A New Wireless Communication Paradigm through Software-controlled Metasurfaces

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Abstract—Electromagnetic waves undergo multiple uncontrollable alterations as they propagate within a wireless environment. Free space path loss, signal absorption, as well as reflections, refractions and diffractions caused by physical objects within the environment highly affect the performance of wireless communications. Currently, such effects are intractable to account for and are treated as probabilistic factors. The paper proposes a radically different approach, enabling deterministic, programmable control over the behavior of the wireless environments. The key-enabler is the so-called HyperSurface tile, a novel class of planar meta-materials which can interact with impinging electromagnetic waves in a controlled manner. The HyperSurface tiles can effectively re-engineer electromagnetic waves, including steering towards any desired direction, full absorption, polarization manipulation and more. Multiple tiles are employed to coat objects such as walls, furniture, overall, any objects in the indoor and outdoor environments. An external software service calculates and deploys the optimal interaction types per tile, to best fit the needs of communicating devices. Evaluation via simulations highlights the potential of the new concept.

Index Terms—Metasurfaces, HyperSurfaces, Wireless Communications, Wireless Environment, Propagation, Software control.

I. INTRODUCTION

WIRELESS communications are rapidly evolving towards a software-based functionality paradigm, where every part of the device hardware can adapt to the changes in the environment. Beamforming-enabled antennas, cognitive spectrum usage, adaptive modulation and encoding are but a few of the device aspects that can now be tuned to optimize the communication efficiency [1]. In this optimization process, however, the environment remains an uncontrollable factor: it remains unaware of the communication process undergoing within it. In this paper we make the environmental effects controllable and optimizable via software.

A wireless environment is defined as the set of physical objects that significantly alter the propagation of electromagnetic (EM) waves among communicating devices. In general, emitted waves undergo attenuation and scattering before reaching an intended destination. Attenuation is owed to material absorption losses, and the natural spreading of power within space, i.e., the distribution of power over an ever-increasing spherical surface. Wave scattering is owed to the diffraction, reflection and refraction phenomena, which result into a multiplicity of propagation paths between devices. The geometry, positioning and composition of objects define the propagation outcome, which is, however, intractable to calculate except for simple cases.

Apart from being uncontrollable, the environment has a generally negative effect on the communication efficiency. The signal attenuation limits the connectivity radius of nodes, while multi-path propagation results into fading phenomena, a well-studied effect which introduces drastic fluctuations in the received signal power. The signal deterioration is perhaps the major consideration in forthcoming mm-wave and THz communications. While these extremely high communication frequencies offer unprecedented data rates and device size minimization, they suffer from acute attenuation owed to molecular absorption, multi-path fading and Doppler shift even at pedestrian speeds, limiting their present use in short line-of-sight distances [1]. Existing mitigation approaches propose massive MIMO and 3D beamforming at the device-side [2], and passive reflectors/active reflectarrays carefully placed at intermediate points within a space [3], [4]. However, while these approaches provide a good degree of control over the directivity of wireless transmissions, they pose mobility and hardware scalability issues. Moreover, the control is limited to directivity and does not extend to full EM manipulation. As a result, the wireless environment as a whole remains unaware of the ongoing communications within it, and the channel model continues to be treated as a probabilistic process, rather than as a software-defined service.

The key-enabler for building a programmable wireless environment is the concept of metamaterials and metasurfaces [5]. Metamaterials are artificial structures, with engineered EM properties across any frequency domain. In their most common form, they comprise a basic, simple structure, the meta-atom, which is repeated periodically within a volume. Metasurfaces are the 2D counterparts of metamaterials, in the sense of having small-but not negligible-depth. While materials found in the nature derive their properties from their molecular structure, the properties of metamaterials stem from the form of their meta-atom design. Thus, when treated macroscopically, metamaterials exhibit custom permittivity and permeability values locally, even beyond those found in natural materials.
Fig. 1. Programmable wireless environments can exhibit user-adapting, unnatural wireless behavior, manipulating EM waves to match the requirements of users. Wireless power transfer, Quality of Service (QoS) and Security scenarios are exemplary illustrated.

