Reflective surfaces in wireless networks

Report

10 January 2024
Amended 12 January 2024

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Section

Scope of this document

Ofcom continues to promote competition and investment in new networks and the use of radio spectrum for the benefit of consumers in the UK. We share the Government's commitment to 'world-class digital infrastructure' for the UK, and our work under the theme 'enabling wireless services in the broader economy' demonstrates how we are continuing to manage radio spectrum in an efficient and effective way.[1] In addition, Ofcom reports on the availability of different types of networks in the UK, including mobile services, in our Connected Nations reports.

As wireless communications continue to develop and play an increasingly significant role across many sectors of the economy, we consider it important to keep abreast of technological developments to inform our future work.

In this report, we describe the technology foresight work that Ofcom has undertaken in collaboration with Queen Mary University of London about the potential role of reflective surfaces in future wireless networks. Although we may refer to this report and use it to inform Ofcom's views in Ofcom's future work, it does not necessarily represent Ofcom's concluded position on the particular matters discussed in this report.

[1] Ofcom's Plan of Work 2023–24, 28 March 2023, paragraph 3.2, [accessed on 7 Dec. 2023].

Overview

We have undertaken a piece of technology foresight work in collaboration with Queen Mary University of London on the potential role of reflective surfaces in future wireless communications. Reflective surfaces are currently an area of active research. Standardisation in this area is still in its infancy[2] and may be shaped by existing relay and repeater technologies within 3GPP. Reflective surfaces are primarily envisaged as non-amplifying[3] devices and limited to adding advantageous signal paths, referred to as multipath diversity, between wireless terminals under non-line of sight (NLOS) conditions.[4] The driving attraction behind reflective surfaces is to provide a potentially low-cost and low-complexity solution to extend the coverage of wireless networks.

On the basis of the work that we have undertaken,[5] we consider there are potential technical challenges associated with the adoption of reflective surfaces, which may have regulatory implications and require further attention from field experts. In particular, the use of reflective surfaces as a common solution for extending wireless coverage at 'a large-scale' deployment may raise concerns if their use blocks or alters the propagation environment for services and networks in neighbouring frequencies and creates performance dependencies between multiple networks and services. In addition, mobile terminals behind reflective surfaces may suffer from shadowing losses due to high reflectivity, preventing them from accessing critical wireless services. Shadowing effects depend on the frequency range, geometrical design and the levels of diffraction and edge scattering effects of reflective surfaces.

Another effect that may potentially arise in high user density areas is that the reflected images of mobile terminals on a given reflective surface may be equivalent to having many terminals in close proximity. Unless the number of the reflected terminals is limited on a given reflective surface, additional interference may occur due to intrinsic effects related to mutual electromagnetic coupling, edge scattering, spurious sidelobes and lack of spatial isolation between independent beams. As a result, network terminals may require complex design changes[6] to handle such unwanted effects. Additionally, reflective surfaces require implementing secure functions and interfaces to allow them to integrate with the network over the air to authenticate, obtain and process network control information, forward user traffic, and operate efficiently.

As set out above, this report does not necessarily represent Ofcom's concluded position on the potential role of reflective surfaces in future wireless communications. We will continue to engage with stakeholders and monitor any relevant development of this technology, including any standardisation development.

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[2] ETSI - Reconfigurable Intelligent Surfaces, [accessed on 7 Dec. 2023].
[3] Unlike repeater/relay technology, reflective surfaces are, widely, envisaged, as non-amplifying devices.
[4] Increasing path diversity between wireless terminals adds reliability and resilience to wireless communications against deep fading channel paths (i.e., lossy paths).
[5] Of note, all the modelling and numerical simulations were limited to frequencies below 6 GHz. However, the fundamental behaviour behind these findings is relevant to higher frequencies.
[6] This may involve changes in the air interface design specifications and underlaying mechanisms for performing MIMO (Multiple Input Multiple Output) operations and channel tracking to mitigate intrinsic noise/interference and maintain stable performance.

Initial considerations on the basis of our work

While we recognise that reflective surfaces may have potential benefits, we believe that further work is required by field experts to understand the regulatory implications for their deployment, especially in environments where multiple independent networks and services coexist. This is because, on the basis of the work we have undertaken in collaboration with Queen Mary University of London, we consider there are potential technical challenges associated with the adoption of reflective surfaces. In particular:

- Reflective surfaces can produce unwanted scattering effects (technically referred to as “spurious sidelobes”) which can increase interference and degrade the performance of network terminals unless upgraded to cope with additional interference levels.
- Redirecting wireless coverage using reflective surfaces works like a zero-sum game. While using a reflective surface to enhance the coverage in one area, it can weaken the coverage in other areas or the area behind it due to shadowing. Shadowing effects are inversely proportional to the distance between a reflective surface and signal source.
- Reflective surfaces can alter propagation conditions of out-of-band frequencies, which can impose coexistence challenges and impairments to existing services and networks.

