

Review

Optically Transparent Antennas for 5G and Beyond: A Review

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Abstract: As wireless communication technology advances towards faster and higher transmission rates such as Fifth Generation (5G) and beyond, the need for multiple access points increases. The growing demand for access points often results in them occupying any available surface area and potentially disrupting the existing scenery. In order to address this issue, Optically Transparent Antennas (OTAs) emerge as an optimal solution for balancing the aesthetics of a specific setting with the desired communication system requirements. These antennas can be integrated into various infrastructures without interfering with the design of the objects on which they are installed. Research on the techniques and materials for OTA fabrication, which is proposed as a solution to the 5G wireless communication demand for access points, is presented. This work will highlight key antenna characteristics such as gain, bandwidth, efficiency, and transparency, and how the materials used for OTA implementation influence these parameters. Techniques like Metal Mesh (MM), Transparent Conductive Film (TCF), and Transparent Conductive Oxide (TCO) will be explained. The performance of the OTAs will be analyzed based on gain, bandwidth, transparency, and efficiency. This paper also addresses the challenges and limitations associated with OTAs. Finally, it confirms that OTAs offer a compelling solution for this scenario by balancing aesthetics with high antenna performance, making them an innovation for future wireless networks.



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1. Introduction

As technology progresses, advancements in wireless communication systems are changing the way connectivity works, achieving high data speeds and increased transmission capacity. These breakthroughs are enabling the full potential of digital technologies such as the Internet of Things (IoT), artificial intelligence (AI), robotics, and machine learning among others [1]. At the forefront of this evolution are 5G and beyond networks, which promise high-speed connectivity, massive device integration, and low latency, revolutionizing how we communicate with the world around us [2,3].

In this evolving field, Optically Transparent Antennas (OTAs) emerge as an optimal solution, seamlessly integrating into surfaces like windows, screens, and buildings. By blending functionality with aesthetics, OTAs not only preserve the visual appeal of urban and natural environments but also meet the demands of 5G and beyond communications, such as low latency and bandwidth requirements [4]. Their ability to deliver robust performance without compromising design makes OTAs an essential module in realizing the full potential of next-generation networks [5,6].

These advancements and features require more access points in order to sustain such network activity. The access points required for these technologies can be integrated by antennas. The choice of antenna depends on the application, but with the growing demand for networks, the number of antennas must be reinforced [7], increasing the surface area required. Since traditional antennas are opaque, this will result in natural and urban landscapes being filled with antennas that disrupt the aesthetics of various landscapes.

This paper presents a review of the last 7 years of OTAs, organized in a tabular form, with their respective characteristics. The sources for this research were Scopus, MDPI, IEEE Xplore, Google Scholar, and ScienceDirect. Using these databases, a total of 158 articles were retrieved based on the following keywords: 5G, OTA, Metal Mesh (MM), and Transparent Conductive Film (TCF). After a thorough review and analysis of the collected articles, only 114 were considered important and subsequently cited in this paper due to their relation to the topics being approached in this work. The remaining 44 articles were excluded as they were not directly related to 5G communications and did not meet the predefined relevance criteria. These criteria included a publication date prior to 2017 or a lack of alignment with the main objectives of this study, which focus on the analysis of OTA techniques and their applications. This paper aims to provide insights into the implementation of OTAs, achieving high-performance antennas while maintaining optical transparency (OT).

With the intention of researching novel techniques and materials for OTA fabrication, articles from 2022 to 2024 were considered in the above-mentioned collection. This decision enables a better understanding of the state-of-the-art innovations and recent implementations, supporting a more in-depth discussion on the current benefits, challenges, and limitations of OTAs. Therefore, this article explores topics that have not been addressed in the previous studies on this subject or have evolved significantly since their publication. Topics such as graphene and metamaterials being viable options for OTAs, the challenges related to OTA fabrication, and a numerical analysis of previously considered TCF materials are mentioned in this work. These topics are not only relevant to the current state of the art but also provide a comprehensive overview of the advancements made in the field.

In addition, the relationship between efficiency and transparency will be analyzed by observing how different transparent materials and fabrication techniques influence the performance of OTAs. Essential parameters like sheet resistance (R_s), transmittance (T) and radiation efficiency are analyzed to understand their implication on the transparent materials for the design of antennas.

Although OTAs offer a solution for integrating communication systems into infrastructures without compromising aesthetics, the implementation still presents some challenges. A more detailed explanation is provided in this paper regarding the integration of OTAs into existing environments, particularly concerning long-term durability and cost-effectiveness. These issues are important to ensure the efficiency and sustainability of OTAs in real-world situations involving 5G and beyond communication systems. The challenges mentioned can be overcome by the different options of materials and techniques that are presented in this work.

Figure 1 presents a chart with different surfaces where OTAs have been used. To obtain Figure 1, the previously mentioned collection of articles was organized into categories. These categories were based on the surfaces where the antennas were applied. This allowed for a better comprehension of the OTA applications. The data indicate that transparent antennas could be placed on surfaces of buildings, houses, ceilings or clear surfaces like mirrors, windows, and screens, in favor of more access points throughout the needed areas. This graph shows that OTAs have been used for applications where the OT is an important factor. If the antennas were opaque, the surfaces would be visually obstructed, compromising their intended function. For this reason, OTAs have been studied and have

emerged as an optimal solution to this issue, allowing surfaces to remain unobstructed while functioning as necessary access points [8,9].