As a consequence, metamaterials enable exotic interactions with impinging EM waves, being able to fully re-engineer incoming waves. Finally, the dynamic meta-atom designs can be altered with simple external bias—such as a binary switch—endowing metamaterials and metasurfaces with adaptivity. The naming of metamaterials is a testament to their simple and scalable internal structure, which classifies them as materials rather than as antenna arrays.

The methodology for introducing software control over the EM behavior of a wireless environment consists at coating objects, such as walls, furniture, overall any objects in the indoor or outdoor environments, with HyperSurfaces, a forthcoming class of software-controlled metasurfaces [6]. HyperSurfaces merge networked control elements with adaptive metasurfaces. The control elements apply the proper bias to adaptive meta-surface meta-atoms, thereby attaining a desired macroscopic EM behavior. Additionally, the HyperSurface has interconnectivity capabilities, which allow it to enter control loops for adapting their performance. In this paper we introduce the HyperSurface tile architecture and the process of using them to build programmable wireless environments. We discuss the high-level programming interfaces for interacting with tiles, and detail the enabling of a new class of software that will treat wireless propagation as an application. We proceed further to study the practical incorporation to existing networking infrastructures and to evaluate the novel capabilities of the programmable environments via raytracing-based simulations.

The remainder of this paper is organized as follows. Section II presents the programmable wireless environment concept and Section III details its architecture. Evaluation via simulations takes place in Section IV. Research challenges are discussed in Section V and the paper is concluded in Section VI.

II. PROGRAMMABLE WIRELESS ENVIRONMENTS: THE CONCEPT

Consider a scenario of wireless communications within a space, as shown in Fig. 1. Several users require connectivity, each with different requirements. Users A and D are interested in optimal connection quality, user B is interested in wireless power transfer, and user C requires eavesdropping avoidance measures. Finally, user E represents unauthorized access or interference attempts, which may be deliberate or random. In the common, passive environment, such objectives cannot be met efficiently. Devices employ beamforming to find promising wave transmission directions, but the environment remains oblivious to the process. EM waves scatter uncontrollably upon objects, sharply losing their focus and carried power, causing interference, performance drop and security concerns.
In the case of a programmable wireless environment, objects such as walls, ceilings, etc., receive HyperSurface-tile coating that enables them to re-engineer impinging waves in a software-defined manner. Each tile incorporates a lightweight Internet-of-Things (IoT) gateway which enables it to receive commands from a central configuration service and set its custom EM behavior accordingly. In collaboration with existing device beamforming mechanisms and location discovery services, the programmable environment allows for novel capabilities, essentially treating EM propagation in a manner reminiscent of routers and firewalls in classical networking. As shown in Fig. 1, users A and D receive maximum signal-to-interference power levels by carefully focusing the EM waves in a lens-like manner and avoiding mutual interference. Moreover, the wave propagation is groomed further to achieve constructive superposition at the user devices, optimizing their power-delay profile (PDP) and avoiding the negative effects of multi-path fading. The environmental response for user B targets maximum wireless power transfer using a combination of custom wave steering and focusing, but without PDP concerns. For user C, the environment establishes a “private air-route”, that avoids all other users to reduce the risk of eavesdropping. Finally, the unauthorized user E is blocked by instructing the environment to absorb his emissions, potentially using the harvested energy in a constructive way, such as powering some HyperSurface tiles.

We proceed to detail the architecture of the HyperSurface tiles that comprise a programmable environment. Moreover, we discuss its incorporation to existing network infrastructures, as well as the process for modeling and treating wireless propagation as an app.

III. THE ARCHITECTURE OF PROGRAMMABLE ENVIRONMENTS

We begin by presenting some prerequisite knowledge on the structure and properties of metasurfaces. Here we focus on the basics required to subsequently describe the HyperSurfaces.

A metasurface is a composite material layer, designed and optimized to function as a tool to control and transform EM waves. They commonly comprise a conductive pattern repeated over a dielectric substrate. Examples of meta-atom patterns constituting the building blocks of some of the most common metasurfaces are shown in Fig. 2. The operating principle of metasurfaces is as follows. When EM waves impinge on a metasurface, it creates currents in it via induction. In the case of static meta-atoms (Fig. 2a), the total current pattern within the surface is fully defined by the meta-atom geometry and composition. In dynamic designs (Fig. 2d), the current pattern also depends on the states of the switching elements. The inducted current also creates a response field, following the laws of electromagnetism. The meta-atoms are engineered to yield a custom response field.

