Institution: The University of Nottingham		
Unit of Assessment:10		
Title of case study: Enabling the rollout of 5G in Italy and optimising vibration and noise control in vehicles using wave modelling		
Period when the underpinning research was undertaken: 2008 to present		
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:**
Gabriele Gradoni	Associate Professor of Applied Mathematics & Electromagnetics Engineering	2013 - current
Gregor Tanner	Professor of Applied Mathematics	1998 - current
Stephen C Creagh	Associate Professor	1998 - current
Period when the claimed impact occurred: 2013 to present		
Is this case study continued from a case study submitted in 2014? N		

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

Working in partnership with a leading communications provider, Telecom Italia, software and modelling developed at the University of Nottingham were applied to real-life wireless communication scenarios to inform operational planning in the rollout of 5G in Italy.

Research confirmed that electromagnetic fields (EMF) transitioning from outdoor-to-indoor environments would remain under Italy's exposure limit of 6V/m. [TEXT REDACTED]

The same underpinning research informs the design and manufacturing process for a range of complex structures for minimised noise and vibration, including tractor cabins (Yanmar Ltd) and others through new licensed software (inuTech).

2. Underpinning research (indicative maximum 500 words)

Simulating the distribution of electromagnetic and vibro-acoustic wave energy in complex structures (e.g. buildings, vehicles, networks of internet-enabled devices) at high frequencies is extremely challenging for standard numerical tools, such as Finite or Boundary Element Methods and Finite Difference Time Domain methods, due to the large scales and time-consuming calculations required.

Professor Tanner began researching alternative methods in 2008, developing *Dynamical Energy Analysis* (DEA). DEA approximates wave transport in terms of ray dynamics which is described using linear phase space operators **[1]**. In 2013, Professor Tanner and Dr Stephen Creagh formed the *Wave Modelling Research Group (WAMO)* with the *George Green Institute for Electromagnetics Research* of the Faculty of Engineering. Dr Gradoni joined WAMO in the same year. WAMO has enhanced Nottingham's reputation for wave modelling, introducing methods such as DEA combined with Wigner function techniques, and the transfer operator formalism in engineering contexts.
The WAMO electromagnetic wave modelling research led by Dr Gradoni and Professor Tanner consists of novel high-frequency asymptotic methods based on DEA developed to simulate

energy transfer in large-scale scenarios (e.g. buildings, cities, vehicles) and small-scale scenarios (e.g. chip-to-chip wireless communications inside internet-enabled devices).

Large-scale scenarios
In 2015, to support the planning and roll out of 5G in Italy **[10]**, a simplified version of DEA, the power balance method based on impedances simulations within the random coupling model (RCM), was used to predict the signal energy leakage between two adjacent rooms coupled through windows and doors **[2]**.

DEA can also be used to simulate the distribution of vibrational and acoustic wave energy in vehicles. In vehicle cabins, for example, it is an efficient way to ensure the safe design of vehicles, including reducing unwanted movement and lowering sound levels that may otherwise damage human hearing, as well as to maintain comfort. In these scenarios, the basic DEA algorithm **[1]** is applied to a mesh **[6]**. Since 2015, this method has been further refined for efficiency **[7]** and extended to 3D **[8]**.

Small-scale scenarios
Working in collaboration with industry partners, DEA has been extended to simulate energy transfer between EMF in small-scale environments (chip-to-chip interconnects within printed circuit boards and device-to-device communications within networks) using RCM-based channel matrices **[3, 11]**.

Linking small- to large-scale scenarios
Professor Tanner and Dr Gradoni developed techniques using DEA based on the Wigner function method **[4, 5, 9]** to link wireless energy transfer from small-scale electronics such as smartphones and tablets to large-scale environments such as buildings and cities.

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

NB: University of Nottingham staff (at the time of publication) have been **bolded** in the following publication list.

