Editorial
A Decade of Green Radio and the Path to "Net Zero": A United Kingdom Perspective

AROUND ten years ago, several major research projects have studied wireless energy efficiency (EE), including the U.K. Green Radio, EU EARTH and GreenTouch projects. These projects showed that a range of techniques need to be adopted in base stations to save energy, including the following concepts [1], [2]:

- Use of more efficient radio frequency chains;
- Reductions in base station signalling, especially under low load conditions;
- Sleep mode techniques to switch off unused parts of base stations (BSs).

Extensive studies were also performed to investigate how a network of BSs could be adapted to reduce energy consumption, for example by adjusting the cell size [3] or using wireless relays/small-cells.

Following the success of the U.K. Green Radio project, which was completed in 2012 [1]–[3], many of its findings have influenced the development of technology and practices related to the EE of radio access networks. In particular, work on BS sleep modes and equipment shutdown is found in the 5G standards on network operation and management [4] whereas discussions on energy metrics is found in ETSI standards relating to measuring EE in deployed wireless networks [5]. 5G networks also offer more flexible settings on signalling traffic, to improve the EE of lightly loaded BSs.

The Paris COP22 conference in 2015 established the importance of restricting global temperature rises due to global warming to below 2 degrees Celsius. Around the world, governments and businesses are planning how to meet these targets in time to deliver net zero carbon emissions by 2050. Information Communication Technology (ICT) is estimated to contribute around 1.8-2.8% of global carbon emissions [6]. There are significant deviations between the data presented in [6] due to differing assumptions in modelling and about the definition of ICT technologies themselves. One issue that adds to the complexity is the relationship between efficiency and use, going back to Jevon's paradox from 1865.

The English economist William Jevons noted that the use of coal had soared in England after the development of James Watt's steam engine [7]. While Watt's engine had hugely increased the efficiency of burning coal, improved efficiency actually led to increased overall coal consumption as it became so widely used. The paradox thus notes the rebound effect that can occur with improvements in EE. While Jevon's paradox originally related to coal use, similar effects have been observed in many other contexts [6]. The practical impact of Jevon's paradox in modern energy systems is debated in [7], [8]. However, it is clear that ICT carbon emissions must start to be reduced very significantly in order for the COP22 targets to be met in the next 20-30 years. As ICT systems mainly run on electricity, they stand to benefit from the huge growth in renewable energy sources, such as wind and solar.

In this article we will reflect on the importance of EE issues in wireless networks one decade on. Firstly we review current industrial perspectives on EE in networks. Secondly, we briefly discuss some U.K. views on EE, reviewing how energy consumption has evolved in the last ten years and exploring current initiatives to improve the situation in future. We will also report on the outcomes of a panel discussion involving the authors on future research directions that was held in March 2022.

I. INDUSTRIAL PERSPECTIVE

Reducing the power consumption of network equipment has always been an engineering challenge for the telecommunications sector. As mobile operators' roll out continues to provide connectivity to an increasing proportion of the population, the importance of the energy impact of the sector has become an area of scrutiny. Over 10 years ago the U.K. Green Radio programme was initiated through a strategic partnership between the Mobile VCE and U.K. Government, securing a combination of public and private sector R&D funds to ensure the holistic system design issues were researched. That research spawned further U.K. activities in both the industrial and university sectors.

How has the supply side evolved over the last 10 years: For industry, network architecture platforms and the enabled product lines have moved at pace over the past 10 years. Whilst the public mobile network macro towers retain their prime status as the heavy lifters for providing connectivity, the proliferation of small-cell options and the business models that support them continue to evolve. There are more and more at-scale neutral host and system integrators in the supply chain. The emergence of private networks into the vertical industry sectors along with dedicated and shared spectrum creates a new dynamic in digital infrastructure. The convergence of fixed and

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wireless systems and cloud-based approaches to delivery have also matured.

Pillars to the established industrial approach: Three fundamentals of energy efficient telecoms technologies have emerged:

- Transition to renewable energy: The annual reports of telecom operators show this trend is well underway in Europe, e.g., see [9]. A recent report [10] suggests that the ICT carbon footprint would reduce by 80% if all electricity used was from renewable sources.
- Improved network equipment efficiency: Examples include high efficiency power amplifiers and powering down unused sub-systems. This can be more difficult to implement for mixed networks comprising both small-cell and macro-cell networks due to interoperability issues.
- Low carbon data centre applications: The main end to end services are moving away from voice towards a plethora of low-energy data-centre-driven applications as the main value creation mechanism.