Introduction

Background

1.1 Reflective surfaces exploit antenna theory and design fundamentals, particularly in providing a ground plane that redirects one-half of the radiation, effectively doubling the transmit power, in the desired direction. This report focuses on their use to enhance the radio propagation environment for wireless networks. Although the use of reflective surfaces was researched in the past,[7,8,9] it has regained strong interest recently as a potential building block in the next generation wireless technology. The application of this concept can be traced back to the mid-20th century, when reflective surface elements were integral to the Instrument Landing System (ILS). These elements were deployed on the glide path to add path diversity between the landing aircraft and glide-path antenna to ensure a safe landing.[10]

1.2 Extending the reach of wireless communication remains the fundamental driver behind the continuous advancement in terminal and network design since its inception.[11] Addressing this challenge involves considering the densification of network deployment, or the use of relay and repeater technologies to extend wireless coverage. Often, repeater and relay solutions provide only coverage extension by detecting, amplifying, and forwarding signals. Some relay solutions can serve as base stations, regenerate signals, schedule and manage radio resources to provide new cells. Related solutions currently in development within 3GPP include Integrated Access and Backhaul (IAB), Vehicle-Mounted Relay (VMR), and Network-Controlled Repeater (NCR).[12,13,14]

1.3 Reflective surfaces have recently attracted research efforts as a potential solution for enhancing wireless coverage. While they share the design objective of repeater/relay technology in extending the reach of wireless networks, they differ on how they operate and interact with radio waves. Reflective surfaces, in the simplest form, are non-amplifying and mirror-like devices that can interact with radio waves, reflect, and redirect them towards the intended user terminal under non-line of sight (NLOS) conditions or disperse radio waves to create advantageous channel conditions. The behaviour of a reflective surface can be understood using a generalised Snell's law which defines the relationship between the angle of reflection and the angle of incidence at the interface of two different media - free space

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[7] Techniques for analyzing frequency selective surfaces-a review | IEEE Journals & Magazine | IEEE Xplore, [accessed on 7 Dec. 2023].
[8] Controlling propagation environments using Intelligent Walls | IEEE Conference Publication | IEEE Xplore, [accessed on 7 Dec. 2023].
[9] Frequency Selective Buildings Through Frequency Selective Surfaces | IEEE Journals & Magazine | IEEE Xplore
[10] An Airport Glide-Path System Using Flush- Mounted, Traveling- Wave Runway Antennas, 1961 - Link, [accessed on 7 Dec. 2023].
[11] Anniversary of Marconi's First Patent | Nature, [accessed on 27 Nov. 2023].
[12] Release 17 Description; Summary of Rel-17 Work Items, Specification # 21.917 (3gpp.org), [accessed on 7 Dec. 2023].
[13] Study on architecture enhancements for vehicle-mounted relays, Specification # 23.700-05 (3gpp.org), [accessed on 7 Dec. 2023].
[14] Study on NR Network-controlled Repeaters, Specification # 38.867 (3gpp.org), [accessed on 7 Dec. 2023].

and a reflective surface. In essence, reflective surfaces are mirror-like devices that can interact with radio waves, involving zero-sum game coverage management.

Purpose of our work and relevant scenarios

1.4 The primary goal of the work that we have undertaken in collaboration with Queen Mary University of London ("QMUL") was to explore the fundamental behaviour of reflective surfaces and highlight potential implications, noting that the exact behaviour/impact of reflective surfaces on radio environments is scenario specific.[15] We recognise that challenges are not equal across all deployment scenarios or the electromagnetic spectrum.

1.5 Based on the physics of electromagnetics, reflective surfaces may become problematic if their use blocks or alters the propagation environment for services and networks in neighbouring frequencies and creates performance dependencies between multiple networks and services. Additional interference may arise due to resonance, mutual coupling, edge scattering, spurious sidelobes, and lack of spatial isolation between independent beams. As a result, network terminals may require complex design changes to handle such unwanted effects.

1.6 Ofcom has worked in collaboration with QMUL to investigate whether the issues described above would arise in the following three scenarios in the sub-6 GHz spectrum, by carrying out "full-wave"[16] simulations:

a) Scenario A investigates the fundamental behaviour of a reconfigurable reflective surface, widely referred to as Reconfigurable Intelligent Surface ("RIS"). It explores the scattering characteristics of the reflected signals and their potential impact on network terminals.
b) Scenario B investigates shadowing effect and how it varies with distance.
c) Scenario C investigates how frequency-specific RIS coexists with other out-of-band signal sources. The study examines whether reflective surfaces can block or alter the propagation environment for services and networks in neighbouring frequencies.