Underpinning references:

1. *Dynamical Energy Analysis - determining wave energy distributions in vibro-acoustical structures in the high-frequency regime*, **G. Tanner**, Journal of Sound and Vibration 320, 1023–1038. DOI: 10.1016/j.jsv.2008.08.032 (2009)
2. *Coupling Between Multipath Environments through a Large Aperture*, L. Gagliardi, D. Micheli, **G. Gradoni**, F. Moglie and V. M. Primiani in *IEEE Antennas and Wireless Propagation Letters*, vol. 14, pp. 1463-1466.DOI: 10.1109/LAWP.2015.2411621 (2015).
3. *Near-Field MIMO Communication Links*, **S. Phang**, M. T. Ivrlač, **G. Gradoni**, **S. C. Creag**h, **G. Tanner** and J. A. Nossek, in IEEE Transactions on Circuits and Systems I: Regular Papers, vol. 65, no. 9, pp. 3027-3036, DOI: 10.1109/TCSI.2018.2796305 (2018).
4. *A phase-space approach for propagating field-field correlation functions*, **G. Gradoni**, **S. C. Creagh**, **G. Tanner**, **C. Smartt**, and **D. W. Thomas**, New J. Phys. 17 093027; DOI: 10.1088/1367-2630/17/9/093027 (2015).
5. *Wigner function-based propagation of stochastic field emissions from planar electromagnetic sources*, **G. Gradoni**, L. R. Arnaut, **S. C. Creagh**, **G. Tanner**, M. H. Baharuddin, **C. Smartt**, and **D. W. P. Thomas**, IEEE Transactions on Electromagnetic Compatibility, 60; DOI: 10.1109/TEMC.2017.2738329 (2018)
6. *Dynamical energy analysis on mesh grids - a new tool for describing the vibro-acoustic response of complex mechanical structures*, D. J. Chappell, D. Löchel, N. Søndergaard and **G. Tanner**, Wave Motion 51, 589-597 (2014).
7. *High-frequency structure- and air-borne sound transmission for a tractor model using Dynamical Energy Analysis*, **T. Hartmann**, S. Morita, **G. Tanner** and D. Chappell, Wave Motion **87**, 132-150 (2019); doi.org/10.1016/j.wavemoti.2018.09.012.7.

8. *Transport of phase space densities through tetrahedral meshes using discrete flow mapping*, J. Bajars, D. J. Chappell, N. Søendergaard and **G. Tanner**, Journal of Computational Physics 328, 95–108 (2016).

Underpinning grants*:*

9. EPSRC, *Characterising electromagnetic fields of integrated electronic systems in enclosures - a ray-wave approach*, 3-year research project (GBP582,976; September 2013 – August 2016; EP/K019694/1).
10. Research project with Telecom Italia, on *Random Coupling Model for Semi-open Wireless Electromagnetic Environments* (GBP15,000; September 2015 – August 2016; 5003355778).
11. Future Emerging Technology Grant (FETopen) - H2020 program, *Noisy Electromagnetic Fields - A Technological Platform for Chip-to-Chip Communication in the 21st Century*, NEMF21; Partners: Universities of Nottingham (Lead partner), CNRS InPhiNi Nice, TU Munich, ISAE Toulouse, IMST GmbH, NXP Semiconductors und CST AG (EUR3,419,638; October 2015 - December 2018; 664828).
12. EU COST IC1407 (ACCREDIT) *Advanced characterisation and classification of radiated emissions in densely integrated technologies* (http://www.cost-ic1407.eu/) (GBP400; July 2014 – July 2018; COST IC1407).
13. Royal Society Industry Fellowship, *MIMO channel hardening by compact antenna arrays.* British Telecommunications, Network Physics Group, Maxwell Centre, Cavendish Laboratory, University of Cambridge. (GBP110,000; March 2020 – September 2022; INF\R2\192066)
14. EU FP7 *Industrial and Academic Partnership & Pathways* (IAPP), Midfrequency Energy Analysis (MIDEA), (EUR794,401; January 2009 - December 2012; 230597).
15. EU FP7 *Industrial and Academic Partnership & Pathways* (IAPP), *Mid-High frequency modeling tools for Vehicle Noise and Vibration* (MHiVec), (EUR1,944,975; September 2013 - August 2017, 612237)
16. EPSRC *Transfer operator methods for modelling high frequency wave fields – advancements through modern functional and numerical analysis* (GBP634,829; February 2018 – May 2021; EP/R012008/1).