Recent industry surveys at a Telecom TV Green Networks event point to limited consensus on the priorities going forward. Artificial Intelligence (AI) and analytics, power-efficient technologies, sharing of physical network resources, and self-generation of green energy within the sector are all currently considered to be important. As industry seems divided on the priority focus, there is a research opportunity to provide evidence for policy makers to determine strategy towards 2030.

Looking forward for the next 10yrs: Telecoms equipment hardware platforms oscillate between software and hardware oriented approaches. The trend of the last few years has been to virtualise systems, particularly with the recent appearance of Open Radio Access Network (Open-RAN) systems and interfaces [11]. This has increased the demand on software architecture approaches and general-purpose processors (GPP). The pendulum will inevitably swing back to hardware acceleration as pressure increases to improve both capacity and EE.

Collaborative ecosystems for product development constitute an enabling concept that is appearing on the horizon and will certainly impact the way in which mobile networks will evolve. In the telecoms domain, some research and innovation (R&I) as well as standards development organisations (SDOs) already have 6G technologies on their 5-10yr roadmap, e.g., [12]. A number of governments worldwide are placing significant importance on the development of diversified supply chains in maturing 5G and 6G – bringing Open-RAN, Open Networks and Open Standards to increased attention.

The shifts in business and technical platforms are likely to be significant. Fixed networks and solar-charged satellites have some inherent advantages in their energy consumption compared to wireless networks. However, the indoor-enterprise, satellite and fixed network sectors place requirements on their business-critical telecoms solutions that will affect the overall energy consumption. Standardised energy metrics, perhaps building on those reported in [13], are needed to unify the approach across a converged deployment architecture. The ability of industry to include whole life cycle analysis in their procurement processes for ICT solutions will increasingly shape buyers' decisions in the future.

II. U.K. VIEWS ON 6G RESEARCH TO APPROACH NET ZERO

In the United Kingdom, many government and industry bodies are currently discussing the development of 6G technologies, with a major focus on EE. In 2021, the U.K. Spectrum Policy Forum organised several major research workshops, which led to the preparation of a White Paper on 6G research. This identifies net zero carbon operation a particular priority research area for the U.K. to pursue [14]. The UK5G Climate and Environment Working Group was also set up in 2021 to explore EE issues around 5G networks, in order to advise the U.K. government and promote further research on the topic [15]. Currently, the UK5G Climate and Environment Working Group is examining EE in 5G deployments in terms of operational energy consumption and cradle-to-grave life cycle analysis.

In order to explore how energy consumption in wireless networks has evolved, Table I shows an indicative comparison of energy consumption figures that were used in the U.K. Green Radio project discussions and other publications circa 2010 for the U.K. These are compared to recent figures for the 2021 period, mainly based on references [16], [17]. The report [16] presents average energy figures from mobile networks in 28 countries in Europe, Africa and Asia. It should be understood that this is not a fair and direct comparison, as the two sets of data were generated in very different ways. However, the results give some general indication of how energy consumption figures have changed over time.

The figures in Table I show that the energy consumed by mobile BSs in a mobile operator's energy budget has increased from around 57% in 2010 to as much as 77% in 2021. This indicates that many mobile operators have significantly improved the overall efficiency of their operations, excluding BS sites. While BS designs have also improved significantly in efficiency, there are fundamental lower limits on the power required to transmit radio signals, as defined by Maxwell's equations. The average network energy consumption per wireless link is observed to have reduced by about 45% over ten years, though the 2021 data is calculated for a wide range of different countries. Similarly, the quoted figures for power consumed for one BS site is observed to reduce by a factor of around two in the last decade. As noted in Section I above, renewable energy sources are now being rapidly adopted by mobile operators in many countries leading to a significant increase compared to 2010. However, in many countries, diesel generation is still used for powering on average 11% of BSs in 2021, especially in remote regions where electrical grid connections are typically not available.

