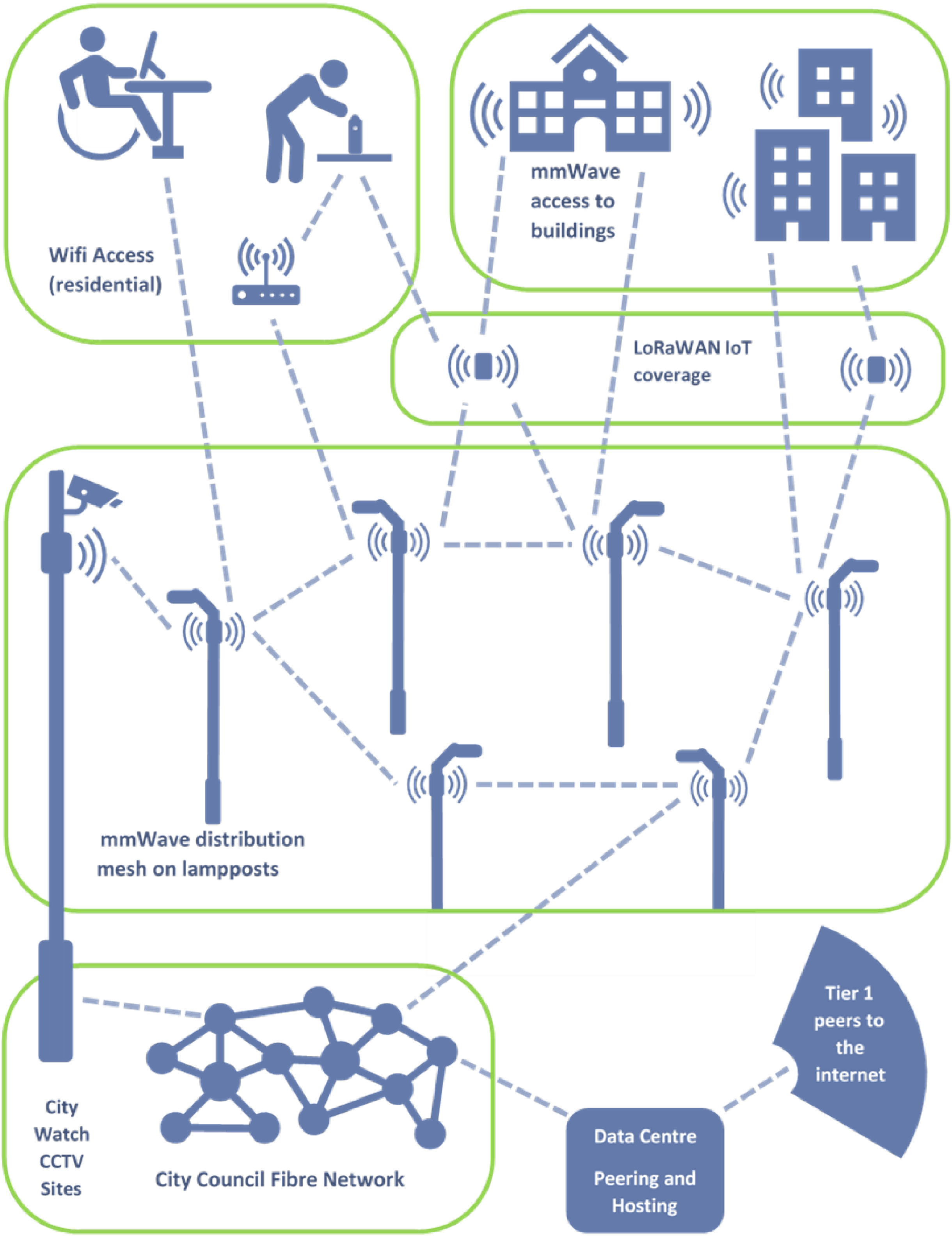
Liverpool 5G
Health and Social Care Testbed

Developing the Network

January 2020

Network Architecture



Background and Scope

The Liverpool 5G Health and Social Care Testbed ran from April 2018 to November 2019.

The project aim was to see if 5G technology could provide measurable health and social care benefits in a digitally deprived neighbourhood.

A suite of reports have been produced as a summary of the Liverpool 5G Health and Social Care Testbed.

This report covers the technology used in the trial, other aspects are covered in the companion reports:

- **Liverpool 5G Health and Social Care Testbed: Overview**

  Why we did it, what we did, who benefited, key learning and what's next

- **Liverpool 5G Health and Social Care Testbed: Benefits, Outcomes and Impact**

  The project outcomes, who benefited, and the overall impact and analysis of combined data from use cases

- **Liverpool 5G Health and Social Care Testbed: Developing the Network**

  Planning, installation and deployment of the network - 5G, WiFi, LoRaWAN - what we did, management and monitoring, and research and development as part of the project

All of the reports can be found on the resources page of our website

The project was delivered by the **Liverpool 5G Consortium**.

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Liverpool 5G and the Health and Social Care testbed

Background

The Liverpool 5G Health and Social Care Testbed started in April 2018 as part of the DCMS 5G Testbeds and Trials Programme and the greater 5G strategy, and ran for 20 months.

The project, the first 5G supported health trial of its kind in Europe, was given £4.9 million to see if 5G technology could provide measurable health and social care benefits in a digitally deprived neighbourhood. It is also part of the UK5G, national innovation network for the sector.

The Liverpool 5G Consortium

Liverpool 5G is a unique and innovative consortium of public sector health and social care suppliers, the NHS, university researchers, third sector organisations, agile local SMEs and a leading UK 5G technology vendor, who came together to deliver the Liverpool 5G Health and Social Care Testbed.
The partners and subcontractors:

- Sensor City
- Liverpool City Council
- University of Liverpool
- Liverpool John Moores University
- BluWireless Technology
- CGA Simulation
- Defproc Engineering
- AIMES
- Royal Liverpool and Broadgreen University Hospital Trust
- Digicredis (first 12 months)
- eHealth Cluster
- Safehouse Technologies
- The Medication Support Company
- Broadway Partners
- Derand
- Finch Electronics

Throughout the project, the consortium tried to address the following question:

> ***"Can 5G connectivity be sufficiently cheap and effective in health and social care provision that it will be cost effective to give free access to those unable to afford either phone or broadband access?"***

We knew that to answer this question we needed a series of technological solutions that care services could easily adopt and use.

We also focused on:

- Reducing the digital divide
- Providing affordable connectivity with the necessary level of service
- Creating capacity within social care services
- Improving efficiency in health and care services
- Improving people's quality of life and reducing social isolation

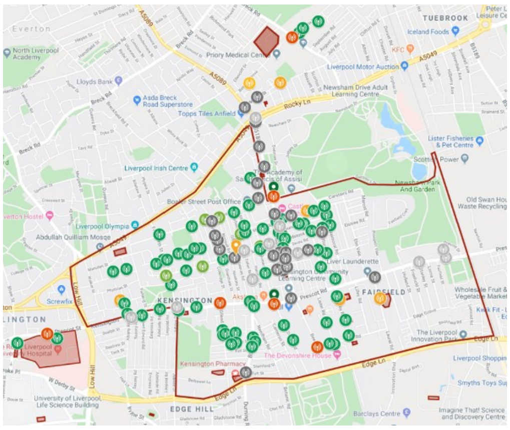
The largest mmWave network in Europe

The Liverpool 5G Health and Social Testbed brought together the challenges currently facing health and social care services and the opportunities created by 5G mmWave technology to develop a private mesh network to support services in the Kensington area of Liverpool.

We have shown how the 5G concept brings together new and existing communications technologies, with a focus on enabling health and social care applications in the field more cost effectively.

We combined Blu Wireless' British mmWave technology with WiFi and LoRaWAN connected to Local Authority backhaul, an independent data-centre hosting applications and internet carrier peering.

Nodes installed on a lamppost in Kensington, Liverpool



Node deployment

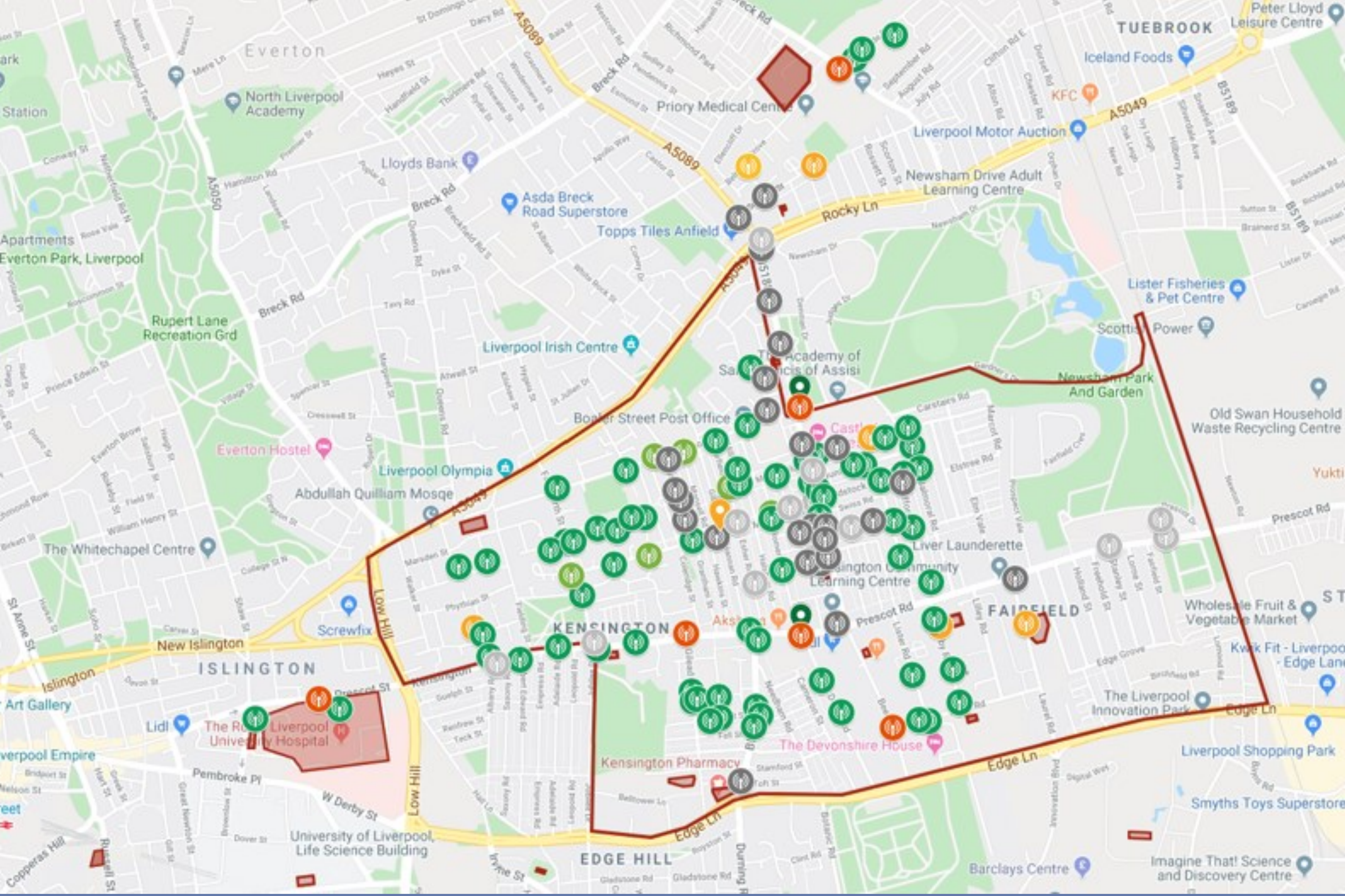
To tackle the challenging and conventionally expensive 'last-mile' access problem we built a network using 220 mmWave nodes and established network planning methodologies based on the learning from deploying the testbed.

