power consumption data (e.g., peak usage, duration and time of day, etc.) which are taken periodically from individual customers in the service area to forecast the future demand to prevent a supply-demand mismatch. In advanced implementations, dynamic DR can be used to allow utilities to dynamically choose when and how to cover real-time consumption with a latency of only a few seconds [CHA13]. In addition, predicting the consumption demand of consumers for the next few hours helps a utility plan for additional generation requirements. Prediction of larger scale generation and consumption behaviour should be done by cooperation and clustering of different loads in power grid. This will reduce variability in energy consumption and improve reliability and predictability of the grid as a whole.

In the following sections the candidate communication technologies to collect the data from customer will be introduced and key challenges will be discussed in detail.

4.2 The M2M Communication Architecture

In last few years, the European Telecommunications Standards Institute (ETSI) has been working actively to develop the required standards for M2M communications. The main goal of these activities is to improve interoperability between M2M applications and devices and existing wireless technologies [ETSI13] [3GPP14]. To meet this goal, ETSI proposed the following architecture, as shown in Figure 3:

1) The device and the gateway domain: this where M2M devices are able to communicate data to a local gateway node using short range communications.

2) The network domain: this connects data at the gateway to the application server through long range communications such as the internet or the optical core of cellular networks.

3) The application domain: this coordinates different applications are defined depending to how the data is to be used.

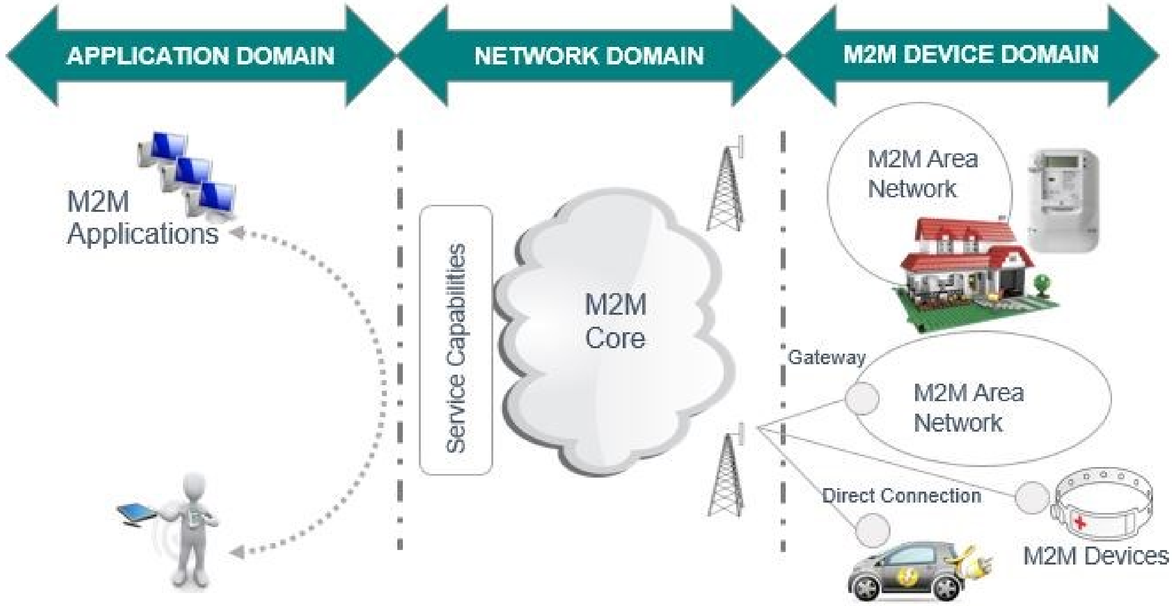

Fig 3: The ETSI M2M Architecture

M2M devices can be either fixed or mobile. The access network connects M2M devices to the infrastructure using either wired or wireless links. Wireless access methods can be either short range (i.e., wireless local area networks (WLAN) or short range systems such as Bluetooth and ZigBee, etc.) or cellular (i.e., Global System for Mobile Communications (GSM), third generation (3G), Long-Term Evolution (LTE), LTE-Advanced (LTE-A), etc.). Although wired solutions can provide high reliability, high rate, short delay, and high security, they cannot be a suitable solution for M2M communication applications because of limitations in scalability, mobility and the high cost of implementation. On the other hand, wireless solutions, are cheaper to implement, and generally scalable. However, the small coverage area, low data rates, weak security and sensitivity to interference, along with the lack of universal infrastructure/coverage is a major limitation for M2M communications. In contrast, wireless cellular networks offer excellent coverage, mobility/roaming support, good security, and ready-to-use infrastructure, making M2M over cellular a promising solution for M2M communications. Therefore, a major focus of this work will be on M2M communications based on 3GPP LTE/LTE-A mobile networks [3GPP12] [FAN13].