Table II also shows how a typical U.K. operator has evolved from 2010 to 2021. In the last ten years, fourth generation (4G) networks have been widely deployed and 5G BS roll out is presently underway. The amount of radio spectrum owned by

TABLE I
ENERGY COMPARISONS 2010 (U.K.) VS 2021 (28 COUNTRIES)

Metric	**2010 (UK)**	**2021 Data (28 Countries)**
Base Station Energy Consumption % of total	57% [2]	73-77% [16,17]
Network Power Consumed per user/link	3W[1]	1.69 W [16]
Power Consumption of One Base Station Site	7.3 kW [19]	3.3 kW [16]
Renewable Energy Sources Used	6.5% [20]	46% [16]
Diesel Generation	N/A	11% [16]

[1] Informal estimate discussed in the Green Radio project, based on a typical UK mobile operator energy consumption and number of subscribers.

TABLE II
TYPICAL U.K. MOBILE OPERATOR CHARACTERISTICS 2010 VS 2021

Metric	**2010 (UK)**	**2021 (UK)**
Network Types	2G + 3G networks	2G + 3G + 4G + initial 5G deployments
Spectrum Ownership	Typical 40 MHz [21]	Typical 250-350 MHz [22]
Data Volume	1x	300x [18]
Service Type	voice/short message service with some data	mainly data services

operators has increased by about 6-8 times and data traffic figures from Ericsson in [18] suggest a 300-fold increase in network data being processed. It is quite remarkable that the energy consumed by a network on a per link basis has reduced, despite the huge growth in mobile data and the bandwidths used to support mobile connections.

Reference [23] has evaluated the carbon emissions per hour for different wired and wireless technologies, specifically for video streaming applications. The results show that 5G networks are around 2.6 times more energy efficient than older 4G networks and around 18 times more efficient than third generation (3G) wireless systems. In terms of the bits per joule metric, 5G is also recognised as an energy efficient RAN technology in the study in [24] which illustrates the EE of 5G when delivering video services. Nonetheless, there are concerns about the absolute energy consumption in practical 5G deployments, which is expected to exceed levels in previous generations of wireless networks [25], [26]. For example, early 5G BS evaluations reported by China Mobile in [27] have shown that a 5G BS using massive multiple input multiple output (MIMO) technology could deliver sixteen times higher data throughput, but requires almost four times higher peak power consumption. That is, while 5G's EE as measured in bits per joule is higher so is its underlying energy consumption, which could hinder reaching net-zero goals [15].

There are multiple reasons for this expected increase in energy consumption in 5G deployments [28]. The primary causes are attributed to an increase in the number of deployed radio units, the coexistence of "always on" RATs at BS sites and the use of more frequency bands as seen in Table II. In the near future, mm-wave bands above 24 GHz may also be used for data services. As shown in Table I, BSs consume the largest amount of energy in a RAN, for example, in large networks up to 77% of energy use is attributed to BSs in 2021. In 5G more BSs will be deployed through small-cells due to the short propagation distances of mm-wave carriers. Even though each small-cell consumes less energy, the densification of the RAN with more radios and backhaul connections increases the energy consumption per unit area. As noted above, a similar situation arises in massive MIMO deployments where the plurality of radio units at the BS site increases the absolute energy consumption. Often, 5G BSs will share cell sites with 2G, 3G and 4G equipment, resulting in multiple RATs concurrently consuming energy at each BS site. In the long term, solutions such as those discussed in [27] will enable more energy efficient 5G network operation. Until legacy 2G and 3G networks are decommissioned [17], which is expected in the U.K. by 2033, the independent control signalling in each technology may affect the ability to shutdown lightly loaded services on a temporary basis to save energy.

With the ongoing deployment of 5G and standardisation of 5G-Advanced, the U.K. research community is pursuing 6G research for 2030 wireless networks [12], [14], [29]. A key facet of this research is sustainable 6G, aimed at attaining United Nations net-zero goals [30] as well as reducing energy consumption in other sectors such as transport, manufacturing and energy supply [31]. As the vision for 6G encompasses enhanced human communication and pervasive machine communication for robots, data consumption is expected to far exceed that in 5G. Pathways to meet such unprecedented data demand include sub-THz frequency bands for sub-THz radios, extremely large antenna arrays for massive MIMO in conjunction with reflective intelligent surfaces (RIS), softwaraised RAN functions for realising distributed cloud and communications systems and trusted native artificial intelligence (AI) for managing network operation are initial examples of 6G technologies being researched in the U.K. [32]. However, these developments carry significant EE challenges if 6G networks are to meet net-zero goals. Higher frequency bands create even shorter propagation ranges as well as greater electronics inefficiencies making even denser deployments of infrastructure inevitable compared to 5G. Addressing these complexities through the careful co-design of radios, networks and intelligent management systems will form the basis of the U.K.'s research strategy for developing 6G technologies.

