DISSEMINATION BEATRICE

Beyond Massive MIMO: living at the interface of electromagnetics and information theory

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The long-awaited rendezvous of Shannon and Maxwell.

"Thoroughly conscious ignorance is the prelude to every real advance in science."

James Clerk Maxwell (1831-1879).

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Exactly 190 years since the birth of James Clerk Maxwell, who is widely regarded as the father of electromagnetism, the term 'wireless waves' is the most appropriate way to describe the world of wireless communications. In the context of wireless policy, 'radio waves' is shorthand for a portion of the broader spectrum of electromagnetic (EM) radiation. In physics, EM radiation is defined in a unified way as a self-propagating transverse oscillating wave of synchronised electric and magnetic fields.

More recently, in the late 1940s, Claude Elwood Shannon (1916-2001) harnessed the skills gained in the field of cryptanalysis for national defence during World War II to develop his groundbreaking information theory (Shannon, 1948): a mathematically tractable framework for the quantification, storage, and communication of digital information.

Whilst information theory has served the wireless communications community particularly well for 70 years; it is a statistical tool based on mathematical logic, not the laws of physics. For example, it does not consider the electromagnetic propagation of communications signals as governed by Maxwell's equations.

Classical information theory now needs to be extended and reshaped to incorporate the main feature of future communication systems, namely their capability of sensing the system's response to the radio waves, thereby informing its modification. The fundamental concept behind the BEATRICE project is the unification of information theory and EM theory to characterise 'wireless waves' to expand the frontiers of wireless communications. This is a challenging exercise: information theory is based on probabilistic tools, while electromagnetic theory encompasses Maxwell's wave equations. As such, the interface between these two theories is inherently a challenging landscape.

The massive MIMO paradigm

Among various technological advances that have been incorporated in 5G standards compared to 4G, **the key technology that stands out as the catalyst is undoubtedly massive multiple-input multiple-output (MaMi).** MaMi was originally proposed as a new academic concept in 2010 in a breakthrough paper from Marzetta (2010). Barely ten years later, MaMi is being taken up across the telecom space, from academic researchers to senior industrial managers and policymakers (Release 15). With MaMi, we refer to cellular systems that deploy an unconventionally large number of antennas (hundreds or even thousands) at base stations (BSs) to serve dozens or even hundreds of users.

The importance of MaMi stems from the extra degrees of freedom it offers, thanks to an excessive number of antennas. It enables strong signal gains from coherent reception/transmit beamforming, gives nearly orthogonal user channels, and provides resilience to imperfect channel knowledge and hardware imperfections.

Our group at Queen's University Belfast (QUB) has pioneered research in the MaMi space, developing novel theoretical and commercially friendly solutions, modelling frameworks, and signal processing algorithms that enabled the commercial exploitation of this technology. Our early ideas and contributions contradicted the early scepticism by the industrial and engineering communities against MaMi, since it was not perceived to be practical from an engineering, cost or power perspective.

The QUB group, spearheaded by Dr Matthaiou, developed the first-ever MaMi beamformers using lens arrays at the critical band of 28GHz (allocated for 5G use by FCC in 2019). One of these prototypes (Figure 1) uses a 2D Rotman lens and represents a viable alternative to lossy and power-hungry state-of-the-art architectures. This demonstrator won the Grand Prize at the 2019 Mobile World Congress (110,000 attendees, including 2,400 exhibitors and 8,000 CEOs) Scholar Challenge for the best innovation in mobile technologies.

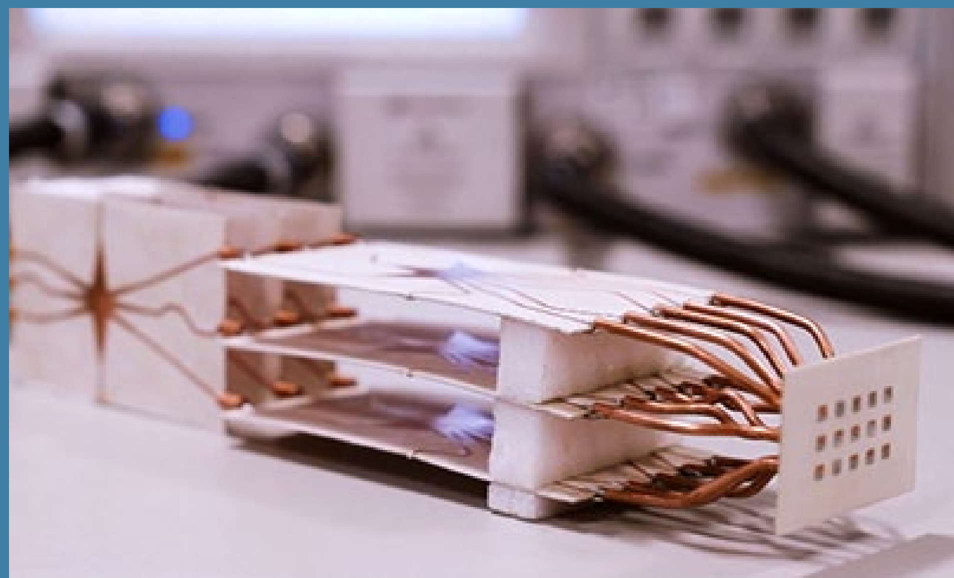

Figure 1: Physical prototype of 2D Rotman lens array at 28GHz recognised as the best innovation in mobile technologies for 2019.