4.3 Overview of Cellular Communications protocols

The Open System Interconnection (OSI) reference model is a helpful map to have a better understanding of different communication systems architecture. It explains how various communication technologies communicate using any of several different sets of protocols, even simultaneously and differences between interconnection of communication elements such mobile terminals, base stations (eNodeBs) and the core networks in LTE systems. As M2M communication systems should be integrated into LTE networks, it necessary to have an overview of the major protocols used in such systems.

The core network in System Architecture Evolution (SAE) is the evolved version of the second generation GSM core network which is called the Evolved Packet Core (EPC). The simplified version of EPC is a combination of four major components including the Mobile Management Entity (MME), the Home Subscriber Server (HSS), the Packet Data Network Gateway (PDN) and the Serving Gateway (SG). These entities communicate using their interface connections between themselves, the wider internet and the Radio Access Network (RAN). As illustrated in Figure 3, the core network interface and protocols of M2M communication architecture are classified within the network domain [DAH07].

One of the key protocols used in the SAE system is the S1 Interface which connects the eNodeB to EPC. It split into two interfaces, one for control signals and the other for user data communication. The S1-MME interface is the reference point for the control data between the wireless network and the MME entity. The protocol structure of the S1 control plane is based on the Stream Control Transmission Protocol / IP (SCTP/IP) stack. The other part of S1 interface, S1-U is the communications interface between eNodeBs and the serving gateway to the internet. The S1-U protocol transports internet traffic but is agnostic to the content of the packet sent. The X2 interface is another major protocol which may be established between one eNodeB and some of its neighbour eNodeBs in order to exchange signalling information. Two types of information may typically need to be exchanged over X2 to drive the establishment of an X2 interface between two eNodeBs: load- or interference-related information and handover-related information [ALC09].

One of the most important parts of the OSI model is the medium access control layer which deals with how a communication device on the network gains access to the data and permission to transmit it. MAC layer protocols and its issues in the M2M communication architecture can be classified as part device domain according to Figure 3. It is good to be aware of MAC layer requirements and designing issues in connection with the other layers so that this knowledge can be used for designing the higher layer architecture in the OSI model which will be studied as part of this project. MAC protocols for M2M communications should be efficient, scalable, low power consumption, low latency, and possible to implement with low cost. MAC protocols can be classified into three classes [RAJ15]:

A. Contention-Based MAC Protocols: Contention-based MAC protocols are among the simplest protocols in terms of setup and implementation such as ALOHA and slotted-ALOHA. The main drawback of these protocols is the lack of scalability due to the increase in the number of collisions between concurrent transmissions.

B. Contention-Free MAC Protocols: Contention free protocols eliminate the issue of collisions by pre-allocating multiple transmission resources to the nodes in the network. Common contention-free protocols include time division multiple access (TDMA), frequency division multiple access (FDMA) or code division multiple access (CDMA).

C. Hybrid MAC Protocols: Hybrid protocols have been proposed that combine aspects of contention-based and contention-free protocols to have the advantages of both classes of protocols.

4.4 M2M communications in HetNets Deployments for smart grid

To provide ubiquitous wireless connections for devices, 3GPP LTE-A introduces a heterogeneous network (HetNet) as a special network architecture, characterized by a both hierarchical and multi-tier structure. Mobile Network Operators (MNOs) tend to deploy denser heterogeneous 3G and 4G networks in outdoor environments by adding more macro and small outdoor cells, with the latter referring to micro- and pico-cells. Such dense outdoor deployments are intended to cope with the required service levels, but may fall short of providing the required network capacity and QoS for indoor traffic at reasonable deployment costs and power consumptions [LAY14b].

As illustrated in Figure 4, a HetNet includes four parts: conventional macrocells, picocells formed by small transmission power enhanced base stations, femtocells formed by home base stations to improve signal strength in indoor environment, and relay networks deployed at the coverage edges of macrocells. Higher layer connections among all the above stations can be provided by 3GPP LTE/LTE-A infrastructure. Cell densification is also giving rise to large scale deployments of small cell sites to improve coverage and offload capacity from high power macrocells. The ability to provide a cost effective backhaul solution will increase the speed of implementation and ease deployment for small cells [HOA12], [BHA12].

