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Pinching Antennas: Providing Last-meter Coverage in Non-Line-of-Sight Channels

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Abstract
Pinching antennas are a new class of flexible antenna systems which can be deployed to provide strong line-of-sight (LoS) links to users within multipath-rich wireless environments. They are realized by clipping movable dielectric structures on dielectric waveguides such that the resulting radiation provides reliable last-meter wireless links to user equipment in their vicinity. This paper presents a discussion of the operating principles, deployment strategies and potential applications of pinching antennas. It also suggests some potential areas of further exploration geared towards the mainstreaming of this technology in sixth-generation (6G) wireless networks.
Keywords*: coverage extension, dielectric waveguide, multipath, non-line-of-sight, pinching antenna system, sixth-generation (6G) wireless networks*

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I. Introduction

Sixth-generation (6G) wireless communication networks are expected to leverage on novel technologies to provide extremely high data rates, ultra-high reliability, and seamless interconnectivity in massively densified and diverse wireless communication environments. The wireless channel exerts a significant influence on these performance objectives, making it imperative for the development of various techniques to surmount adverse channel conditions. The ideal communication link provides a clear line-of-sight (LoS) communication path between transceivers, leading to reliable links characterized by low signal distortion and attenuation. However, such conditions cannot always be ensured as obstacles along the signal path reflect and diffract signals, leading to non-line-of-sight (NLoS) links between transceivers characterized by various signal degradations.

Fading, a significant NLoS channel impairment, is conventionally controlled by manipulating multipath propagation within the wireless channel. Multiple-input multiple-output (MIMO) technology is a notable example which suppresses short-scale fading effects and takes advantage of the spatial diversity inherent in NLoS wireless channels to improve link performance [1]. Reconfigurable intelligent surface (RIS) systems have also emerged, and provide the utility of redirecting signal paths in real-time, without human intervention, to optimally reconfigure a multipath-rich channel [2]. Other promising solutions include the deployment of flexible antenna systems such as fluid antennas and movable antennas to reconfigure the wireless channel.

Pinching antenna systems are a novel flexible antenna solution, consisting of a transmission line and movable dielectric attachments. These external dielectrics can be clipped at any position along the transmission line in response to requirements of the wireless channel, so that signals propagating through the line are radiated at the point of clipping. Such *pinched* waveguides can be installed such that they provide clear last-meter LoS channels to user equipment in their vicinity.

Major limitations of other flexible antenna solutions are circumvented by pinching antennas. The physical reconfiguration afforded by pinching antenna systems is not confined to the antenna aperture but traverses the whole length of the waveguide. Also, changing the antenna configuration is a simple and straightforward operation, i.e. clipping the external dielectric to a different point along the waveguide in order to provide radiation coverage to a specific target area within the surrounding environment.

This paper presents a concise overview of pinching antennas. After this brief introduction, the operating principle of pinching antennas is discussed. This is followed by a highlighting of deployment scenarios. Also, potential applications of this technology in 6G wireless networks are explored. Finally, promising research directions for this novel solution are suggested.

II. Fundamentals and Operating Principle

2.1 Overview of microwave transmission lines

At microwave frequencies, the most commonly used transmission lines are coaxial cables, metallic waveguides and dielectric waveguides. The cross-section of a typical coaxial cable consists of two conductors, namely an inner conductor lying along the longitudinal axis of the cable, which is surrounded by a shielding concentric conductor. Both conductors are separated by a dielectric, while the whole structure enclosed in a dielectric sheath. The ideal coaxial cable supports a propagating electromagnetic (EM) field only in the space between the two conductors, giving rise to a transverse EM (TEM) propagation mode, where both electric and magnetic field components are transvers to the direction of propagation. At higher microwave frequencies, coaxial cables become quite lossy, and pave way for single-conductor waveguides.

Metallic waveguides are characterized by cross-sections where a conductor surrounds a dielectric, which could be air or an inert gas. The cross-sectional dimensions are determined by the target frequency of the EM wave to be propagated through it, with lower frequencies leading to larger sizes. The lack of an axial conductor enables such waveguides support either transverse magnetic (TM) or transverse electric (TE) propagation modes. For structural reasons, however, metallic waveguides are more often widely deployed in outdoor rather than indoor environments.

