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Coverage Extension for the UK Smart Meter Implementation Programme Using Mesh Connectivity

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Abstract: Smart meters (SM) with wireless capabilities are one of the most meaningful applications of the Internet of Things. Standards like Zigbee have found a niche in transmitting data on energy usage to the user and the supplier wirelessly via these meters and communication hubs. There are still certain difficulties, notably in delivering wireless connectivity to meters situated in difficult-to-reach locations such as basements or deep indoors. To solve this issue, this paper investigates the usage of mesh networks at 868 MHz, particularly to increase coverage, and proposes an additional mounted antenna to significantly increase outside coverage while providing the necessary coverage extension for hard-to-reach indoor locations. Extensive measurements were made in Newbury in both suburban and open environments for validation and delivery of a simple statistical model for the 868 MHz band in United Kingdom conurbations. Results presented in this paper estimate that mesh networks at 868 MHz can accommodate large areas constituting several SMs with the proposed coverage extension method. With our findings and proposed methods on mesh connectivity, only 1% of UK premises will require mesh radios to achieve the desired coverage.

Keywords: mesh; 868 MHz; 2.4 GHz; smart meter deployment; coverage extension

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1. Introduction

With the help of intelligent sensors in smart cities, data can be sent wirelessly over long distances at a low cost with low energy consumption. Several high-data rate transfer protocols and technologies are now available, but none of them appear to be compatible with the communication standards used by intelligent sensors and control equipment. In addition to data speeds, this connection requires low tenancy and power consumption at narrower bandwidths. Authors in Ref. [1] presented a comprehensive survey on the challenges in smart cities, and one of the most pressing challenges is the network interconnectivity and subsequent transfer of data. This interconnectivity, especially for the Internet of Things, requires ubiquitous and veracious wireless coverage. Depending on the application, these requirements vary as some may require a low bandwidth, longer distances, and a lower frequency of data transfer. This paper focuses on the deployment of smart meters for collecting energy consumption data from households spread across a wide area.

Since ZigBee technology meets all these requirements, it is “a best match” for several embedded applications, including consumer and industrial control systems in smart environments, such as smart cities. According to IEEE 802.15.4 standards for Wireless Personal Area Network (WPAN), Zigbee is mostly utilised for sensor and automation control networks. The kind of communication standard determines how many devices may contact the MAC layer at low data rates. Depending on the application, this technology can work at frequencies of 868 MHz, 902–928 MHz, and 2.4 GHz; nevertheless, a data rate of 250 kbps is ideal for two-way communication between several sensor nodes and controllers [2].

Smart metering is one of the most popular IoT applications and is a contender for Zigbee technology; however, good coverage for these devices over long distances requires extending coverage into hard-to-reach locations, such as deep indoors and basements. There do not appear to be many studies looking particularly at 868 MHz low-power transmission within house-to-house propagation scenarios. There was a study conducted by the University of Sheffield which considered the problem of extending the transmission range of a ZigBee radio, and their work noted that the antenna technology used has a strong influence on the transmission range of a smart meter terminal. However, their study did not take into account the practical deployment scenarios within the UK housing stock. Further work in Refs. [3–11] provides more related and background information for these measurements, and these references have been used as background material to extend our work.

The authors of Ref. [12] carried out coverage evaluations of Zigbee technology in the 2.4 GHz band. With experiments carried out in a home environment, they showcased how linear interpolation theory can be used to evaluate the working of each node. They conducted theoretical analysis, which lacks the understanding of physical large-scale deployment. Similarly, for coverage evaluation and extension, Qin in Ref. [13] took advantage of a heterogeneous network consisting of WiFi and Bluetooth in addition to Zigbee operating at 2.4 GHz. With experiments, the authors showed how coverage can be expanded into hard-to-reach regions of a house; however, their evaluation was based on a small-scale network within a single-house environment. Similarly, the authors of Ref. [14] carried out simulations to evaluate the Zigbee performance for smart homes. There have been multiple studies investigating the coverage enhancement of LoRa networks [15–19] using mesh and/or multi-hop connectivity; however, these studies lack the evaluation of Zigbee networks at a large scale with physical deployment and at the 868 MHz band.

