My Electric Avenue (I²EV)

Evaluation of Power Line Carrier communication for direct control of electric vehicle charging

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The ‘My Electric Avenue’ project is the public identity for the Low Carbon Networks Fund Tier 2 project “I²EV.” The formal title “I²EV” is used for contractual and Ofgem reporting purposes.
### Version Tracking

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Executive summary

This report sets out the My Electric Avenue (MEA) project’s learning on the use of Powerline Carrier (PLC) communication for Low Voltage (LV) network applications. My Electric Avenue used PLC for communication between distribution substations and electric vehicle chargers to limit electric vehicle (EV) charging when required by the LV distribution network.

PLC was found to be effective for 65% of all measurements across the MEA participants. The MEA implementation of PLC – using sparsely populated networks with relatively long communication distances – is not capable of delivering highly reliable communication. A number of factors have been investigated to establish their impact on PLC:

- There is an exponential correlation between distance and reduced reliability of communications for the participants where distance could be isolated. However, the certainty of this correlation is low due to the relatively low number of participants.
- The system implemented by My Electric Avenue allowed units to relay messages along the LV network. It was found that increasing the number of units relaying messages increased communication reliability and allowed communication with participants at distances of up to 300 meters.
- The presence of cable joints on the network was not commonly found to influence PLC communication reliability across the trials. However, in one instance (South Shields 1) the PLC communication reliability was found to have failed as a result of a cable joint on the network.
- PLC communication reliability was shown to improve with an increase in the number of viable signal paths. However, the results were not comprehensive for high numbers of signal paths due to the sparsity of the networks.
- There was a strong correlation between the PLC communication reliability and the load on the network. PLC communication reliability was found to reduce with increased network load.
- Interference caused by solar photo-voltaic (PV) generation was not generally found to reduce PLC communication reliabilities. However, for one participant there was indication of reduced communication capability when PV generation was occurring.
- There was no correlation observed between PLC communication reliability and EV charging.

My Electric Avenue has demonstrated the use of PLC on sparsely populated distribution networks. Communication reliability was found to be slightly lower than previous projects, reflecting the sparse nature of the PLC networks and the extended distances involved. Due to the number of factors shown to influence PLC reliability, it is recommended that future projects test PLC reliability before installation and only utilise the technology where a high proportion of customers are connected. Where a very high number proportion of customers cannot be connected, it is recommended that other communications technologies be researched and deployed.
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1 Introduction

The My Electric Avenue (MEA) project is trialling Esprit technology which controls Electric Vehicle (EV) charging to mitigate its effect on electricity distribution networks. As part of My Electric Avenue, the project has conducted investigations into the performance of Power Line Carrier (PLC) communications. Esprit uses PLC to transmit measurements and control signals between the system’s components.

This report outlines the evidence obtained from investigations conducted through the trial period, and provides learning with regard to the factors which influence the effectiveness of PLC.

1.1 My Electric Avenue

My Electric Avenue is an innovative project run jointly by EA Technology and Southern Electric Power Distribution that demonstrates a solution to the impact that the charging of EVs has on the Low Voltage (LV) distribution networks. The project is funded by Ofgem’s Low Carbon Networks (LCN) Fund.

The project is trialling a new solution, called Esprit, which is designed to directly control and manage the power drawn by high load devices, such as EV charging, on LV feeders. Esprit is designed to provide an alternative approach to traditional network reinforcement, which is anticipated to increase with greater uptake of Low Carbon Technologies (LCTs) including EVs and heat pumps in coming years. In the My Electric Avenue project, EVs were used to provide the controllable load for testing of the Esprit technology.

1.2 Esprit

Figure 1 shows a schematic of an Esprit installation. Esprit comprises two components:

1. A Monitor Controller (MC)
2. A number of Intelligent Control Boxes (ICBs)

The MC is installed at the LV distribution substation and monitors the current on a particular feeder; the feeder is shown in Figure 1 as a solid blue line. The MC has a defined threshold for allowable current and recognises this as a limit for the feeder. When the threshold is exceeded the MC sends ‘curtailment’ messages to the other component of Esprit, the ICBs.