1.7 As all the modelling efforts were limited to frequencies below 6 GHz, use cases targeting millimetre-wave (mmWave) frequencies were not considered. Reflective surfaces tuned for mmWave might interact with lower frequency signals through resonance. Coexistence studies are recommended to assess their out-of-band impact on much lower or higher frequencies.

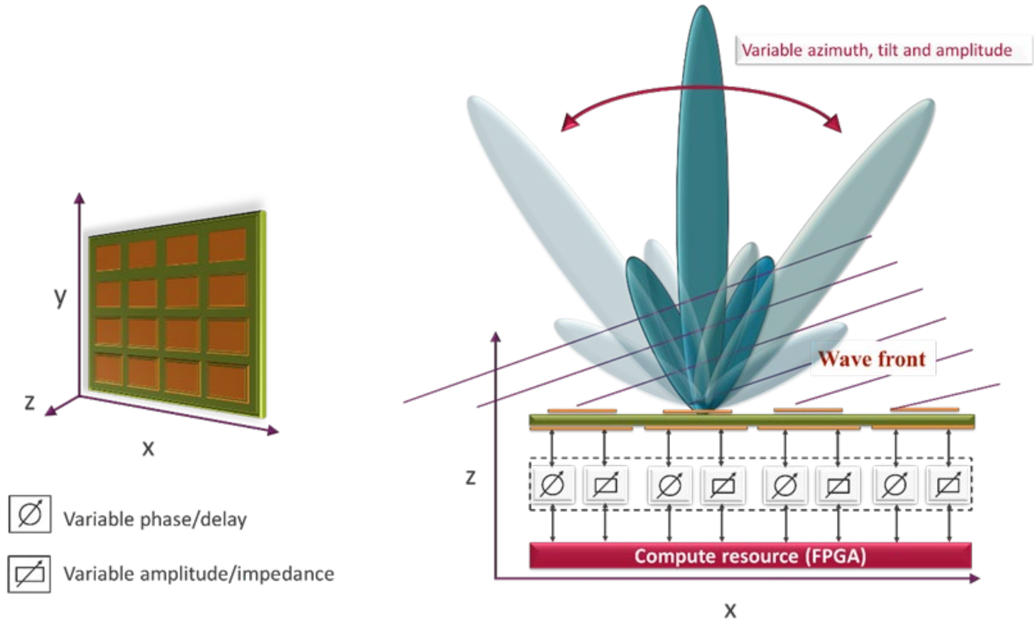
[15] All the modelling efforts were limited to frequencies below 6 GHz. Use cases targeting millimetre wave (mmWave) frequencies were not considered. Reflective surfaces tuned for mmWave might interact with lower frequency signals through resonance. Coexistence studies are recommended to assess their out-of-band impact on much lower or higher frequencies.
[16] Full-wave solutions require specialist electromagnetic wave solvers to take into account all the physics parameters, i.e., solving maxwell equations and taking into account the problem geometries and all their electromagnetic properties rather than using empirical models.

Scenario analysis

Types of reflective surfaces

2.1 The common types of reflective surfaces are passive and active. A passive surface is widely understood to be static and non-configurable, which can be as simple as a metallic sheet with optimised geometries for target frequency bands. Active reflective surfaces, a common type is known as “reconfigurable intelligent surface” (“RIS”), require power, active electronics, and computing resources, as illustrated in Figure 1. RIS can be made of an array of active reflective elements, often referred to as unit cells, arranged in either a periodic or an aperiodic pattern.[17] The design could be made of microstrip patches in the form of planar elements, where each element has a variable amplitude and phase response controlled by an FPGA (Field Programmable Gate Array). These elements allow manipulating electromagnetic waves by controlling the electromagnetic properties of the individual reflective elements such as dielectric constant, or/and impedance which as a result affect the levels of mutual coupling across the reflective elements and the overall frequency response of RIS. The models used in this work aimed at exposing the fundamental behaviour of RIS in wireless communications, with predefined functions to activate tuneable materials, using linear and non-linear configurations.