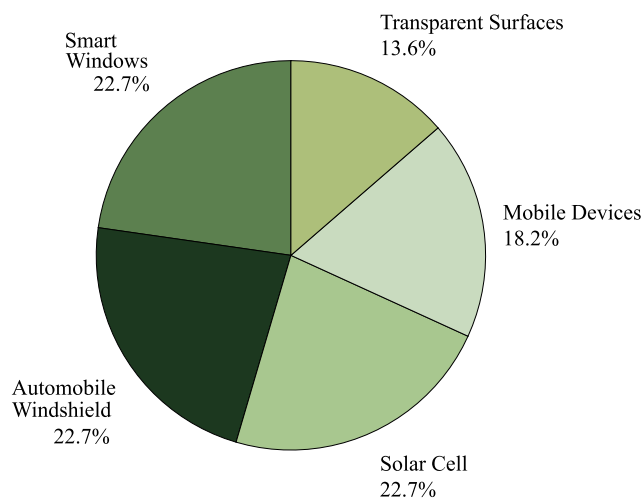


Figure 1. Type of surfaces used for OTAs.

This paper is organized as follows: Section 1 introduces the advancements made in wireless communications, such as 5G and beyond, as well as the challenges and need for access points. From this necessity, OTAs are introduced as a potential solution with a brief presentation behind this approach. In Section 2, the key characteristics of OTAs will be defined, emphasizing the relationship between OT and antenna efficiency and presenting a performance metric to evaluate this relationship. Section 3 explores the implementation techniques for OTAs reported in the literature, providing an overview of the techniques and the challenges associated with each. Within this section, potential transparent substrates that are essential for achieving OT will be studied. Section 4 reviews OTAs implemented in the literature, categorizing them by technique and presenting tables that compare characteristics such as operating frequency, materials used, gain, bandwidth, efficiency, and transparency. These comparisons include both MM and TCF techniques. Section 5 offers a discussion of the results from the previous sections, analyzing the trade-offs between efficiency and transparency, identifying characteristics for antenna implementation, and suggesting future improvements for OTA development. Finally, Section 6 concludes the paper with a summary of OTA limitations and highlights the importance of material selection in achieving optimal performance.

2. Optically Transparent Antennas

OTAs can be implemented as microstrip antennas, or other topologies, and are composed of a ground plane, a substrate material, and a conductive material on top of it [3]. Figure 2 shows a representation of the previously described composition of a microstrip antenna.

These elements and their characteristics influence the electromagnetic behavior of the antenna. Parameters like width, length, and thickness of the conductive element will influence the working frequency, and the height of the substrate will impact the bandwidth. Due to the transparent nature of the materials used in OTAs, the final product differs from the traditional microstrip antennas by incorporating OT.

OTAs function as a typical antenna, but the materials used to design the radiating component are optically transparent. However, the properties of the materials cause the performance of these antennas to differ from the traditional antennas [3]. For an antenna to perform effectively, it must have higher conductivity, resulting in fewer ohmic losses. Using transparent materials brings a new correlation between the OT and efficiency of the antenna [10,11].

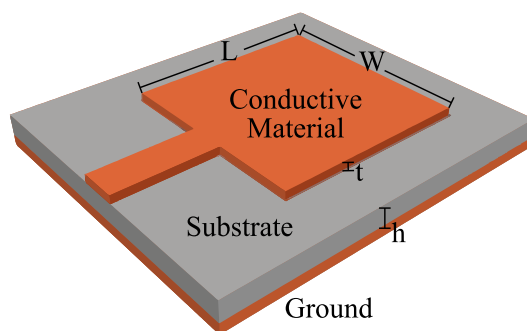


Figure 2. Structure of a microstrip antenna.

As previously mentioned, an OTA is designed with the intent of replacing a traditional opaque antenna and maintaining functionality while not being obstrusive [9]. These antennas have been studied, and the main concern is related to how the conductive material and substrate can maintain optical transparency. Optical transparency refers to the material's ability to transmit wavelengths from ultraviolet to longwave infrared [9].

Equation (1) is used to calculate the correlation between the electrical performance and transparency of a conductor [9].

$$\phi_{TC} = \frac{T^{10}}{R_s} \quad (1)$$

where T^{10} represents the transmittance, which refers to the OT of the conductor, as a decimal and not as a percentage in order to give more importance to this characteristic of the material. R_s is the sheet resistance of the conductive material. ϕ_{TC} is expressed in %, where higher values indicates better performance; if the transparency is high, the sheet resistance is lower.

A perfect transparent conductor should have 100 % optical transmittance and infinite conductivity [12]. The result from Equation (1) returns the Figure of Merit (FoM), which allows us to quantify the electrical and optical characteristics of a material. Based on this value, OTAs can be compared in order to find the one that is most compatible with the application. Besides the effort to achieve high transparency with high conductivity, environmental factors like humidity and temperature [13] can influence the performance of the antenna. These natural variables can change the characteristics of the materials such as the dielectric constant, for example, which will change the resonant frequency [14]. These variations can be compensated by increasing the substrate height, although at the cost of the antenna's OT [14]. To implement an OTA, the substrate used must also be optically transparent. This can be achieved by using materials like glass, polyethylene terephthalate (PET), and polyethylene naphthalate (PEN) [9]. These materials are used as they have a high OT, which is important for the surface where the antenna will be integrated. The different substrates used in the literature have different physical characteristics that will influence the final product.

Research on OTAs has advanced towards achieving both effectiveness and improved aesthetics for integration. An OTA has the distinct characteristic of a high OT, matching the surface or object of the final placement [15].

To implement an OTA, the material must be optically transparent or allow visible light frequency to pass through it. For that, implementation techniques have been studied and grouped based on the conductive material used to produce the radiating element. The following three main techniques have been identified in the literature: Metal Meshes (MMs), Transparent Conductive Films (TCFs), and Transparent Conductive Oxides (TCOs) [3].

