Institution: King's College London		
Unit of Assessment: Computer Science and Informatics (UoA 11)		
Title of case study: Pioneering 5G research impacts global telecommunications industry		
Period when the underpinning research was undertaken: 2013-2018		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed:**
Dr Toktam Mahmoodi	Director of Centre, Reader,	TM 2011-present
Prof. Mischa Dohler	Ex-Director of Centre, Prof.,	MD 2013-present
Dr Nishanth Sastry	Senior Lecturer	NS 2011-2020
Period when the claimed impact occurred: 2014-2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact (indicative maximum 100 words)

Mobile connectivity is truly pervasive and underpins a wide range of commercial and societal applications. Telco has thus become a trillion-pound industry with 2G-4G mobile networks serving more than eight billion connections today. 5G systems were seven years in the making and are now being deployed with an expected market value of GBP500,000,000,000 by 2030.

A key factor in the success to acquire parts of this market is the ability to enter the 5G market early with innovative offerings, and to cut operational costs through standardised solutions. To this end, King's fundamental research contributions on 5G telecommunication systems impacted industry and standards developments alike:

- **Ericsson** (5G market leader): King's impacted **[text removed for publication]**.
- **Konica Minolta** (enterprise printing market leader): King's impacted **[text removed for publication]**.
- **3GPP** (global telecommunications standards body, 700 industry members): King's provided standards-essential contributions to two standards on converged 5G architectures, which provide significant benefits in terms of customer experience and affects all network and broadband providers globally.
- **GSMA** (global operator alliance with 750 operator members): King's introduced cost-saving Generic 5G Slice Templates, initially included in the de-facto industry guidebook and which are now being adopted by **[text removed for publication]** telecoms operators globally.

2. Underpinning research (indicative maximum 500 words)

5G provides significant improvements in performance over 4G in that capacity (data rate in bits/s), reliability (number of dropped calls) and latency (e.g. time for a website to load) are improved by several orders of magnitudes. This enables unprecedented applications, such as untethered industrial control for Industry 4.0 or remote robotic surgery. The improved performance is achieved through a departure from legacy design principles, some of which King's has contributed to through pioneering research.

Notably, 2G – 4G telecommunications systems are cell/network-centric in that capacity and quality of experience (QoE) are dictated by the location of the basestation. Departing from this design approach, King's has contributed to fundamental research enabling the transition to device-centric architectures where capacity and QoE are dictated by the degree of connectivity experienced from the mobile terminal's point of view. This has become the guiding architecture approach for 5G systems. Specifically, King's pioneered and contributed to i) decoupled up and downlinks; ii) fixed-mobile convergence; iii) application-centric edge-cloud design; and iv) software-enabled network slicing:

2.1 Decoupled up and downlink architecture

In 2014, we introduced a paradigm shift in cell-centric telecommunication networks by allowing up and downlinks to terminate at different basestations. We showed significant capacity gains but also reliability and latency gains. One research contribution was to design a viable protocol allowing for two prior non-related basestations to handle the same call flow; this has been achieved through a complete decoupling of both data and control channels. The biggest challenge was to formally analyse the new system, since analytical models to represent this system were entirely missing. We had thus introduced a novel analytical framework quantifying the gains of decoupling in the lower frequencies but, surprisingly, showing that gains for higher frequencies such as millimetre wave systems eroded unless highly directional antennas were used [1]. This fundamental body of research resulted in several milestone publications, including a Best Paper Award at IEEE's flagship conference which laid the groundwork for [1], with many citations indicating the opening of a new field of research. **[text removed for publication]**.

2.2 Fixed and 5G mobile convergence

Another important transition in 5G is reconciling the different wireless technologies under the same network management. We made a prominent contribution in changing the way fixed and mobile broadband networks operate by converging their capacity and enabling them to *jointly* deliver critical services. Given these networks follow different protocols and often reside on different infrastructures, the main challenge was how to seamlessly bring them together. Through theoretical research and experimentation, we have shown how aggregating the two networks at higher layers, and using Multi-Path TCP (MPTCP), can result in better performance and QoE than the combined capacity of two separate streams [2]. **[text removed for publication]**.