III. PANEL DISCUSSION: MAJOR DIRECTIONS FOR FUTURE WIRELESS RESEARCH

On Thursday 3rd March 2022, the authors held a panel meeting to talk about their views on what future research the wireless community should be engaged in. This led to a lively discussion that identified the following trends in EE research:

a) *Energy Consumption for New Applications:* As 6G technology is developed, new applications are coming into view. One example is metaverse type of applications which will offer users fully immersive experiences in ultra-high realistic virtual worlds [33]. These applications are highly multi-modal and real-time interactions might also include ultra-reliable tactile sensory perception of virtual objects in the metaverse. To this end, continuously updating a 360-degree 24k video based panoramic synthetic world with a large number of participants (avatars) will require a significant amount of edge cloud and communication resources for both uplink and downlink communication, entailing substantially higher energy consumption levels. These unprecedented requirements for creating ultra-realistic cyber environments at scale beg for a closer synergy between the metaverse creator's ecosystem and the underlying wireless network to optimize energy consumption.

The inherent trade-offs between latency, data-rate support, energy consumption and overall service quality (i.e., quality of end user interactions and perception in 3D virtual spaces) need to be considered together with the optimal service composition in the continuum between the users and edge/core clouds. Furthermore, since the above constitute competing objectives, metaverse-aware multi-objective optimization will have a prominent role to play in providing sustainable network operating points. This will require consideration of flexible operation over the so-called Pareto frontier of different parameter settings, as described further in item c) below.

b) *Energy Impacts of Open-RAN Technology:* It will be important to define a benchmark for energy and spectral efficiency performance for 5G networks. This will allow the future enhancements to be compared with a suitable baseline. This is particularly important given the current interest in evolving the design of the RAN towards Open-RAN networks as mentioned above in Section I. This approach is very different from current BS products which are typically made by a single manufacturer and are thus vertically integrated. This enables cross-layer optimization of networks and permits high EE operation if desired. However, currently there is a trend in Open-RAN networks where individual network components are procured from different companies, enabling diversification of the network.

New technical approaches are urgently needed to measure the EE of Open-RAN networks. These systems will instead be horizontally integrated and there is a concern that without careful design they may be less energy efficient than current commercial BSs. In March 2022, the Open-RAN alliance technical priorities 2 were released, including initial specifications on EE requirements of future Open-RAN networks [34]. By comparison with existing BSs, optimizing the EE of Open-RAN will require a more granular approach to assess and optimize the energy consumed by the individual components of each BS. The radio unit (RU) of the Open-RAN system is likely to consume significant energy along with the centralised units (CU) and distributed units (DU) that provide data and signal processing functions. The RAN intelligent controller (RIC) will thus have an important role in managing overall energy consumption. There is clearly an open research opportunity to explore how new technologies, such as artificial intelligence and software defined networks, can permit EE to be measured and optimized in future.

c) *Flexibly Using the Full Pareto Boundary:* Taking a step back in history - following Shannon's legendary treatise [35] on the attainable system capacity - decades of research effort has been invested into designing near-capacity systems before the above-mentioned bandwidth-vs. power-efficiency trade-off crystalized during the U.K. Green Radio era of predominantly power-optimized systems. Typically as the spectral efficiency increases, there will be a substantial degradation in terms of the corresponding power efficiency. Based on this understanding, during the run-up to 5G standardization it became broadly recognized that a single operational mode is unable to cater for the rather heterogeneous and almost conflicting requirements of the enhanced mobile broadband (eMBB), massive machine-to-machine (mM2M) and ultra-reliable low-latency communication (URLLC) specifications. This realization heralded the era of multi-component system optimization [36]. Briefly, multi-component optimization goes way beyond the typical constrained optimization problem of wireless systems, where for example the system's sum-rate is maximized under the constraint of a fixed power budget.