3. Manufacturing of Optically Transparent Antennas

The challenge of fabricating OTAs involves balancing transparency and conductivity, as traditional materials like copper and aluminum, although highly conductive, are opaque and can interfere with the aesthetics of the surface on which they are implemented. This section explores the techniques and materials used in OTA fabrication.

3.1. Metal Meshes

The name of the MM technique describes the conductive element of the antenna. A metal sheet is transformed into a mesh through perforation. The resulting mesh, formed with periodic metal patterns, is placed over a chosen transparent substrate to function as the radiating element.

The process begins with selecting a metal sheet, such as copper, silver, aluminum, or another metallic material with a thickness (t), as metals present low electrical resistivity which is important for the effectiveness of the antenna.

After selecting the base metal, it is important to evaluate and select the mesh characteristics, as they will influence the transparency and effectiveness of the antenna [16]. These characteristics include the gap size (g), gap shape, and number of gaps.

Figure 3 presents a model of an MM antenna, with the corresponding variables labeled.

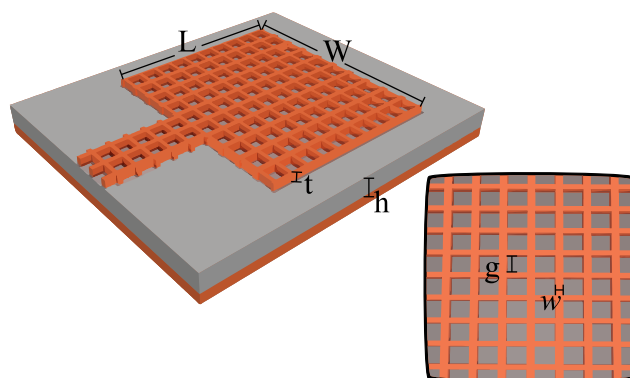


Figure 3. Characteristics of Metal Mesh Antenna.

The gaps influence the transparency of the mesh. The ratio between the area of the gaps and the total area of the metal sheet is expressed by the fill factor (Ψ), which is a percentage that represents the OT of the metal sheet [9]. Equation (2) gives Ψ as a function of the width of the gap lines (w) and the size of the gap (g). The area of the gap depends on (g) and the number of gaps [17]. If the number of gaps increases, so does the OT, or if w decreases, the OT increases, as observed in Equation (2).

$$\Psi = \frac{w}{g + w} \quad (2)$$

Even though the metal sheet has high electrical conductivity and low R_s , this characteristic is limited by Ψ . Adjusting Ψ will alter the OT. This technique has limitations due to the fabrication process of the mesh and the specific requirements of the application; however, the limitations are also related to the Ψ , which is determined by the amount of conductive material used for the mesh. If this mesh has more conductive material, meaning lower Ψ and OT, the R_s of the mesh will decrease, increasing the efficiency of the antenna, as it would have more conductive material. On the other hand, if the mesh is intended to have a higher OT, that would happen at the cost of reducing the amount of conductive material, increasing the R_s , and decreasing the efficiency of the antenna [9].

In this technique, transmittance (T) is defined as the open area of the mesh, as described in [9]. Equation (3) allows us to obtain the value of the transmittance (T) in a mesh.

$$T_{\text{mesh}} = (1 - \Psi)^2 \quad (3)$$

The shape of the gaps also influences the antenna performance. The square lattice is the most common, but studies have been done on the diamond shape [18] and the honeycomb shape [19], where the different configurations influence the OT and the performance of the antenna. Depending on the size of the MM, it is possible to group them as follows: MM, μ MM, and grating MM [3]. The categories are organized by the size of the mesh used. MM uses a mesh of millimeter size, which has lower OT but better electrical conductivity. μ MM uses a mesh of micrometer size, which lowers electrical conductivity but increases OT. Even smaller meshes can be implemented like the AgNWs, which are gaining attention; such techniques are explored in [20]. The grating MM is characterized by the non-uniformity of the mesh, which improves the OT.

To implement an MM, other methods besides perforation can be used, including the following: ink-jet printing, physical vapor deposition (PVD), and electroplating [9]. These techniques are more complex and expensive to implement and do not sufficiently increase the performance of the antenna to justify the cost of implementation [21].

Since metals have better conductivity when compared to any TCO, the resulting mesh will have lower sheet resistance, making this approach more suitable for Radio-Frequency (RF) applications [12].

3.2. Transparent Conductive Films

This technique utilizes fully transparent materials to implement the antenna, including the conductor, substrate, and ground plane.

To obtain different properties that may be beneficial depending on the application, the transparent material can be combined with an MM to achieve flexibility, as the transparent material alone is rigid and brittle.

Materials that fall into the TCF category include AgHT-4 [22], AgHT-8 [23], graphene [24], polymers [25], and metamaterials [26]. The aforementioned materials are known for possessing both OT and electrical conductivity. Although their conductivity is lower than that of metals, properties such as T and R_s vary depending on the material selected [27].

Materials such as AgNWs, characteristic for their smaller size, have been implemented and are gaining attention [20,28]. Although they are smaller, the conductivity of the film formed results in the production of antennas with better performance. The previously mentioned graphene has also been studied as a viable high-conductivity TCF alternative derived from carbon [29–31]. These materials show promising results for OTA implementation, as they have high OT and better electrical conductivity as compared to previously used materials.

When working with TCFs, the material needs to be thin enough to maintain OT but thick enough to minimize ohmic losses (low R_s). These materials are applied in thin layers that are susceptible to increased losses at higher frequencies due to the skin effect [32]. The skin effect refers to the phenomenon in which the current density is concentrated near the surface of the conductor [33]. This effect depends on the skin depth, δ_s , which can be calculated using Equation (4) [9], as follows:

$$\delta_s = \sqrt{\frac{1}{\pi f \mu_0 \sigma}} \quad (4)$$

where μ_0 is the permeability of free space, σ is the electrical conductivity of the conductor, and f is the operating frequency.

