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Institution: University of Bristol

Unit of Assessment: 12) Engineering

Title of case study: Enabling the 5G Networked Society

Period when the underpinning research was undertaken: September 2013-January 2020		
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:**
Dimitra Simeonidou	Professor of High Performance Networks	09/2012-present
Reza Nejabati	Professor of Intelligent Networks	09/2012-present
Mark Beach	Professor of Radio Systems Engineering	09/1987-present
Period when the claimed impact occurred: June 2014-November 2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact

Society is now benefiting from the higher data rates, lower latency and higher reliability afforded by 5G, thanks to research undertaken by the University of Bristol's Smart Internet Lab. This research directly influenced Government policy, yielding the GBP200 million national 5G testbeds and trials programme, and culminating in a strategy for securing the UK's telecommunication supply chain. The Lab's pioneering research into new 5G technologies and control methodologies has been adopted by international standardisation bodies, influenced the architecture of BT's 5G network roll-out, as well as initiating the adoption of 5G connectivity by multiple vertical industries. Samsung has exploited the research in their mobile edge computing product portfolio, and Zeetta Networks, a spin-out with >30 staff, is commercialising NetOS®, a suite of software tools for 5G network virtualisation and orchestration deployed in 4 German cities, a football stadium and city festival.

2. Underpinning research

Pioneering research in 5G software and hardware technologies conducted by the University of Bristol (UoB) has accelerated the understanding and development of 5G networks in the UK.

Highly Flexible End-to-End Network Architecture and City-Scale Deployments
From 2014, Simeonidou led the EPSRC TOUCAN programme **[i]**, achieving end-to-end multi-technology network convergence and yielding two innovations which now form key components within 5G Networks: technology agnostic optical-wireless architectures for converged networks through programmable hardware interfaces and Software Defined Network control (SDN) **[1]**; and agile end-to-end service provision through Network Function Virtualisation (NFV) and orchestration **[2]**. The first definition of a reconfigurable optical-wireless backhaul/fronthaul (H2020 5G-xHaul **[ii]**) and novel solutions for programmable edge components (5G-Picture) were adopted in the EU H2020 5GPPP Architecture White Paper (https://5g-ppp.eu/wp-content/uploads/2020/02/5G-PPP-5G-Architecture-White-Paper_final.pdf).

Laboratory prototypes from **[1]** and **[2]** were deployed in city-scale testbeds where real-life experimentation and validation were carried out with end-users. The work was supported by EU H2020 funding 5GinFIRE, FLAME, REPLICATE, 5G City and also by the DCMS 5G Testbeds and Trials Programme **[iii]**. Importantly, this work validated 5G systems at scale through the integration of software and hardware solutions, allowing further optimisation and driving the early demonstration of benefits in terms of application performance and user experience.

Mobile Edge Computing and Service Orchestration
Research on 5G enabling technologies such as Service Orchestration and Mobile Edge Computing **[2]** was conducted by Nejabati through H2020 projects MATILDA and METRO-HAUL. These technologies are fundamental for delivery of ultra-low latency services (well beyond 4G) as demonstrated with deployments in cities around the world (Bristol, Barcelona, Lucca). These innovations enabled latency sensitive applications such as AR/VR, gaming,

music, tourism etc., as well as multi-domain orchestration. This work has been prototyped and deployed in the DCMS 5GUK Test-beds and Trials infrastructure **[iii]** as the "5GUK Exchange" **[3]**.

Advanced Wireless Connectivity – High Spectrum Efficiency
Beach with PhD students **[iv]**, alongside strategic collaborations with the University of Lund and National Instruments, has driven forward the science and application of Massive Multiple-Input Multiple-Output (Ma-MIMO) technology for spectrally efficient wireless access to provide high capacity and throughput connectivity for 5G and beyond **[4]**. This included architecture design, development, optimisation of algorithms, and demonstrating world-leading spectrum wireless efficiency gains of more than twenty times that of 4G. This culminated with a system deployment with BT, for which the team received The Engineer Collaborate to Innovation 2018 award. Concepts were further developed as part of the 5G Urban Show Case as well as a methodology to estimate wireless bearer Error Vector Magnitude **[5]**.

Quantum Secure Communications
From 2014 to 2019, Nejabati and Simeonidou pioneered technology and implementation of Dynamic and Software Defined Quantum Secure Networking via the UK National Quantum Communication Hub **[v]**. Utilising principles of quantum physics, they have driven forward the science of secure information transportation **[6]**, enabling the world's first dynamically switched quantum secured mesh network: The foundation of the Quantum Internet. This research has accomplished a major technological break-through in quantum switching hardware technology, as well as control plane software and algorithms for establishing quantum secured links in a network.