Figure 1 Basic Architecture of Reflective Intelligent Surface



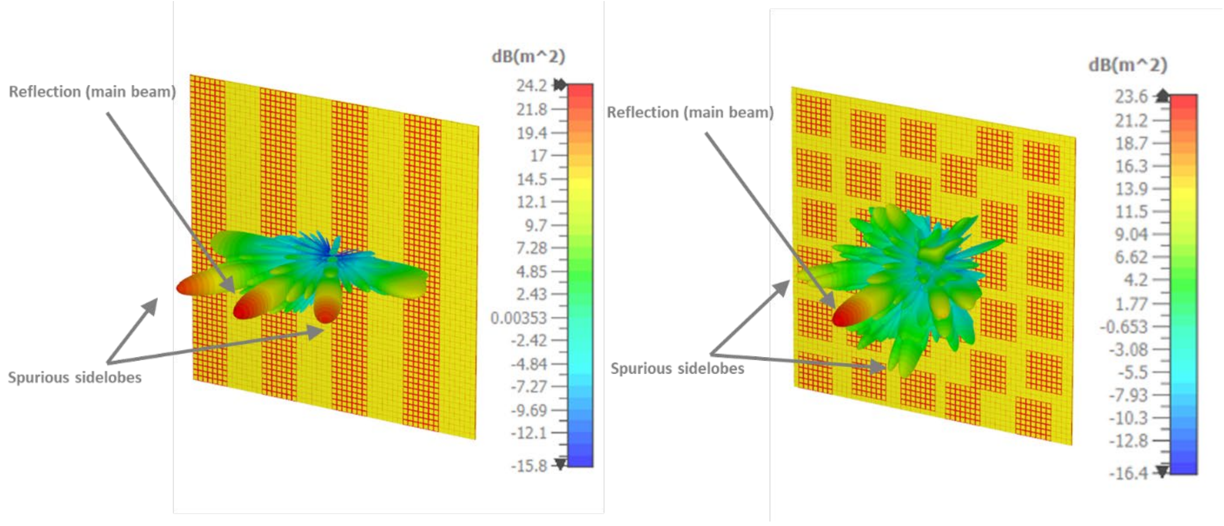
[Source: Ofcom]

[17] Array pattern may follow a regular periodic structure as well as an aperiodic structure. Periodic structures provide easier estimation of the array pattern and faster design/simulation. However, irregular array patterns with aperiodic placement of unit cells can randomise the location of side-lobes and, in this way, manage the effects of grating lobes. Additionally, irregular patterns can achieve broader bandwidths.

Scenario A: fundamental behaviour of reconfigurable reflective surfaces

2.2 The simulation excluded the limitations of practical RIS and instead modelled and simulated an idealised RIS which is infinitely large.[18] The excitation method is modelled using an idealised source, i.e., plane wave,[19] to expose the fundamental behaviour of the RIS. The full-wave simulation suggests that configurability of the RIS produces additional beam patterns (spurious sidelobes) with irregular directivity, as shown in Figure 2 A & B.[20] These sidelobes originate at the RIS and as part of the reflections rather than from the excitation source. Linear configurability,[21] Figure 2 A, has lower computational complexity however provides less suppression to spurious sidelobes. Pseudo random, i.e., nonlinear, configurability, shown in Figure 2 B, can reduce spurious sidelobes but is deemed more computationally exhaustive. The behaviour of an idealised RIS is analogous to a shattered or fragmented mirror, where a perfect beam of light can be both reflected and scattered over the individual fragments at the same time. While scattering may be advantageous to multipath diversity in low Signal-to-Noise Ratio (SNR) regions, it can be disadvantageous for spatial multiplexing (multi-user MIMO) in high SNR regions, where the unwanted sidelobes lead to additional levels of interference. For practical systems, these behaviours can be amplified and directly influence the performance of mobile and network terminals.

Figure 2 A) Idealised RIS with linear configurability. B) Idealised RIS with nonlinear configurability



[Source: Queen Mary University of London]