The ICBs are units which are installed in series with the EV charging points; each has a relay which can switch off the power to the charging point. The ICB receives the MC’s communications and reacts accordingly, either curtailing or reactivating power to the charging point. Instructions sent by the MC are communicated using PLC communication, shown in Figure 1 as a dotted blue.

![Figure 1 – Network Schematic of Esprit Technology.](image-url)
1.3 Data Collected during the MEA Project

Throughout the MEA project, data have been collected from each of the Esprit components to enable delivery of the project learning, including assessment of Esprit’s performance. The following data were used to perform the analysis of PLC reliability:

- **MC data**: Ten-minute averaged measures of phase current, on each of the three phases of the associated LV feeder, recorded every minute.
- **ICB data**: Instantaneous values of voltage and current, recorded every ten minutes.
- **CARWINGS data**: Collected from Nissan’s CARWINGS telematics system installed in each Electric Vehicle: EV charging (including start and end timestamps and state of charge) and EV journeys (start and end timestamps, distance, energy consumption). The Vehicle Identification Number (VIN) was used to link the MEA participants with their CARWINGS data.

1.4 Use of Power Line Carrier Communications

For Esprit to operate as intended, there is a reliance on the communication between the MC and ICBs to allow both operation instructions and measurements to be sent and received.

The performance of PLC has an impact beyond the Esprit technology trialled by the MEA project: there are also implications for other demand-side response applications which may use, or consider using, PLC. The MEA project recognises the importance of sharing the learning gained and has produced this report to disseminate the analysis of PLC conducted during the MEA trials.

1.5 Aims and Objectives

This report provides an overview of the learning gained from investigations conducted as part of the MEA project, specifically the reliability of PLC communications and its influencing factors in the MEA implementation.

The following specific factors are explored:

1. Availability of alternative signal paths
2. Distance between Esprit components
3. Cable Joints
4. Load on the network
5. Interference from low carbon technologies including EV charging and solar photovoltaic (PV) generation.

This report aims to provide readers with an overview of factors which affect PLC communication, their level of influence, and to provide recommendations for others wishing to use PLC in similar applications.
2 Powerline Carrier

2.1 Background to PLC

PLC communication, as the name implies, is the technology of data transfer through electrical power networks. When first developed, PLC involved superposition of low frequency signals onto the 50 Hz power frequency which resulted in long transmission ranges but low data rates. More modern implementations of the technology can be categorised as narrowband and broadband: Narrowband systems often operate in the Cenelec Band A (3 – 95 kHz) which allows two way communication at relatively low data rates; broadband systems use more advanced modulation techniques to enable higher data rates suitable for consumer Internet connections but these can result in reduced range.

2.2 Previous Projects Using PLC

A number of trials using PLC have been carried out across mainland Europe and in the UK since 2001. Previous projects included delivery of demand-side response; communication between the distribution substation and end customer for metering; and provision of Internet connections to customers, known as the ‘last ‘mile’, motivated by the avoidance of the requirement for additional infrastructure. A summary of these projects is included as Appendix A.

The results of these trials suggest that PLC communication performed satisfactorily, with the following findings of particular note. These findings summarise the understanding of PLC capabilities prior to MEA:

- Western Power Distribution reported an average success rate of 70-75% in PLC communications on UK LV networks.
- Trials comparing narrowband and broadband communication reported better performance with narrowband than broadband, primarily due to network loading influencing broadband performance.
- Previous projects included the facility to relay messages across the PLC network, this involves a signal being passed to the receiver via intermediate transmitter/receivers. This was reported to improve performance as distance increased.
- Harmonic disturbances within the operating frequency of PLC was found to reduce PLC communication reliability.
- Increased distance was reported to reduce PLC reliability.

3 My Electric Avenue investigations

The MEA team undertook investigations to understand the reliability of PLC communications and, more specifically, which factors influenced that reliability. This analysis was undertaken to enable ongoing improvement of project delivery. However, results are presented here as additional project learning.

This section records the method used to investigate the reliability of PLC communication for the Esprit technology and high level results.

3.1 Calculation of PLC Communication Reliability

The results discussed consider the parameter described as PLC Communication reliability, which was calculated for each ICB at various time periods across the MEA project. This was achieved by calculating the proportion of time where the ICB communicated effectively and a valid measurement was received (see Equation 1). This calculation is not trivial. For a particular time period, the total number of minutes was readily calculated but the number of minutes with a valid measurement (i.e. uptime) was more challenging.

