Institution: University of Bristol		
Unit of Assessment: 12) Engineering		
Title of case study: Millimetre wave technology enables fast, reliable WiFi on the move		
Period when the underpinning research was undertaken: 2012 – 2019		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed by submitting HEI:**
Mark Beach	Professor of Radio Systems Engineering	09/1987 – present
Simon Armour	Senior Lecturer in Software Radio	03/2001 – present
Andrew Nix	Dean of Faculty of Engineering	10/1991 – 07/ 2019
Evangelos Mellios	Lecturer in Electrical & Electronic Engineering	10/2013 – 01/ 2019
Period when the claimed impact occurred: 2014 – 2020		
Is this case study continued from a case study submitted in 2014? No		

1. Summary of the impact

Mobile phone coverage of the UK's 19,000 miles of railway is notoriously poor. Underpinned by research from the University of Bristol, FirstGroup through evo-rail (www.evo-rail.com) has now deployed 5G-rail millimetre wave wireless technology to provide gigabit connectivity from trackside to train. Their passengers can now access the internet on the move via conventional WiFi, offering a through-put 100 times faster than with cellular networks. The research also influenced government policy mandating train operators to improve broadband connectivity as well as facilitating a Bristol-based SME, Blu Wireless Technology Ltd, to develop and sell products, greatly expanding their business through trialling and deployment of their millimetre wave technology by FirstGroup Holdings on their South-West train franchise.

2. Underpinning research

Millimetre wave technology can unlock significant additional radio spectrum for 5G (and beyond) wireless connectivity, not available through previous generation cellular and Wi-Fi systems. However, greater attenuation due to increased path loss and blockages at these higher frequencies requires the use of dynamically aligned high gain directional antennas.

In 2014, University of Bristol (UoB) researchers, in collaboration with a Bristol based SME, Blu Wireless Technology Ltd [i], developed and showcased a new millimetre wave propagation model and novel link throughput performance tool, to demonstrate the use of antenna beam steering to support high bandwidth point-to-moving-point connections. Fig 1 typifies the results for a Manhattan grid and route, showing key performance indicators (KPIs: modulation coding scheme and throughput predictions). This dynamic link performance modelling tool was ahead of work elsewhere focusing on static indoor coverage and signal strength analysis. Subsequent research enhanced the tool through modelling path loss for indoor and outdoor environments, as well as incorporation of real-world maps for predicting realistic system performance [1]. This was followed by millimetre wave channel measurements [ii], to further understand the complex interactions (diffraction and scatter as well as impact of surface roughness) between objects at such high frequencies [2]. Importantly, the equipment used by UoB (strategic donation from Keysight Technologies) offered both high measurement bandwidths and spatial resolution alongside rapid data acquisition, thus supporting multiple measurement campaigns for material characterisation (see Fig 2, [iii]) and highly dynamic channels (see Fig 3, [vi]). In parallel, this work supported international collaboration with key wireless researchers in both the US and China yielding a seminal paper [3] on millimetre wave propagation.