To improve the coverage for the 868 MHz band, especially in the mesh scenario, it is imperative to understand the propagation loss at a large scale. With this understanding, we developed and proposed a coverage prediction model by conducting measurements at the Building Research Establishment situated at Watford, UK [20]. With an understanding of the impacts of materials, building geometry, building stock, signal reach inside the building, and the distance to the measured reference point outside the building, along with the gaps identified in the related works, the following is a summary of the contributions made in this paper:

1. We investigate how mesh networks can be used to improve coverage in a large-scale city-wide network, focusing on coverage extension from indoor to deep indoor, from deep indoor to basement, etc.
2. A roof-mounted antenna is proposed to improve outdoor coverage to a sufficient level to provide the required coverage extension.
3. We also report the performance of the propagation of the 868 MHz mesh radio system, providing results from a study conducted in the town of Newbury, Berkshire, of building-to-building propagation.
4. A simple statistical model for the 868 MHz band, representing most UK conurbations, is presented.

These measurements were made in the 868 MHz, 900 MHz, 1800 MHz, and 2.4 GHz bands, which are the primary bands for SM Wide Area Networks (WAN) in the UK. The results of this study have allowed the improvement of coverage in hard-to-reach areas, as well as the planning of the mesh constellations, for houses without coverage. The typical size of the mesh network is 100 m to 500 m. The rest of the paper is organised as follows: Section 2 presents the methodology of our research, discussing the materials and methods. In Section 3, results are presented (with classical analysis of mean, standard deviation, min, and max values) and discussions are made. Section 4 draws conclusions from our work and discusses future work.

2. Methodology

The measurement system for the 868 MHz mesh radio system consisted of a narrow band ZigBee transmitter and receiver. The transmitter was mounted in a box on top of tripod as shown in Figure 1a; the receiver was mounted in a backpack with a GPS, laptop, and battery as shown in Figure 1b. The system was then powered up and synchronised so that we could measure both signal level and a proxy packet for service management. The height of the surrounding roof tops was noted, using a laser inclinometer, as was the road width in each direction (near side and far side).

Figure 1. (**a**) Mesh transmitter setup; (**b**) mesh receiver setup.

Two sets of experiments were carried out in this stage: test 1 and test 2. These tests were carried out in the vicinity of Newbury, UK (Figure 2) which is a typical UK town with a mix of buildings. In test 1, we used the following equipment:

- 1 × 868 MHz mesh Transmitter (26.9 dBm max output, 250 KHz bandwidth, 869.5 MHz centre frequency)
- 2 × uBlox 1 m accuracy GPS
- 2 × 0 dBi antenna
- Tripod Stand for the TX
- Backpack for the RX