Where there is a requirement for structural flexibility and lower loss at high frequencies, dielectric waveguides are the transmission lines of choice. Structurally, a dielectric waveguide consists of a bar-shaped higher-permittivity dielectric surrounded by a lower-permittivity dielectric. This arrangement confines propagating EM waves within the inner dielectric.

2.2 Waveguides as antennas

There is very little leakage of the EM wave propagated through a shielded cable, and as such the coaxial cable offers excellent guided wave propagation up to a few GHz. However, any gap in the lattice of the shielding outer conductor becomes a window through which EM waves can escape from the cable. Hence, when gaps are intentionally introduced in the outer conductor, the coaxial cable is transformed into a leaky coaxial cable, where the radiated EM waves can be used to provide signal coverage in zones that are hard to reach by conventional antenna deployments. This concept is also employed with metallic waveguides, where slots on the waveguide are windows from which propagated EM waves radiate out of the structure, transforming the waveguide to a leaky-wave antenna.

The radiation of EM waves from a dielectric waveguide is achieved using a slightly different approach. If an additional dielectric structure is externally attached to a dielectric waveguide, some of the propagating EM wave couples into that attachment and causes an intentional leakage of the EM wave. So the point at which a dielectric waveguide is *pinched* with a dielectric clip becomes a location from which EM waves are radiated out from the waveguide. As first introduced by DOCOMO in 2022 [3], the simplicity of the concept lies in the fact that pinching antenna systems can be realized using plastic clips or clothespins clipped on to a dielectric waveguide. This concept is illustrated in Figure 1.

2.3 Pinching Antennas: Operating Principle

A pinching antenna system can be conceived as an open-ended directional coupler, which enables modelling of the power flow arising from EM coupling from the dielectric waveguide to the external dielectric using the coupled-mode theory [4]. If and represent the power in the pinching dielectric and the waveguide after the pinching location, respectively, they can be approximated as [5], [6]:

(1)

(2)

So that.

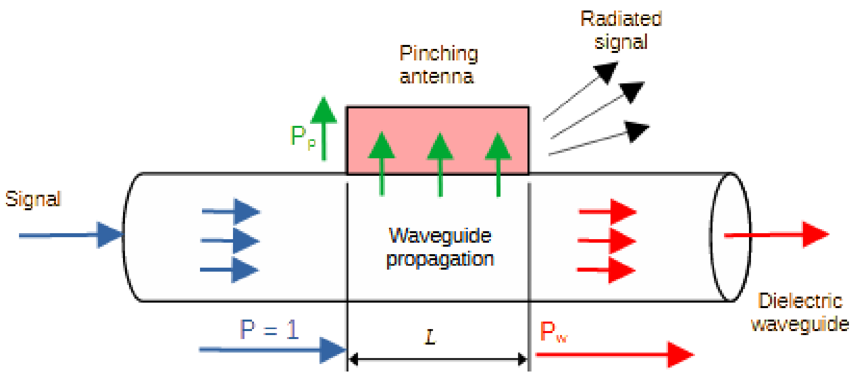

Figure 1. Coupling model of a pinching antenna system

In this expression, is the maximum coupling efficiency and is the coupling coefficient. These two variables are influenced by various dynamics in the propagating modes of the waveguide and external dielectric, among others. As illustrated in Figure 1, the coupling length , is a parameter that can be adjusted to either increase or decrease the power coupled into the pinching antenna . In other words, the coupling length determines the amplitude of power radiated by the external dielectric at the pinched point, with the maximum power radiated when (see equation 1) [4].

The key utility of pinching antenna systems is to establish LOS channels to target user equipment. Multiple pinching antennas can be installed on a dielectric waveguide to achieve this goal. If a signal with wavelength is fed into the waveguide, from a signal-theoretic perspective, the signal received by the user from the *n*-th pinching antenna is [4]:

(3)

is the power radiated by the *n*-th pinching antenna for a wavelength of , while is the channel gain. On the other hand, represents the effective refractive index of the waveguide expressed as the product of relative permittivity and permittivity. The distances and are from the *n-th* pinching antenna to the user, and the distance of waveguide propagation to the pinching antenna, respectively. This model reveals that changes in the position of the pinching antenna, which alter and , will ultimately modify the amplitude and phase of the received signal .