The meta-atom size and the thickness of the tile are important design factors, which define the maximum frequency for EM wave interaction. As a rule of thumb, meta-atoms are bounded within a square region of $\lambda/10 \leftrightarrow \lambda/5$, $\lambda$ being the EM interaction wavelength. The minimal HyperSurface thickness is also in the region of $\lambda/10 \leftrightarrow \lambda/5$. Thus, for an interaction frequency of $5\,GHz$, the meta-atom would have a side of $\sim 8\,mm$, with similar thickness.

We note that dynamic meta-atom designs constitute an extensively studied subject in the literature, offering a wide variety of choices. An extremely wide array of EM interaction types (denoted as functions) have been achieved across any spectrum, e.g. wave steering, polarizing, absorbing, filtering and collimation resulting from fascinating metasurface properties such as near zero permittivity and/or permeability response, peculiar anisotropic response leading, e.g., to hyperbolic dispersion relation, giant chirality, non-linear response and more [5], [7], [8].

A. The HyperSurface

A HyperSurface tile is envisioned as a planar, rectangular structure that can host metasurface functions over its surface, with programmatic control. It comprises a stack of virtual and physical components, shown in Fig. 3 which are detailed below.

The Functionality & Configuration layers. A HyperSurface tile supports software descriptions of metasurface EM functions, allowing a programmer to customize, deploy or retract them on-demand via a programming interface with appropriate callbacks. These callbacks have the following general form:

\[
\text{outcome} \leftarrow \text{callback}(\text{action_type, parameters})
\]

The action_type is an identifier denoting the intended function to be applied to the impinging waves, such as STEER or ABSORB. Each action type is associated to a set of valid parameters. For instance, STEER commands require: i) an incident wave direction, ii) an intended reflection direction, and iii) the applicable wave frequency band. ABSORB commands require no incident or reflected wave direction parameters.
The functionality layer is exposed to programmers via an API that serves as a strong layer of abstraction. It hides the internal complexity of the HyperSurface and offers general purpose access to metasurface functions, without requiring knowledge of the underlying hardware and physics. Thus, the configuration of the phase switch materials that matches the intended EM function is derived automatically, without the programmer’s intervention.

The Metasurface Layer. It is the metasurface hardware comprising dynamic meta-atoms, whose states are altered to yield and intended EM function. This layer comprises both the passive and active elements of meta-atoms. For instance, the example of Fig. 3 comprises conductive square patches (passive) and switches (active). It is noted that even simple, ON (most conductive) / OFF (most insulating) switches are sufficient for building metasurfaces supporting an impressive range of EM functions [5].

Large area electronics (LAE) constitute very promising approaches for manufacturing the metasurface layers [9]. LAE can be manufactured using conductive ink-based printing methods on flexible and transparent polymer films, and incorporate polymer switches (diodes) [9]. Apart from minimal cost, the LAE approach favors scalability and deployment of HyperSurfaces. Tiles can be manufactured as large films with metasurface patterns and diode-switches printed on them, and be placed upon common objects (e.g., glass, doors, walls, desks), which may also play the role of the dielectric substrate for the metasurface.

The Intra-tile Control Layer. This layer describes the hardware components and wiring that enables the programmatic control over the switches of the metasurface layer. A highly promising, cost-effective and highly scalable approach, is to control the metasurface switches as a diode array [10], i.e., as a common light-emitting-diode (LED) display works. Meta-atoms are treated as very simple “pixels”, with just two “colors” (ON/OFF). The diode array approach results in a very simple control layer, which comprises just the wiring to connect each meta-atom switch to the gateway (discussed below). Moreover, it entails a very low power drain. For instance, assume a meta-atom with size $8 \times 8 \ mm$, which can interact with waves modulated at 5 GHz. A total number of 324,375 meta-atoms are required for coating a $5 \times 3 \ m$ wall.