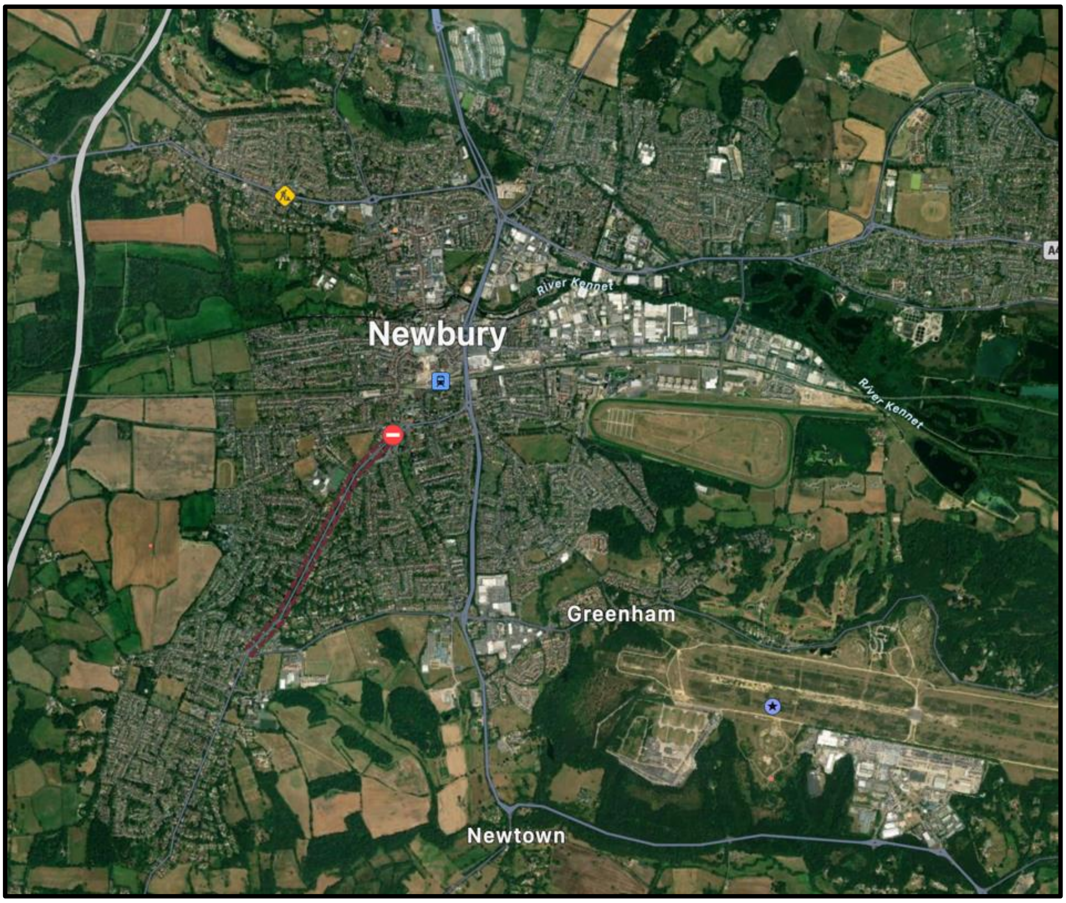

Figure 2. Map of Newbury, a typical UK town, with a mix of 1- and 2-storey buildings. (Source: Google Earth Maps).

The LOS 2.4 GHz Zigbee measurements used a similar setup to the 868 MHz mesh measurements, but focussed on 2.4 GHz frequency, with a bandwidth of 15 MHz. This was measured using the TSMU Continuous Wave (CW) receiver, using the same antenna as the coordinator. The same route was walked as Test 1.

In test 1, we used ZigBee dongles (PRoBeeZU10) with the 1.6 standard transmission distance. One unit was set up as a coordinator and the other was set up as the endpoint. A unicast broadcast was used to send data from the coordinator to the endpoint. The data packet size was 100 bytes, with 90 bytes of data and 10 bytes of addressing. The coordinator was mounted in a rucksack with a GPS. The ZigBee antenna was mounted clear of obstructions. A custom program monitored the bytes sent from the endpoint. If the bytes do not arrive within 1.5 s or are less than 100 bytes in size, then the sent packet is considered a failure.

In test 2, we set up a CW signal source which transmitted through the same antenna as the receive point. For this test, we used the following equipment:

- 2 × ProBee ZU10 with ZigBee standard 1.6 (+18 dBm max output, 2.44 GHz centre frequency, 15 MHz)
- 1 × uBlox 1 m accuracy GPS
- 1 × TSMU CW receiver and ROMES software
- 1 × 2.4 GHz Signal source
- 2 × 2.4 GHz 0 dB antennas

A single set of measurements was made on Greenham Common Airbase, shown in Figure 3, which consists mainly of open scrubland and gravel paths.

Figure 3. Map of the Greenham Common Airbase test area. (Source: Google Earth Maps).

3. Results and Discussion

We made a significant number of measurements in Newbury. The aim here was to evaluate the propagation measurements based on normal performance metrics for error: minimum, maximum, mean, standard deviation, and count.

Because of the absence of actual in-premise data and un-observed locations, we made measurements on the streets outside houses across Newbury as shown in Figure 4. This area was chosen to test each of the methodologies against baseline measurements. That way, the measurement points could be excluded from those that would be used to calculate coverage at that location; this exclusion distance was set to 10 m. We needed to include enough sample points to ensure a statistically significant result for prediction; however, with over 17,000 sample points, this was not a problem. Shown below is a subset of the results, representative of the complete set of data obtained through these measurements.