3. References to the research

[1] Tzanakaki A, Anastasopoulos MP, **Simeonidou D** (2019). Converged optical, wireless, and data center network infrastructures for 5G services, *IEEE/OSA Journal of Optical Comms and Networking*, **11(2)**, pp.A111-A122, https://doi.org/10.1364/JOCN.11.00A111

[2] Anastasopoulos MP, Tzanakaki A, **Simeonidou D** (2019). Scalable Service Chaining in MEC–Assisted 5G Networks, *Journal of Lightwave Technology*, **37(16)**, pp.4115-4124, https://doi.org/10.1109/JLT.2019.2923079

[3] Gkounis D, Uniyal N, Muqaddas AS, **Nejabati R**, **Simeonidou D** (2018). Demonstration of the 5GUK Exchange: A Lightweight Platform for Dynamic End-to-End Orchestration of Softwarized 5G Networks, *IEEE 2018 European Conference on Optical Communication*, Rome, pp.1-3, https://doi.org/10.1109/ECOC.2018.8535288

[4] Harris P, … **Beach M** (2017). Performance characterization of a real-time massive MIMO system with LOS mobile channels, *IEEE Journal on Selected Areas in Communications*, **35(6)**, pp.1244-1253, https://doi.org/10.1109/JSAC.2017.2686678

[5] Hasan W, ….**Beach M** (2019). Adaptive User Grouping Based on EVM Prediction for Efficient & Robust Massive MIMO in TDD, *IEEE Access*, **7**, 162683-162696. https://doi.org/10.1109/ACCESS.2019.2951547

[6] Wang R, **Nejabati R**, **Simeonidou D** (2020). End-to-end Quantum Secured Inter-Domain 5G Service Orchestration Over Dynamically Switched Flex-Grid Optical Networks Enabled by a q-ROADM, *Journal of Lightwave Technology*, **38(1)**, pp.139-149, https://doi.org/10.1109/JLT.2019.2949864

[v]   Spiller T (PI), **Nejabati R** & **Simeonidou D** (CIs), *UK Quantum Technology Hub for Quantum Communications Technologies*, EPSRC (EP/M013472/1) 2014-19, GB627,000

4. Details of the impact

The research has led to impacts encompassing Government strategy, technology and standards adoption, alongside sector and societal engagement. The Department for Digital, Culture, Media & Sport's (DCMS) Programme Director for 5G Testbeds and Trials has stated that '*the University of Bristol Smart Internet Lab's skills and world-leading expertise in advanced telecommunications technologies have contributed to the UK's position as a world leader in 5G, benefiting the country's economic growth and prosperity*' **[Ai]**.

Government Strategy and UK Leadership in 5G

In 2016, DCMS established the Future Communications Challenge Group (FCCG) to consider '*what the UK should do to be a world leader in 5G*' **[Bi]**. FCCG membership was drawn from wireless and communication network experts from industry, academia, and government agencies, with Prof. Beach bringing '*his applied research skills in advanced wireless connectivity for 5G*' **[4] [Bi]**. The FCCG report **[Bii]** in January 2017 informed HM Treasury's development of the Next Generation Mobile Technologies: A 5G Strategy for the UK **[Biii]**. Alongside the work of FCCG, Prof. Simeonidou, with expertise in '*end-to-end network design and optimisation*' **[1] [2]** and '*experience in real world deployments and large-scale experimentation*' **[3]**, engaged with treasury at the request of DCMS '*to advise on UK's digital infrastructure development and deployment*' **[Ai]**. Based on these recommendations, DCMS made the decision to invest GBP16 million (July 2017) in the 5GUK Test Networks, culminating in the first 5G Urban Showcase, 'Layered Realities' (see below). Building on this success, DCMS invested a further GBP200 million, through a multi-staged programme, which engaged vertical industries (e.g. manufacturing, health, transport, arts) in the use of 5G and its benefits in driving digital transformation in key sectors **[Ai]**. Through this programme, the UK engaged a large ecosystem of 5G technology providers and users, and established international leadership in the adoption of 5G in key industrial sectors **[Ai]**.

Simeonidou has worked closely with DCMS throughout the last 4 years (2017-20) as well as providing evidence to the UK Parliament's Select Science and Technology Committee inquiry into the '*UK telecommunications infrastructure and the UK's domestic capability*' (June 2020). She was subsequently appointed to the UK Government Telecom Diversification Taskforce, as one of only seven specialists reporting to Lord Livingston **[Aii]**. This taskforce produced the UK Government 5G supply chain diversification strategy, published on 30 November 2020, which resulted in an initial investment of GBP250 million to ensure growth in the supply chain of UK telecommunications infrastructure, as well as ensuring it is resilient to future trends and threats [text removed for publication] **[Aiii]**.