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

Research by WAMO has informed operational planning, and research and development in international industry settings. The main impact has been on:

- Communications - extensions to the DEA energy propagation model have been used by the telecommunications industry and service providers to address challenges in modelling 5G.
- Manufacturing – the same DEA extensions have been used to simulate the distribution of vibrational and acoustic wave energy in vehicles to enable optimal vibro-acoustic design of vehicles.

1) Communications

Enabling the rollout of 5G in Italy

An exponential increase in the number of mobile communications devices has been accompanied by an accelerated spread and increase in the density of urban environments, and a greater demand from users for higher network speeds. 5G deployment is expected to create a market value of USD 33.72 Billion by 2026 (The IT Infrastructure Report, 2020).

Italian legislation published in 2003 **[D, page 3]** imposed an electromagnetic exposure limit of 6V/m in the environment. This arbitrary limit is very strict (restrictively so for telecommunication operators) compared to the *International Commission on Non-Ionizing Radiation Protection* (*ICNIRP*) which advises an exposure limit of 41V/m **[C]**. Ordinances published in 2012 **[D,**

n.245, page 13, 14 and n.294, page 89], 2014 **[D, n.262, page 61]**, and 2016 **[D, n. 252, page 6, 9]** progressively increased restrictions on emitted EMF, that significantly constricted operational planning of the 4G and later 5G rollout in Italy. The 2016 ordinance **[D, page 6, 9]** was particularly restrictive and problematic for the telecommunications industry as it assumed that walls and windows did not have any blocking effect and did not reduce the wireless signal entering a building.

In collaboration with Telecom Italia, WAMO models were used to predict EMF by considering the effects of room-coupling and absorption by the building walls, as well as interference caused by complex geometry and irradiation structures within the room. *"In addition to accurately measuring the difference between [outdoor and indoor] environments, WAMO models predicted that the EMF indoors would remain under 6V/m even after the roll-out of 5G...WAMO models predicted that EMF levels in the indoor environment had been largely overestimated by the model which informed the 2016 ordinance and that building geometry and walls significantly lower EMF indoors compared to outdoors. Thanks to the WAMO study, Telecom Italia recognised that the 2016 ordinance assumed a wall absorption value in the outdoor-to-indoor transition that was mathematically inaccurate and too restrictive from an operational point of view*." **[B]**

[TEXT REDACTED] The Global System for Mobile Communications (GSMA, the industry organisation that represents the interests of mobile network operators worldwide) reported in their case study for Italy that as much as 64% of the antenna network would have been rendered unusable for Long Term-Evolution (i.e. for transition to 5G and beyond) under the 2016 ordinance **[C, page 3].**

More recently in collaboration with British Telecom, WAMO's research has identified that reflective surfaces could play a role in overcoming areas of poor radio coverage (known as not-spots) in the roll out of 5G, changing operational planning. *"The work being done [by Gradoni on the fellowship] to simulate the use of reflective surfaces...is important not just for the testbed project...but also for the wider industry... To overcome not-spots, operators typically erect additional masts and antennas, at great cost to the industry. If reflective surfaces are able to play even a small part in improving coverage without the use of additional antennas, the operational saving could be very significant."* **[K]**

In addition, the research has led to the creation of an international professional standard**,** the IEEE Guide (accessed on 27 November 2020).This publication is the first standard providing practitioners and professional services with best practice guidance on near-field measurement methods and characterisation of stochastic electromagnetic fields emitted by complex multifunctional electronics. It is designed to be used as a reference protocol for conducting tests on electronic devices in any accredited laboratory, with certification of compliancy provided in accordance with national scale limits. The chair for the Working Group for the IEEE Guide Development expects "...*final publication within 2021..."* **[A]**.