These materials can be compared using their ϕ_{TC} , as defined in Equation (1), to determine which materials are best suited for the application [12].

3.2.1. Transparent Conductive Oxides

This technique involves doping existing metal oxides with other elements, allowing the materials to achieve high OT with better electrical conductivity. Although TCOs exhibit higher conductivity than TCFs, it is still low as compared to the metals used in traditional antennas [3]. The resulting antennas fabricated using TCOs are typically monolayer structures, which make them mechanically fragile.

A TCO film is characterized by its refraction index (n), attenuation coefficient (α), extinction coefficient (κ), thickness (t), and transmission (T) [34]. The properties vary depending on the chosen TCO, which affects its conductivity. The transmittance (T) for the TCO technique can be calculated using Equation (5) [9].

$$T_{TCO} = e^{-\alpha t} \quad (5)$$

The α is defined by Equation (6), where λ denotes the wavelength corresponding to the operating frequency, and κ is the extinction coefficient.

$$\alpha = \frac{4\pi\kappa}{\lambda} \quad (6)$$

The most commonly used material in this category is Indium–Tin Oxide (ITO) [35]. Although ITO is a common material, its extraction raises concerns regarding health risks from prolonged exposure and environmental pollution, as indium mining generates toxic waste that is harmful to both the environment and workers [30]. The environmental concerns regarding ITO mining come from the long-term use and depletion of this material. Indium is a scarce element in the Earth's crust and is thus considered a critical raw material [36]. Due to this concerning aspect, other viable options have been studied including Gallium-Doped Zinc Oxide (GZO) [37], Aluminum–Zinc Oxide (AZO), [30] and Fluorine–Tin Oxide (FTO) [38]. The alternatives mentioned have been studied; the resistivity of AZO and GZO is greater than that of ITO. However, studies have shown that they can be used to implement antennas with a similar efficiency and can thus be used as a viable alternative [39,40]. These alternatives show that changing the base metal oxide influences the resulting characteristics of the antenna, providing benefits for various applications and representing a more sustainable material alternative.

3.2.2. Multilayer Film

As mentioned in Section 3.2, transparent conductors such as TCOs are often implemented by layering different transparent materials to achieve traits like flexibility or better conductivity. This fabrication process is referred to as Multilayer Film (MLF).

An antenna implemented with the MLF technique uses a sandwich structure composed of a TCO and a metal as follows: *TCO/metal/TCO*. An example of this is the Indium–Zinc–Tin Oxide (IZTO) configuration in the following structure: *IZTO/Ag/IZTO* [41]. The use of TCO already shows enhanced durability, and when combined with the multilayer structure, increases the mechanical and electrical performance of the antenna.

Layering films enhances OT, electrical conductivity, and durability while potentially reducing the fabrication costs of the antenna. This method mitigates the brittle nature of the TCOs and provides additional alternatives, besides those discussed in the previous section [42].

3.3. Transparent Substrates

To fabricate an OTA, the substrate on which the conductive element is placed must be optically transparent. The previous sections presented ways to implement that element. This section provides information about the available optically transparent substrate. These materials include glass [43], quartz glass [30], polyethylene terephthalate (PET) [44], polydimethylsiloxane (PDMS) [45], acrylic [42], and sapphire [37].

Choosing a substrate material depends on the properties and application of the antenna being implemented. The selected substrate, along with its physical dimensions, will influence the OT and conductivity of the final product, having an effect on the radiation performance and conduction losses [3].

Physical characteristics such as durability and flexibility are also important, as they affect the antenna's performance and endurance. OTAs must be durable and resistant to environmental conditions in order to maintain consistent performance [30]. The flexibility of the substrate is important, as it enables the antenna to be placed on curved or irregular surfaces, expanding the range of surfaces that are able to support OTAs [42].

Substrates for an OTA can be categorized into the following three types: solid (rigid and flexible), liquid, and pre-fabricated [34].

3.3.1. Solid Substrates

Solid substrates are conventional rigid materials used for OTA fabrication, including glass, quartz, sapphire, soda-lime, lexan, borosilicate, plexiglass, among other materials. These options provide the required OT; however, their main drawback is fragility, which makes them prone to shattering depending on the application surface.

This category also includes flexible substrates such as PDMS [46], PET, polyethylene naphthalate (PEN), and polyimide (PI). These substrates can bend and endure mechanical deformation, making them more durable compared to their rigid counterpart [13].

3.3.2. Pre-Fabricated Substrates

Pre-fabricated substrates are also classified as solid substrates. However, this category differs from the previous one as it includes materials coated on a transparent substrate, such as conductive oxides on glass. The pre-fabricated category refers to inherently transparent surfaces that can be directly used for the antenna. Examples include solar cells, OLED screens [47], automobile glass (e.g., windshields and rear windows) [48], Liquid Crystal Display (LCD) [49], and textile-foam composites [34].

3.3.3. Liquid Substrates

In comparison to the previous substrates, the liquid substrates are distinct due to their physical state being liquid, as demonstrated in [50]. Common liquids used for OTAs include distilled water, liquid metals, and ethyl acetate [51], among others. These liquids must be enclosed in a transparent container made from materials such as plexiglass or PDMS [52].

3.4. Technique Comparison

This section presents a comparative analysis of the number of antennas implemented using the MM and TCF techniques. The objective is to identify the most used fabrication process for wireless communication systems.