We now have the largest mmWave mesh network in the UK.

The network has enabled us to deploy a significant number of IoT devices in the community and supported health and social care products for 179 people.

During the second year we provided gigabit wireless links to two community buildings: a local care home and a community learning centre, and added a significant deployment of IoT devices in the community.

The testbed has enabled us to develop cost models that compare the costs of a network under public ownership with existing commercial models.



02

The Network

Network Planning, Deployment and Installation

Planning

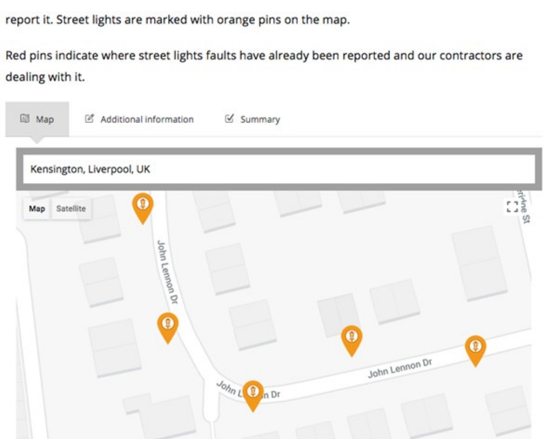
The Liverpool 5G mmWave network makes use of:

- Liverpool's Wide Area Traffic Control (WATC) fibre network
- mmWave modems at street-lamp locations
- dual-band WiFi Access Points (APs)
- mmWave modems on selected public and community buildings
- Local LoRaWAN network

The range of technologies, locations and ownership of resources meant that planning was always going to be complicated.

Target areas for coverage were established in conjunction with the Liverpool City Council to maximise the probability of accessing service users

Identification of suitable lamp-post sites as hosts for the mmWave distribution network was the most significant part of the deployment planning process, with planning constrained by the need of line of sight between nodes.



Lamp post data on Liverpool City Council website

For expediency, suitable posts were identified manually at first using the City Council's lamp-post location data-base, mapping and inspection. Google's map and street view tools provided a platform for collaboration for this purpose.

Early planning also involved liaison with Liverpool City Council City Watch, for access to Liverpool's Wide Area Traffic Control (WATC) fibre network. In principle this is available at any of Liverpool's CCTV camera sites, however some were unsuitable for back-haul due to congestion or limited capacity.

The Liverpool 5G mmWave network was connected to the AIMES data centre and to the AIMES Trustworthy Research Environment (TRE), which allows the collection of data, and access to other services.

Planning the site deployments manually was time consuming , taking approximately two days to plan, check and write up 20 sites.

Once developed, the CGA Simulation 5G Network Planning Tool was used, both to check the optimization of existing nodes and to facilitate further deployment.

Planning tools for a large scale network roll out will need further development to include the latest maps for site planning, and understanding the use of a planning tool for mmWave obstacle sensitive networks.

Wide Area Traffic Control network

The Wide Area Traffic Control fibre network provides a ring (now interrupted) of bundles of digital transport fibres around the city in support of the City's traffic control infrastructure and a CCTV network. It also provides dedicated links to AIMES specialist NHS data centre.

The fibre network assets are administered by the City Watch team in Liverpool City Council, and connections and upgrades are contracted exclusively to Siemens. The Liverpool 5G Testbed project had direct access to representatives in both City Watch and Siemens.

In principle access to the WATC fibre network is available at any of Liverpool's CCTV camera sites. However, some may be unsuitable for back-haul (congestion or limited capacity). Where feasibile, additional links were established from preferred Points of Presence (PoPs) for the 5G Testbed in Kensington and via mmWave links from the nearest viable PoPs.

A protocol was established whereby Siemens assess technical feasibility of proposed PoPs on request by Blu Wireless and then City Watch approve Siemens' work at the CCTV sites to make the capacity available and install Blu Wireless equipment.

For the Liverpool 5G Testbed network, traffic was routed to AIMES data centre transparently via the City's fibre network under Siemens' control.

Lamp-post site network

Access to suitable lamp-post sites as hosts for the mmWave distribution network was key to the deployment process.

The aim was to achieve acceptably uniform coverage of the area without excessive deployment of plant, crucially achieving a lower total cost of deployment per home than with conventional gigabit wireless equipment and so accelerating the provision of fibre -class service.

A protocol was established with Liverpool City Council Street Lighting department and an experienced approved contractor, Derand Ltd., to obtain approval of proposed sites in principle, subject to survey and then final approval after survey by the contractor.

Access to lamp-post sites was constrained by construction (use of concrete posts is not permissible), survey (mainly space for mains power modifications) and approval.

At each approved site LCC required modification of the mains supply to enable individual control and cut-out of the light and radio equipment. The approved contractor made the necessary adjustments to the mains power configuration at agreed sites and completed the installation of the equipment according to a method statement agreed with the council.

mmWave radios were attached to posts in groups of up to four using brackets and bands.

Node Manufacture and Installation

The DN101LC is a single radio 60GHz wireless node designed by Blu Wireless. Each unit consists of several parts and the main constituent components are as follows:

- (Printed Circuit Board Assembly) PCBAs – manufactured by ASK
- High speed RF radios – designed and manufactured by SiversIMA
- Cavium network processing unit (NPU) – suppled by Interface Masters
- Metalwork – CAM
- Internal cables – SWAN

The items were shipped to IEW who assembled the units then sent back to Blu Wireless, where configuration and final test were performed. The units were then shipped to Finch for kitting, final packaging, and labelling before sending to Derand for installation.

Node installation in action

In the second year of the project Blu Wireless established a formal supply chain with agreed responsibilities with the following entities:

- Finch Electronics: Stocking against Blu Wireless specified bill of materials, node configuration and kitting of installation sites
- Derand: Multi-node site installation on lampposts
- Siemens: Multi-node site installation on CCTV posts
- Broadway Partners: Network monitoring

Substantial time and effort went into establishing the necessary tools, processes and work instructions for each entity in the supply chain, and these were accompanied by training and support in order to seed the supply chain.

Nodes installed during the second year included internal hardware changes to accommodate the latest revision of baseband modem and PoE output but remained compatible with the first year deployment. Feature-set and performance were also determined by software release.

Nodes were installed during the second year with two versions of software: R1.1 initially and R2.0 introduced in June 2019.

WiFi Access Points

Commodity outdoor dual band WiFi Access Points from Ubiquiti (UAP-AC-M) were deployed at each site to provide end-user coverage for conventional devices in residential areas.

The Access Points were selected based on

- specified performance
- maturity in public access applications (including access security)
- packaging
- mesh capability
- power arrangement
- remote management tool
- cost

The selected WiFi Access points are designed to be attached to the pole using independent straps and were connected to one of the mmwave nodes at the site by gigabit Ethernet with PoE.

The remote management tool includes provision for automated channel planning. Only 5GHz channels were enabled initially, consistent with bandwidth and to avoid unnecessary interference to home WiFi in the more congested 2.4GHz band.

Nodes installed on a lamppost in Kensington, Liverpool

The mesh capability of the selected WiFi access points makes it possible to increase the density of the WiFi access if necessary independently from the mmWave distribution network.

Wifi coverage

The project team recognised at an early stage the importance of providing connections to a wide range of device types to enable a broad range of applications.

Of the available technologies supported by common devices (Cellular, WiFi, maybe Bluetooth and Ethernet) only WiFi was seen as practically useful for the end device link.

The intention was to enable connections either directly from WiFi APs on nearby street-lamps or, where necessary, with the addition of an in-building repeater compatible with the test-bed WiFi network.

Nodes installed on a lamppost in Kensington, Liverpool

A range of end devices have been attached to the network, including consumer tablets for games, lap-tops, smart-phones for care staff, and specialist devices for the PAMAN pharmacy assistant, chromatic camera and Docobo remote consultation terminal.

Chromatic Sensor, Paman medihub device, Docobo telehealth device

Unsurprisingly, we observed that location, building type and distance from the nearest WiFi AP had an effect on the success of connection.

The devices themselves also varied in capability with lap-tops, the Docobo devices and some tablets benefiting from larger antennas or able to use the less congested 5GHz band while smaller devices relied more heavily on the installation of repeaters or less economical fall-back connections.