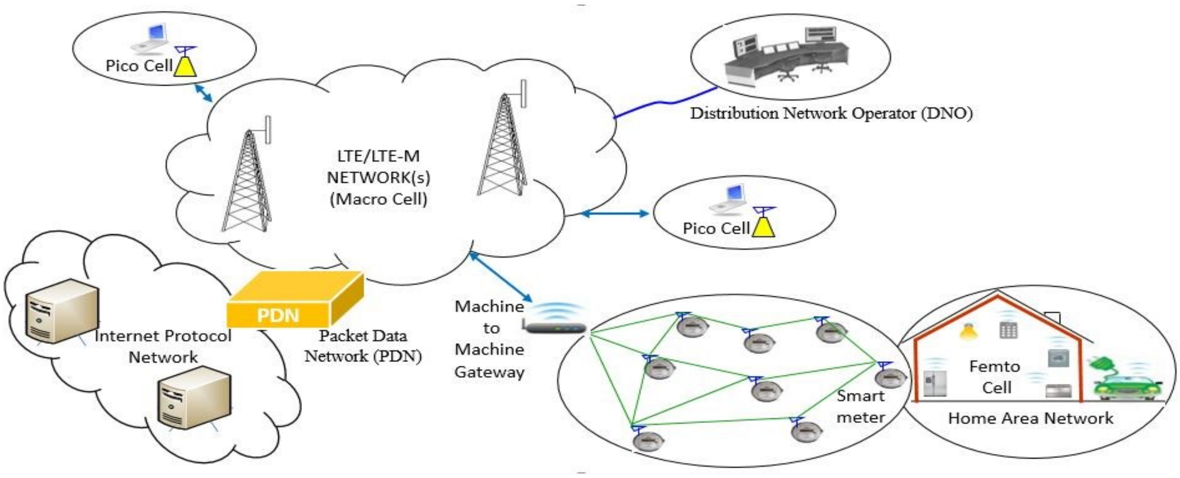

Fig 4. A heterogeneous network deployment. M2M communications through LTE technology

In a HetNet network, interference between macrocells and small cells leads to a degradation of the network quality. M2M communications start to be successfully implemented in recent 3GPP LTE/LTE-A efforts, however several research issues still remain open [DEM13], [RAT15]. Deployment and operation of small cells comes with a number of challenges, namely:

- Self-organization. There will be large number of small cells to be deployed. Small cells should have possibility of self-organizing to optimize cell performance.

- Inter-cell interference. Increasing the number of user-deployed cells in each macrocell will create new cell limitations, in which end users may suffer from strong inter-cell interference.

- Energy efficiency. The deployment of a large number of small cells will increase the total energy consumption.

- Scalability is essential to support a large number of devices with very low complexity.

- Low latency and high reliability: some applications will require highly reliable data transmission link over an unstable channel with low latency, particularly for control signals in the smart grid.

- Traffic characteristic of the network: the network should support different traffic characteristics of M2M communications, such as small message size and different transmission intervals.

- Backhaul networks. By embracing outdoor small cells as part of a heterogeneous mobile network, MNOs face the challenge of backhauling the traffic from small cell sites to the core network.

5 KEY RESEARCH OBJECTIVES FOR WORK PACKAGE

The key research objectives for WP2 can be summarized as follows:

- To work towards efficient noise mitigation technique to enable highly reliable communication in power lines (ESR4),
- To work towards feasibility of MIMO technique implementation for high capacity communication systems designed for sophisticated smart grid applications (ESR4),
- Employ efficient radio resource management strategies to enable an optimized operation of D2D communications under cellular networks according to the QoS requirements posed by fundamental operations in smart grid NANs (ESR3),
- Identify potential limitations and bottlenecks in current LTE network structure and propose novel network design approaches to support NAN applications (ESR3),
- Propose innovative decentralized smart grid communication architectures relied on the peer-to-peer type of communication, where the decision logic is built locally in the substation LANs (ESR3),
- Study smart grid applications to understand signal processing and communication requirements for different purposes such as load clustering, virtual power plants, etc. (ESR5),
- Study how smart grid applications can be supported in cellular networks including consideration of network architecture, higher layer protocol issues and identify potential solutions for limitations and problems in current networks (ESR5).

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