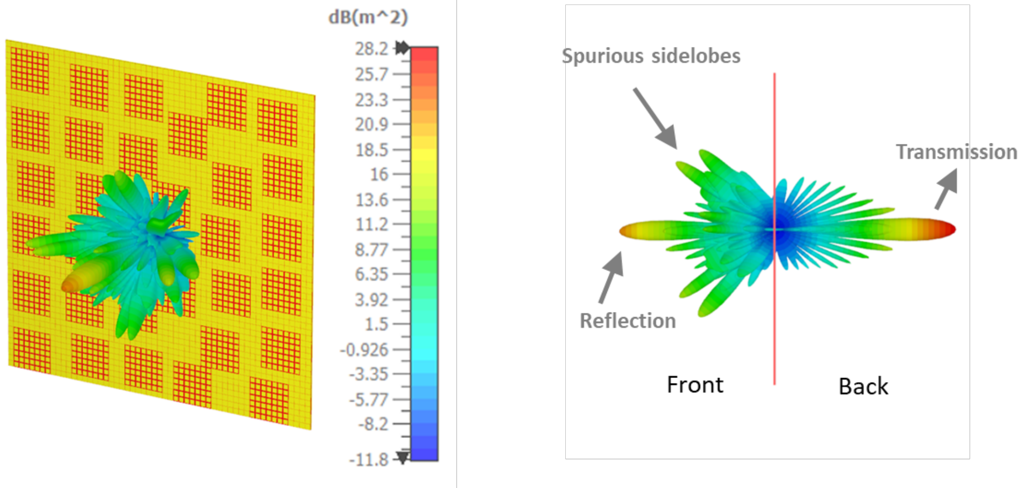
[18] An idealised reflective surface has maximum efficiency without edge effects or diffraction losses.
[19] Meaning that the entire surface area of a RIS is equally and fully excited, i.e., idealised excitation.
[20] Note: a recent white paper from Rohde & Schwarz demonstrated a similar effect, discussed under section 5, [Link](), [accessed on 12 Dec. 2023].
[21] Configurability in general is an optimisation for the phases and amplitudes of all the RIS elements in an attempt to form an ideal beam without spurious sidelobes in the context of our work.

Scenario B: Shadowing effects

2.3 In order to test shadowing effects and the efficiency of the RIS, a finite RIS in size was simulated using 48x48 unit elements, resulting in approximate dimensions of 700mm x 700mm at 3GHz. It was found that:

a) when a RIS is located far away from the signal source, the excitation beam can be approximated as a plane wave, i.e., idealised excitation. In this scenario, a significant portion of the wave energy ‘propagates through’ the RIS, as shown in Figure 3. This suggests that finite RIS in size are unlikely to cause extreme shadowing effect due to wave diffraction at the edges. However, it is important to note that the efficiency of RIS becomes inversely proportional to the distance between the source and RIS.

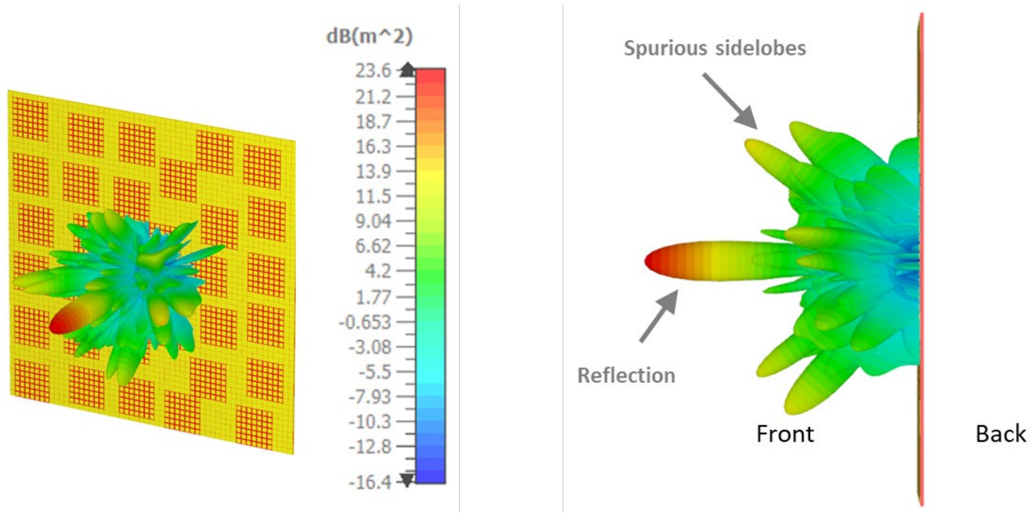
Figure 3 Evaluation of shadowing when 3GHz RIS is located far from the source



[Source: Queen Mary University of London]

b) when a RIS is located in close proximity to the source, the shadowing effect caused by the finite RIS in size becomes prominent, where the incoming signals are totally reflected, as shown in Figure 4.

Figure 4 Evaluation of shadowing effect when 3GHz RIS is in close proximity to the source