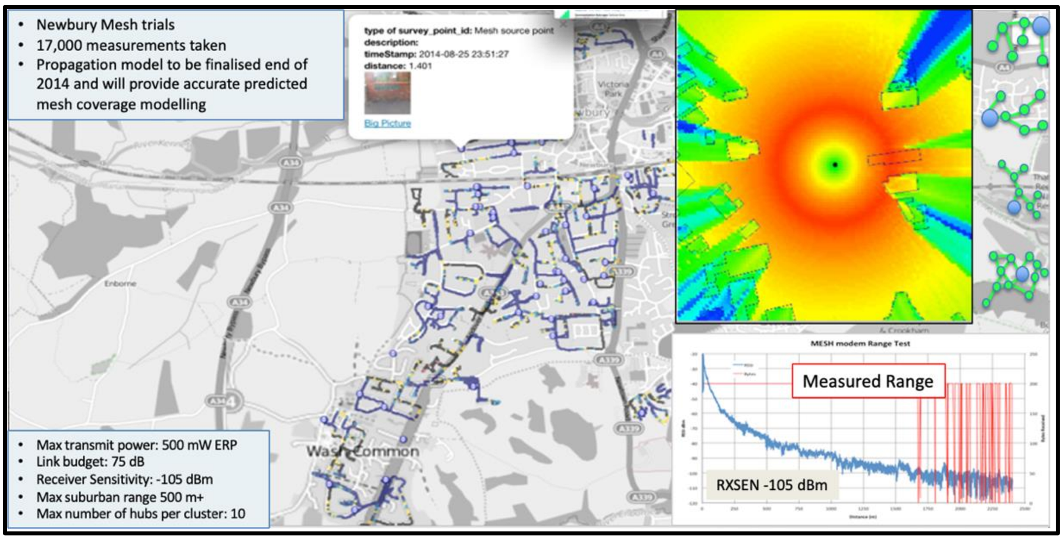

Figure 4. Coverage map of where the measurements were made in Newbury.

From Figures 5–7, the first failure point occurs at −101.29 dBm, which reflects the manufacturer's specification of −102 dBm quite well.

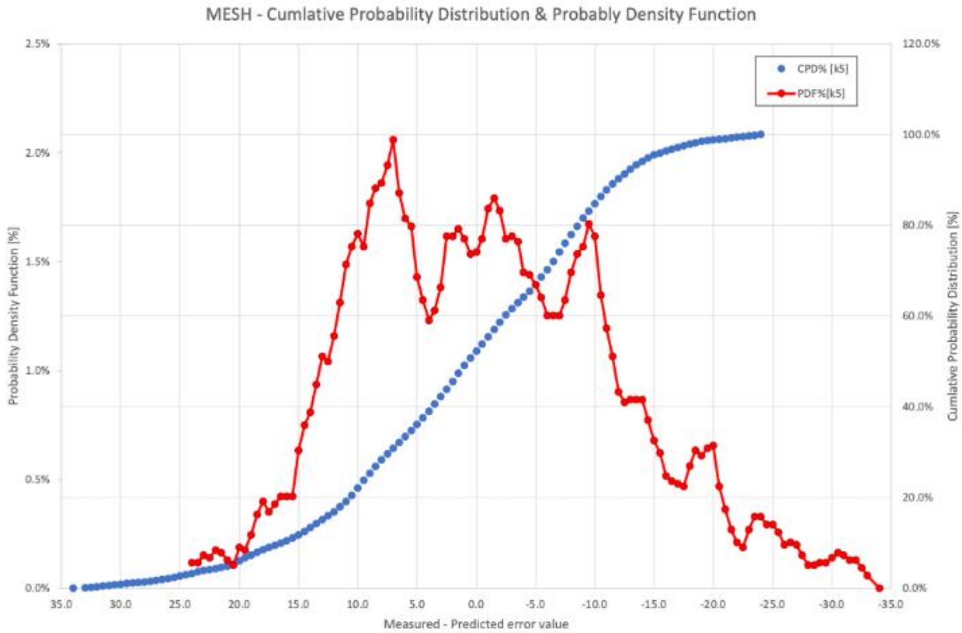

Figure 5. CDF and PDF based on a simple slope intercept model.