In their study for Ofcom on the use of WiFi for Metropolitan Area applications (April 2013), Aegis spectrum engineering and Quotient Associates estimated the extent of WiFi coverage from an outdoor access point in a dense urban area. They concluded that a WiFi access point spacing of 60m would provide continuous outdoor coverage.

Based on 10dB attenuation per wall (each black line), their illustration below (Fig. 1) indicates a similar level of indoor coverage through two walls for homes within 15m of the access point and through one wall for a further 10m.

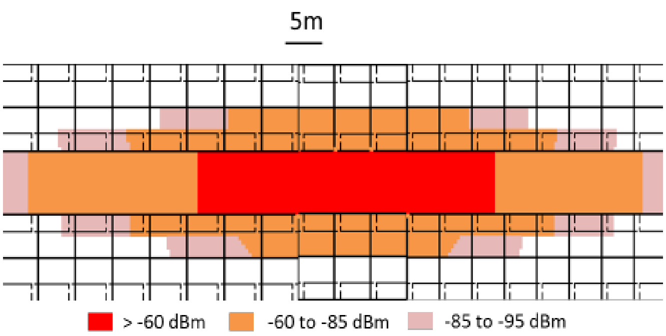


Fig. 1 *Note: the purpose of the study was to assess the risk of contention between access points and impact on spectrum use.*

For the typical street-lamp spacing of 30m in Kensington and Fairfield we could then expect workable indoor coverage throughout the residential areas with a WiFi access point on every street-lamp.

The deployment in Liverpool placed WiFi access points with each mmWave node at typical intervals of 100m, about one third of the street-linear density of street-lamps in served areas.

To validate the viability of this density of WiFi access points experimentally we have to review sites that have a WiFi AP within around 15m of a user's home or 25m where indoor coverage is augmented by an indoor repeater.

The following trial sites had these characteristics:

- Location 1 - In this location the WiFi AP was 42m from the home and provided connectivity to a PAMAN pharmacy assistant device with a WiFi repeater placed in the home in a window facing the node.
- Location 2 - PAMAN device was installed at this maisonette property. Initially connectivity was achieved to the WiFi access point at a CCTV site on the corner of a nearby junction at a range of 60m using a repeater placed in a window. Subsequently a WiFi access point was installed with a new mmWave site at a range of 21m from the property, achieving connectivity to a PAMAN device directly.
- Location 3 - A Docobo tele-health unit in a modern single story home successfully connected with a WiFi access point on a nearby street-lamp. The range from the access point to building was 15m.
- Location 4 - At this location a Docobo device in a traditional terraced home connected successfully with a nearby WiFi access point on a street-lamp across the road, 10m from the building.

The WiFi coverage observed in the trial was consistent with the Ofcom study model.

We would expect to deliver consistent indoor coverage in residential areas with public access WiFi with a WiFi access point on each street-lamp, noting that only one in three (or about one per street) would need mmWave back-haul, the rest being low-cost repeaters.

While the project demonstrated the value of WiFi repeaters in bridging transitions into and within buildings, their acceptance and maintenance in ad-hoc installations was less straightforward.

In community buildings including Kensington Community Learning Centre, installation was possible through the cooperation of facilities staff but to be useful they had to be positioned near openings and within reach of power which was sometimes impractical in the long term.

Node installed on building

For residential applications a self-contained plug-top repeater design would have been the least intrusive but offered insufficient flexibility in location to be effective. The cabled alternative adopted for the test-bed could be placed to good effect in a window on a side of the house with coverage but proved inappropriately intrusive in most cases.

In summary, an installation supporting a wide range of devices needing access by WiFi would ideally include installation of an in-building access point (as for home broadband) and whilst this is in no way an onerous requirement it can't be ignored for ubiquitous coverage. 3G or 4G coverage provided by small cells on the network could improve indoor coverage as a result of the more favourable link budget and more consistent device performance at the cost of restricting the types of device served (also generally more expensive) and increasing operating costs.

The LoRaWAN coverage across the area was increased as more gateways were installed. Valuable lessons were learnt in terms of access to buildings and co-locating with the mmWave nodes at sites naturally combining power and back-haul.

Our ideal, elevated location for wide area coverage from a single device on the fire station tower had to be abandoned as although we had the support of the local managers, gaining official approval was not achievable due to the complexity of building ownership and the public sector approval procedures.

Network Performance (Latency Requirements)

The devices and services that were used across the network had differing performance requirements.

The most demanding use case was the Loneliness Quizzing and Gaming App, from CGA Simulation, where several participants use the video feature of the game simultaneously. This was the only use case where latency was relevant to performance. Contention for upload speed was also important, with the more contention the more TCP/IP packets lost and the more difficult it is for the server to keep the game clients in synch.

This use case was chosen as the most suitable for investigating network performance and latency. The key learning points were:

- Reliable internet connection is required for the application to work. It needs 80 Megabit and low latency so the players have a responsive experience. The main latency requirement is that the loop back time between the game server and client should feel responsive i.e. be under half a second. On poorly performing networks any lost packets have to be rebroadcast, packet loss builds up and the servers become sluggish. The application also runs differently on different internet connections so extensive testing must be carried out in each location on the 5G network before performing a live user trial.
- Testing the app on various internet connections as well as 5G allowed for direct comparison, identifying which solution was better. It was clear the 5G handled the app much better and allowed the sessions to run without any interruption or loss of signal. All users were able to use the video chat when connected to the 5G network , unlike on other connections where video chat would sometimes be disabled to stop it interfering with the game.

ITU studies into latency for interactive computer apps show that below 100ms round-trip few users find delay unacceptable but, as a budget, most of this has to be allocated to display, computation and I/O processes leaving little as 50ms for communication. VR apps become sensitive to latency with round-trip delays as low as 7ms.

Uncongested 3G and 4G cellular networks achieve 50ms – 60ms to a national data centre . VDSL broadband introduces around 5ms round trip delay in the modems in addition to carrier delays to points of hand-over (1ms round trip per 100km on fibre).

Blu Wireless mmWave links deliver round-trip times of around 0.4ms per link with the possibility to trade delay for efficiency. The indication is that up to 17 links can satisfy the requirement for VR and AR applications. Whilst multi-hop links are slower than dedicated fibre to the premises they remain faster than VDSL, opening the possibility of VR and AR applications with centrally hosted processing.

LoRaWAN Public Access Network

As part of the Liverpool 5G testbed, DefProc Engineering provided a public access LoRaWAN Network using The Things Network with 5G backhaul.

The LoRaWAN gateways installed were a customised product from Dynamic Devices Ltd. Working directly with them ensured that the gateways were suitable for outdoor mounting and use, and included humidity and temperature sensors to allow remote monitoring of internal environment of the gateway's enclosure.

DefProc Engineering modified the supplied software on the gateways to allow for remote monitoring and maintenance of the gateways, and added alerts to proactively notify of any interruption of gateway operation.

Working with BluWireless, DefProc Engineering planned and identified 5G node locations that would be the most suitable for gateway deployment.

Early installation was made on two CCTV sites and an 8m lamppost site, however it proved difficult for the LoRaWAN signal to travel through the tightly packed streets of terraced houses, and it suffered heavy attenuation.

It was decided that in order to ensure connection at the participants home locations additional, high-level gateways should be installed.

DefProc Engineering made arrangements with AIMES to mount a gateway on the roof of their building in the Liverpool Innovation Park, which enabled a LoRaWAN signal to cover the whole of Kensington & Fairfield and also be supported by the gateways in the more densely populated area that have the 5G backhaul. This proved to be successful and solved the network difficulties .

In order to provide full cooperation to the project, the LoRaWAN message forwarding for one of the LoRaWAN Gateways was remotely updated to be dual forwarding. The gateway sends and receives LoRaWAN messages for both The Things Network and Stream LoRaWAN providers. This offered extra support to Safehouse Technology's sensors, that use the Stream provider.

A further two gateways were later deployed within the Kensington area.

The location of the LoRoWAN gateways was also mapped into the CGA planning simulation.

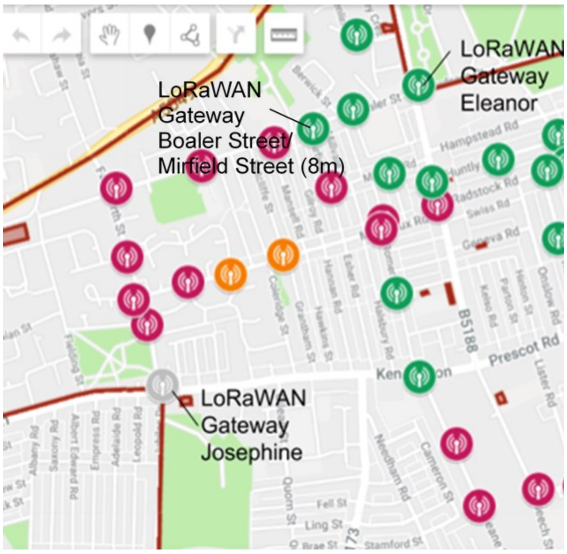
Completed gateway mounting at Breckside Park Care Home

Using 5G as a backhaul

LoRaWAN is a low bandwidth protocol where each LoRaWAN device can send a maximum of 1kB/month of upstream messages, and each LoRaWAN gateway forwards any LoRaWAN messages it receives via it's radio antenna (uplink messages) to a known point on the internet (the LoRaWAN provider's routing server) for that provider to either decrypt into the correct LoRaWAN application, or to drop as unroutable.

Similarly, the gateways have to forward any LoRaWAN packets they receive from the LoRaWAN provider (downlink messages) and send those out unchanged, as the provider has already encrypted those for a specific device that has been calculated to be in range.

As a result the latency and stability of the route to the internet (backhaul) for each gateway is critical to the performance of the LoRaWAN network as a whole.



First network plan using two CCTV sites and one 8m lamp post

The location of a LoRaWAN gateway also influences the choice of backhaul technology. While gateways can be sited indoors with good access to power and network connections, for maximum coverage area across an area of a city, gateways benefit in range and signal fidelity by being placed outdoors, up high, and clear of surrounding structures.