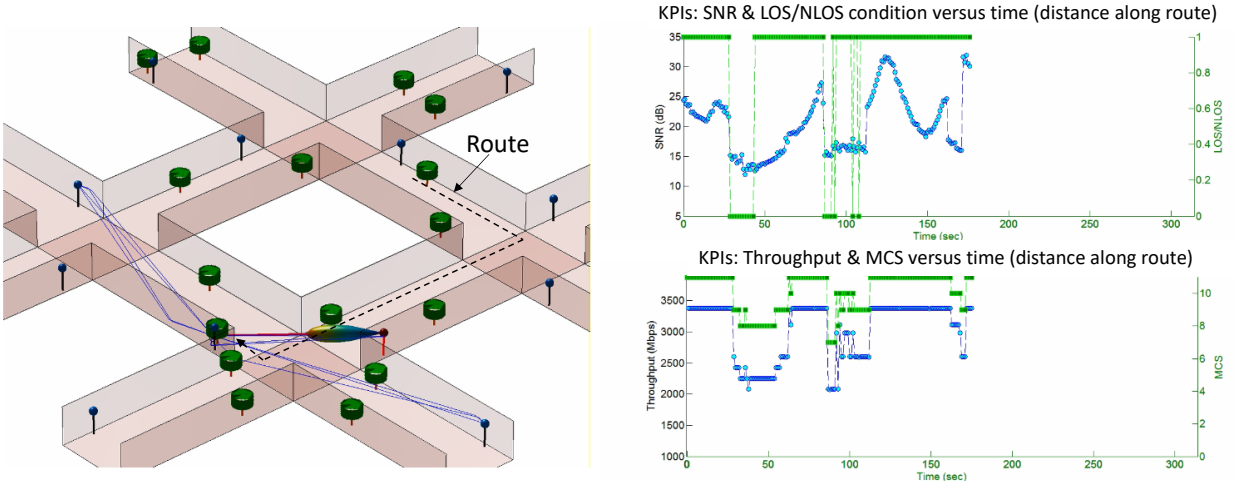

Fig 1: Dynamic Link Performance for Outdoor Millimetre-Wave Wireless Access

Further to [1] and [2], research supporting performance benchmarking and throughput enhancements [4] to Blu Wireless's first-generation millimetre wave wireless modems (Lightning product family) was jointly conducted through H2020 5GXhaul [iv], as well as a train passenger safety application and trial [5], in H2020 5G Picture [v].

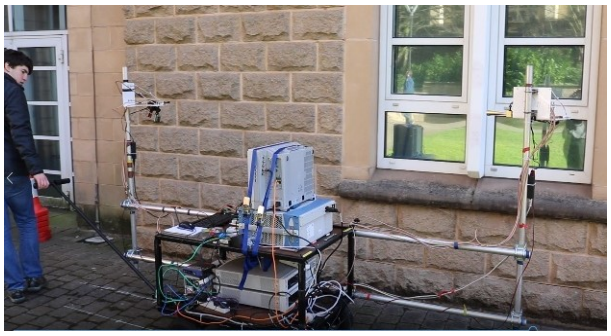

Fig 2: Wall Reflections at Millimetre-Wave

Building on UoB recommendations from leaky feeder research in 2012 for broadband wireless communications to trains, alongside knowledge from [1] and [2], FirstGroup (2015) secured joint funding from the Railway Safety & Strategy Board (RSSB) and Great Western Railways (GWR) [vii], to develop an early proof-of-concept of the UoB trackside to train wireless communication architecture, including technology field trials of Millimetre Wave Access Networks for TRAins (MANTRA). Here, millimetre wave propagation measurements and analysis were undertaken for railway environments [6] (Fig 3), confirming the concept. An initial technology trial using track and rolling stock from the historical Great Central Railway in Nottingham (GCRN) demonstrated an operational millimetre wave link to a moving train (March 2017). MANTRA culminated with a final trial using facilities at Network Rail's Rail Innovation & Development Centre (RIDC) at Melton Mowbray, where the UoB-led team used millimetre wave modem technology from Blu Wireless to demonstrate train to trackside communications at 1Gbps from a moving train. This included a deployment using FirstGroup's new rolling stock (Hitachi C700), see Fig 4, in May 2017.

Fig 3: Trackside measurements (MANTRA)

Fig 4: MANTRA trials on Hitachi C700

3. References to the research

[1] N.F. Abdullah, [**Beach, Nix, Armour**] et al., 'Path-Loss and Throughput Prediction of IEEE 802.11ad Systems', IEEE Vehicular Technology Conference, Glasgow, UK, May 2015. doi:10.1109/VTCSpring.2015.7145996

[2] T.H. Barratt, [**Beach, Nix**] et al., 'Measured and modelled corner diffraction at millimetre wave frequencies', IEEE PIMRC, Valencia, Spain, Sept 2016, doi:10.1109/PIMRC.2016.7794755

[3] T.S. Rappaport, [**Mellios**] et al., 'Overview of Millimeter Wave Communications for Fifth-Generation (5G) Wireless Networks with a focus on Propagation Models'. IEEE TAP, vol. 65, no. 12, pp.6213-6230, 2017. doi:10.1109/TAP.2017.2734243

[4] V. Kalokidou, [**Mellios, Nix**] et al., 'Link performance evaluation for mm-Wave systems', IEEE ECNC, Bologna Sept 2018, doi:10.1109/PIMRC.2018.8581018

[5] V. Kalokidou, [**Mellios, Nix**] et al., 'Performance Evaluation of mmWave in 5G Train communications', IEEE PIMRC Sept 2018, Bologna, Italy, doi:10.1109/PIMRC.2018.8581018

[6] B. Bulut, **[Armour, Beach, Nix]** et al, 'Millimeter wave channel measurements in a railway depot', IEEE PIMRC, Montreal, Canada, Sept 2017, doi:10.1109/PIMRC.2017.8292516

Grant funding

[i] **Beach M** (PI). Blu Wireless Technology, West of England LEP award, 2014, GBP248,000