Fig. 3. The functional and physical architecture of a single HyperSurface tile. A desired and supported, EM function is attained by a switch state configuration setup. Inter-tile and external communication, is handled by standard gateway hardware.
As shown in [10, p. 497], a single elastic diode exhibits a drain of $5 \cdot 1.6 \mu A = 8 \mu W$ when powered. Thus, the total coating of the wall will drain $\sim 1.88 W$ at a maximum—i.e., when all diodes are set to 'OFF'—or 125 mW/m$^2$, which constitutes a very promising indicative value.

Apart from the presently realizable diode array control approach, forthcoming nanonetwork technologies may also be considered as control agents in the future [11]. Nanonetworks comprise a network of wireless nano-sized electronic controllers, each with responsibility over one active meta-atom element. The controllers are able to exchange information, in order to propagate switch configuration information within the tile. Nano-controllers are envisioned to be autonomic in terms of power supply. While still at its early-stages, the nanonetwork approach promotes the seamless integration of control elements within a material, while it may also enable materials with embedded intelligence, able to tune their EM behavior in an autonomous fashion.

The Tile Gateway Layer. It specifies the hardware (Gateway) and protocols that enable the bidirectional communication between the controller network and the external world (such as the Internet), as well as the communication between tiles. This provides flexibility in the HyperSurface operation workflow, as follows. In general, multiple tiles are expected to be used as coating of large areas, as discussed in Section [11]. Moreover, the tile hardware is intended to be inexpensive, favoring massive deployments. Based on these specifications, existing IoT platforms can constitute promising choices for tile gateways [1]. The sensing capabilities of existing IoT platforms may optionally facilitate the monitoring of the tile environment, such as the impinging wave power measurements, enabling the adaptive tuning of the tile functions [12].

The described interconnectivity approach can also be employed during the tile design phase, for the automatic definition of the supported EM functions and their input parameter range. Since deriving the tile behavior via analysis is challenging in all but static meta-atom cases, an approach based on learning heuristics can also be employed instead [5]. According to it, an intended EM function is treated as an objective function and, subsequently, the tile is checked for compliance via illumination by an external wave (input) and reflection/absorption measurements (output). A learning heuristic is then employed to detect iteratively the best switch configuration that optimizes the output of the objective function. Once detected, the best configuration is stored in a lookup table for any future use. It is noted that metasurfaces are generally not known to exhibit an inherent limitation regarding the EM functions that they can support.

B. Incorporation to networking infrastructure

Programmable wireless environments can be incorporated to existing network infrastructures without altering their workflow. Especially in the case of Software-Defined Networks (SDN) [11], the programmable environments can be clearly modeled as a set of software services, as shown in Fig. [4] SDN has gained significant momentum in the past years due to the clear separation it enforces between the network control logic and the underlying hardware. An SDN controller abstracts the hardware specifics ("southbound" direction) and presents a uniform programming interface ("northbound") that allows the modeling of network functions as applications.

Using the SDN paradigm, HyperSurface tiles can be considered as wave routing hardware. Notice that the tiles employ common IoT devices as gateways, whose communication protocols are mainstream and typically supported by SDN controllers. The custom environmental behavior to serve a set of users is calculated by a wireless environment configuration application. The application receives the device positions, the user objectives and the global policies as inputs and calculates the fitting air paths. A control loop is established with existing device position discovery and access control SDN applications, constantly adapting to changes in the security policies and user device location updates.

C. Workflow of the environment configuration service

A HyperSurface-coated environment can treat the EM wave propagation similar to the routing process in classic networking. Connecting two wireless devices becomes a problem of finding a route over HyperSurface tiles, while blocking access to a wireless device is achieved by absorbing or deflecting its EM emissions. An example is given in Fig. [5] which studies a possible EM routing configuration to serve the objectives of the scenario shown in Fig. [4]. Software commands are combined and sent to the proper tile gateways, manipulating EM waves, steering, absorbing and focusing them as needed. Finding the air-routes that fulfill the objectives of multiple users can be treated as a network embedding problem. When an EM beam from a device impinges on, e.g., a wall, the affected tiles can be seen as the user entry-points in the graph of connectable tiles. The tile graph comprises a node for each tile and a link between any two tiles can steer EM waves to each other. User objectives can be treated as air-route requirements, e.g., selecting the K-Shortest paths to connect

Fig. 4. Schematic of the programmable wireless environment incorporation workflow of the HyperSurface network graph. 1. Receive updated user device positions. 2. Perform user access control. 3. Express user objectives and global policies as air-route restrictions. 4. Calculate air-route embeddings in the HyperSurface network graph. 5. Deploy air-routes.
the device entry-points, using routes that avoid other users for increased security, etc. These requirements can then be embedded to the tile graph using well-known techniques [13].