To be effective, the backhaul needs a stable connection and low latency. These can be provided in several ways, however each have their limitations:

- Ethernet - a preferred solution for low latency and stability, but no available local network point to connect to in many locations.
- WiFi - link stability often insufficient on permanently sited outdoor gateways; if a local WiFi hotspot is needed can be costly to install.
- Satellite - costly and have a high latency (up to 2 seconds each direction).
- Mobile data (3G/4G) - not a low latency solution - latency in the backhaul link may be around 0.6 secs (600ms), and choice of SIM card provider can be critical for continual operation of devices.

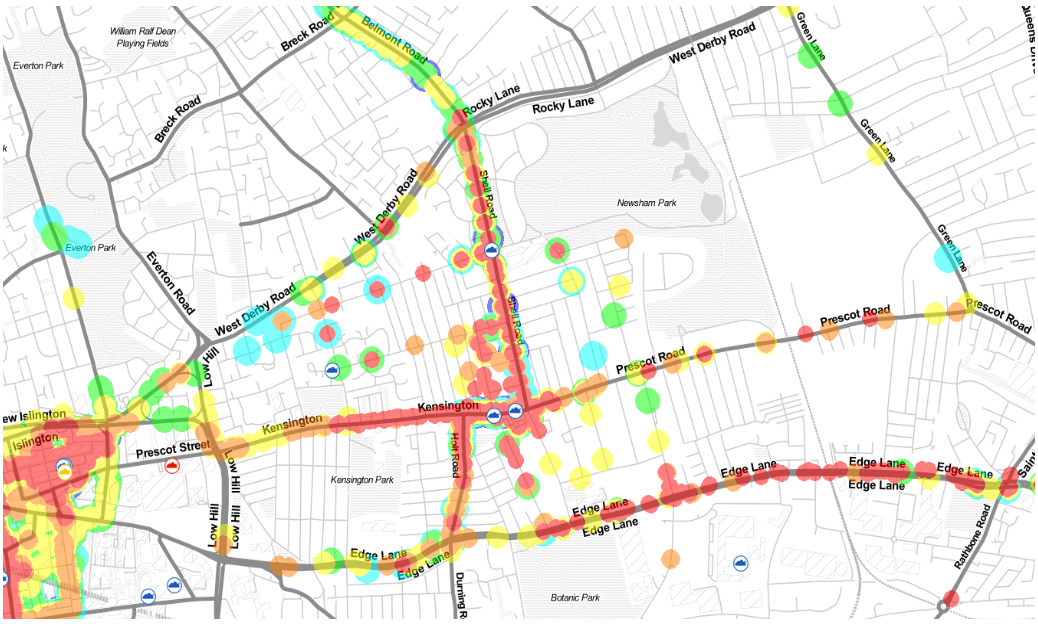
By using a 5G connection for the backhaul, the Liverpool 5G testbed offers ease of networking to type of position of LoRaWAN gateways — providing a high bandwidth, stable connection in outdoor locations that can be placed without the cost associated with having to dig or wire the entire route — with the low latency that benefits the end devices using LoRaWAN.

To determine the exact coverage area of the LoRaWAN gateways, a number of signal tests were performed. Using the public mapping application from ttnmapper.org, the GPS coordinates of the messages sent a LoRaWAN device sending regular messages is referenced to each of the gateways that receive each message, and the reported signal strength from each one.

When these transmission positions were plotted, along with a colour indicating the received signal strength indication (RSSI), a heatmap of the coverage area was created. The main roads around the testbed area are shown with many more recorded points, but mapping activity through the more dense residential streets shows complete coverage over the whole testbed area.

To try and determine the latency of the 5G network connection, a "ping test" was performed from each gateway to a common network device. The ping utility measures the time it takes from sending a single Internet Control Message Protocol (ICMP) to a chosen target computer and reports the time elapsed until a reply is received. Latency is therefore a measure of the amount of time it takes for a message to traverse a network path to the target device.

Even with multiple radio hops, the 5G connections showed lower latency than other available radio technologies (and are in the same order of magnitude as a wired broadband connection out to the ISP's first hop). The minimum latency added by each 5G hop was calculated to be approximately 0.25ms (250µs), so packets can be expected to take a minimum of 125µs to cross each 5G radio link. On average each hop added 2.15ms of latency (1.08ms per radio link), though it is worth noting that occasional packets show an order of magnitude greater latency.



A heatmap of TTN LoRaWAN received signal strength at tested locations across the testbed

Monitoring and Network Management

Blu Wireless mmWave nodes are equipped with mobile data modems for out-of-band access for configuration of network parameters. These modems operate within a closed private network via an L2TP Network Server (LNS) hosted by Blu Wireless.

Monitoring tools developed by Blu Wireless in the first year were:

- Telegraf - retrieves technical performance data from the nodes and transmits to the centralized Influxdb database
- Influxdb - the database that holds the information from the devices such as radio statistics
- Grafana - the GUI used for data visualization and analysis

The monitoring solution continued to work seamlessly as new nodes were installed and all new nodes were tracked and displayed within the tool.

Blu Wireless also initiated integration of alerting, triage and maintenance of the network with Broadway Partners' Network Operation Centre (NOC), and Broadway Partners were trained in the use of the monitoring tools.

For the LoRaWAN network, DefProc Engineering developed a dashboard system to track the performance of each gateway, and carried out the monitoring of this network.

The data for the dashboard comes from the Things Network API, who are the LoRaWAN network service provider. The API is checked periodically and the recorded data then displayed onto an overview dashboard. This also provides email alerts if a gateway goes offline. There are there are two further dashboards; 'Local Data' and 'Remote Data'. These give more specific and detailed information about any selected gateway. The data comes from monitoring programs that run directly on the gateways themselves, Prometheus and Node Exporter.

Dashboard view of all monitored LoRaWAN gateways

Broadway Partners became part of the project in the second year, to provide 24/7/365 network monitoring of the backhaul, 60Ghz and 5Ghz access network.

They provided:

- Alerts and notifications to service users, management and local installers in the event of an outage, using Simple Network Management Protocol (SNMP)
- Network capacity management – having enough bandwidth to keep the system working.
- Installer commissioning support – network acceptance during installation.
- Service user support for accessing the network and reporting network performance issues.

From a central Network Operations Centre, Broadway monitored the network using Blu Wireless's in house management tools. The tool allowed Broadway to visually monitor the network, providing a quick and accurate means of diagnosing network issues.

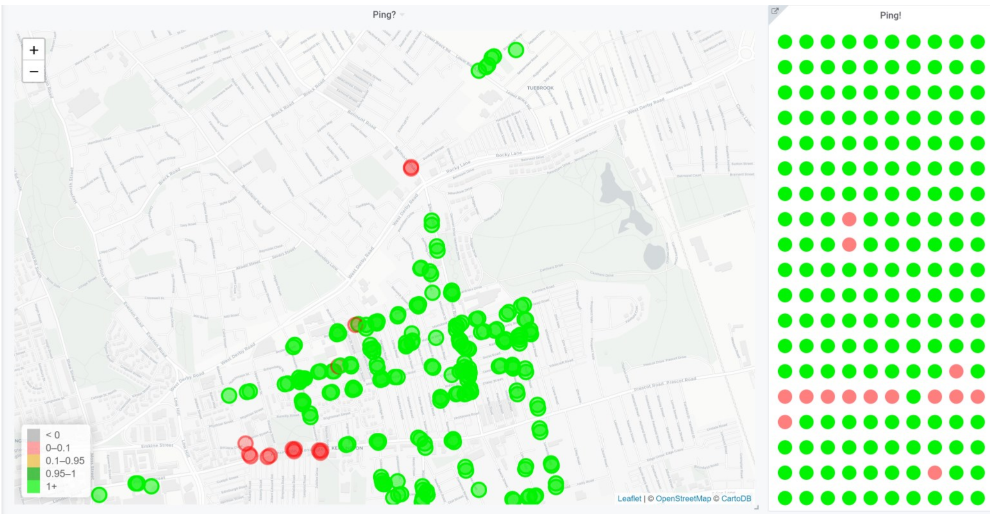
The tool shows problem nodes down to the exact location as well as degraded services, maximum TCP throughput of links, modulation history, link distances, radio temperature and SNR margins.

On several occasions Broadway were able to manually alert service users of an outage and report to the exact node where they felt the issue was.

Network administration and patch management was achieved through close collaboration with BluWireless and a separate ticketing system.

The BluWireless system was found to be very versatile and continued development will enable the service to allow for more automation.

Blu Wireless have taken an action to provide an SNMP agent for Broadway to integrate with their NOC, which will enable automated alerting of issues with the network and reduce fix time. The Blu Wireless SNMP agent is outside the scope of this project.



Blu Wireless network management tool

Trustworthy Research Environment (TRE) and cloud services

The Liverpool 5G network is connected to the AIMES data centre at Kilby House Liverpool Innovation Centre, through the Liverpool City Council dark fibre network.

This is then connected into the AIMES TRE and AIMES cloud services, allowing the collection of data and access to further services.

For services based in the public cloud (i.e. AWS, Azure, Google) connectivity is provided by either VPN across the internet, or direct physical connection.