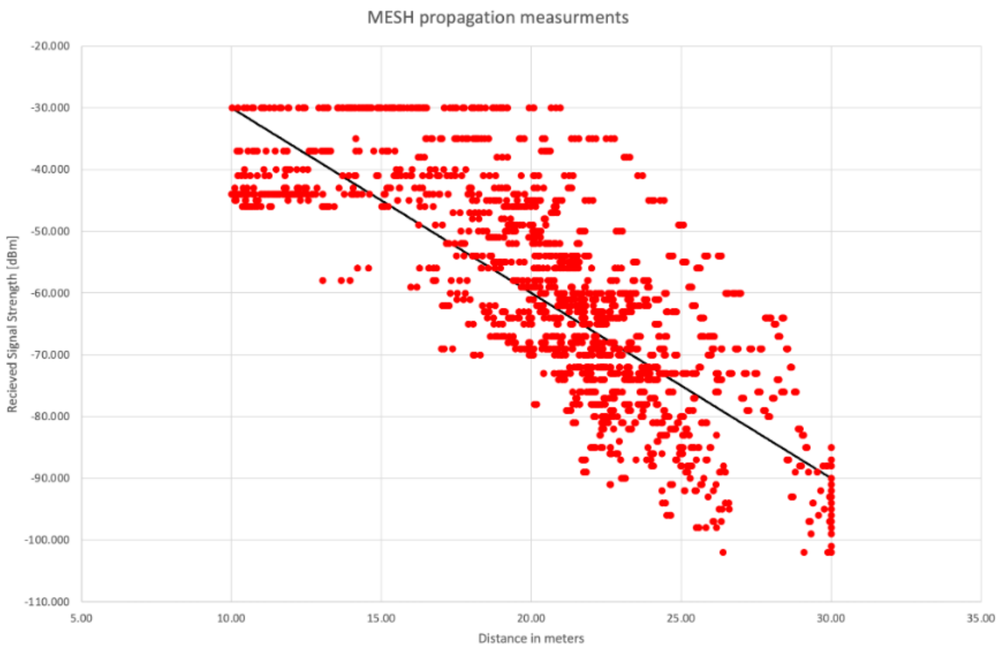

Figure 6. The log of the distance versus the log of the signal graph with a simple slope intercept model.

It can be seen from the results in Table 1 that simple slope intercept models perform well. However, there are some strange distance artefacts that are close to Base Station (likely to be GPS issues) and some signal level artefacts limiting the distance (likely related to fast fading).

Table 1. Performance of the 868 MHz prediction models.

Model	Min Error	Max Error	Mean Error	Std	Count
30 log (d/m)	−23.77 dB	+33.29 dB	1.42 dB	11.05 dB	1708