Enabling Technology Adoption by Corporates – Standardisation and Rollout

Massive MIMO (Ma-MIMO) wireless access is a key enabler for 5G New Radio (NR), with the University of Bristol's Smart Internet Lab focusing on a Time Division Duplex (TDD) framework **[4]**. National Instruments (NI) took these results to the standardisation body 3GPP **[Ci, ii]**, '*illustrating for the first time the benefits of a TDD based Ma-MIMO architecture allowing the exploitation of channel reciprocity for downlink transmission. Early studies in 3GPP working groups focused on FDD (*Frequency Division Duplex*) for 5G NR in FR1 which is unable to fully exploit channel reciprocity and reap the associated spectrum efficiency gains demonstrated by Bristol"* **[Ci]**. In September 2019, TDD was adopted by 3GPP for multi beam operation **[Ciii]**. Contributions have also been made to open-source standards (ETSI MANO **[Di,ii]**), driving forward innovation within the 5G core for controllable low latency services (see 5G Exchange and 'Music for All' below).

The Smart Internet Lab's work with BT on spectrally efficient Ma-MIMO **[4]** enabled BT to become the first UK operator to launch 5G commercial services, with the Lab's researchers helping BT '*to architect* [their] *converged 5G network*' **[Ei]**. The BT video **[Eii]** exemplifies the benefits from this collaboration; '*realising the potential of Ma-MIMO technology in more dense environments, offering additional capacity such that mobile networks can support HD video and*

superfast broadband'. As a result, BT is now rolling out its 5G network, with 71 towns and cities covered in March 2020, and upgrading more than 100 base stations per month **[Ei]**.

Furthermore, BT's and the Lab's joint experiments and field trials of Quantum Secured Virtualised Network Services using the Lab's Quantum Secured 5G test bed *'also accelerated* [BT's] *internal research roadmap and strategy applying quantum security within our national infrastructure.'* **[Ei]**. The first industrial deployment of a quantum-secure network occurred in October 2020. The Head of Optical Technology at BT stated that this *'…is a significant milestone as we move towards a quantum-ready economy…The power of quantum computing offers unprecedented opportunity for UK industry, but this is an essential first step to ensure its power can be harnessed in the right way and without compromising security.'* **[Eiii] [6]**.

Multi-access Edge Computing (MEC) is yet another key component in 5G networks. The Lab's research **[2]** was critical for the development of Bristol's 5GUK Test Network in 2018, and for the support of use-cases in the '5G Smart Tourism' project, both funded by UK Government's (DCMS) 5G Testbeds and Trials Programme **[F]**. This has guided corporates such as Samsung, who stated that: '*The pioneering work on MEC architectures at the University of Bristol, the technical delivery at Roman Baths and the profound impact it has generated, has greatly influenced our product roadmap, design and offering.'* **[G]** The company is developing its next generation MEC product, '*with the University providing key technical enhancements to allow applications to move between MEC nodes without delays in the service they are providing. Mobile gaming, video streaming, and connected car applications will all be enhanced by this technology.*' **[G]**.

5G Technology Commercialisation through Spin-out Zeetta Networks
In 2015, Zeetta Networks was established to commercialise Network Virtualisation and Orchestration research **[2]** as a software platform product (NetOS®) and to develop open networking solutions for the automation of ICT network parameters. Zeetta has received over GBP5 million in funding from venture capital investors, growing from 3 FTE in 2015 to over 30 in 2020, with revenues of GBP1.3 million in 2019. Zeetta Networks has developed its product roadmap to include support for 5G through its key product, NetOS® Automate, a private 5G network orchestrator. The Smart Internet Lab's research and technology expertise has resulted in the following commercial success for Zeetta **[Hi]**:

i. Deutsche Telecom's Fibre to the Home (FTTH) network: Zeetta helped design the network architecture and deployment of the network now providing multigigabit delivery to 4 cities.
ii. Ashton Gate Stadium: Zeetta installed the high-density Wi-Fi network and deployed its Enterprise software controller providing flexible connectivity to different end users.
iii. Bristol's Harbourside Festival: Zeetta deployed their NetOS Rapide® to "slice" and "splice" the network infrastructure to deliver bespoke connectivity to different user groups, devices, and applications, thus supporting the needs of Public Safety, Retail and Video Streaming.