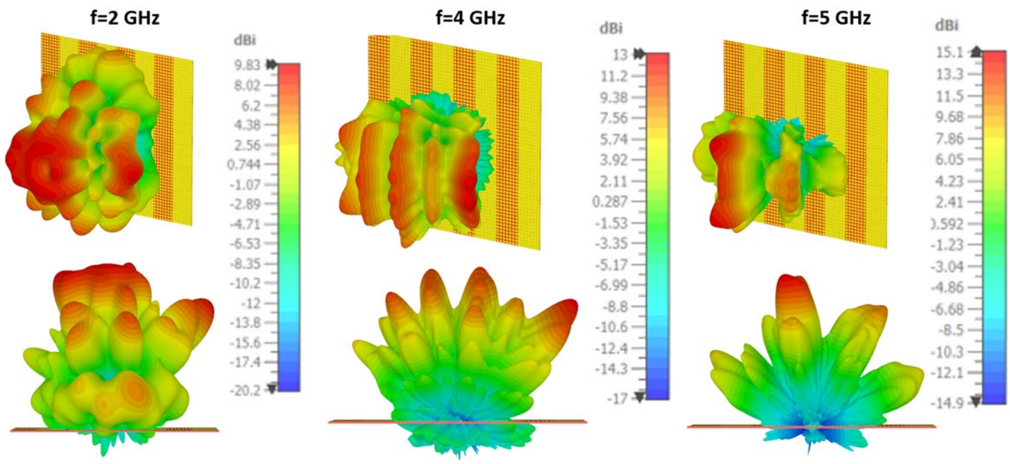


[Source: Queen Mary University of London]

Scenario C: Coexistence and out-of-band effects

2.4 To investigate the out-of-band effects of reconfigurable reflective surfaces, a wideband frequency response of an idealised RIS tuned for 3 GHz is simulated and excited using idealised sources around the operating frequency. Figure 5 shows that the frequency response of the 3 GHz RIS, when excited by idealised sources operating at 2, 4 and 5 GHz. The results clearly demonstrate that a RIS designed and tuned for a specific frequency can also react and alter out-of-band frequency radiations.

Figure 5 Out of band effects: 3GHz RIS frequency responses to idealised sources operating at 2, 4 and 5 GHz



[Source: Queen Mary University of London]

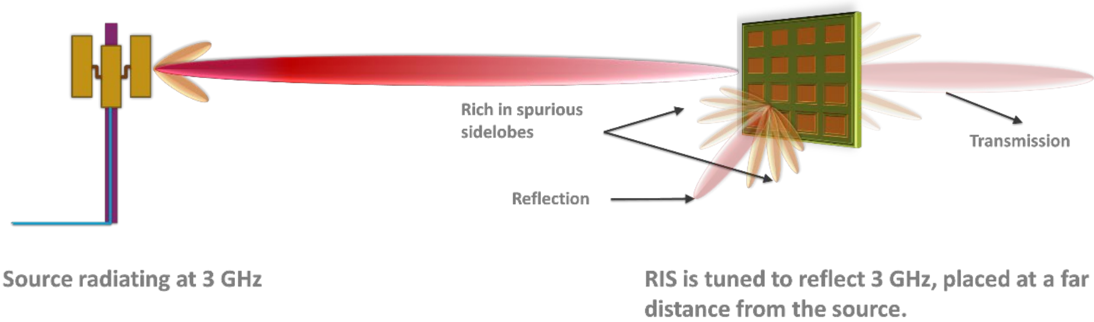
Initial considerations relating to practical scenarios

3.1 In this section, we provide a simplified interpretation of the results shown in Figures 2, 3, 4, & 5, relating to practical scenarios within cellular networks.

3.2 **RIS at the cell edge:** Assuming RIS is placed at a far distance from the source, as shown in Figure 6. The distance involved allows the travelling wave from the source to be approximated as a plane wave - meaning that the entire surface area of the RIS is uniformly and fully excited, i.e., also referred to as “idealised excitation”. Under such conditions, RIS behaves as a refractive surface, where both reflections and transmissions occur at the same time. This implies the following:

- Shadowing effect/loss is less significant, allowing terminals to receive transmission even if they are located behind a RIS.
- Reflection is less effective, especially under low SNR conditions and with less directional sources, e.g., mobile handsets.
- The reflected incident can be rich in spurious sidelobes which may either result in more channel/multi-path diversity or interference.