[ii] Bull (UoB PI), **Beach** (CI). CDT in Communications, EPSRC EP/I028153/1, 2011-22, GBP2.2 million

[iii] **Beach M** (PI) H2020 mmMAGIC, 2015-16, GBP249,000

[iv] Simeonidou (PI), **Beach** (CI), H2020 5GXhaul, 2015-2017, GBP642,000

[v] Simeonidou (PI), **Nix** (CI), H2020 5G Picture 2017-19, GBP715,000

[vi] **Beach** (PI), FirstRail Holdings, WiFi Communication with High Speed Trains, 2012-13, GBP3,500

[vii] **Armour** (PI), FirstGroup/RSSB MANTRA 2016, GBP350,000

4. Details of the impact

In today's ultra-connected world, the ability to stay connected while on the move is essential. Passengers expect this connectivity on trains as smartphone usage and working on the move become more widespread. The impact resulting from UoB research has brought forth a step change in the provision of broadband connectivity for the traveling public:

Influencing Government Policy and Enabling Connectivity on the Move

In 2016, UoB research in 5G and millimetre wave wireless access [1] , attracted the interest of the National Infrastructure Commission (NIC), tasked by the Chancellor of the Exchequer to advise the Government on what the UK should do to become a world leader in 5G infrastructure deployment. A visit to Bristol by NIC Commissioners to discuss the ongoing applied research [1,2], identified millimetre wave as a potential efficient technology option for gigabit connectivity. A former NIC commissioner noted that the research demonstrated *'that it was indeed possible to enhance both coverage and internet speed on trains and to connected cars by means of suitable track-side and road-side infrastructure'* and *'millimetre wave solutions as well as their small form factor identified them as a potential efficient technology option for gigabit connectivity'* [A].

The NIC Connected Future report [B], included the recommendations that: '*Rail passengers should have high capacity wireless connectivity. This should be achieved through a delivery model that utilises trackside infrastructure to provide an open and accessible mobile telecommunication and backhaul network that is fit for the future'* (Recommendation 3), and '*as*

well as lower frequency radio spectrum, 5G expects to make use of very high frequency millimetre wave radio spectrum' (Recommendation 6). The NIC report and recommendations were incorporated into the UK Government's 5G strategy (2017) [C (p.8)], which committed to improving coverage where people live, work and travel - including on trains [C (p.14)]. This included mandating train operating companies to provide minimum connectivity standards as part of their franchise agreements [C (p.43)].

Commercialisation & Roll-out by FirstGroup (evo-rail)

Through collaboration with UoB dating back to September 2012, initially on the use of leaky feeder technology, FirstGroup Holdings were ahead of the Government announcement [C] in the application of millimetre wave technology. The Group Head of Digital (Engineering), states that the UoB recommendation to use millimetre wave technology *'was considered by FirstGroup as a scalable solution offering 'Fast, Reliable Wi-Fi on board' our trains'* [D]. Further, the '*underpinning work through MANTRA* [2016] [6] *has since been developed by Blu Wireless and FirstGroup into a commercial solution that can be seen at www.evo-rail.com'* [D].

Through integration and patenting [E] of the sub-components from MANTRA [F], alongside demonstrations to Network Rail, communications regulator OFCOM, and the departments of transport and digital, *'1Gb/s of connectivity being continuously maintained between a moving train and trackside poles along 17km of track at the Rail Innovation and Development Centre'* was showcased [G@2:20]. From here, FirstGroup achieved a *'global first on the Isle of Wight* (Fig 5) *with rail-5G delivering over a gigabit onto a train in a commercial railway setting covering 10 miles of track. Here passengers can access via on-board WiFi with a throughput 100 times that of mobile access via cellular networks'* [G@0:00] (Fig 6). The Isle of Wight was chosen as a self-contained railway system on which all trains could be covered, with a complex geography that would test the placement and performance of masts and antennae. From the Isle of Wight, FirstGroup *'will then cover the busiest section of Britain's busiest railway: 70km of Southwestern Rails commuter and intercity route into London Waterloo; from Basingstoke to Earlsfield'* [G@3:10].