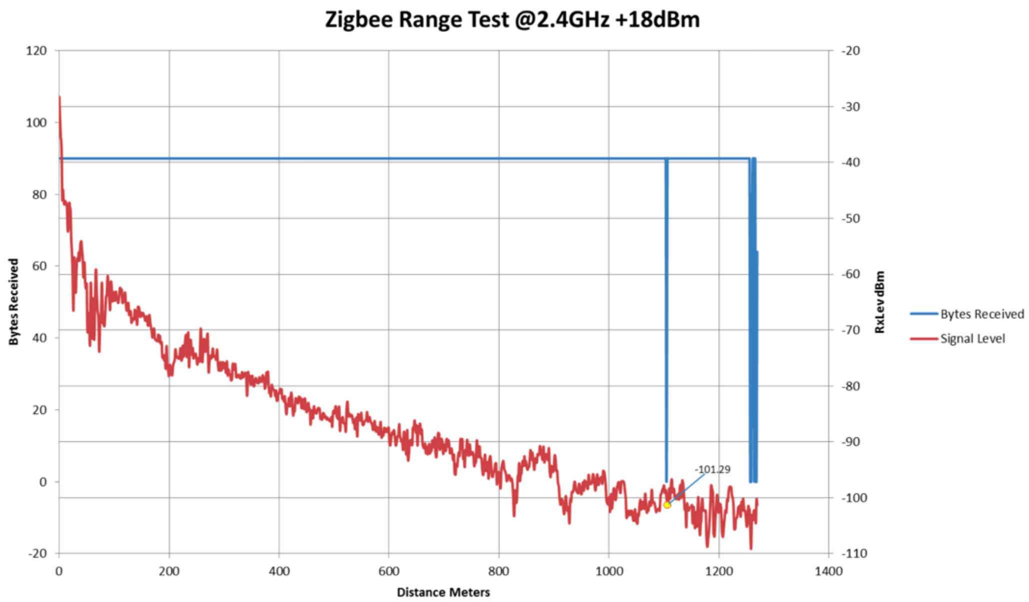

Figure 7. Line-of-sight test at 2.44 GHz ZigBee radio.

Processing this model through a limited set of measurement results, based on GPS and low signal artefacts, provides the results shown in Table 1. This allows planning of mesh networks with reasonable accuracy.

Mesh networks will make up a small but important percentage of the overall SM coverage. These homes form small clusters which we decided to call constellations, as they resemble constellations of stars; understanding how data messages will flow through these constellations is vital if we are going to deliver high-performing mesh networks for the Smart Meter Implementation Programme.

Furthermore, mesh networks will be used to augment coverage in three ways. We have estimated that the 868 MHz mesh radio system will be required at less than 1% (195,000) of all UK premises, amounting to approximately 28 million homes. However, to support that, we need to deploy enough units with mesh connectivity in cellular coverage to support the mesh-only areas. In summary, we have estimated that there will be three types of mesh deployments (example provided in Figure 8):

- Ad-hoc Mesh (0.5%): "Install and leave", where a cellular + mesh hub has been installed as cellular only cannot connect. This is shown as the yellow locations in the blue coverage area. Additional adjacent premise is automatically identified for cellular + mesh hub installation prior to any installation.
- Boundary Mesh (4%): installed to provide a cellular gateway for a mesh area. This is shown as the red locations adjacent to the white no coverage areas, and will include antennas.
- Planned Mesh (0.5%): where the property doesn't receive adequate cellular coverage. This is shown as the yellow location in the white no coverage area. Installations did not start until late 2019, but this allowed adequate testing of the mesh wide area solution.

The ZigBee radio measurements showed that even at low power, the signals propagate up to 1 km outdoors line-of-sight and still provide service. Due to these findings and solutions provided as discussed here, Zigbee is used by the Smart Meter Implementation Programme (SMIP) to provide a Local Area Network connecting smart Gas Meter and in-home display to electric meters and the Communication Hub.