As an example, consider Shannon's continuous input continuous output memoryless channel (CCMC) capacity theorem [35]. He implicitly assumed having the idealized simplifying assumption that the channel inflicts random uncorrelated errors and that a potentially infinite-length as well as infinite-complexity channel code may be used. However, if we use a realistic finite-length, finite-complexity block code, finite-block-length (FBL) information theory [37] quantifies the attainable capacity. Again though, even FBL information theory fails to consider the complexity of a block-code capable of achieving it. The Pareto front of all optimal configurations will contain the specific capacity (throughput), delay and complexity associated with each individual legitimate channel coded block length. It becomes plausible that it is not possible to operate closer to Shannon's CCMC capacity for example without increasing either the codeword length and hence the delay and/or the decoding complexity or in fact potentially both.

Consider also the two prior research topics in items a) and b) above related to metaverse applications and Open-RAN networks. Again, in these cases, a range of parameters need to be optimized. As the state-of-the-art evolves, the single-component constrained optimization approach is expected to be gradually extended to twin-component, three-component and multi-component optimization, which requires the joint development of the correct objective functions (OF) to be optimized and the optimization algorithms to find the best solutions. Every time the OF incorporates a new parameter, the search-space of optimal solutions is expanded, which imposes potential challenges in terms of developing good optimization tools for solving these radical research problems. We note in closing that a range of other practical Pareto-optimization problems were listed in [38].

d) *Resolving Conflicting Requirements Through Machine Learning:* In all of the above research topics, we have identified the notion of managing complex, interdependent systems with many operating choices and potentially conflicting requirements. In this part, we discuss how novel machine learning approaches can be used to handle such situations to establish good practical operating choices.

As a first example, consider densely deployed BSs in future networks which could provide massive short-range connectivity at lower power consumption cost and higher spectral efficiency, if the interference barrier is efficiently alleviated. Powerful optimization techniques have played pivotal roles in designing efficient power allocation algorithms in cellular networks. However, their excessive need for side-information and coordination through backhaul links could lead to a failure in tracking channel and traffic variations in a densely deployed network. These overhead requirements, however, can be significantly minimized by exploiting recent advances in optimization and online machine learning, namely online foresighted optimization [39]. An outcome of this approach can lead to online learning-based distributed optimization of power allocation. Each BS adjusts its own transmit power based on locally available statistical prediction of the transmit power levels of the other dominantly interfering BSs as well as the past historical information. In such a setup, each BS can be viewed as an intelligent agent making instantaneous autonomous decisions on its own transmit power strategy. This allows the system overall to find effective operating points in a competitive multi-agent environment of distributed BSs. The online foresighted optimization also accounts for the coupling of the optimization variables across time. This results in near-optimum instantaneous decisions at all times for the network operation.

Other applications of this approach that have already been studied include management of hybrid use of renewable energy sources and the conventional power grid to power wireless networks. Control policies can be developed for energy storage units, which are capable of storing energy in advance during low-cost off-peak intervals and supplying energy when intermittent renewable sources, such as wind or solar are unable to meet the energy demands of the network [40]. A third example arises in the emerging multi-access edge computing (MEC) that can potentially extend cloud computing power to the edge of the network. It is a very promising technology to support user applications with low latency and alleviate energy shortage issues at smart devices. Online foresighted optimization can cope with the time-varying cost and constraint functions of such massively distributed scenarios by devising online control mechanisms for task offloading management [41]. Thus, this approach has the potential to manage complex decision making that has been discussed in research topics a)-c) above.

IV. SUMMARY

Ten years on, there is still a plethora of research topics leading to improved energy efficiency in the telecoms sector. Much of the research from that time is still pertinent and can be used as a springboard for research today. Power efficient radio is important from an industrial perspective as low power consumption is imperative to being competitive in the market. The issue is compounded by the diversification of the network through Open-RAN technologies and new metaverse applications. As networks become more complex the search space for optimal solutions expands. Multi-component system optimization and machine learning can prove valuable in optimizing certain aspects of the space but achieving full Pareto efficiency remains a massive challenge, providing many exciting research opportunities for the decade to come.

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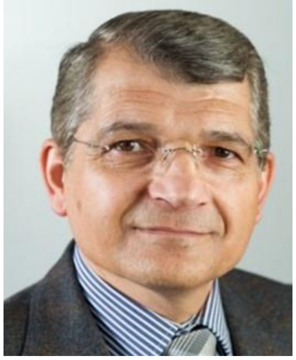

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