Institution: Liverpool John Moores University (LJMU)		
Unit of Assessment: UOA11 – Computer Science and Informatics		
Title of case study: What to do With the Wi-Fi Wild West (Wi-5)		
Period when the underpinning research was undertaken: 2015-2020		
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:**
Dr M. Mackay	Senior Lecturer	2010-present
Dr F. Bouhafs	Senior Lecturer	2009-2020
Dr A. Raschella	Lecturer	2015-present
Prof Q. Shi	Professor	1994-present
Period when the claimed impact occurred: 2015-2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact

Wi-Fi devices should operate in a way to reduce interference between them and thus increase spectrum capacity to meet growing service demands. The EU H2020 funded Wi-5 project developed novel algorithms for such a solution. Its impact includes (a) *the text here redacted*, (b) solution exploitation for securing two government grants worth £7.8m to create 5G-supported digital health and social care services with estimated annual savings of £247,688 per hundred users, (c) consultation with 16 telecommunication operators in 7 countries (e.g., *the text here redacted*), and (d) 16 contributions to standardisation bodies.

2. Underpinning Research

Wi-Fi has been facing growing pressure to provide quality-of-experience support through Access Points (APs) to an ever-increasing number of mobile devices (e.g., smartphones) driven by a surge of bandwidth-intensive services (e.g., online meetings). This rising demand is causing Wi-Fi saturation and hence interference among competing APs, particularly in dense areas like university campuses and business centres, which negatively impacts users' experience in Wi-Fi services.

The EU H2020 funded Wi-5 project coordinated by LJMU [7] aimed to rectify the above interference problems by proposing smart solutions based on Software Defined Wireless Networking (SDWN) techniques to cooperatively reduce interference between neighbouring APs and provide optimised service connectivity. The main novel results [1]-[6] produced from the project by the UOA staff (Bouhafs, Raschellà, Mackay, Shi) in collaboration with the project partners, which underpin the impact of this case study, include:

- Spectrum programming architecture for Wi-Fi radio resource management [1], which introduces the first definition of a spectrum control plane for fine-grained allocation of radio resources, flexible configuration of wireless networking parameters, and continuous monitoring of the network status.
- AP selection framework [2], which is among the first contributions to address Quality of Service (QoS) awareness in enterprise Wi-Fi networks using SDWN to determine the most suitable APs for satisfying users' QoS requirements with minimal interference and associate their devices to these APs.
- Interference management algorithm [3], which considers the network-wide impact of Wi-Fi to dynamically adjust the allocation of radio resources with respect to users' service quality requirements while minimizing its effect on neighbouring APs.

- AP selection algorithm [4], which is among the first to use a centralized game theory-based approach to address high AP interference problems by seamlessly reallocating connected users to more suitable APs for better services when their connections are negatively affected by interference.
- Channel assignment algorithm [5], which is able to jointly optimise the transmission power and RF (Radio Frequency) channel assignment of APs by taking into account users' required service qualities while minimising their interference impact throughout the Wi-Fi network.

The above results were evaluated based on extensive simulations to demonstrate their effectiveness and performance, e.g., the channel assignment algorithm evaluation in [6]. They were also integrated into a smart Wi-5 platform to provide channel assignment and AP cooperation for systematic Wi-Fi resource management [1]. In collaboration with the project partners "Universidad de Zaragoza" (UNIZAR) and AirTies, the solution was implemented on Wi-Fi equipment and incorporated into a testbed provided by AirTies to further evaluate its performance in real-world scenarios. Then another project partner PrimeTel PLC performed field trials to widen the evaluation in practical settings.

The above thorough evaluation concluded that the Wi-5 solution is capable of optimising AP interference reduction and thus Wi-Fi resource utilisation systematically, dynamically and automatically. Particularly, when many devices are deployed in close proximity, the solution shows significant improvements over existing techniques (e.g., a reduction of users' service dissatisfaction by up to 83% [4]), as their performance deteriorates considerably under dense deployments in terms of data rates, delays and connectivity.

3. References to the research

All the outputs below have been through a rigorous peer-review process.

[1] Bouhafs, F, Mackay, M, Raschella, A, Shi, Q, den Hartog, F, Saldana, J, Munilla, R, Ruiz-Mas, J, Fern·ndez-Navajas, J, Almodovar, J and van Adrichem, N (2018) Wi-5: A Programming Architecture for Unlicensed Frequency Bands. IEEE Communications Magazine, 56 (12). pp. 178-185. ISSN 0163-6804

Link: http://researchonline.ljmu.ac.uk/9608/

[2] Raschella, A, Bouhafs, F, Seyedebrahimi, M, Mackay, M and Shi, Q (2017) Quality of Service Oriented Access Point Selection Framework for Large Wi-Fi Networks. IEEE Transactions on Network and Service Management, 14 (2). pp. 441-455. ISSN 1932-4537