ICB data were recorded at ten-minute intervals for the majority of the MEA project. Therefore, the number of minutes with a valid measurement (i.e. uptime) was calculated using the assumption that where a valid measurement was recorded, it applied for the preceding 10 minutes (see Equation 2). However, measurements were sometimes recorded at intervals other than the 10 minutes; typically where communications were re-established after an outage or where curtailment occurred. Therefore, Equations 1 and 2 are more involved than may appear necessary upon initial inspection.

\[ \text{Communication Reliability} = \frac{\text{Number of minutes with a valid measurement}}{\text{Total number of minutes during that period}} \]

Equation 1 – Calculation of PLC Communication reliability

\[ \text{Number of minutes with a valid measurement} = \sum \text{time between measurements} |_{\text{times}10} \]

Equation 2 – Calculation of uptime

The MEA project trialled the Esprit technology at 10 different locations, or clusters. Throughout the project, software and hardware upgrades took place at each of the clusters. Due to the geographic spread, and different network configurations, upgrades at each cluster took place at different times.

This analysis sought to show the factors influencing PLC reliability, and the scope excluded variation due to Esprit software or configurations which were specific to MEA. Therefore, it was necessary to select a subset of the MEA data, to mitigate the impact of different software and hardware configurations. Unless stated otherwise, the analyses set out below were conducted on the basis of 15 consecutive days of data per cluster. Due to the varying timeline of upgrades across the project, the dates used for each cluster are not consistent, but rather reflect equivalent software and hardware configurations. This method was selected to best isolate the results of this analysis from the variations in software and hardware configuration, which are not relevant to future projects considering PLC.

3.2 Summary of PLC Reliability Results

The overall PLC communication reliability has been calculated, as set out in Section 3.1, for the MEA project and for each of the trial clusters. The average communication reliability between MC and ICBs across the trial was 65%: further detail is shown below in Table 1. This result was lower than that of previous projects in the UK\(^3\),\(^4\); this is likely to be due to a combination of the factors discussed in Section 4.
### Table 1 – PLC Communications Reliability for MEA Clusters

<table>
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<tr>
<th>Cluster</th>
<th>Aggregated PLC Communications Reliability (%)</th>
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<tr>
<td></td>
<td>Mean</td>
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<tr>
<td>Chineham</td>
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<tr>
<td>Chiswick</td>
<td>57.06</td>
</tr>
<tr>
<td>Lyndhurst</td>
<td>69.59</td>
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<tr>
<td>Marlow</td>
<td>80.09</td>
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<tr>
<td>South Gosforth</td>
<td>89.10</td>
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<tr>
<td>South Shields 1</td>
<td>38.75</td>
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<tr>
<td>South Shields 2</td>
<td>33.69</td>
</tr>
<tr>
<td>Whiteley</td>
<td>70.98</td>
</tr>
<tr>
<td>Wylam</td>
<td>77.51</td>
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<tr>
<td>Your Homes</td>
<td>95.15</td>
</tr>
<tr>
<td>All ICBs</td>
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### 4 Factors Influencing PLC Reliability

A number of factors were expected to influence PLC communication reliability. Each of these factors was identified from the results of previous projects (see Section 2.2); the effect of each factor was analysed and results are set out in this section.

#### 4.1 Number of Alternative Signal Paths

**4.1.1 Concept of a Signal Path**

The Esprit technology includes the concept of a “repeater”. Repeater units are able to re-transmit messages for ICBs further away from the MC, allowing units to communicate across distances which were not plausible for independent communication. MEA installed dedicated “repeater” units which operated on all three phases in some clusters. In addition, ICBs acted as repeaters for other ICBs’ signals, where they were connected to the same phase.

This functionality was intended to improve PLC communication reliability where ICBs were installed further away from MCs, and allowed an ICB communicating via a repeater to communicate via a number of different routes – or signal paths – as shown in Figure 2. Increasing the number of signal paths between the ICBs and MC introduced redundancy to the system. Therefore, increased numbers of signal paths were expected to increase the overall PLC communication reliability.