Having described the tile configuration process as an embedding problem, we proceed to outline the total workflow of the configuration service. The service forms a continuous loop with device location discovery systems: it receives the updated locations of user devices and tunes the behavior of the wireless environment accordingly. It is noted that tiles can facilitate the device location discovery process [12]. The existing user access mechanisms of the network infrastructure are executed. If a device is deemed unauthorized, a “block” objective is formed for it. Authorized devices that are aware of the programmable environment can express their specific objectives by posting a request to the configuration service. Unaware devices are treated by global policies. The environment configuration service produces the matching air-routes and proceed to deploy them by sending corresponding EM manipulation commands to the tile gateways. The continuous control loop is established to adapt to localization errors or changes. It is noted that the configuration service may have control over the beam-forming capabilities of the infrastructure access points. The user device-side beam-forming adapts automatically by scanning and selecting the best beam direction automatically using the device’s standard process.

IV. Evaluation

In this section, we present preliminary results to show the potential of HyperSurfaces in mitigating undesired path loss effects in a real-world wireless communication scenario. Specifically, we demonstrate the performance improvement with the focus and steer function implemented in a typical indoor environment.

As shown in Fig. 6, the indoor space shows a dimension of 15 m in length and 10 m in width and a height of 3 m. The room is divided by a middle wall (with a length of 12 m and a thickness of 1 m) into two sections (i.e., line-of-sight and non-line-of-sight sections, respectively), each with a width of 4.5 m. All walls are coated with HyperSurface tiles with a size of 1 × 1 m. An EM transmitter, with a height of 2 m as shown in red color in Fig. 6, is located on one side of the room and equipped with a half-dipole antenna and transmits at 60 GHz with 25 MHz bandwidth. The transmission power is set to 100 dBm. In total 12 receivers (shown in blue color in Fig. 6) are uniformly distributed on the non-line-of-sight side of the room with a same height of 1.5 m and half-dipole

**Fig. 5.** The wireless environment configuration process as a routing problem. The illustrated case corresponds to the scenario of Fig. 1.

**Fig. 6.** Simulation results for wireless environment optimization study at 60 GHz. The baseline, non-HyperSurface setup (top) shows a poor coverage. The use of HyperSurfaces (middle) shows significantly improved signal coverage and received power overall. An illustration of the deployed focus and steer functions is shown at the bottom inset.
signals from transmitter to desired receiver. This work principle of tuning the HyperSurface tiles in the example is the following: we begin with the most distant receiver (top-right position) and assign focus and steer commands to the tiles that offer the shortest air-route. The used tiles are marked and are not used again for other receivers. We note that this is a simplification, as metasurfaces can achieve beam splitting functionalities. Thus, in reality, a single tile could be tuned to affect more than one user. The process is repeated for the rest of the users. In the context of studied, static scenario, the number of tiles to be used for each user is deduced by a generic optimizer, which seeks to maximize the minimum received power over all receivers. As discussed in Section VII however, real-time operation is expected to require specialized optimization processes. Figure 6 bottom provides an example of a single focus and steer function deployment. The tiles with green-colored paths impinged upon will adjust their azimuth and elevation angles to focus the signals from transmitter to desired receiver.

V. CHALLENGES AND RESEARCH DIRECTIONS

Further research in programmable wireless environments can target the tile architecture and the inter-tile networking, the tile control software, and many applications such as mm-waves, D2D and 5G systems.