Link: http://researchonline.ljmu.ac.uk/5494/

[3] Bouhafs, F, Seyedebrahimi, M, Raschella, A, Mackay, M and Shi, Q (2019) Per-Flow Radio Resource Management to Mitigate Interference in Dense IEEE 802.11 Wireless LANs. IEEE Transactions on Mobile Computing, 19 (5). pp. 1170-1183. ISSN 1536-1233

Link: http://researchonline.ljmu.ac.uk/id/eprint/10241/

[4] Raschella, A, Bouhafs, F, Mackay, M, Shi, Q, OrtÌn, J, G·llego, JR and Canales, M (2019) A Dynamic Access Point Allocation Algorithm for Dense Wireless LANs Using Potential Game. Computer Networks, 167. pp. 1-12. ISSN 1389-1286

Link: http://researchonline.ljmu.ac.uk/id/eprint/11759/

[5] Seyedebrahimi, M, Bouhafs, F, Raschella, A, Mackay, M and Shi, Q (2017) Fine-Grained Radio Resource Management to Control Interference in Dense Wi-Fi Networks. In: IEEE

Wireless Communications and Networking Conference (WCNC). 19 March 2017 - 22 March 2017, San Francisco, USA.

Link: http://researchonline.ljmu.ac.uk/5470/

[6] den Hartog, F, Raschella, A, Bouhafs, F, Kempker, P, Boltjes, B and Seyedebrahimi, M (2017) A Pathway to Solving the Wi-Fi Tragedy of the Commons in Apartment Blocks. In: 27th International Telecommunication Networks and Applications Conference (ITNAC). 22 November 2017 - 24 November 2017, Melbourne, Australia.

Link: http://researchonline.ljmu.ac.uk/id/eprint/11596/

Details of key research grants or end of grant reports

[7] EU Horizon 2020, What to do With the Wi-Fi Wild West (Wi-5), €2,106,084 (€778,640 for LJMU: Shi, Bouhafs and Mackay), 01/01/2015-04/30/2018, Grant ID 644262.

Link: https://cordis.europa.eu/project/id/644262

4. Details of the impact

The main impacts of the Wi-5 solution outlined in Section 2 include improved Wi-Fi services, new service exploitation and informed technology choice. These three impact areas are elaborated separately below:

- *Wi-Fi service improvements: The text here has been redacted.*
- *New service exploitation:* The Liverpool 5G Testbed project (03/2018-01/2020) involving 12 partners was funded by the DCMS (Department for Digital, Culture, Media & Sport) to showcase the feasibility of 5G technology for improving health and social care services [a]. The Wi-5 solution helped to secure the funding (£3.5m) as it was used to formulate the part of the proposal regarding unlicensed 5G mmWave wireless network management fundamental to the project. Specifically, the SDWN-based platform [1] developed by the Wi-5 project was employed to build a Self Organising Network (SON) management system in collaboration with an industrial partner, Blu Wireless, specialising in mmWave network products and services. Such SONs provided network flexibility and intelligence to support the proposed use cases of health and social care services.

  The project resulted in promising impact on the considered care services [b]. Notably, the cost savings from the implementation of the tested use cases for care services were estimated to be £247,688 for every hundred users per year. Also, the project was mentioned in over 160 press and media articles for its impact dissemination and had over 60 organizations interested in partnerships and/or collaborations. The significant benefits demonstrated by the project led to a further DCMS grant of £4.3m for the follow-up Liverpool 5G Create project (08/2020-03/2022) to further develop and widen the benefits in selected areas of Liverpool [c].

  The text here has been redacted.

- *Informed technology choice:* The Wi-5 consortium actively engaged with industry and the community for result sharing. For example, the project established an Operator Board with 16 telecommunication operators in 7 countries and met 5 times over the project period [d] to inform them of the project progress and demonstrate the results [1]-[6], which influenced their choices of Wi-Fi technologies. *The text here has been redacted*. Additionally, the Wi-5 project made 16 contributions to three standardisation bodies: IETF (Internet Engineering Task Force,

9), HGI (Home Gateway Initiative, 2) and BBF (Broadband Forum, 5) for result dissemination [d].

5. Sources to corroborate the impact

[a] DCMS, Liverpool 5G Testbed, £3.5m (£211K for LJMU: Mackay, Bouhafs and Waraich), 03/2018-01/2020.

Link: https://uk5g.org/discover/testbeds-and-trials/liverpool-5g-testbed/

[b] Project report: Liverpool 5G Health and Social Care Testbed Benefits, Outcomes and Impact.

Link: https://liverpool5g.org.uk/wp-content/uploads/2020/04/Liverpool-5G-Testbed-Benefits-Outcomes-Impact.pdf

[c] DCMS, Liverpool 5G Create, £4.3m (£255K for LJMU: Mackay, Bouhafs, Waraich, et al.), 08/2020-03/2022.

Links: https://uk5g.org/discover/testbeds-and-trials/liverpool-5g-create/

https://www.computerweekly.com/news/252487100/Liverpool-scores-win-with-5G-health-and-social-care-project

[d] Wi-5 project deliverable, D6.5 Final Dissemination, Exploitation and Standardisation Report, 2018.