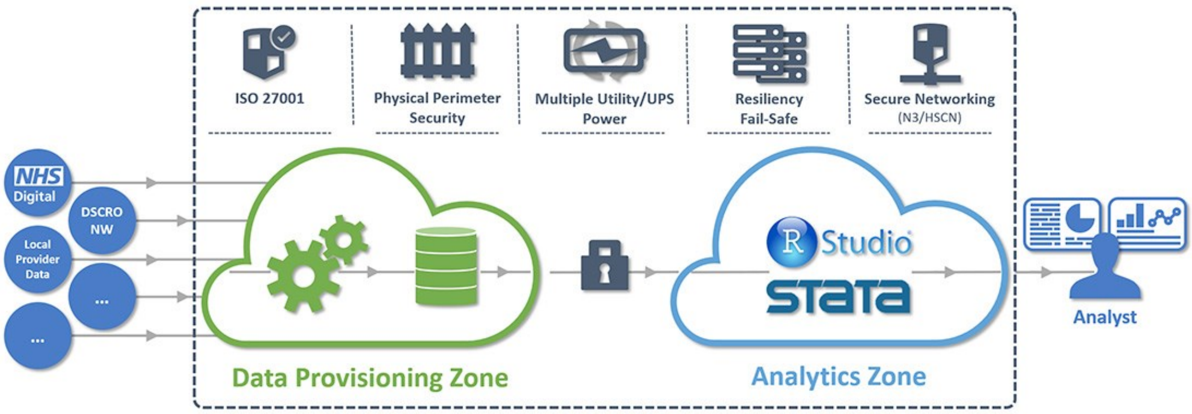
The data centre has three independent internet providers, configured as multi-homed in BGP failover, with bandwidth of up to 3Gbps. AIMES is a full member of RIPE, allowing them to operate as a Local Internet Registry (LIR) under the Autonomous System (AS) Number 48954.

AIMES is the leading commercial provider of TREs in the UK and provide a range of bespoke environments for NHS bodies and health researchers throughout the country.

Integrating the TRE into the network has created an ecosystem where Personally Identifiable Data can be collated, pseudonymised or anonymised and accessed by researchers, under GDPR/ DPA 2018 and robust DSP information governance compliant conditions.

By connecting to a scalable environment where data can be securely hosted and curated, the data can be made appropriately available not only to clinicians and care workers but also to academic, public and private sector researchers in a Trustworthy Research Environment (TRE).

Those with access to the data can use effective monitoring technologies and collect data safely and securely, and researchers can use the data (via the TLE) to make new logical connections offering opportunities for environmental impact, epidemiological, cohort and geographic (both City wide and local area) based studies.



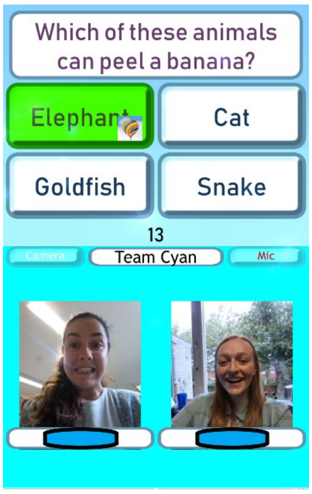
Trustworthy Research Environment Diagram

Summary of devices and services used over the network

A range of end devices have been attached to the network, including consumer tablets for games, lap-tops, smart-phones for care staff, and specialist devices for health and social care support. These included:

Loneliness Quizzing and Gaming App, from CGA Simulation

This is a social gaming app that brings people together to take part in online quizzing, games and chat. It features video communication to allow users to meet and take part in the game from different locations.



Testing CGA's app

Push to Talk, from Defproc Engineering

Push to Talk users press a button, indicating they want a chat, and are connected via their phone to another user who has also pushed their button.

Chromatic Sensors from the University of Liverpool

The Chromatic Sensor is installed in the home, and provides alerts to carers about any unusual event (e.g. a fall, seizure, intrusion etc.) raising the level of concern and sending an alert.

Paman Service, from The Medication Support Company

Paman service uses a simple video-audio device (Medihub) to link to a pharmacy team who assist with taking medications. After a medication review with a clinical pharmacist, users are provided with a device in their home.

Safehouse Sensors, from Safehouse Technologies

The Safehouse system sensors monitor conditions and environment in the home and provide telecare alerts that notify friends, family & professional carers of any problems, via a dashboard app.

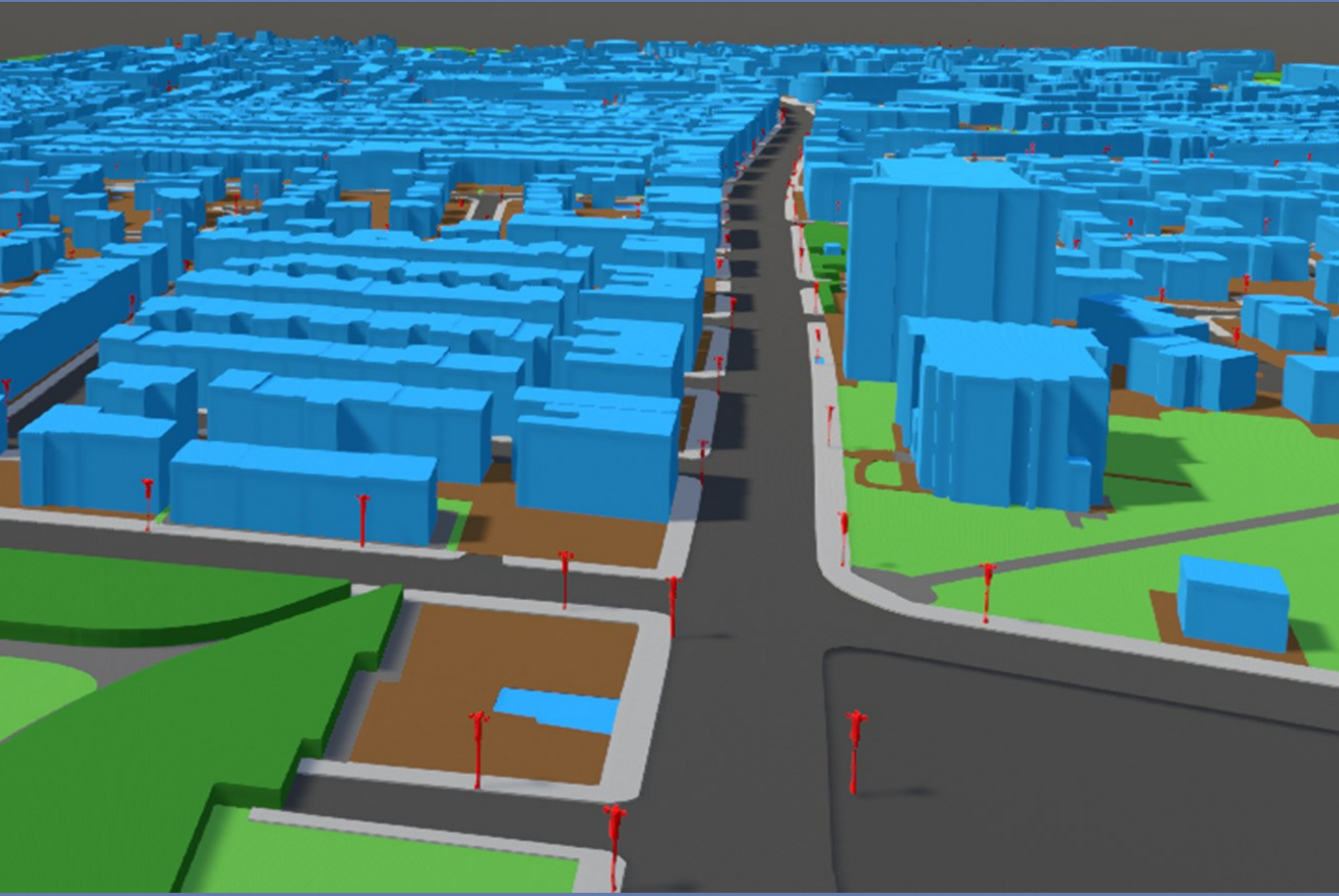
Telehealth and VR headsets from NHS RLBUHT

Telehealth in a Box uses a portable multi-media telehealth monitor, supplied by Docobo, to record clinical, life style and quality of life data each day, and deliver information to patients.

Patient using a VR headset

VR Headsets in Palliative Care, where Samsung Gear VR headsets are used to provide the virtual reality experiences as a distraction pain management.

Please see Liverpool 5G Heath and Social care Testbed: Benefits Outcomes Impact for further information on the outcomes of the use cases



03

Research and Development

Overview

Research, development and implementation of emerging technology played a key role in our 5G network.

- Blu Wireless' innovative British 5G mmWave technology was developed and refined throughout the project, responding to feedback and learning as it went along.
- CGA Simulation designed a 5G network planning tool that uses a 'digital twin' simulation of Kensington, 3D mapping and new time-saving algorithms to automate planning and node placement, saving both time and money.
- The University of Liverpool produced algorithms to reduce power consumption across the network.
- Liverpool John Moores University built a simulator to model the properties and parameters of 802.11ad Networks. The team integrated CGA Simulation's 5G network planning tool into their simulator, to model optimal placement for 5G nodes and to make sure the simulator faithfully represents the Liverpool 5G network.
- Our academic partners both produced papers and theoretical work; their findings were applied to the network to improve and optimise different elements of the technology.

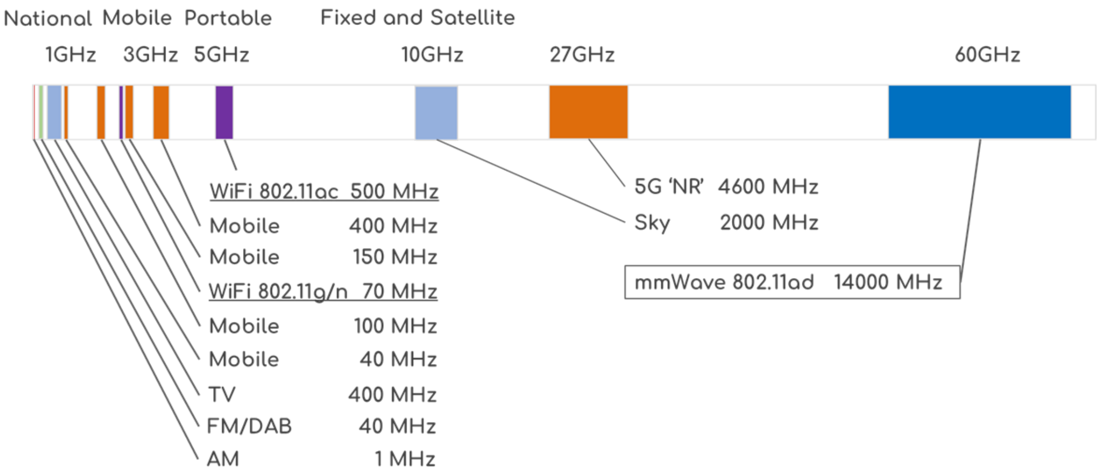
Blu Wireless Technology - 5G mmWave nodes and mesh network

Blu Wireless Technology specialises in the development and delivery of gigabit rate millimeter wave (using wireless spectrum at 26, 28, 57-71 GHz) wireless technology for consumer and telecom infrastructure applications. To enable 60GHz as a channel for high-quality mobile data experience consumers expect in the 4G/5G era, they developed a new class of 5G mmWave Systems IP that is compliant with WiGig IEEE 802.11ad specifications.