Where a signal path involved direct communication over too great a distance, it was deemed to not be viable. In order to establish whether a signal path was viable, the maximum allowable distance for direct communication was initially taken to be 250 m, based on manufacturer recommendation.

To illustrate this point, consider the signal paths available to ICB 3 in Figure 2: Signal path ‘A’ requires direct communication over a distance of 300 m (ICB 3 to MC) and would not be viable. Similarly, signal path ‘C’ required direct communication over a distance of 275 m (ICB 1 to MC) and would not be viable. However, signal paths ‘B’ and ‘D’ are both viable because they both involve direct communication over a maximum distance of only 150 m.

10
4.1.2 Impact of Increased Number of Signal Paths

The data considered for this analysis comprised a measurement of communication reliability (R), for each ICB, calculated as set out in Section 3.1; each ICB relies on multiple signal paths (N) of variable length (D). The single-path data (ICBs with N=1, any D) showed a weak correlation between R and D (r-squared = 0.48) but there was too much scatter in the data for any consistent improvement in R to be seen in the multiple-path data; this result is shown in Section 4.2.

So rather than looking for a relation between R and N and/or D it was decided to use a binomial approach, splitting the data into two groups according to their R and D values, counting the numbers in each group, and seeing how these numbers varied with the number of signal paths N.

Cut-off values of >90% for R and <250 m for D were selected on the basis that a reliability of 90% was deemed to represent strong performance and manufacturers have indicated that one should not expect reliable communication for signal lengths greater than 250 m.

It was found that the fraction of data with R > 90% and D < 250 m (and hence the probability of a single case fitting these criteria) increased significantly with increasing number of signal paths, from 58% with a single path to 89% with five paths, see Figure 3.

For R > 80% and D < 250 m, the corresponding figures are 70% for a single path and 92% for five paths, see Figure 4.

One, two, four and five signal paths were chosen for this analysis as they had sufficient data points (more than 2) and gave good correlation (r-squared = 0.664). The data for 10 signal paths was deemed to be an outlier. To obtain the weighted fit shown in the figures below, the original data is modified (divided by the square of the standard deviation), to account for distance between the data point and the point of estimation.
The probability of communication reliability being over 90% is 58% for one path and 89% for five paths. And the probability of communication reliability of greater than 80% is 70% for one path and 92% for five paths.

The impact of different path lengths can be explored by comparing the results where paths are consider viable with length of up to 250m (shown in Figure 3) with those for lengths up to 200m (shown in Figure 5). The improvement rate with additional paths (dp/dN, corresponding to the weighted fits shown in Figure 3 and Figure 5) decreases for shorter path lengths from 0.057 to 0.037. This is because the reliability for one signal path is higher, 79% (for 200 m) compared to 58% (for 250 m) for communication reliability of greater than 90%; therefore, there is less room to improve. Therefore, we conclude that communication reliability is higher for paths up to 200 m than for paths up to 250 m. However, improvement as a result of increased numbers of paths is more significant.
Key results from this analysis are:

- There is a statistically significant increase in communication reliability with an increase in number of signal paths.
- The limited number of ICBs with access to more than one viable signal path means statistically significant results are difficult to obtain and the results are limited to the binomial analysis described above. This reflects the design the MEA trials which sought to establish single viable signal paths for each ICB but which did not include significant PLC redundancy.

4.2 Communication Distance

It was expected that increased distance between MC and ICBs would correlate well to reduced PLC communication reliability, based on the results of previous projects, manufacturer input and the unavoidable signal attenuation over distance. This section presents results analysing the influence of distance on PLC communication reliability.

For the MEA project, ICBs were located at a range of distances from the substation and on a range of network topologies. The availability of additional signal paths (as defined in Section 4.1) allowed data to be re-transmitted along the route between MC and ICB. Therefore, it is difficult to compare directly between distance from ICB to MC and communication reliability.

Figure 6 shows 100% minus the PLC communication reliability (calculated as per Section 3.1) plotted against the distance between each ICB and the relevant substation. To mitigate the influence of multiple signal paths, these results only include ICBs which cannot communicate via another device. PLC communication reliability exhibits an exponential correlation with distance for the 24 ICBs included in this analysis.