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Project vision and objectives

Looking ahead to the next 15 years, we will see antenna arrays move from the 4,8,16 elements into the hundreds and even thousands, and we are going to see that upscaling happening on a much wider range of frequencies. This presents a significant challenge for us in efficiently designing future communication systems. The challenge is that the electromagnetic theory modelling and manufacturing development of these antenna structures are becoming increasingly complex and challenging. Additionally, we do not fully understand how these wireless channels behave, and it is not completely clear how we would use conventional information theory to describe what the physical tradeoffs are in the way we have exploited them to date. Therefore, we urgently need to crystallise what changes should be made in the information-theoretic models based on these new electromagnetic properties. To this end, the analysis of electromagnetics can provide us with a much more rigorous understanding of the physical constraints, which we have to apply back into the information-theoretic channel models. Only then will we be able to understand the realisable potential of future communication systems.

BEATRICE will address this fundamental challenge by unifying EM theory and information theory and pave the way for an extended range of applications supported by massive antenna arrays after 2025.

The specific project objectives are to:

O1) Redefine the information-theoretic modelling of concurrent and future MaMi-based systems using knowledge of unique EM characteristics, thereby quantifying their realisable potential.

O2) Develop new topological designs and modulation techniques for robust communication by harnessing knowledge about the EM properties of the transceivers and the propagation medium.

O3) Leverage the world-class test and measurement facilities at QUB, to design, fabricate and measure novel array topologies which will be able to support a plethora of MaMi-based applications.

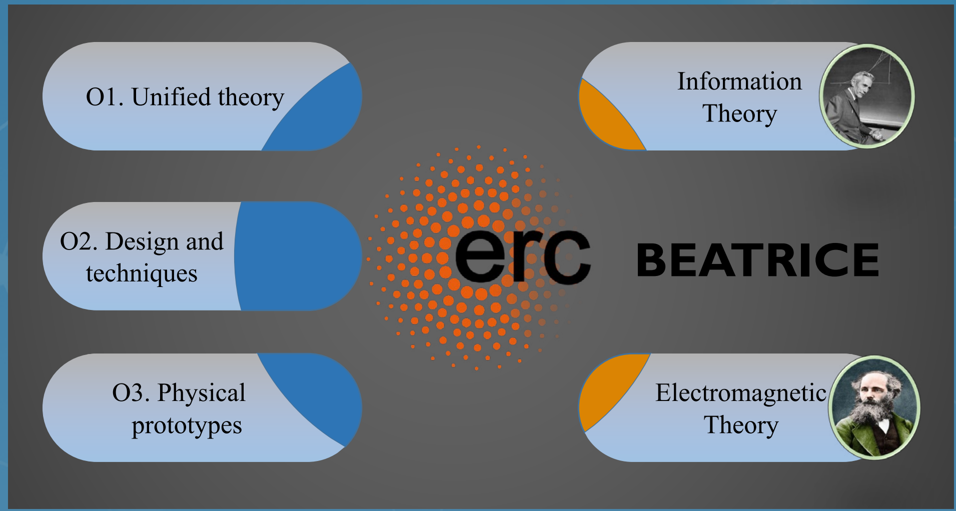

Figure 2: A visualisation of BEATRICE's concept with the required tools and theories to be used within the BEATRICE project.

A visualisation of BEATRICE's concept is depicted in Figure 2, along with the required tools and theories that we will harness to pursue the particular objectives (O1–O3) of the project.

Research methodology

BEATRICE centres around three symbiotic work packages (WPs). Firstly, we will elaborate on super-directive antenna arrays, an old concept that has faced criticism. Yet, there is strong evidence that super-directive antennas will constitute a critical component of many future communication systems since they can offer extremely sharp energy focusing and much lower interference levels. For these reasons, it is essential to go back to first principles and develop solutions for their practical integration.

Secondly, BEATRICE is going to develop a radical technological paradigm called resonant intelligent metasurfaces. The novelty here is to utilise a portion of the antenna modules for cellular services and the remaining portion for maximum power transfer at resonance in the near-field by intelligently tuning the EM properties of the transceivers. This WP will exploit some recent advances in software-controlled metasurfaces and near-field analysis.