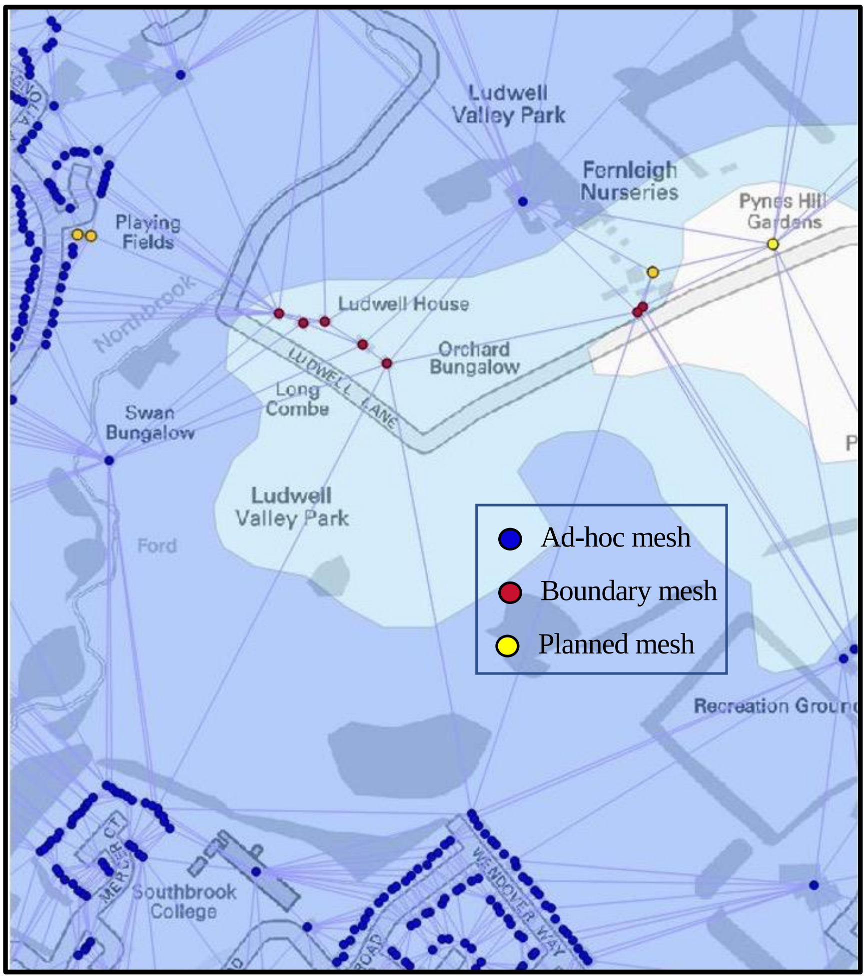

Figure 8. The complexity of the structure of the mesh networks.

4. Conclusions and Future Work

In this paper, we investigated the use of mesh networks at 868 MHz to increase coverage and proposed an additional mounted antenna to increase outside coverage while providing the necessary coverage extension for hard-to-reach indoor locations. Extensive measurements carried out in Newbury in both suburban and open environments for the 868 MHz band in UK conurbations shows that the 868 MHz mesh radio system propagates well in suburban environments and will provide a valuable contribution to coverage obligations required by the SMIP, providing coverage to those hard-to-reach locations. The outlook for the UK SMIP remains on track, to deliver the benefit promised to the UK population.

Coverage being a challenge for large-scale IoT deployment can be perturbed by costs associated with coverage extension. With the measurements, models, and coverage enhancement proposed in this work, we are able to make greener choices and manage our homes and their energy usage more efficiently. With the three types of practical mesh deployments discussed in this article, further wide-scale deployments can be carried out across the UK and globally. In this work, we showed how with our approach, only about 1% of UK homes will require mesh connectivity to achieve the desired coverage.

Understanding how these mesh constellations perform is vital to confirm the levels of coverage that can be provided. In addition, further testing of the 868 MHz propagation of the slope intercept model should be carried out. Investigation into more deterministic modelling will be the scope for future research, which will require more work and cost due to the required database describing the building outlines.