However, there is low confidence in correlation \(R^2 = 0.4775\). It should also be noted that the MEA clusters were designed to minimise the number of ICBs with one signal path, particularly where the ICB was more than 200 m from the substation. Therefore, these results have a lower number of data points than would be desirable for a trial investigating PLC, particularly at distances greater than 250 m.
4.3 Cable Joints

The MEA project demonstrated the Esprit system with a variety of different network topologies, locations and conditions. A significant number of cable joints are present on LV networks in GB, including both service joints and those to enable junctions and connections in the main feeder. To illustrate this, the topology of the MEA Marlow cluster is shown in Figure 7, which shows three joints in the main cable in addition to over 50 service joints.

Service joints are extremely prevalent in LV feeders serving residential customers. Therefore, it has not been possible to separate the impact of service joints from the impact of increased distance. The impact of service joints is implicitly included in the analysis of the impact of distance between transmitter and receiver in Section 4.2. However, it has been possible to analyse the impact of joints in the main LV feeder.

The number of joints (excluding service joints) between MC and ICB was determined for each participant in the MEA project. The mean communication reliability (as defined in Section 3.1) was then calculated for participants with different numbers of cable joints, shown in Figure 8. The results from this analysis are largely indeterminate and allow very limited conclusions.

If the results shown in Figure 8 are considered at a lower confidence interval of 75%, only one statistically significant conclusion can be drawn: ICBs with no cable joints have higher communications reliability than those with two cable joints. Based on these results, a trial with significantly greater numbers of participants would be required to draw meaningful conclusions on the relationship between cable joints and PLC reliability.
Figure 7 – Topology of the My Electric Avenue Marlow Cluster (Main cable shown in blue, service cable shown in red, substation shown as black triangle)

Figure 8 – PLC communication variation with Number of Cables Joints between MC and ICB
One qualitative result from MEA shows the impact of cable joints, for the case of a particular circuit. Consider the schematic of the South Shields 1 cluster shown in Figure 9. A single junction is shown, and ICBs are allocated to three groups, based on their position relative to the cable joint. Table 2 shows the number of ICBs in each group and the mean and maximum PLC reliability. All of the ICBs in group 2 have zero communication reliability. No other factors which could influence the PLC reliability are known. Therefore, it is concluded that the cable joint is severely limiting PLC reliability for those ICBs. It is possible that this result is due to a poor quality cable joint. However, it has not been possible to investigate the cable joint during the MEA project.

![Figure 9 – Participants grouped into different segments with respect to cable joints in South Shields 1 cluster](image)

<table>
<thead>
<tr>
<th>Group</th>
<th>Number of ICBs</th>
<th>Mean PLC Reliability</th>
<th>Maximum PLC Reliability</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>58.6 %</td>
<td>58.6 %</td>
</tr>
<tr>
<td>2</td>
<td>5</td>
<td>0.0 %</td>
<td>0.0 %</td>
</tr>
<tr>
<td>3</td>
<td>5</td>
<td>73.5 %</td>
<td>99.9 %</td>
</tr>
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</table>

Table 2 – PLC Reliability for Different Groups of ICBs on South Shields 1

### 4.4 Load on the network

Based on the results of the Western Power Distribution project ‘Network Management on The Isles of Scilly’, network load was anticipated to have some negative impact on PLC communication, although the project on the Isles of Scilly used broadband PLC and so was not directly comparable. Increased load causes heating of the network, it also adds parallel paths to ground. Both of these factors are likely to reduce network impedance, which increases the attenuation of PLC signals.

To study the influence of network loading on PLC communication reliability, a sample of data from all ICBs was taken, for the same five week day period to reduce seasonal variability in load. The sample was taken in March 2015. The load and the communication reliability across the five-day period were monitored to establish any relationship.

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5 The sample was taken on a 5 day period, across week days (only) from March 23rd to March 28th
To combine the load profiles from the different trial clusters the data for each cluster was first normalised so that the phase currents recorded by each cluster’s MC ranged between zero and one in all cases. The normalised values were then averaged across all clusters and across the five days to create a representative daily load profile.