From Figure 4, we can observe the distribution of antennas implemented using the MM and TCF techniques. The data suggest that the TCF techniques are widely adopted, as indicated by the higher number of reported implementations. Additionally, while the MM technique represents a single fabrication method, the TCF category encompasses both the TCO and MLF techniques, with MLF-based implementations being slightly more preva-

lent. This indicates that TCF-based antennas offer greater material condition, additional flexibility, and used more frequently, due to their advantageous combination of OT and electrical conductivity, making them a preferred choice for OTA fabrication.

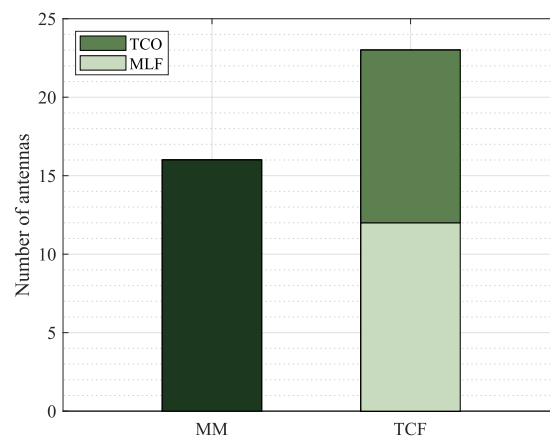


Figure 4. Number of transparent antennas with each technique.

4. Analysis of Transparent Antennas

This section presents the antennas developed for 5G and beyond. The implementations will be presented as examples, where the motivation and results are reported. The subsequent tables summarize the implemented antennas, comparing key parameters such as resonance frequency, gain, bandwidth, materials used, OT, and efficiency. These tables are categorized into implementations using either the MM and TCF techniques, respectively.

4.1. Metal Mesh Antenna

As 5G communications expand, the demand for antennas capable of operating at millimeter-wave (mmWave) frequencies with minimal loss has increased. Studies [53,54] have demonstrated OTAs implemented with MM techniques that provide the necessary characteristics of reliable antennas. These antennas operate at high-band 5G wireless communications frequencies [55], with positive gains that are helpful in the transmission. For emerging technologies such as beyond 5G (B5G) and millimeter-wave (mmWave) 5G, relevant research has been presented in [56] and [57], respectively. The referenced studies employed MMs fabricated using metals such as copper [57] and silver [53] placed on transparent substrates such as PET [54] and glass [56,57].

The integration of antennas with OLED screens—known as Antennas on Display (AoD)—offers a method to increase the number of antennas. This approach offers seamless integration, as these antennas use the device’s screen as a substrate and employ an MM as the radiating element. Previous studies [58–60] have demonstrated this technique’s usefulness, achieving high transparency while operating at frequencies supported by 5G systems. The study in [59] used a hexagonal-shaped mesh, distinguishing it from the other referenced implementations. This innovation allowed antennas to be embedded within display screens, preserving device aesthetics without compromising performance.

To advance the MM techniques, new approaches have been explored such as the use of metasurfaces and alternative materials. For the study of metasurfaces, [61] proposed a metasurface made of Ag deposited on top a polymethyl methacrylate (PMMA) substrate, achieving both high transparency and the electromagnetic performance for 5G mobile applications. Regarding alternative materials, [62] introduced a printing process on polymers, resulting in an OTA suitable for 5G telecommunications. These innovations provide alternative fabrication processes that meet the essential performance requirements for antennas in 5G communications while enhancing sustainability.

Following this overview, Table 1 presents OTAs implemented using the MM technique, along with their respective characteristics. In this table, both antennas designed for 5G communications and OTAs for other applications are presented in order to analyze different implementations and better understand transparent conductors.

As shown in Table 1, copper is the most frequently used material for this technique due to its high electrical conductivity and well-established fabrication processes. Additionally, glass is the most frequently used substrate, offering excellent OT and compatibility with various conductive materials. However, glass lacks the flexibility of materials such as PET, which may be advantageous for wearable applications.

An analysis of the OTAs implemented with MM reveals that antennas obtain a higher gain by compromising their OT. From an efficiency perspective, performance increases as the OT decreases, similarly to the gain, since the antenna becomes more conductive. While the operating frequency depends on the requirements of the application, it is possible to conclude that the losses decrease with higher frequencies [9].

Table 1. Corrosion time and corrosion rate η .