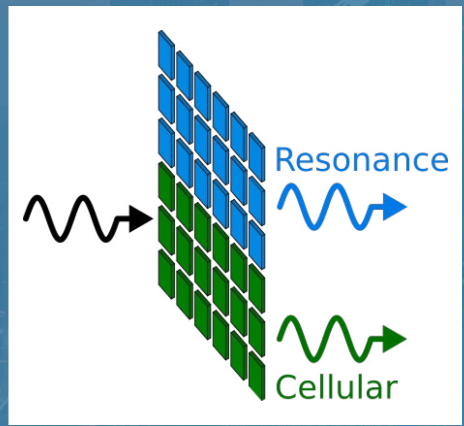

Figure 3: Resonant intelligent metasurfaces system for cellular and wireless power transfer services.

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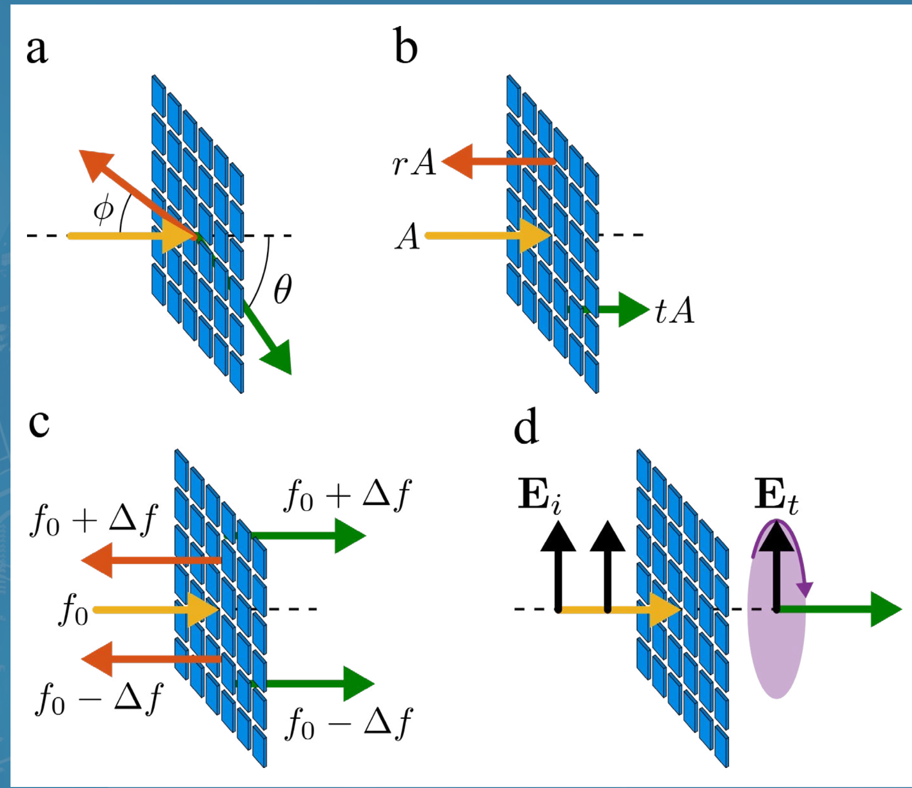

Figure 4: (a) Angle modulation; (b) Amplitude modulation; (c) Frequency modulation; and (d) Polarisation modulation.

More specifically, the recently proposed spatio-temporal coding (Cui *et al.*, 2014) by means of intelligent metasurfaces will lead to a breakthrough in the way we encode/decode information in future wireless networks as it will enable the highly desirable 'recycling' of radio waves. Transforming the breakthrough idea of intelligent metasurfaces to a rigorous modulation technique is a very challenging exercise and will be one of the main objectives of this WP. To this end, we will develop a theoretical framework to cover angle, amplitude, frequency and polarisation modulation (see Figure 4).

Finally, we will physically synthesise and validate the proposed solutions using our extensive, world-class lab facilities at QUB. These novel prototypes will have a substantial impact on diverse research fields, such as electronics, microwave engineering and antenna design, to name but a few.

References

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PROJECT NAME

BEATRICE

PROJECT SUMMARY

Information theory, proposed by Claude Shannon in 1948, has served the wireless communications community particularly well for seven decades. Looking ahead, this theoretical framework needs to be extended to account for the unique electromagnetic properties of concurrent (e.g. 5G) and future (e.g. beyond 5G, 6G) massive multiple-input multiple-output systems. This is a challenging exercise: information theory is based on probabilistic tools whilst electromagnetic theory encompasses Maxwell's wave equations. BEATRICE aims to use these two theories in parallel to create new fundamental understanding, modulation techniques and physical prototypes. These findings will have a far-reaching impact on cellular communications, wireless power transfer, radar, and optical wireless communications.

PROJECT LEAD

Michalis Matthaiou is Professor of Communications Engineering and Signal Processing, and Deputy Director of the Centre for Wireless Innovation at Queen's University Belfast. Under his co-leadership, CWI has become one of the world's leading research and innovation centres in wireless communications systems. Michalis' seminal research contributions have underpinned the development of 5G/6G wireless technologies, with his breakthrough work on massive MIMO removing major scepticism about this technology. He is the recipient of numerous prestigious accolades to date, including a 2019 EURASIP Early Career Award and a 2018-2019 RAEng/Leverhulme Trust Senior Research Fellowship.

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