The mean PLC communication reliability was calculated for the five-day period for all of the ICBs in the MEA trials. ICBs which did not communicate at any point in the week were excluded from this analysis. Figure 10 shows the mean PLC communication reliability over the five-day period as a function of time of day with the normalised daily load profile for the MEA clusters.

The reliability and load data shown in Figure 10 were collated and plotted in Figure 11, each point in Figure 11 corresponds to a specific time interval in Figure 10. There is a clear relationship between communication reliability and normalised feeder load. The correlation coefficient ($r^2$), based on a linear relationship, indicates that 72% of the daily variation in communication reliability is explained by the linear relationship between daily load variation and communication reliability.

However, the daily variation represents a 12% change in communication reliability which is not sufficient to explain the wider communication variability seen across the project. It should also be noted that these results refer to the daily variation aggregated across My Electric Avenue feeders; it has not been possible to isolate the impact of feeder load sufficiently to comment on the variation between heavily and lightly loaded feeders, in general.

![Aggregated Communication Reliability for Communicating ICBs for One Week of the My Electric Avenue Trials](image)

*Figure 10 – Mean Residential Load Profile and communication reliability for one week of the My Electric Avenue Trials*
4.5 Interference caused by Low Carbon Technologies (LCTs)

4.5.1 Interference caused by Solar Photovoltaic Generation

Electrical generation from solar photovoltaic (PV) panels can introduce power quality issues such as harmonics and voltage distortion. Previous projects found that voltage and current distortion in the frequencies used by PLC communication reduces reliability. In the MEA trials, three participants had PV installed at their properties: JD10 (Whiteley cluster), SS206 (South Shields 2 cluster) and CRG07 (Chineham cluster).

To understand the effect of solar PV on PLC communication reliability, it was assumed that although PV generation can be significantly reduced during daylight hours, for instance by shadow or cloud cover, generation occurs only between sunrise and sunset. Therefore, because any interference due to PV generation would only occur during daylight hours, the correlation of communication reliability with the sunrise and sunset times was investigated.

No significant correlation between PLC communication reliability and sunrise/sunset times was found for two participants JD10 and SS206. However, the data provided by CRG07 showed a strong correlation between PLC communication reliability and sunrise/sunset times. Figure 12 shows communication availability for participant CRG07 (in blue); the graph shows a “high” value when communication occurs and a “low” value when communication failed. Figure 12 also shows sunrise and sunset times for this participant (in yellow); the graph shows a “high” value during daylight hours and a “low” value overnight. A very strong correlation is shown between daylight hours and communication failure for participant CRG07.

To investigate whether an external influence could be causing this effect, the two participants closest to CRG07 were also shown in Figure 12. Neither the closest participant – electrically – nor the closest participant – physically – exhibited a similar correlation. Therefore, it is concluded that

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6 P. J. Milanovic, Lecture notes on Quality of Supply, Manchester: School of Electrical and Electronics Engineering, University of Manchester, 2014.
this effect is localised to participant CRG07; and most likely caused by the presence of PV generation at the property.

Figure 12 - PLC communication reliability and sunrise/sunset times for Participant CRG07 and closest neighbours in the Chineham cluster

4.5.2 Interference caused by Electric Vehicle Charging

EV charging can potentially influence PLC communication by introducing noise onto the electrical network, in a similar way to PV generation. Routine data checks during the project highlighted unusual PLC communication for participant MC03, located in the Marlow cluster. These reports were investigated and a small number of instances were found where PLC communication was not successful during an EV charge, but immediately resumed following the end of the charge. However, a greater number of EV charge events did not show any correlation between EV charging and PLC communication. Therefore, we conclude that there is no consistent evidence from the MEA project that EV charging reduces the reliability of PLC communication.
5 Conclusions

Following the analysis set out above, the MEA project makes the following conclusions on PLC communication reliability and its efficacy on LV networks:

1. PLC communication reliability, defined as the proportion of time where PLC had communicated effectively, across the trial was 65%.
2. The MEA implementation of PLC – using sparsely populated networks with relatively long communication distances – is not capable of delivering highly reliable communication.
3. There is an exponential correlation between distance and reduced reliability of communications for the participants where distance could be isolated. However, the certainty of this correlation is low due to the relatively low number of participants.
4. The system implemented by My Electric Avenue allowed units to relay message along the LV network. It was found that increasing the number of units relaying messages increased communication reliability and allowed communication with participants at distances of up to 300 meters.
5. The correlation between distance and communication reliability was weak and a significant number of other factors influence the results.
6. The presence of cable joints on the network was generally found not to influence PLC communication reliability. However in one instance (South Shields 1) a particular cable joint on the network was found to cause communications failure in all downstream properties.
7. PLC communication reliability was shown to improve with an increase in the number of viable signal paths, at least over the range from 1 to 5 paths. However, the results were not conclusive for higher numbers of signal paths.
8. There was a strong correlation between the PLC communication reliability and the load on the network. PLC communication reliability was found to reduce with increased network load.
9. The interference caused by solar PV generation was generally not found to reduce the PLC communication reliability for one participant. However, for one participant where a definite correlation with daylight hours was found.
10. There was generally no correlation between EV charging and PLC communication reliability.

6 Recommendations

6.1 Future use of PLC on Low Voltage Networks

Based on the results of this work, the following recommendations should be considered when deploying PLC on LV networks in the future:

1. PLC should only be deployed where the network can be well populated, to minimize communication distances.
2. Repeaters – or repeater functionality – should be deployed to reduce the communication distances required and increase the number of signal paths; particularly on spurs or LV feeders with significant distances between substation and the first customer.
3. Where networks cannot be well populated with PLC repeaters, it is recommended that other communications technologies are investigated.
4. Systems to mitigate power quality issues caused by PV generation should be considered. However, it should be noted that it is not clear whether installation, equipment or other local factors are the cause of the power quality issues found by My Electric Avenue.

5. Given the potential for low carbon technologies and cable joints to influence PLC, communications checks should be undertaken to establish the viability of PLC before use.

6.2 For Further Analysis

MEA has identified a number of areas where further investigation into PLC behaviour may be valuable:

1. Investigation of the properties of cable joints which impede PLC reliability to determine if any changes to cable laying or jointing practices would be required for wide scale adoption of PLC.

2. Analysis of a large number of participants in a more heavily populated network to determine the impact of increased number of signal paths.

3. Analysis of a large number of participants in a more heavily populated network to determine the effect of signal path length.
Appendix A. Previous Projects which used PLC Technology

To inform the analysis of PLC undertaken during the MEA project, a literature review was conducted to evaluate previous learning. Table A3 summarises the projects and the remainder of this Appendix sets out summaries of the projects and their key learning.

Table A3 – Summary of Projects that have used PLC Technology

<table>
<thead>
<tr>
<th>No.</th>
<th>Project Name</th>
<th>Year</th>
<th>Company</th>
<th>Country</th>
<th>Number of units</th>
<th>Voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Powerline as an Alternative to Local Access(^1)</td>
<td>2001</td>
<td>AIL</td>
<td>Switzerland</td>
<td>8 Nodes</td>
<td>16 kV</td>
</tr>
<tr>
<td>2</td>
<td>Broadband Powerline in the UK(^1)</td>
<td>2002</td>
<td>Withheld (GB DNO)</td>
<td>UK</td>
<td>One HV and three LV trials</td>
<td>LV / 11 kV</td>
</tr>
<tr>
<td>3</td>
<td>Broadband Powerline Trial(^1)</td>
<td>2003</td>
<td>ENDESA SA</td>
<td>Spain</td>
<td>85 PLC Links</td>
<td>20 kV and LV</td>
</tr>
<tr>
<td>4</td>
<td>STP Powerline Carrier Trial(^2)</td>
<td>2010</td>
<td>STP (GB DNOs)</td>
<td>UK</td>
<td>Two trials with 11 and 14 nodes respectively</td>
<td>LV</td>
</tr>
<tr>
<td>6</td>
<td>Isles of Scilly Smart Grid(^4)</td>
<td>2013</td>
<td>WPD LCN Fund Tier 1</td>
<td>UK</td>
<td>27 PLC links</td>
<td>11 kV</td>
</tr>
<tr>
<td>7</td>
<td>Smart Hooky(^5)</td>
<td>2013</td>
<td>WPD LCN Fund Tier 1</td>
<td>UK</td>
<td>70 participants</td>
<td>LV</td>
</tr>
</tbody>
</table>

**Powerline as an Alternative to Local Access (Switzerland, 2001)**

This trial used the medium voltage (6 – 20 kV) distribution network and deployed a narrowband communication system. The aim of the project was to test efficacy of PLC at ranges of up to 4 km between PCs installed at each of seven distribution substations and a central PC located at a nearby primary substation. The target application was to transfer data to facilitate response to dynamic energy pricing.