III. Deployment Scenarios

The authors in [7] envisage two broad deployment scenarios for multi-user communications with pinching antennas. The first scenario is one where each user is served by activating a single pinching antenna among several pinching antennas provided on a waveguide. Multi-access in this situation can be provided through a time-division multiple access (TDMA) scheme. For example, different spatially disperse users can be individually served by activating pinching antennas placed at different locations along the waveguide in different time slots. Alternatively, each pinching antenna could serve a cluster of users simultaneously in an assigned time-slot, if the number of users is in excess of the number of pinching antennas. This alternative, however, requires a careful positioning of the pinching antennas to provide an optimal trade-off between user fairness and system throughput. A variation of the single waveguide approach could see the simultaneous activation of multiple pinching antennas on a single waveguide, thereby providing a beamforming structure for the single data stream passed through the waveguide. This setup provides the added flexibility of modifying beamforming coefficients, phase shifts and path loss parameters by adjusting the positions of the pinching antennas.

The second deployment scenario envisages the use of multiple waveguides in the operational environment, with each waveguide fed through a separate RF chain. Just as in the single waveguide scenario, each one of these waveguide could have single activated pinching antennas or multiple simultaneously activated pinching antennas. This setup enables the exploitation of digital beamforming, allowing for the implementation of novel MIMO solutions.

IV. Potential 6G Applications

There are a number of potential applications for pinching antenna systems in the envisaged 6G wireless communication ecosystem. The most direct application is the improvement of signal coverage, in both indoor and outdoor environments. This is done by creating short-distance wireless channels dominated by LOS components, thereby mitigating the impacts of long-distance path loss, and multipath effects due to signal reflection and diffraction [4]. Such channels can be effectively utilized for integrated sensing and communication (ISAC), which is expected to feature prominently in 6G networks [8]. Coverage enhancements are also crucial for the deployment of large-scale distributed artificial intelligence models that require continuous real-time learning [9]. Also, pinching antennas can aid the deployment of next-generation multi-access schemes through providing additional latitude for the novel configurations, including extensions of the non-orthogonal multiple access (NOMA) technique [4], [7].

V. Promising Research Directions

Pinching antennas can be harnessed to provide a means of powering deployed IoT sensor nodes. This can be achieved within the framework of simultaneous wireless information and power transfer (SWIPT) or wireless powered communications (WPC). The fact that the positions of pinching antennas along the waveguide can be adjusted enables the use of this system for wireless power transfer to different target users as may be required in the deployment scenario. This concept could be extended to provide high-quality device-specific WPT, where power transfer is tailored to the requirements of each device [4].

Data-rate maximization is an important aspect of achieving optimal link performance in multi-user pinching antenna systems. Specifically, in order to maximize the minimum data rates between user devices served by pinching antennas, it is necessary to optimise the positioning of pinching antennas along a waveguide, as well as the resource allocation in the system [10]. Positioning of the pinching antennas is also crucial to maximizing the downlink data rate [11]. Already, it is known that maximal array gain can be obtained by optimizing the number of antennas and the inter-antenna spacing [12]. Also [13], shows that the positions and the number of antennas to be activated can be optimized to provide maximum throughput in a system where users are served by NOMA. In addition to these, the impact of the spacing of pinching antennas on physical layer security objectives could also be explored.

The hybrid beamforming potentials of pinching antenna systems also deserve some attention. Determination of optimal conditions to maximize beamforming gain from pinching antenna systems is an interesting research direction. A recent study of downlink beamforming in a multi-user MIMO system based on an array of pinched antennas has numerically demonstrated the optimization of the access point digital beamformer and the activated locations of the pinching antenna [14]. In [15], a graph neural network-based architecture is used to learn the pinching and transmit beamforming, leading to an optimization of the spectral efficiency of the system. To further extend these preliminary studies, the intersection of model-based and learning-based beamforming methodologies could be explored for real-time implementations.

In summary, the flexibility provided by pinching antenna systems compared to fixed-location antennas can be harnessed to provide significant link performance improvements, as well as new services. Following this, it is imperative to develop automated techniques for manipulating the positions of pinching antennas in order to achieve desired goals.

VI. Conclusion

This paper has provided a brief discussion of the emerging pinching antenna technology. Key features of this system have been introduced, and some deployment scenarios involving single and multiple pinching antennas and dielectric waveguides have been described. In addition, a few potential 6G applications for this technology have been highlighted. Lastly, based on recent works, the paper suggests a few promising directions for future research.

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