Ref.	Date	Frequency [GHz]	Substrate	Substrate Thickness [mm]	Patch Material	Patch Thickness [μm]	Gain [dBi]	Efficiency [%]	Transparency [%]
[63]	2017	[2.4, 2.48]	Glass	1.09	MMMCF	5	0.74	43	75
[64]	2017	[5.15, 5.8]	Quartz	2.25	Ag Epoxy	-	2.3	46	94.2
[27]	2017	[2.37, 2.42]	Acrylic	1	Cu	5	7.23	-	94.2
		2.45					2.63	42.69	61.46
[48]	2018	[0.088, 0.108]	Glass	3.1	-	5	1.1	-	61.6
		[0.174, 0.216]					8.8	-	
[65]	2018	[37, 39] *	Glass	0.7	Ag	-	3.2	68	88
[42]	2018	2.44	Acrylic	1.2	Cu	35	5.28	50.93	68.63
		2.49					4.38	49.18	77.77
[44]	2019	[5, 6.4]	PET + PMMA	9	Ag/Cu/Ni	100	[2.4, 2.9]	75	80
[66]	2019	[2.4, 2.5] *	Borosilicate Glass	3.175	MM	200	5 *	-	-
[67]	2019	2.45	PET	0.144	AgNWs	0.237	-	52	85
					AZO				
[68]	2019	[2.2, 2.5] *	Glass	-	AgNWs	-	-	-	80.28
[69]	2019	2.4	Quartz	-	MM	-	-	90	95
							-	90	78
[70]	2019	[24.23, 29.78]	LCP	0.05	Cu	-	9.16	41.21	88
							6.66	24.15	
[8]	2019	[2.38, 2.64]	PDMS	3	Zn/Ni/Cu	1520	3.2	48	52
		[4.4, 5.4]					3.5	46	
[71]	2019	[5.59, 5.9]	Lexan	2.9	-	5.3	[6.2, 7.2]	84.50	77.80
[53]	2019	[18, 44]	-	0.05	-	-	1.45	55	90
[72]	2019	[2.38, 2.50]	Glass	6	Cu	1000	5	72.40	92.40
[73]	2020	[0.47, 0.77]	PET	1.2	Cu	5	6.2	83.80	70
[74]	2020	[8.51, 9.10]	Glass	2	Ag	-	20.14	38.70	88
[41]	2020	[5.45, 6.03]	PDMS	1.6	VeilShield	7	3.2	56	66
		[4.4, 5.0]		0.2		5	3.8	85	93
[75]	2021	26 & 27	PET	0.201	Ni	10	9.70	61	86
[76]	2021	[1.5, 3.0] *	Polyimide	0.23	Cu	18	3.56	-	85
							3.6	-	
[77]	2022	[0.78, 20.00]	PET	0.1	Cu	0.5	10.4	-	72
[29]	2022	9.8	Quartz Glass	-	Graphene	-	-1 *	52.50	90.10
[18]	2023	[5.1, 9.9] *	Glass	1	Ni/Cu/Sn(Tin)	7500	5.01	71.90	69.80
[21]	2023	[3.2, 11.8]	FR-4	0.6	MM	-	[3.0, 7.3]	[83, 95]	77
[56]	2023	3.5	Glass	-	-	-	5.81	-	90
[78]	2023	[5.7, 5.9]	PET	1	Metal	-	3.55	64.50	83
[79]	2024	6.40 & 20.96	PET	0.25	Ag NWs	-	-	97.48 & 98.20	63
[80]	2024	[25.08, 28.92]	COP	0.1	Cu	100	7.02	-	85.10
[81]	2024	[24.6, 31.6]	COP	0.002	Cu	2	7.65	44.20	86.80
[57]	2024	[27.1, 29.7]	Glass	1	-	0.06	37.5	-	70
[82]	2024	[2.86, 4.06]	Quartz Glass	0.7	Ag	-	7.9	85	92

* Results taken from the given graphs. - Results not given in the article.

4.2. Transparent Conductive Films

As 5G wireless communication advances, the need for reliable antennas continues to rise to accommodate the growing number of services. As mentioned in Section 1, this rise in the number of antennas can be addressed with the fabrication of OTAs. The studies performed in [83–86] provide examples of many OTAs implemented with different TCFs, offering diverse characteristics that can benefit various communication systems. For in-

stance, the antenna described in [83] exhibited flexibility, enhancing durability and allowing the antenna to conform to irregular surfaces, a valuable trait for certain applications.

Antennas fabricated using TCF techniques are highly transparent, making their integration into everyday surfaces more feasible. This characteristic enables OTAs to be embedded into mobile screens [87], vehicle windows [88], and surfaces such as solar panels or glass windows [89], maintaining the aesthetics of the surface while providing communication services.

Additionally, [90–92] explored OTAs in UWB applications, such as mmWave 5G. These antennas demonstrated the ability to operate at higher frequencies while delivering increased accuracy.

Notably, 5G and beyond communications operate over different frequency bands, driving research towards antennas capable of functioning across multiple bands. As demonstrated, a multi-band operation enables a single antenna to function in dual bands [23,93] or triple bands [94], enhancing versatility in wireless communication systems.

Similar to the previous technique, the following table will showcase OTAs implemented with TCF techniques, along with their respective characteristics.

From Table 2, it can be concluded that Ag-HT4, Ag-HT8, and ITO are the most commonly used materials, as they provide a balance between conductivity and transparency, making them suitable for OTA applications, as discussed in the previous sections. Among the substrates, glass is the most frequently used due to its high OT, further confirming its sustainability for TCF-based implementations. However, the high fragility of this substrate remains a drawback.

Analyzing the OTAs implemented with the TCF techniques, the antennas were found to have higher OT due to the materials used for their implementation. The operating frequency influenced the gain and efficiency of the antenna, where higher frequencies had higher gains and efficiencies. There was no common operating frequency, as the OTA could be implemented at the value intended for the application. The chosen value will determine whether more complex or simple antennas are required, as the frequency is highly related to the losses in these antennas [9].

Table 2. Comparison of OTAs using TCF techniques.