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References

1. Javed, A.R.; Shahzad, F.; ur Rehman, S.; Zikria, Y.B.; Razzak, I.; Jalil, Z.; Xu, G. Future smart cities requirements, emerging technologies, applications, challenges, and future aspects. *Cities* **2022**, *129*, 103794. [CrossRef]
2. Saeed, M.A.; Amin, I.; Mumtaz, F. Energy Management Using Wireless Technologies: A Comprehensive Study. In Proceedings of the 2018 9th International Renewable Energy Congress (IREC), Hammamet, Tunisia, 20–22 March 2018; pp. 1–6.
3. Whitteker, J. Measurements of path loss at 910 MHz for proposed microcell urban mobile systems. *IEEE Trans. Veh. Technol.* **1988**, *37*, 125–129. [CrossRef]
4. Rappaport, T.S.; Seidel, S.; Singh, R. 900-MHz multipath propagation measurements for US digital cellular radiotelephone. *IEEE Trans. Veh. Technol.* **1990**, *39*, 132–139. [CrossRef]
5. Cox, D.C.; Murray, R.R.; Norris, A.W. 800-MHz Attenuation Measured In and Around Suburban Houses. *AT&T Bell Lab. Tech. J.* **1984**, *63*, 921–954. [CrossRef]
6. Harley, P. Short distance attenuation measurements at 900 MHz and 1.8 GHz using low antenna heights for microcells. *IEEE J. Sel. Areas Commun.* **1989**, *7*, 5–11. [CrossRef]
7. Rustako, A.; Amitay, N.; Owens, G.; Roman, R. Radio propagation at microwave frequencies for line-of-sight microcellular mobile and personal communications. *IEEE Trans. Veh. Technol.* **1991**, *40*, 203–210. [CrossRef]
8. Mogensen, P.E.; Eggers, P.; Jensen, C.; Andersen, J.B. Urban area radio propagation measurements at 955 and 1845 MHz for small and micro cells. In Proceedings of the IEEE Global Telecommunications Conference GLOBECOM '91: Countdown to the New Millennium, Conference Record, Phoenix, AZ, USA, 2–5 December 1991; pp. 1297–1302. [CrossRef]
9. Goldsmith, A.; Greenstein, L. A measurement-based model for predicting coverage areas of urban microcells. *IEEE J. Sel. Areas Commun.* **1993**, *11*, 1013–1023. [CrossRef]
10. Kelly, K. Flat suburban area propagation at 820 MHz. *IEEE Trans. Veh. Technol.* **1978**, *27*, 198–204. [CrossRef]
11. Ikegami, F.; Yoshida, S.; Takeuchi, T.; Umehira, M. Propagation factors controlling mean field strength on urban streets. *IRE Trans. Antennas Propag.* **1984**, *32*, 822–829. [CrossRef]
12. Ding, F.; Song, A. Development and Coverage Evaluation of ZigBee-Based Wireless Network Applications. *J. Sens.* **2016**, *2016*, 2943974. [CrossRef]
13. Qin, Z.; Sun, Y.; Hu, J.; Zhou, W.; Liu, J. Enhancing Efficient Link Performance in ZigBee Under Cross-Technology Interference. *Mob. Netw. Appl.* **2020**, *25*, 68–81. [CrossRef]
14. Rajaei, H.; Mirzaei, F. IoT, Smart Homes, and Zigbee Simulation. In Proceedings of the Communications and Networking Symposium, Baltimore, MD, USA, 15–18 April 2018; pp. 1–10.
15. Jiang, X.; Zhang, H.; Yi, E.A.B.; Raghunathan, N.; Mousoulis, C.; Chaterji, S.; Peroulis, D.; Shakouri, A.; Bagchi, S. Hybrid Low-Power Wide-Area Mesh Network for IoT Applications. *IEEE Internet Things J.* **2020**, *8*, 901–915. [CrossRef]
16. Dangana, M.; Ansari, S.; Abbasi, Q.H.; Hussain, S.; Imran, M.A. Suitability of NB-IoT for Indoor Industrial Environment: A Survey and Insights. *Sensors* **2021**, *21*, 5284. [CrossRef] [PubMed]
17. Citoni, B.; Ansari, S.; Abbasi, Q.H.; Imran, M.A.; Hussain, S. Impact of Inter-Gateway Distance on LoRaWAN Performance. *Electronics* **2021**, *10*, 2197. [CrossRef]
18. Citoni, B.; Ansari, S.; Abbasi, Q.H.; Imran, M.A.; Hussain, S. Comparative Analysis of an Urban LoRaWAN Deployment: Real World Versus Simulation. *IEEE Sens. J.* **2022**, *22*, 17216–17223. [CrossRef]
19. Cotrim, J.R.; Kleinschmidt, J.H. LoRaWAN Mesh Networks: A Review and Classification of Multihop Communication. *Sensors* **2020**, *20*, 4273. [CrossRef] [PubMed]
20. Owens, D.; Ansari, S.; Cruickshank, H.; Tafazolli, R.; Imran, M.A. Building penetration loss measurements and modelling in the 900 and 2100 MHz band for smart meter installation. *Front. Commun. Netw.* **2022**, *3*, 1011754. [CrossRef]