2.3 Multi-tier 5G edge-clouds

We have pioneered the notion of an application-centric caching-as-a-service in cloud and edge-cloud 5G networks. We have formulated the service delivery as a formal trade-off between cost and performance [3]. The result was a clear multi-tier cloud strategy with analysis supporting a strong case for edge-cloud deployments. **[text removed for publication]**.

2.4 Generic 5G slice templates

Another area of significance in the transition from 4G to 5G is moving to softwarised, virtualised, and cloud-supported systems. One of our major contributions in this area has been the development of a programmable multi-domain and national scale testbed [4,5]. That allowed us to research and contribute to the definition of network slicing. Network slicing is a means to establish and guaranteeing personalised end-to-end services through re-programming the 5G network. Our main research contribution was the introduction of Slicing Templates, as a solution to addressing technical and business aspects of network slicing over an infrastructure with *multiple* ownerships [6]. **[text removed for publication]**.

2.5 Co-creation of 5G use-cases

The ensemble of above research contributions enabled a fresh look at mobile architectures able to deliver 5G applications. Enabled by [4,5], King's engaged in interdisciplinary co-creation research in health, transport and the arts. This has inspired numerous societal 5G applications at global scale and has led to ample media coverage. Furthermore, it stimulated research in King's pioneering concept of the Internet of Skills, a next-generation internet powered by 5G, AI and robotics, able to execute physical skills remotely. **[text removed for publication]**.

3. References to the research (indicative maximum of six references)

[1] Elshaer, H, Kulkarni, MN, Boccardi, F, Andrews, JG & **Dohler, M** 2016, 'Downlink and uplink cell association with traditional macrocells and millimeter wave small cells', IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS, vol. 15, no. 9, 7493676, pp. 6244-6258. https://doi.org/10.1109/TWC.2016.2582152 *(based on IEEE Globecom 2014 Best-Paper: Elshaer, H, Boccardi, F,* ***Dohler, M****, Irmer, R, 'Downlink and Uplink*

Decoupling: A Disruptive Architectural Design for 5G Networks', IEEE Globecom 2014, December 2014, Austin, Texas, US.)

[2] Condoluci, M, Johnson, SH, Ayadurai, V, Lema Rosas, MA, Cuevas, **M, Dohler, M** & **Mahmoodi, T** 2018, 'Fixed-Mobile Convergence in the 5G era: From Hybrid Access to Converged Core', IEEE NETWORK, vol. 33, no. 2, pp. 138 - 145. https://doi.org/10.1109/MNET.2018.1700462

[3] Ghoreishi, SE, Karamshuk, D, Friderikos, V, **Sastry, NR**, **Dohler, M** & Aghvami, A-H 2019, 'A Cost-Driven Approach to Caching-as-a-Service in Cloud-Based 5G Mobile Networks', IEEE Transactions on Mobile Computing. https://doi.org/10.1109/TMC.2019.2904061

[4] 5G Testbeds & Trials Programme, Hub 1 Project; Department for Digital, Culture, Media & Sport, **Dohler, M.**, Holland, O., Friderikos, V., **Sastry, N.**, Shikh-Bahaei, M., **Mahmoodi, T.** et al.; GBP3,000,000; 1/07/2017 30/03/2018.

[5] The UK Programmable Fixed and Mobile Internet Infrastructure (INITIATE); EPSRC - Engineering and Physical Sciences Research Council, **Mahmoodi, T.**, **Dohler, M.**, GBP1,676,408, 1/02/2017 31/01/2021.