One of Zeetta's key investors has stated that the NetOS Rapide® product is: "*a software platform which in our opinion is among the first in the market to democratise the operation and orchestration of telecom network infrastructure, and the service creation environment of network services. It does this in a way analogous to what Google Android and Apple iOS have done for the mobile phone ecosystem.*" – Co-Founder and CTO, Bloc Ventures Ltd **[Hii]**.

Public Engagement and Increased Societal Awareness of 5G
The University of Bristol's Smart Internet Lab has succeeded in bringing the public on board through a series of exciting showcase events, commencing with the UK's first large-scale urban 5G testbed, the 'Layered Realities Weekend' (March 2018). This was co-created with Watershed **[I]** to jointly explore the potential of 5G through a series of experimental events. Over 3,000 members of the public came to experience interactive activities from spectacular 3D-like projections (Millennium Constellations), virtual reality dance and a guided tour ('Billennium

Square – walking back through time'). BT stated that '*This novel event both introduced the wider public to the benefits of 5G and engaged with creative industries to explore new use cases which in turn drive the design of capabilities in the supporting network.*' **[Ei]**. Extensive press and media coverage reached over 14 million people and Watershed said afterwards, the event "*was important, not only because it increased the public's awareness of how 5G can be used to improve their lives, but most importantly because SMEs and… leading figures from the creative sector pioneered new products and cultural experiences.* [The] *tech sector gained access to creative minds and creative content with which to innovate and a chance to reach out to new audiences to test the technology further than conventional consumer testing.*" **[I]** The collaboration was recognised by DCMS in 'Culture is Digital' as a stellar example of creative and technology partnership **[I]**.

Following this event, 5G Smart Tourism delivered enhanced experiences for tourists using Augmented Reality (AR) and Virtual Reality (VR), 3D motion tracking, and 4k 360° content streaming technology, at major attractions in Bath and Bristol, including the Roman Baths and Millennium Square. This provided '*environments where UK businesses (including SMEs like Mativision Ltd and Zeetta Networks Ltd.), could test and develop 5G applications, services and products*' **[Ai]**. 5G Smart Tourism directly exploited the pioneering development of the 5G Exchange **[3]**, offering the opportunity to automate the provision of deterministic low latency services between multiple interconnected sites, enabling very new and exciting applications; for example, 'Orchestrating the Orchestra' demonstrating the ability of multiple musicians who are geographically separated to play together. Connection latency via services from online platforms such as Zoom is variable and cannot be predicted, inhibiting precise synchronisation between musicians and limiting audience experience. The world's first ever online music lesson (Music for All), using the 5G Exchange, was led by musician Jamie Cullum and proved highly successful. The Principal of the Royal Birmingham Conservatoire stated that: '*All children and young people deserve access to music… It's fantastic that this kind of technology* [5G] *is now existing that you can literally give a lesson in real time, anywhere in the world*' **[J @ 1:43]**. The Chairman of Music for All remarked that '*5G will now enable musicians ultimately to play with other musicians from anywhere in the world without actually having to be in the same room, which would create a wonderful opportunity for cross-pollination*' **[J @ 1:09]**.

5. Sources to corroborate the impact

[A]   i) DCMS – Corroborating statement (2020), Programme Director, 5G Testbeds and Trials; ii) Membership of Telecoms Diversification Task force [Accessed 24/1/2021]; iii) Guidance document (7 December 2020) *5G Supply Chain Diversification Strategy* [Accessed15/2/2021]
[B]   i) Letter from Chair of FCCG (2020); ii) FCCG Report: UK strategy and plan for 5G & Digitisation (2017); iii) Next Generation Mobile Technologies: A 5G Strategy for the UK (2017) p.8
[C]   i) National Instruments – Corroborating statement (2020), Director of Marketing, Wireless Research / SDR; ii) RAN1, Korea, 2016, R1-162238; iii) 3GPPP R1-162238
[D]   i) Digital Catapult (2020) – Corroborating statement, CEO; ii) ETSI Open Source MANO (Orchestrating the Orchestral) [Accessed 24/1/2021]
[E]   i) BT – Corroborating statement (2020), MD Applied Research; ii) YouTube video [Accessed 22/12/2020]; iii) BT Press release (2020) [Accessed 4/12/2020]
[F]   UK Government/DCMS press release (2017), *Three universities to develop £16m 5G test network* [Accessed 20/04/2020]
[G]   Samsung – Corroborating statement (2020), VP Communications Research
[H]   i) Zeetta Networks Ltd – Corroborating statement (2020), CEO; ii) Bloc Ventures Ltd – Corroborating statement (2020), Co-founder and CTO
[I]   Watershed – Corroborating statement (2020), CEO
[J]   Music for All, video (July 2019), World's First 5G Music Lesson; see also Music For All website [Accessed 28/4/2020]