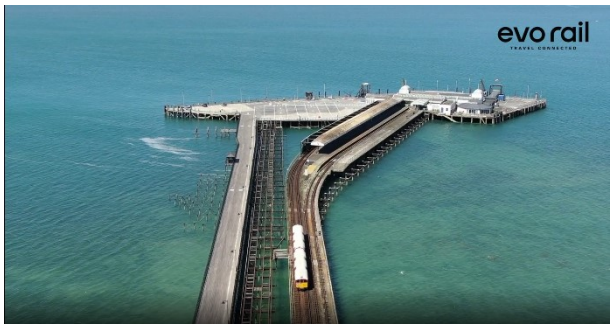

Fig 5: Isle of Wight Commercial Deployment

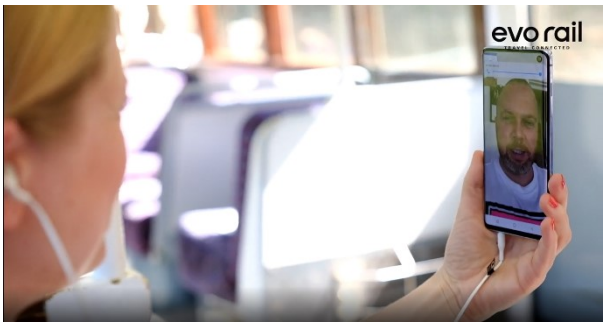

Fig 6: On Board WiFi [G@0.32]

SME Product Development & Growth of Business – Blu Wireless Technology Ltd

UoB collaboration with Blu Wireless to improve understanding of millimetre wave propagation predication and performance estimation [1, 4], underpinned the launch of the company's first millimetre-wave product (Lightning Modem) in 2015. Building on this, *'a significant use case and market opportunity arose through collaborative work funded by FirstGroup (projects MANTRA and DALI), taking* [Blu's] *technology track side and the first demonstration providing proof of concept of millimetre wave communications from track to train. MANTRA and the 2 technology*

trials we jointly conducted demonstrated 1 Gbit/s wireless connection to a moving train was a major milestone for Blu Wireless and also a world first' – Blu Wireless CMO [H].

These achievements helped Blu Wireless secure a further investment of GBP12 million for global 5G tech rollout in May 2019 [H]. The funding round was led by existing investors Arm, Calculus Capital, Kendall and MGL, with new investor Guinness Asset Management. The CMO of Blu Wireless described the collaboration with UoB as *'fundamental to our success in securing the multi-phase investment required to develop our business'* [H].

With a new product-range (Typhoon), Blu Wireless is now providing the core modem technology and know-how for the roll-out of South West Trains millimetre wave trackside to train broadband passenger connectivity, initially for the Isle of Wight [I], and ultimately for the Basingstoke to Waterloo SWR lines. In addition, Blu Wireless is supplying millimetre wave products to the 5G 'Autoair' V2Xproject [J], one of 6 5G Test Bed and Trials projects funded by the DCMS in 2018. This includes the delivery of a 2 mile high-speed test bed at the Millbrook Proving Ground to demonstrate data rates of more than a gigabit to vehicles travelling at over 200 kmph [H].

The CMO at Blu Wireless stated [H] that *'As a direct result of the proof of concept work carried out in the MANTRA research project…Blu Wireless took the decision to extend its business … towards becoming a leading supplier of state of the art 5G mmWave products'.* In order to achieve this, the company has invested in building a product development team, which now comprises over 40 engineers. '*There remains a strong connection to the technology and understanding of millimetre wave propagation emanating from the early work with UoB'*, with Blu Wireless now embodying a more "systems engineering" approach to their product delivery, seeing the company grown from 7 founding employees in 2013 to over 110 in 2020. Additionally, despite the impact of Covid-19, Blu's revenue has grown by over 200% over the last 12 months due to their leveraging of systems activities in the rail sector into complementary markets with similar levels of growth expected in 2021 based on market demand for 5G Private Network applications [H].

5. Sources to corroborate the impact

[A] Ofcom (2020). Corroborating statement – Former role with NIC and Director for Telecoms, Department for Digital, Culture, Media and Sport

[B] NIC (2016). Report: Connected Future *See recommendation 3 (p.16) and 6 (p.20).*

[C] UK Government (2017). Policy Paper: Next Generation Mobile Technologies: A 5G Strategy for the UK (accessed 15/04/2020)

[D] First Group (2021). Corroborating statement - Head of Digital (Engineering)

[E] Nix A, Tila F, Waugh D, Communication with a Mobile Device, WO2019002867A1, Jan 2019

[F] evo-rail (2020). About us (accessed 15/12/2020)

[G] evo-rail (2020). Video, (accessed 15/12/2020)

[H] Blu Wireless Technology Ltd (2020). Corroborating Statement – CMO

[I] Global Railway Review (2019). South Western Railway to become the UK's first 5G railway, (accessed 7/1/2021)

[J] UK5G Innovation Network (2018). Testbeds & trials: AutoAir, (accessed 16/04/2020)