Research Articles	Date	Frequency [GHz]	Substrate	Substrate Thickness [mm]	Material	Gain [dBi]	Efficiency [%]	Transparency [%]
[43]	2008	[1.6, 2.4] *	Glass	3	AgHT-4	5	68	70
[95]	2014	[2.49, 2.58]	Glass	2	AgHT-4	9.8	-	-
[37]	2017	[2.19, 2.58]	Sapphire	0.375	GZO	2.10	43	85
[27]	2017	[2.1, 2.58] *	Acrylic	1	IZTO/Ag/IZTO	−4.23	7.76	80.78
[96]	2017	[10.5, 11.4] *	Poly-Si	-	AZO	4.7	60	86
[30]	2017	[20, 21] *	Quartz	1	Graphene	-	-	-
[97]	2017	[5.72, 5.85]	Glass	1	ITO	−6	-	80
[89]	2017	[2.2, 2.5]	PDMS	2	Polyester	-	75	90
[98]	2018	[23.92, 43.8]	Plexiglass	1.48	AgHT-8	[1.47, 1.94]	[23.92, 43.8]	[87.45, 90.57]
[90]	2018	[23.5, 32]	Glass	0.3	ITO	12.1	-	80
[23]	2018	[2.34, 2.54]	Borosilicate Glass	2	AgHT-8	0.64	62	-
		[5.26, 5.4]				1.2	83	-
[99]	2019	[2.5, 6.5]	Glass	1.1	ITO	−5 *	-	95
[100]	2019	[4.5, 5.3]	Soda Lime Glass	2.2	FTO	5.16	90	80
[101]	2019	[2.305, 2.53]	Plexiglass	1.48	AgHT-8	3.6	74	-
		[3.29, 4.11]				7.1	84	-
[102]	2019	[1.9, 6] *	Glass	1.1	ITO	−3.9	14	90
[69]	2019	2.4	Soda-Lime Glass	-	ITO	-	64	85
[103]	2019	[17, 30]	Pyrex Glass	3	ITO	11.5	92.30	-
[104]	2020	[2.4, 3.5] *	PDMS	1.5	NCM	0.8	-	-
		[7.55, 8.4] *	Acrylic			13.6	-	-
		[3.49, 3.86] * &			AgHT-8	-	48.02 &	-
		[5.37, 5.66] *					53.14	-
[22]	2020	[3.58, 3.9] * &	Glass	2	AgHT-4	-	59.25 &	-
		[5.47, 5.68] *					49.20	-
[105]	2020	[25.62, 30.38]	Glass	0.7	ITO	25.8	37.3	-
		[2.35, 2.55] &						
[94]	2020	[3.75, 3.9] &	Polyimide	0.125	ITO	-	83	-
		[5.35, 5.95]						

Table 2. Cont.

Research Articles	Date	Frequency [GHz]	Substrate	Substrate Thickness [mm]	Material	Gain [dBi]	Efficiency [%]	Transparency [%]
[106]	2020	[24.10, 27.18]	Plexiglass	0.177	AgHT-8	3	75	-
[107]	2020	[33, 44.13]	Glass	2	AgHT-8	5.5	-	-
[88]	2020	[25, 27] *	Glass	-	-	1.5	-	-
[105]	2020	[27.85, 27.93]	Glass	0.7	ITO	73	81	-
[26]	2021	[25.62, 30.38] *	Glass	2.2	ITO	-	-	63
[83]	2021	5.8	Soda Lime Glass	0.635	AgHT-4	0.53	41	-
[87]	2021	[2.21, 6]	Melinex	-	FTO	-6	-	-
[108]	2021	[3.3, 4.8]	PET	-	AgHT-8	7.5	63.7	-
[84]	2022	[52.5, 67.5] *	PET	0.5	-	6	-	-
[86]	2023	[2.46, 2.75]	PMMA	7.5	-	-3.70	-	-
[85]	2023	[32, 48] *	Glass	0.4	ITO	2.11	-	-
[109]	2022	[2.35, 2.45] *	FR4	1.6	In203/Au/Ag	2.57	72.3	71
[110]	2023	[2, 2.3] *	PET	0.2	LCL	-4.40	40	-
[38]	2023	[2, 2.5] *	PDLC	0.31	-	-	-	-
		[0.5, 1.53] *	Soda Lime Glass	2.2	FTO	4.34	70	82
		[3.1, 10.9] *						95
[111]	2024	[8, 10] *	F4BM220	1	DM	-	-	-
[112]	2024	[24.77, 27.22] *	Glass	0.7	FPC	14.2	67.10	81
[113]	2024	[5.5, 6.1] *	PC	2	ITO	6.7	68.70	81
					AgHT-8	4.88 & 4.23 & 4.37	-	90
[114]	2024	3.54 & 5.4 & 6.82	PVC	4	ITO	5.87 & 3.7 & 4.66	-	-
[93]	2024	[3.4, 3.8]	-	-	-	0.5	-	-
[92]	2024	[20, 46]	Plexiglass	1.48	AgHT-8	6	-	-
[115]	2024	2.4	Plexiglass	2.35	ITO	-	-	-
[116]	2024	3.6	Plexiglass					
		5.4						
		10	PET	2	Metasurface	10.8	-	54.5

* Results taken from the given graphs. - Results not given in the article. NCM—Nano Composite Metasurface. DM—Drude Metasurface.

5. Discussion

This section analyzes the findings presented in the earlier sections, focusing on their implications for OTA design and integration. These insights into the field of OTAs contribute to a clearer understanding of OTA fabrication techniques and the current research trends. Both MM- and TCF-based antennas provide OT, which is essential for integrating wireless technology into environments while preserving aesthetics. These techniques enable the seamless integration of functional antennas into different surfaces and objects.

TCFs are widely adopted for integration due to their excellent OT [117]. Antennas fabricated using TCFs are nearly invisible to the human eye, making them ideal for integration into clear surfaces such as glass, touchscreens, and solar panels. This ability to blend into surfaces without obstruction is particularly advantageous when preserving the aesthetics or function is a priority, as in the case of solar panels.

On the other hand, MM-based antennas offer a more practical implementation with superior electrical performance while preserving some aesthetic appeal [118]. Composed of a perforated metal sheet, as illustrated in Figure 3, these antennas are better suited for larger surfaces. However, the visible mesh may not be suitable for applications requiring full transparency, such as integration into smartphone displays [87].

TCFs and MMs are distinguished by different physical phenomena. TCFs enable transparent conductors to maintain OT and conductivity in the μm and mm regions. In contrast, the MMs function as a high-pass filter, reflecting certain frequencies while allowing transmission depending on their structural characteristics [9].