Regarding the tile architecture, the optimization of the dynamic meta-atoms constitutes a notable goal towards minimizing the supported function range of a tile. Ultra-wideband meta-atoms designs able to interact concurrently with a wide variety of frequencies, e.g., from 1 to 60 GHz, constitute a notable research goal. Formal tile sounding procedures need to be defined, i.e., simulation-based and experimental processes for measuring the supported functions and parameters per tile design. Additionally, the tile reconfiguration speed needs to be studied, in order to yield the adaptivity bounds of the programmable environments. In this sense, inter-tile networking protocols need to be designed to offer fast, energy-efficient wireless environment reconfiguration, supporting a wide range of user mobility patterns. Adaptation to user mobility can also target the mitigation of Doppler shift effects.

The HyperSurface control software needs to be optimized regarding its complexity, modularity and interfacing capabilities. Low-complexity, fast configuration optimizers can increase the environments maximum adaptation speed. Towards this end, both analysis-based and heuristic optimization processes need to be studied. Additionally, following the Network Function Virtualization paradigm, the various described and evaluated optimization objectives can be expressed in a modular form, allowing their reuse and combination. For example, the tiles may be configured to maximize the minimum received power within a room, subject to delay spread restrictions. Well-defined tile software interfaces can allow for a close collaboration with user devices and external systems. For instance, the power delay profile towards a user can be matched to the Multiple-Input Multiple Output arrangement of his device. It is noted that such joint optimization can be aligned to the envisioned 5G objectives of ultra-low latency, high bandwidth, and support for massive numbers of devices within an environment.

We note that the HyperSurface concept is applicable to any frequency spectrum and wireless architecture. Therefore, solving the corresponding path loss, fading, interference and non-line-of-sight problems in general using HyperSurfaces constitute promising research paths. Such directions can further focus on indoors and outdoors communication environments. In indoors settings, the HyperSurface tiles can cover large parts of the wireless environment, such as walls, ceilings, furniture and other objects and offer more precise control over electromagnetic waves. In outdoors settings, the HyperSurface tiles can be placed on key-points, such as building facades, highway polls, advertising panels, can be utilized to boost the communication efficiency. In both settings, i.e., in indoors and outdoors, the automatic tile location and orientation discovery can promote the ease of deployment towards “plug-and-play” levels. Moreover, the joint optimization of antenna beam-forming and tile configurations need to be studied, to achieve the maximum performance.

Studying the use of HyperSurfaces in mm-wave systems, 5G systems and THz communications is of particular interest. For example, mm-wave and THz systems are severely limited in terms of very short distances and LOS scenarios. The HyperSurfaces can mitigate the acute path loss by enforcing the lens effect and any custom reflection angle per tile, avoiding the ambient dispersal of energy and non-line-of-sight effects, extending the effective communication range. Dynamic meta-atoms that can interact with THz modulated waves need to be designed. This has been shown to be possible for graphene-based metasurfaces. The tile sensing accuracy and reconfiguration speed must also match the extremely high spatial sensitivity of THz communications, calling for novel, highly
distributed tile control processes. Optical tile inter-networking is another approach to ensure that the tile adaptation service is fast enough for the THz communication needs.

Finally, the control of EM waves via HyperSurfaces can find applications beyond classic communications. EM interference constitutes a common problem in highly sensitive hardware, such as medical imaging and radar technology. In these cases, the internals of, e.g., a medical device can be treated as an EM environment, with the objective of canceling the interference to the imaging component caused by unwanted internal EM scattering. Such interference can be mitigated only up to a degree during the design of the equipment. Common discrepancies that occur during manufacturing can give rise to unpredictable interference, resulting into reduced equipment performance. However, assuming HyperSurface-coated device internals, interference can be mitigated, or even negated, after the device manufacturing, via simple software commands.

VI. CONCLUSION

The present study introduced software control over the electromagnetic behavior of a wireless environment. The methodology consisted of coating size-able objects, such as walls, with HyperSurface tiles, a novel class of planar materials which can interact with impinging waves in a programmable manner. Interaction examples include wave absorbing and steering towards custom directions. The tiles are networked and controlled by an external service, which defines and deploys a configuration that benefits the end-users. Notable applications are the mitigation of propagation loss and multipath fading effects in virtually any wireless communication system, including mm-wave and THz setups. The study defined the HyperSurface tile architecture and the structure of the programmable wireless environments that incorporate them. Evaluation via simulations demonstrated the exceptional potential of this novel concept.

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