Figure 6 The behaviour of RIS at the cell edge

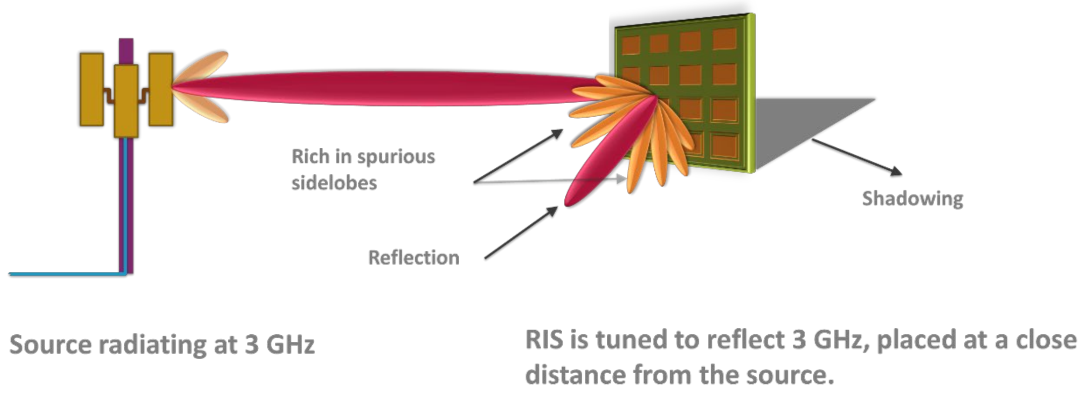


[Source: Ofcom]

3.3 **RIS at the cell centre:** If RIS is in close proximity from the signal source, i.e., high SNR region, as shown in Figure 7, RIS behaves as an idealised reflector/mirror.[22] This implies the following:

- The shadowing effect/loss can be excessive with zero transmission. Hence RIS may potentially block transmission for terminals located behind it. The shadowing region depends on several factors including operating frequency, RIS geometries and placement.
- Reflection is more effective since RIS can capture enough radiation under high SNR conditions and behave more like an idealised mirror.
- The reflected incident can be rich in spurious sidelobes which may either result in more channel/path diversity or interference. However, it is more likely to lead to more interference in high SNR regions even within the same cell, i.e., inter-cell-interference, as mobile terminals may struggle to cope with this effect.

Figure 7 behaviour of RIS at the cell centre

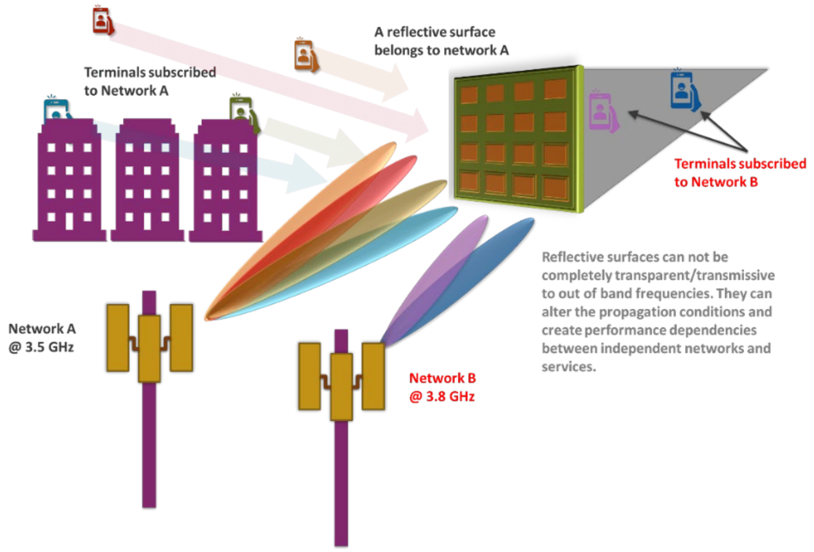


[Source: Ofcom]

[22] The behaviour of an idealised RIS is analogous to a shattered or fragmented mirror where a perfect beam of light can be both reflected and scattered at the same time.

3.4 **Coexistence and out of band:** In multi-operator deployments, as illustrated in Figure 8, our findings suggest that when frequency bands are relatively close and the frequency response of an operator-specific RIS tails off over neighbouring frequencies or generates out-of-band harmonics due to design features, RIS can alter the propagation conditions or introduce interference to other operators or services. In the context of real-world wireless communications, a frequency specific RIS must not alter the characteristics of out-of-band frequencies to avoid creating dependencies or interference among independent services, networks, and operators.

Figure 8 behaviour of RIS across multiple services and networks



[Source: Ofcom]

Additional considerations

4.1 As mentioned above, the analysis carried out as part of this work was limited to frequencies below 6 GHz. Use cases targeting mmWave frequencies were not considered in this work. While the challenges associated with reflective surfaces are expected to be different with higher frequencies, reflective surfaces tuned for mmWave might still interact with lower or higher frequency signals through a combination of diverse effects encompassing wave reflections, scattering and re-radiation. This leaves a question to be examined via coexistence studies to assess the extent of the out-of-band impact on much lower or higher frequencies.

4.2 Both reflective surfaces and repeater technology primarily aim to extend wireless coverage to hard-to-reach areas. RIS may benefit from 3GPP repeater technologies, e.g., Network-Controlled Repeaters (NCR), in forming a benchmark to assess and shape its future design specifications and use cases.