The mmWave mesh radios used for street-level distribution rely on largely clear line-of-site propagation between nodes. The underlying technology is suitable for mobile operation but primarily at short range and not yet widely supported in widely available mobile battery-operated devices. The technology is highly suited to low-cost fixed access (replacing fibre-to-the-premises) and backhaul over distances of several hundred metres per hop.

For public and community buildings the mmWave mesh radios were deployed effectively on external surfaces without special alignment and with power and connectivity carried by a single cable. Along with each mmWave distribution node, a WiFi access point was installed delivering both commonly supported bands (2.4GHz and 5GHz) in parallel.

The chart below summarises consumer wireless access technologies in the context of frequency (left to right) labelled with technology and available bandwidth. The lower frequency bands most suitable for mobile use are to the left (these frequencies penetrate and diffract around buildings) and the mmWave band is to the right, benefiting from massive bandwidth. The technology offering the greatest bandwidth and mobility for applications along with availability and freedom from the licensing control of mobile networks is WiFi IEEE 802.11ac.



Summary of consumer wireless access technologies in the context of frequency (left to right) labelled with technology and available bandwidth.

EMF and Safety

The mmWave modems use radio ICs capable of output power at compression of 12x +12dBm at compression or 23dBm (0.2W). To provide acceptable linearity the radio transmitter is operated with at least 3dB back-off to 20dBm (0.1W). The antenna array used in the mmWave nodes is capable of up to 24dB gain (directivity) with around 2dB additional loss resulting in a maximum EIRP of 42dBm and beam width of 0.05 steradians (or around 14.5deg).

ICNIRP basic restrictions for power density for frequencies between 10 and 300GHz specify 10W/m2 to be averaged over 20 cm2 (equivalent to 0.02W per 20 cm2) and 0.92 minutes with a maximum of 20 times this value averaged over 1 cm2 (equivalent to 0.02W per 1 cm2). FCC has specified a limit of 5 mW/cm2 averaged over 6 minutes for occupational or controlled exposure and 1 mW/cm2 averaged over 30 minutes for general population or uncontrolled exposure.

The mmWave modem antenna illuminates the 20cm2 ICNIRP test area fully at a range of 20cm and falls below the 0.02W limit at 36cm. The signal level falls below the FCC 5mW/cm2 for occupational exposure at 0.16m and the 1mW/cm2 for general population at 0.36m.

Configuration and Monitoring

The mmWave nodes were configured from a central data-base configuring traffic routing at each node with networking parameters via the standard APIs and Blu Wireless radio parameters via a vendor command API. Initially the mmWave network configuration was managed manually by Blu Wireless.

The mmWave nodes provide extensive RF link performance data including currently active Modulation and Coding Scheme selection, measured signal and noise levels, packet error rates. A default set of data was monitored for storage and back-haul with scope to focus on specific parameters and higher sample rates from interesting links and nodes.

The WiFi access points were configured using the vendors commercial centralised configuration and monitoring tool (UniFi Controller).

Initial connectivity to mmWave modems for control and configuration purposes were established via a mobile data modem at each node linked to a private network via an L2TP Network Server hosted by Blu Wireless. (Under exceptional circumstances the nodes can be accessed locally via Bluetooth.)

By default the network provides no access to user devices. Access to the network by user devices (WiFi devices or devices in buildings) were initially managed manually by Blu Wireless, and later by Broadway Partners.

Each node includes a Linux-based network processor that has a number of internal interfaces with Layer 3 addresses used for configuration, operations, administration and maintenance. These internal interfaces are not directly visible to users.

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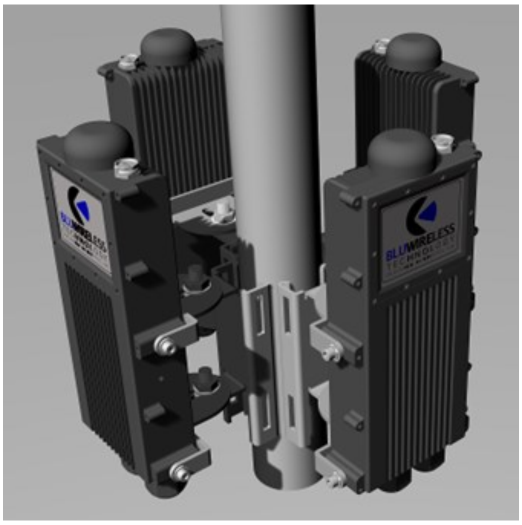
User traffic is tagged by the mmWave modem or WiFi AP at Layer 2 and flows through the network of modems to and from the data centre where all user traffic processing takes place including switching, routing, DHCP, accounting and any segregation. Traffic between users is not switched or routed locally within the distribution network. The wide bandwidth and rapid scheduling of the mmWave packet processing allows store-and-forward processing to be used without significant penalty, even with multiple hops.



5G mmWave nodes in 360° configuration

The route taken by flows between user and data centre through the distribution network can be changed to avoid broken links. A flow may arrive at the data centre via any one fibre PoP.

OA&M connections are made either via separate flows through the distribution network when available or directly to one node at each site via a mobile data modem.

Technology and Adoption Readiness

Blu Wireless' innovative British 5G mmWave technology developed and was refined throughout the project, responding to feedback and learning as the network developed.

Nodes installed during the second year included internal hardware changes to accommodate the latest revision of baseband modem and PoE output but remained compatible with the first year deployment. Feature-set and performance were also determined by software release.

Nodes were installed during the second year with two versions of software: R1.1 initially and R2.0 introduced in June 2019.

Blu Wireless development kit equipment also required modification and additional post-top hardware for mesh deployment.

Blu Wireless has now developed a new generation of wireless node which brings together the NPU and PCBA into a single board to simplify the amount of piece parts and reduce assembly time. This change was incorporated into a specific wireless node targeted at the rail sector. Learnings from this new generation of product can also be transferred to the fixed wireless access segment.

CGA Simulation - Network Planning Tool

CGA Simulation designed a 5G network planning tool that uses a 'digital twin' simulation of Kensington, 3D mapping and new time-saving algorithms to automate planning and node placement, saving both time and money.

In order to plot the optimal placement of nodes a virtual copy of Kensington was created. CGA collaborated with Ordnance Survey to obtain accurate data for road networks, terrain, buildings, street furniture and natural assets to make the accurate 3D model of Kensington.

CGA also collaborated with Liverpool City Council to obtain lamppost data as the nodes are fitted on lampposts to create the mesh network.

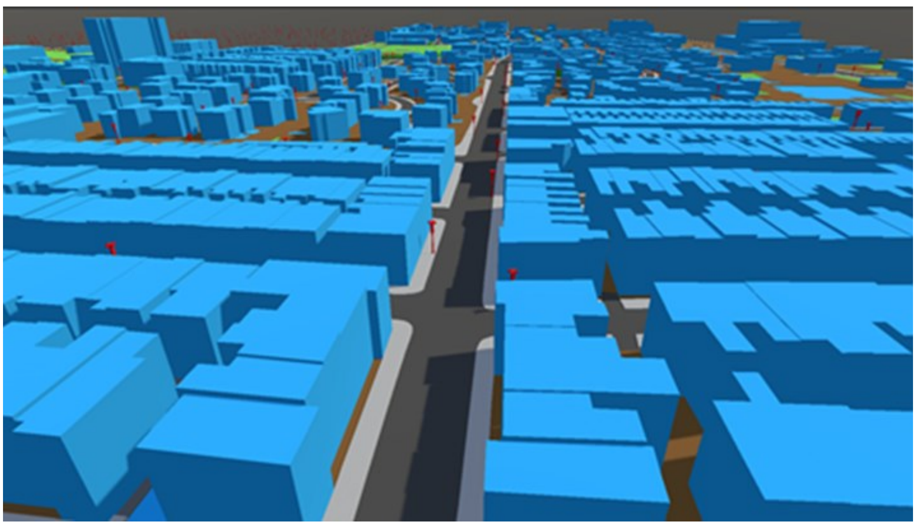
Coordinates of each lamp post in the testbed area were extracted from Liverpool City Council's lamp-post database. The data was processed into and imported into City Engine to create the framework for the 3D scene.

Initial framework for 3D scene development

This information enabled them to plan where to erect 5G nodes on lamp posts in the neighbourhood.

A basic road layout along with buildings was created using the data collected from Ordnance survey. Height data was then used to pull up the buildings, giving them the correct height and creating a 3D scene.

The simulation was edited so it could easily be viewed from all angles and rotated, and the ability to zoom in and out of the map was added.

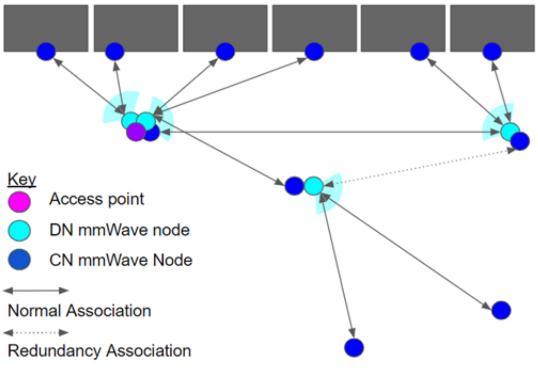


Simulation street view perspective

CGA Simulation also produced a line of sight test, using the planning tool and Blue Wireless technology, to ensure 5G nodes were placed no more than 150 meters apart. This also highlighted obstructions with the potential to affect signal transmission, such as shadows created by buildings at different times of day/ year, shadows created by moving buses, the frustum of the signal from a signal node, trees, and the angle at which a node is placed on the lamp post.