The research presented in [3] highlights the trade-off between efficiency and OT in Optically Transparent Conductors (OTCs). Transparent conducting materials can be compared based on optical properties, often yielding similar results. However, their sheet resistance values vary depending on the selected material. This difference can be seen in Tables 1 and 2, where it is evident that the MM techniques achieve better efficiency. This

comparison can be further quantified using the FoM (Equation (1)), as it considers both the electrical and optical properties [9,12]. Performance is influenced by material characteristics such as sheet resistance (R_s), thickness (t), and electrical conductivity (σ), among others. These factors can contribute to the overall performance of the resulting antenna, as discussed in the previous sections. Physical parameters can also be altered by external factors such as humidity and temperature which affect the antenna's performance. Studies on OTCs and transparent substrates have documented thermal stress rates—mechanical stress caused by temperature variations—ranging from 1 % to 2 % [13]. Using a numerical approach with the FoM, the MM techniques demonstrate superior performance compared to TCF techniques.

According to Equation (2), when the OT increases (w and g become smaller), the metal area decreases, reducing the electrical conductivity of the sheet and the efficiency of the antenna [119]. Equation (3) shows that OT varies with the fill factor (Ψ). If the transmittance (T) is 1, the material is fully transparent. If T is 0, the material is opaque. When the fill factor (Ψ) increases (from 0.01 to 1), the material becomes more filled and opaque thus decreasing T . The opposite happens when Ψ decreases; the material becomes more transparent.

An important factor when working with TCFs is the increasing influence of skin depth loss on antenna efficiency. The skin effect varies with frequency. As frequency increases, the skin depth (δ_s) decreases, forcing the current to flow into a region near the surface. As frequency decreases, δ_s increases, allowing for a more uniform current distribution [32,120].

To mitigate this effect, the thickness of the TCF can be increased, enhancing the conductivity but reducing the OT. When the thickness of the material is lower than δ_s , losses increase at the operating frequency. It has been proposed that the t/δ_s ratio should be as close as possible to three to minimize skin depth loss [121]. Based on this study, it can be concluded that for lower-frequency applications, the requirements for conductors become less stringent as the skin effect is less prominent.

Future research on OTAs should focus on exploring alternative materials and fabrication techniques, such as metamaterials [29], polymers [76], nanowires [20], metals infused with impurities [96], and other materials [26]. These studies have shown promising results, demonstrating the viability of these transparent materials. This indicates that material innovation and optimization strategies are essential to address the unique challenges of OTA design. Advancements should be aimed at enhancing material performance while maintaining high OT and achieving low R_s at high operational frequencies.

6. Conclusions

As 5G technologies evolve and become more integral parts of communication systems, the need for several base stations and access points increases to achieve higher data rates. OTAs appear to be a viable solution to this demand due to their ability to seamlessly integrate onto surfaces such as glass, OLED displays, solar panels, and building structures. These transparent antennas address this need by providing a balance between OT and electrical performance while maintaining the aesthetic environment and ensuring the functionality required.

Depending on the final implementation surface, the characteristics of the antenna like OT, gain, bandwidth, operating frequency, and radiation efficiency are unique to each application and influence the choice of transparent materials for each project. To manufacture an OTA, techniques such as MM, TCF, and MLF have presented themselves as suitable bases for transparent antenna fabrication. Each of these techniques offers distinct advantages and disadvantages depending on the application. MM-based antennas provide higher electrical performance at the cost of transparency. TCF-based antennas provide higher

optical transmittance, which is favorable for display integration at the cost of electrical performance. To address certain limitations such as the fragile nature of TCFs, the MLF technique was introduced, allowing OTAs to be more flexible and durable.

Even though progress has been made, further advancements are needed, as the electrical performance of OTAs has not yet been fully optimized while maintaining high optical transmittance. Future research should focus on finding new materials with improved performance, optimizing fabrication techniques and exploring new designs that could outperform existing ones.

Finally, the development of OTAs is crucial for the development of high-speed, low latency communication technologies with high data rates such as 5G and beyond. These antennas enable the seamless integration of communication networks into everyday environments without scenery disruption while meeting the required performance standards.

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Abbreviations

The following abbreviations are used in this manuscript:

AgNW	Silver Nanowire
AiP	Antenna in Package
AoD	Antenna on Display
COP	Cyclic Olefin Polymer
CTF	Conductive Thin Film
FoM	Figure of Merit
FTO	Fluorine–Tin Oxide
IoT	Internet of Things
ITO	Indium–Tin Oxide
IZTO	Indium–Zinc–Tin Oxide
LCD	Liquid Crystal Display
LCL	Light Control Layer
LCP	Liquid Crystal Polymer
LED	Light Emitting Diode
LTCC	Low-Temperature Co-fired Ceramic
MM	Metal Mesh
MMMCF	Micro-Metal Mesh Conductive Film
MLF	Multilayer Film
mmWave	Millimeter Wave
OLED	Organic Light Emitting Diode
OT	Optical Transparency
OTA	Optically Transparent Antenna
OTC	Optical Transparency Conductor

PC	Polycarbonate
PDLC	Polymer Dispersed Liquid Crystal
PDMS	Polydimethylsiloxane
PET	Polyethylene Terephthalate
PEN	Polyethylene Naphthalate
PI	Polyimide
PMMA	Polymethyl Methacrylate
PVC	Poly Vinyl Chloride
PVD	Physical Vapor Deposition
RF	Radio Frequency
TCF	Transparent Conductive Film
TCO	Transparent Conductive Oxide
UWB	UltraWide Band

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