4.3 Due to their direct dependence on the beam shape and directivity of both the transmitter and receiver, reflective surfaces may have asymmetric downlink and uplink performance. In addition, reconfigurable surfaces, e.g., RIS, may need to be compatible with different duplexing schemes.

4.4 In high density deployments, a reflective surface can reflect many user terminals which may be equivalent to placing a large number of terminals in close proximity to each other. This can result in additional interference that need to be dealt with by adopting more powerful algorithmic solutions in networks terminals.

4.5 The use of RIS as a substitute to larger antenna arrays (widely referred to as Massive MIMO) should be considered with care. While it may be able to bridge the performance gap between smaller and larger arrays in specific scenarios within a cell, the comparison should consider benchmarking the upper capacity limits under a continuum of SNR conditions. At the lower limits of a MIMO array system, i.e., 2-by-2, the number of feeders and antenna elements cannot be further reduced by substituting RIS, regardless of the RIS size and numbers, without halving the upper capacity of this system when operating in spatial multiplexing with sufficient SNR. Spatial multiplexing is essential for spectrum reuse in MIMO systems and for delivering high spectrum efficiency.

4.6 The introduction of reconfigurability to reflective surfaces may contribute to the end-to-end latency of service delivery due to additional computations in adapting to network conditions. The computational complexity of RIS-assisted channel estimation grows exponentially with the number of elements of a reflective surface.

4.7 Unlike passive reflective surfaces, active reflective surfaces may require implementing secure functions and interfaces to allow them to integrate with and terminate network protocols to authenticate, obtain and process network control information and forward user traffic and operate efficiently. Additionally, mechanisms for differentiating signal from interference and for protecting the accuracy measurements, e.g., angle of arrival, for positioning applications are necessary to ensure high quality and reliable operations.

4.8 Networks that use reflective surfaces and provide positioning services may require additional computations and mechanisms to maintain location validity and accuracy.

4.9 Use of switchable metamaterials to allow both reflective and transmissive operations is emerging, and such surfaces may be referred to as “refractive surfaces” rather than only reflective. However, such design may exhibit nonlinear effects and radiations in frequencies other than the desired one. Hybrid functionality often has performance and complexity implications with product engineering trade-offs. Nevertheless, surfaces, whether involving reflective and/or refractive elements, designed to alter radio waves and propagation environments, should be investigated under coexistence scenarios to assess their network effects within the home network and across neighbouring ones.

Methodology and acknowledgment

Ofcom conducted interviews with field experts from industry and academia, complemented by internal research and external modelling efforts by Queen Mary University of London. This work would not have been possible without their input and insightful discussions.

We would like to convey our thanks to:

- Yang Hao FREng*, Professor of Antennas and Electromagnetics, QMUL
- Valentina Cicchetti*, Post-doctoral Researcher, Electromagnetics, QMUL
- Orestis Christogeorgos*, Doctoral Researcher, Electromagnetics, QMUL
- Jonas Kolb*, Doctoral Researcher, Electromagnetics, QMUL
- Jani-Pekka Kainulainen*, Senior Standardisation Specialist, Nokia
- Tobias Schaich*, Cavendish Laboratory, Cambridge University
- Simon Saunders* FREng, Independent advisor, Expert and Professor in Wireless Communications
- Petar Popovski, Professor of Wireless Communications at Aalborg University
- Maha Achour, Founder and CEO of Metawave
- Geoffroy Lerosey, Cofounder and CEO Greenerwave
- Markku Juntti, Professor of Communications Engineering, University of Oulu
- Vincenzo Sciancalepore, Principal Researcher, NEC Europe Lab.
- Henrik Sahlin, Research Manager, Microwave Systems, Ericsson
- Behrooz Makki, Senior Researcher, Microwave Systems, Ericsson
- Per Ödling, Professor of Telecommunications, Lund University
- Jochen Maes, Fixed Access Research Director, Nokia Bell Labs
- Gabriele Gradoni*, Professor of Applied Mathematics & Electromagnetic Theory, Nottingham University
- Simon Perras, Research director, Propagation and Antennas, Communications Research Centre
- Eloy de Lera Acedo*, Associate Professor of Astrophysics, Cambridge University
- Hamidreza Taghvaee*, Research Associate, Nottingham University
- Sergio Terranova*, Research Associate, Nottingham University
- Fraser Burton, Senior Manager, Network Research & Strategy, BT
- Yangyishi Zhang, Research Specialist, Network Research & Strategy, BT
- Mark Beach, Professor of Wireless Communications, Bristol University
- Geoffrey Hilton**, Senior Lecturer in Electrical & Electronic Engineering, Bristol University

*Marked colleagues made significant input towards this report.

**Correction – added 12 January 2024