They created and tested a line of sight tool, that would be used to ensure optimum placement of nodes. Nodes were placed in a prototype scene and the possible path of 5G was established between nodes. Once the visualisation was achieved, it was tested against we Blu Wireless' original system, which showed a good match and identified the viable paths.

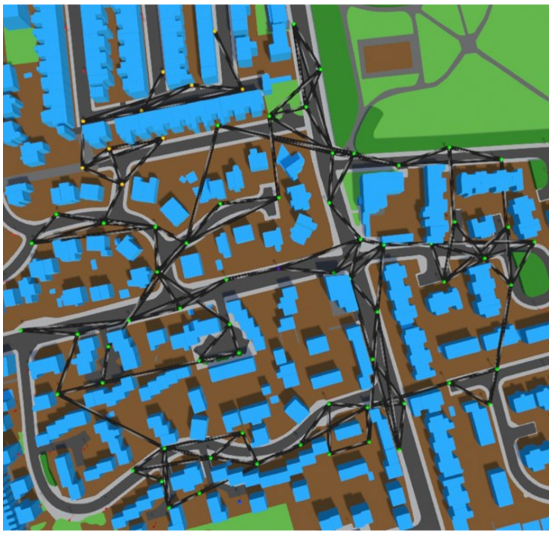
Building on the line of sight test, DN and CN mm waves were incorporated to represent the mesh network more accurately. Also, different algorithms were applied across the network to determine the best way to connect the nodes.



connection between DN mmWave node and CN mmWave Node and the access point

CGA Simulation's mathematician set out to find an algorithm which, for any given set of lamp posts, minimizes the number of mmWave boxes needed to connect them while achieving the desired redundancy of the system.

She found that the Minimum Spanning Tree required less processing time and less memory, and the visualization of coverage was expanded using this method.

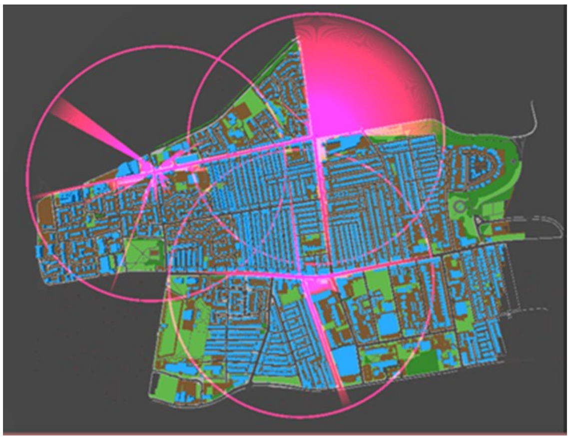


Minimum Spanning Tree -in a medium suburb

Once the simulation was functional and could test different optimisation methods, a user friendly interface was developed for the tool. A range of functions were developed at the request of potential users, with corresponding menus, completing a demonstrable and saleable product.

Additions and Enhancements

As the project moved into its second year, several features and functions were added to CGA Simulation's Planning Tool.

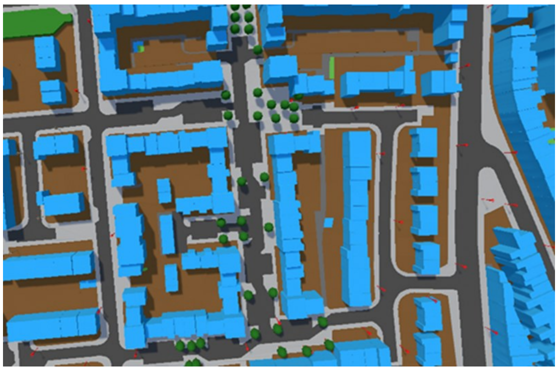


LoRoWAN gateways range

The location of the LoRoWAN gateways were placed them into the simulation . The range of the LoRoWAN gateways is approximately 2km, and a radius was drawn around the gateways to determine the connectivity reach.

To improve the simulation and make it more useful for deployers, several features were added including: save and load work, save instructions for fitters, and save google map version of instructions.

Following feedback during training, Public tree data was also added to the simulation.



Tree data represented in simulation

During the planning, it was established that some sites had a high number of nodes that would be difficult to install, so improvements were added to the simulation to lessen the problems:

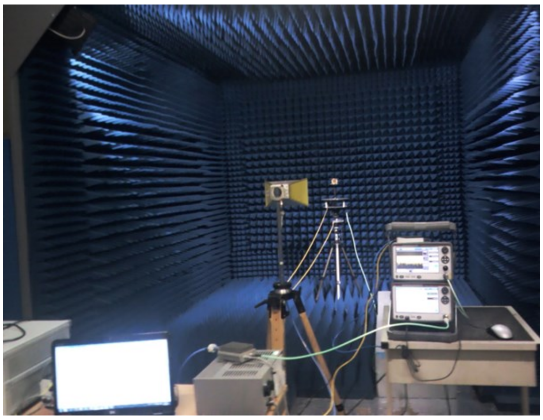
- Improved node placing algorithm reduced the highest number of nodes on any site by evening out the distribution and reducing the number of nodes needed overall.
- Alerting the user if a site has more than 3 nodes (the current preferred maximum).
- Improved network creating algorithm by making it prefer routes that included established links and sites, which reduced the number of nodes used overall.

CGA Simulation and Liverpool John Moores University partners undertook work to integrate their Network Planning tool and the LJMU network performance tool. Data formats produced from the 5G network planning tool were successfully aligned so that they could be used as input for the LJMU simulator. This means that a node deployment plan developed inside the tool can be evaluated for the predicted network performance in the LJMU simulator.

University of Liverpool - Green Demonstrator System

The team from Department of Electrical Engineering and Electronics at project Liverpool University undertook research into reducing power across the 5G network - the Green Demonstrator System. They:

- Developed a physical layer protocol for the demonstration system, that included the functional specifications of transmitter and receiver of the demonstration system.
- Developed channel estimation and equalization algorithms for multipath environments.
- Developed a software package to implement the protocol and high-performance transmission techniques
- Designed radio frequency (RF) devices including antennas for both transmitter and receiver
- Embedded transmitter and receiver with the developed software and RF devices and tunec the system
- Tested and verified the system and evaluated the system performance.



Example test environment of an anechoic chamber for the green demonstration system

They found that filtered-orthogonal frequency division multiplexing (F-OFDM) is a promising candidate waveform for the fifth generation (5G) wireless communications because of its high flexibility and low out-of-band emission (OOBE). However, this found to suffer from a dramatic peak-to-average-power ratio (PAPR), which results in the power amplifier (PA) not working in the high-efficiency region.

Due to this they proposed that a hybrid PAPR reduction scheme be used for F-OFDM systems with independent component analysis (ICA) based blind channel equalization.

The bit error rate (BER) performance of the system with the proposed hybrid PAPR reduction scheme was shown to be close to the ideal case with perfect channel state information (CSI), while no side information and training sequence are required for PAPR reduction and channel estimation, thanks to the effectiveness of the ICA based blind channel equalization.

A paper 'PA-Efficiency-Aware Hybrid PAPR Reduction for F-OFDM Systems with ICA Based Blind Equalization' was presented at the IEEE Wireless Communications and Networking Conference in April 2019

Their evaluation report can be found here:Evaluation Report of the Developed Demo System

Liverpool John Moores University - Modeling efficient RRM

The Liverpool John Moores University (LJMU) team built a simulator to model the properties and parameters of 802.11ad Networks, with the objective of providing efficient radio resource management and link reconfiguration mechanisms for the Liverpool 5G testbed network.

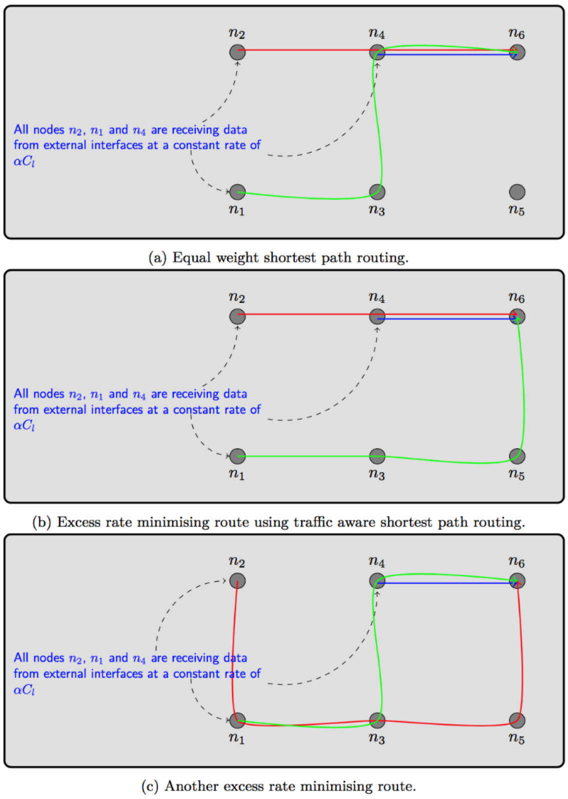
The main aim of this work was to propose RRM techniques and routing recovery that would improve the performance of the 5G backhaul network.

This was done by proposing SDN based solutions for resource allocation upon which various network functions could be deployed at the logically centralised controller to provide consistent and efficient management over the whole backhaul network. With this paradigm, resource allocation, traffic management and network reconfiguration could be easily optimized.

The simulator provided an extensive set of simulations for verifying the effectiveness of the tools and algorithms in realistic environments, for example when some links in the network are not stable.

The work took advantage of SDN technology to monitor and visualize the network, remotely manage nodes, and accomplish radio resource management and achieve flexible spatial coordination in mmWave network.

The model was used to evaluate the performance of the proposed RRM features with respect to their



Different Types of Routing Flow Configurations

performance in throughput, PER, latency and PDF. The simulation results were analysed with comparison to the baseline solutions that did not implement any recovery from failures.