Developing new telecommunications hardware in Europe
The research has also had impact on telecommunications partners elsewhere in Europe. For NXP Semiconductors (France), WAMO provided the simulation technology to conceive a radically different new hardware architecture for (multi-antenna) wireless interconnects for high-capacity chip-to-chip data transfer within the confined environment of digital devices. "...*we can use [it] as a prototype in the development of future hardware solutions to be provided to and embedded by partner organisations in new IoT [devices]*" **[E]**. In Germany, IMST GmbH used the same research to produce accurate energy propagation maps in fields dominated by noise, which were explored in view of IMST's EMPIRE software optimisation **[F]**. Both organisations have adopted the "C2C" design guidelines developed during the Nottingham-led NEMF21 project and acknowledged the role they have played in shaping strategy **[E, F].**

2) Manufacturing

Reducing noise and vibration in vehicles
At Yanmar Ltd (a Japanese diesel engine manufacturer), the software has been adopted to effect design changes to tractor models that minimise noise and vibration; in particular: "*…on our new YM3 tractor series informed by the DEA simulations undertaken in house (since 2018). More recently (February 2020), the design changes led to a structural modification that ensured the YM3 tractor series is in compliance with EU noise level for drivers legislation (directive 2009/76/EC)"* **[H]**. Between 2015-2018, Yanmar committed GBP120,000 to DEA research published in **[7]**. "*...the research has brought about efficiency savings as the company is able to minimize noise and vibration inside the tractor cabin at an earlier stage of design and does not have to rely on less accurate methods that can lead to costly redesigns"* and "*the DEA R&D tool has been very successful in positioning Yanmar as a company who cares for their customers at work*" **[H]**.

Between 2009 and 2012, inuTech GmbH (a German computer software company) invested more than EUR160,000 in the development of the DEA technology and the grant MHiVec **[15]** *"allowed for development of substantial additional R&D efforts to adapt the DEA software to the requirements of the automotive industry and other transport sectors"* and further investment of *more than EUR150,000 was used on staff hiring and training as well as marketing efforts and networking with potential customers*". Since 2016, the software has been marketed under an Assignment and Revenue Agreement **[I]**. More recently, Romax Technology, a leading gearbox designer and manufacturer, committed GBP24,000 to a PhD CASE studentship and a further GBP90,000 in-kind licensing their software to further develop DEA in their applications **[J]**.

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

[A] Email from Chair of the Working Group for the IEEE Guide Development to Pro-Vice Chancellor of the Faculty of Science, University of Nottingham, dated 14 January 2020 (later emails up to December 2020 also available confirming the same)
[B] Letter from Head of Technology Access and Innovation at Telecom Italia, dated 11 December 2020 (Dissemination – Confidential)
[C] Arbitrary Radio Frequency exposure limits: Impact on 4G network deployment, Case Studies: Brussels, Italy, Lithuania, Paris and Poland, dated 2014.
[D] Italian legislation: Decreto 8 luglio 2003; Gazzetta Ufficiale Della Repubblica Italiana (n.245/19 ottobre 2012; n.294/17 dicembre 2012, n.262/11 novembre 2014, n.252/27 ottobre 2016) with relevant information highlighted in yellow.
[E] Letter from Strategy and Partnership Manager at NXP semi-conductors, dated 26 November 2020
[F] Letter from Scientific Director and CEO at IMST GmbH, dated 16 November 2020
[G] Tanner G (2018), NEMF21: C2C design guidelines (Dissemination – Confidential)
[H] Letter from Divisional Manager at the Fundamental Technology Research Centre at Yanmar, dated 16 June 2020
[I] Letter from General Manager at inuTech, dated 25 June 2020
[J] Letter from Head of Solver Development at Romax, dated 29 April 2020
[K] Letter from Research Manager at BT plc, dated 09 December 2020