The trials found that PLC could be used, in this configuration, to inform customers of dynamic pricing, but that the response times were very slow (up to 20 seconds to transfer 180 bytes) and that applications requiring reasonable data rates would not be possible. Additionally, the technology required some fine-tuning during installation and was not deemed to be suitable for untrained installation\(^7\).

**ENDESA Field Trials (Spain, 2003)**

The first large scale commercial trial of “broadband over power lines” (BPL) was undertaken by Spain’s largest electricity utility, ENDESA SA. The project installed 85 PLC links using the 20 kV network; signals were injected at 20 kV substations and then relayed to individual customers over LV from the meter rooms of apartment blocks. The purpose of the field trial was to evaluate the large scale commercial provision of broadband services to homes using the existing MV and LV distribution networks. The trial area covered 20,000 customers and included 140 MV/LV distribution substations. The trial was concluded in 2004, and was regarded as a success with data transfer rates reported to regularly achieve 20 Mbps\(^1\).

Broadband Powerline in the UK (UK, 2002)
In the early 2000s a series of pilot projects were conducted in England and Scotland rolling out broadband Internet connections to domestic and small business customers using broadband PLC technology. Three projects deployed on the LV network, and one on the 11 kV network. It was found that Internet connections could be maintained but there were some difficulties in using high frequencies (> 1 MHz) over the 11 kV networks, particularly underground networks1.

STP Powerline Carrier Trial (UK, 2010)
In 2010 the GB DNOs commissioned a collective small-scale trial, via the Strategic Technology Programme (STP), to review PLC for smart meter communication. A trial was conducted which tested a broadband PLC system and a narrowband PLC system on a LV distribution network which comprised underground cables and overhead lines. Results showed that both technologies were able to communicate with nodes at long distances (more than 250 m). However, communication was unsuccessful for a number of nodes, on a particular street, the reason for this failure was not established. No performance limitations, beyond the group of unsuccessful nodes, were reported2.

Isles of Scilly Smart Grid (UK, 2013)
Western Power Distribution ran the ‘Network Management on The Isles of Scilly’, a Low Carbon Network (LCN) Fund project in 2013. This project deployed and assessed several solutions which were used to create a smart grid including every substation on the Isles.

In this project, Broadband over Power Line (BPL) was trialled on the 11 kV network, allowing fast, low latency communications using existing assets on the Isles. Installation of BPL devices required HV outages and generators were used to maintain supplies during these outages.

Although the BPL devices required extra civil works to install couplers onto the underground HV network, the works could be hidden from view and all equipment was housed in standard substation kiosks.

The results of the tests showed that each of the BPL links provided latency between 5 and 35 ms and bandwidths between 400 kbps and 7,500 kbps, a considerable improvement on the radio technology. It was also noted that the BPL performance changed with the connected load to the HV network and harmonic disturbances within the operating frequency can affect bandwidth and connectivity4.

Networks for a Low Carbon Community (UK, 2013)
Western Power Distribution ran ‘Networks for a Low Carbon Community’3, a LCN Fund Tier 1 project, in 2013. The project was focused on the village of Hook Norton, a rural community in Oxfordshire with around 2,500 residents and 800 properties. One of the main challenges faced by communities such as Hook Norton is the lack of visibility of energy usage, at a personal and community level. Through this project, this challenge was overcome through a combination of substation and consumer energy monitoring.

This project deployed Power Line Carrier (PLC) communications within the low voltage (LV) network, illustrating its potential capabilities for enabling smart grid end point measurement and data aggregation. This technology was trialled to provide last-mile communications between domestic properties and substations. It was found that the PLC communication can work on UK LV networks with an average success rate of 70-75%. On average the nodes successfully transmitted data between 50% and 75% of the time. It was also found that there was a direct correlation between the load on the network and the rate of data transmission through PLC.