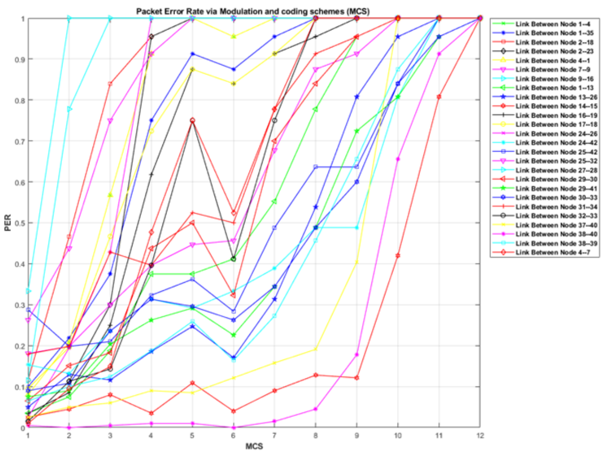
On the basis of the simulations presented, the enhanced network configuration was seen to offer a clear performance advantage over the baseline results.

A research article was published by the LJMU team on completion of the first year of the project, which can be found here: [Radio resource management framework for energy-efficient communications in the Internet of Things]

The work undertaken by LJMU during the second year of the Liverpool 5G testbed project focused on extending the dynamic Self Organising Network (SON) algorithm to predict and enhance the network performance and resilience functionality provided.

To do this, they coordinated with Blu Wireless to refine their understanding of the 802.11ad network and with CGA Simulation to integrate their work into the monitoring, management and mapping functionality provided by the 5G planning tool.

Initial work on network performance analysis showed the characteristics of the links were tied to MCS 1 for the given target PER of 0.01, but they found that different link qualities exist. These can be broadly categorised based on the MCS setting at which the PER raises significantly. When looking into link performance in more detail, they found that this is highly dependent on distance and other metrics such as the propagation model to determine the predicted performance.



Effect of Transmission Rate on PER

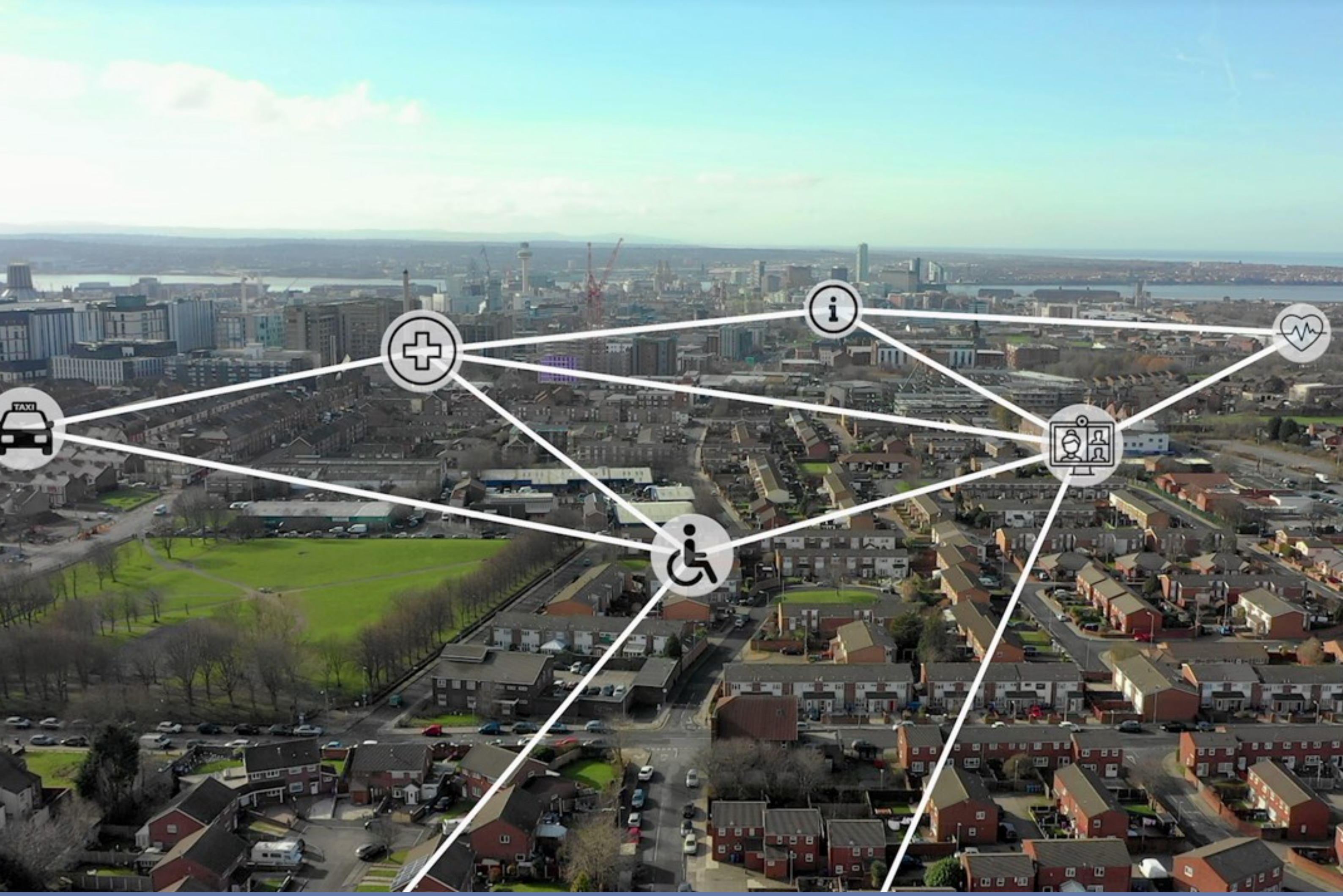
Initial results of simulations showed that the optimal distance between nodes seems to be around 100m, with the performance degrading significantly once this drops below 70m or over 150m.

Further investigations focused on the predicted performance of the backhaul as new nodes were added through simulation. These found that, while adding new nodes does potentially improve certain metrics, it can potentially lead to further issues due to the increased number of hops back to the POP connection.

Working closely with CGA Simulation they aligned the data formats produced from the 5G planning tool and effectively used it as input for the simulator. While there was insufficient time to fully integrate the two packages, enough progress was made to ensure that a node deployment plan developed inside the tool could be evaluated for the predicted network performance in the simulator.

Beyond the project, the LJMU team intend to:

- Optimise the integration with the 5G planning tool to lay the foundation for tighter interoperation with the simulator functionality.
- Continue to verify and investigate the link performance results with BluWreless, which could either be disseminated into their internal systems or published in academic venues.
- Continue investigating overall network performance with the denser mesh backhaul.
- Disseminate their results.



04

Conclusions

Conclusions

We have shown how the 5G concept brings together new and existing communications technologies, with a focus on enabling health and social care applications in the field more cost-effectively.

The number and scale of organisations involved to make this testbed happen has been considerable and stretches beyond the 11 partners and over 15 subcontractors and contractors. The logistics, management and support needed to achieve the common goal of the testbed cannot be underestimated.

Although we trialed specific devices with service users, the main focus of the project was on creating the infrastructure, environment and adoption readiness for all future devices. It was challenging providing continuous connectivity while the network was under development, particularly as the testbed was accessing live health and care services.

Selection of trialed devices

In some cases we started with mobile 4G connectivity and continue to use this as back up or where we were not able to deploy nodes within the timescales of the project. Other devices operate over LoRaWAN networks that overlay the testbed network in this area, often using back-haul and site-sharing provided by the testbed. In each case, the project has shown how 5G supports the full performance and economic viability of each application whilst providing the resilient fallbacks necessary for live trials.

We have demonstrated over the trial that it is imperative that connectivity is provided in parallel with changes in the way services are delivered.

We believe the cost of providing connectivity via a 5G mmWave mesh network is affordable and has the potential to deliver significant cost savings in the way health and social care services are delivered.

The provision of a private network removes the barrier of ongoing data charges to support the use of devices in the home.

To realise the full potential and reduce health inequalities the approach needs to be adopted in a coordinated manner across both Local Authority and NHS delivered services.

Learning

- A key aspect of the success of the project was the involvement of the owner of the city's street furniture, in this case Liverpool City Council, as a partner. This allowed us to agree access to lampposts and the existing fibre network with minimum complication, and facilitated contact with companies already contracted to work on both.
- Local council street services need to be involved from the early stages of installation planning, particularly to ensure traffic management for node installation (where needed) is facilitated, that already planned road closures and works can be taken into account, and that street furniture has the required features for node installation.
- Sufficient time must be allocated to ensure that suitable partners and sub-contractors are available at the start of the project, as bringing new organisations on board in the limited timescale of the testbed implementation can adversely affect the workflow.
- Ensuring that comprehensive protocols and procedures for contractors, activities and installation are drawn up, referencing expertise from relevant partners, is essential. These, plus regular reviews and updates, will help to ensure smooth supply chain management and deployment.
- For a sustainable deployment technical and commercial agreements are necessary for interfaces between partners, to ensure contractual commitment to resolving design and configuration incompatibilities.
- We were able to access social care and community organisations through the knowledge and contacts brought to the partnership by partners eHealth Cluster and Liverpool City Council, which facilitated the installation or network nodes on their buildings.
- Where useful node sites are identified on buildings owned by large or complicated organisations, it is imperative to make contact early - in some cases, establishing ownership of buildings, navigating their existing maintenance arrangements, and the drawing up of legal agreements mean long delays or not completing.
- For an effective service, planning of the location of nodes should take into account the construction of buildings and where within the building access is needed. In some cases a permanent internal fixture may be suitable
- It is important that all staff in care homes/supported living are made aware of the purpose of the device, in order to address the issue of unplugging or moving 5G nodes and repeaters.

Acknowledgements

Thanks to all the partner organisations, their staff, the contractors and sub-contractors who helped to make this project a significant success, and who continue to work with us to maintain and expand the network.

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