[6] Jiang, M, Condoluci, M & **Mahmoodi, T** 2017, Network slicing in 5G: An auction-based model. in 2017 IEEE International Conference on Communications., 7996490, IEEE, 2017 IEEE International Conference on Communications, ICC 2017, Paris, France, 21/05/2017. https://doi.org/10.1109/ICC.2017.7996490

4. Details of the impact (indicative maximum 750 words)

King's research has enabled a departure from legacy protocol and architecture design principles with significant impact on global telecoms industries and standards:

4.1 Impact on Ericsson's [text removed for publication]:
Ericsson is the world's second largest vendor in telco services, software and infrastructure, and 5G market leader with an annual revenue of USD28,000,000,000. "*2.5bn subscribers and 40% of the world's mobile traffic is carried over Ericsson's networks*" [A, page 1], thus powering half of the world's mobile commercial and societal services. Ericsson and King's have engaged in close joint research, innovation and deployment/experimentation over the past seven years. The underpinning research 2.1 and 2.5 achieved impact in four areas:

- **[text removed for publication]** ***use-case developments:*** "*King's played an instrumental role in gauging early 5G architecture capabilities and translating them into viable societal use cases. As a result, Ericsson has spearheaded many use cases* **[text removed for publication]**. *These have been documented on Ericsson's website with specific mention of King's inception; notably in health, education and gaming, and the arts and culture*" [A, p.2]. Important world's first were the output of King's work: "*the world's first robotic surgery over 5G […] which impacted the industry vision in the use of 5G for medical interventions […]"* and "*UK's first 5G 3.5GHz deployment with Vodafone, 5G sliced drone using EE's and Verizon's networks, or the world's first 5G music lesson with Jamie Cullum*". [A p.3, B, C]
- ***Impact on*** **[text removed for publication]*:*** *"Based on the pioneering use case developments and 5G prototyping, the work of King's College London has* **[text removed for publication]** *to address novel 5G use cases"* [A, p.3] and *"it […] is* **[text removed for publication]***"* [A, p.2]. As a result: "*In confidence,* **[text removed for publication]***"* [A, p.3].
- ***Skills development*** **[text removed for publication]*:*** *"Ericsson was able to* **[text removed for publication]***"* [A, p.2].
- ***Marketing, branding and societal outreach:*** *"The work conducted by King's […] has led to significant press and media coverage* [C]. *Notably outlets, such as CNN, BBC,*

Wired, FT, have continuously reported on the technical advances of this work. **[text removed for publication]***"* [A, p.3].

4.2 Impact on Konica Minolta [text removed for publication]:
Konica Minolta (KM) offers a large variety of products in the form of office equipment, medical imaging, graphic imaging, optical devices and measuring instruments at a GBP7,400,000,000 annual revenue. It is market leader in enterprise printing products. King's has engaged with KM over a years-long engagement via **[text removed for publication]**:

- ***Establishment*** **[text removed for publication]***: "The roadmap developed by Prof M Dohler in 2014-2015 outlined a set of opportunities for Konica Minolta around* **[text removed for publication]** *capabilities. Furthermore, King's College London […] advocated for a* **[text removed for publication]**. *[…] Following the KCL report, Konica Minolta focused on* **[text removed for publication]** *known as Distributed Cloud Intelligence (DCI)"* [D, E]. Further, *"the ongoing collaboration has been specifically useful for DCI and has helped* **[text removed for publication]***"* [D].
- **[text removed for publication]***: "An important outcome [of the joint projects] has been Konica Minolta's* **[text removed for publication]** [D, F]. The **[text removed for publication]** benefits are reported **[text removed for publication]** [D]; thus, giving an increased competitive **[text removed for publication]** [D].

4.3 Impact [text removed for publication] via 3GPP standards contributions:
The 3rd Generation Partnership Project (3GPP) is the world's largest umbrella of seven standards organizations which develop cellular telecommunications technologies, including radio access, core network and service capabilities. More than 700 industry partners contribute to 3GPP, making it the largest standards body shaping the £-trillion telco market. King's research on converged 5G telecommunications architectures was integrated into 3GPP with the support of BT. The standards contributions underpinned by the research have been fed directly into Release 16 and 17 Technical specifications [G], i.e. 3GPP TS 23.501 Sections 4.2.10. (Architecture Reference Model for ATSSS Support) and 5.32 (Support for ATSSS) as well as 3GPP TS 23.502 Section 4.22 (ATSSS procedures). The underpinning research 2.2 achieved impact in two areas:

- **[text removed for publication]** ***5G technical specifications:*** *"The work that King's and BT carried out on 5G convergence has been* **[text removed for publication]** *to support both fixed and mobile access technologies, and in particular the ability for operators to make dynamic decisions to route traffic to customers to optimise quality of experience in the most efficient manner"* [H]. The contributions are specification standards, and essential to be implemented, hence confirmed to impact all broadband providers who have both fixed and mobile network infrastructure [H].
- **[text removed for publication]** ***5G feature rollouts:*** *"This [convergence] feature is expected to be incorporated into vendor roadmaps and operator network deployments across the globe as 5G solutions evolve and mature towards a fully converged architecture, delivering significant benefits to customer experience"* [G].

4.4 Development of cost-efficient slicing template for largest telco association:
The Global System for Mobile Communications Association (GSMA) is the world's largest telco association representing and influencing the business practice of more than 750 mobile network operators worldwide.

King's underpinning research 2.4 impacted the pioneering concept of a *Generic Slice Template* that allows multiple operators to exchange the basic information of their network slice without revealing their technical details that could expose their competitive advantage. Hence, for the first time, user services can go across multiple operator domains with the exchange of slice templates between the involved operators. *"These insights have provided independent thought-leadership for the GSMA to push for the creation of the Generic Slice Template (GST)"* [H].

King's work was thus included in the *"The '5G Guide: a reference for operators' [which] is the de-facto industry guidebook on the commercial, policy and technical considerations for the 5G business case. Following its completion, it was distributed to the GSMA Board for adoption at the February 2019 Board meeting and subsequently distributed to the CEOs of the 750 mobile operators in the world in April 2019" [H].* Importantly, *"all the GSMA Board member companies, i.e. the **[text removed for publication]** largest telcos in the world, have now incorporated or are considering incorporating slicing into their 5G network plans, following a similar strategy as outlined in the document"* [H].

King's work *"has impacted the industry's position on how to optimise the creation and management of slices. Two specific recommendations from KCL stand out: i) optimise granularity of network slices so as to balance the need for more differentiation versus the costs of provisioning slices; ii) and [the creation of] standardised slice templates with predefined and optional fields that could bring down the cost and time to deploy of network slices significantly, guaranteeing interoperability and enabling automation of slice management on global scale"* [H].

5. Sources to corroborate the impact (indicative maximum of 10 references)

[A] Ericsson Testimonial: **[text removed for publication]** Ericsson Research; 23 Oct 2020.

[B] Ericsson and King's collaboration on 5G use cases:
i) Ericsson and King's: Reshaping our world with 5G research
ii) 5G Health: Access to remote healthcare specialists
iii) 5G Education: Bringing learning to life with educational technology
iv) 5G Arts: Reaching new audiences through connected culture
v) 5G Gaming: The future of educational gaming

[C] Media articles on King's / Ericsson's 5G collaboration:
i) BBC: "Drones to the rescue!" 30 April 2018
ii) CNN: "How 5G could change everything from music to medicine", 5 Feb 2018
iii) EIN Presswire: "Jamie Cullum leads world's first music lesson for music-making charity", 28 June 2019
iv) Financial Times: "5G future: a world of remote colonoscopies", 28 March 2018
v) BBC: "Hologram phone calls sci-fi or serious possibility?" Sept 2019
vi) Wired: "More UK cities are testing 5G. Here's how it could be useful", 5 Sept 2018.

[D] Konica Minolta Testimonial: **[text removed for publication]** Konica Minolta; 26 Oct 2020.

[E] Konica Minolta's new DCI business unit

[F] Konica Minolta's new product offerings from DCI:
1.) Smart cloud services
2.) Hybrid edge computing

[G] British Telecom Testimonial: **[text removed for publication]** British Telecom, 9 Sept 2020 & 11 Dec 2017.

[H] GSMA Testimonial: **[text removed for publication]** GSMA; 17 Sept 2020.