

Towards a Circular Economy via Intelligent Metamaterials

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Abstract—The present study proposes the use of intelligent metasurfaces in the design of products, as enforcers of circular economy principles. Intelligent metasurfaces can tune their physical properties (electromagnetic, acoustic, mechanical) by receiving software commands. When incorporated within products and spaces they can mitigate the resource waste caused by inefficient, partially optimized designs and security concerns. Thus, circular economy and fast-paced product design become compatible. The study begins by considering electromagnetic metamaterials, and proposes a complete methodology for their deployment. Finally, it is shown that the same principles can be extended to the control of mechanical properties of objects, exemplarily enabling the micro-management of vibrations and heat, with unprecedented circular economy potential.

Index Terms—Circular economy; ecology; material properties; HyperSurfaces; metasurfaces; metamaterials; electromagnetic; mechanical; acoustic; micro-management; security; energy.

I. INTRODUCTION

The industrial and electronic revolution had a tremendous impact on our world at all levels, from micro to macro. Our every-day lives are depended on the facilities of industrial production of goods, transportation, communication and computation. At macroscopic level, the global economy is shaped by the flow of goods and services. However, this revolution was partial and never planned in depth, to account for its ecological sustainability. As a result, the natural resources of the planet are already expended faster than their replenishment rate, while by 2030 the expenditure will be twice the replenishment [1].

Industrial design has been partial due to its fast-paced, antagonistic nature and due to the lack of a central framework for life-cycle management across products. The fast-paced nature means that a company that offers a product to the market is income-driven, and always insecure about another company getting to the market

first. Thus, due to lack of time, products are only partially optimized: they revolve about the immediate facility, disregarding all the rest—sustainability and security included. This fast pace also alter the environment faster than the reaction time of governments. Legislation and frameworks arrive late, while their enforcement is slow as well.

The concept of circular economy seeks to provide a framework for sustainability at micro and macro levels [2]. At micro level (single product), it provides directives for a circular product life-cycle. Instead of the traditional, linear order of life-cycles phases, i.e., i) raw resource acquirement, ii) processing, iii) distribution, iv) use and v) disposal, circular economy creates links from disposal to all preceding phases. According to it, product design should facilitate four links: i) decomposition to raw materials, ii) re-processing or refurbishment, iii) re-deployment and redistribution, and iv) multiple uses. At macro-level (in a horizontal, cross-product approach), it is expected to provide a legal framework for enforcing these approaches. However, this effort will require extra design and development time from companies, which opposes their fast-paced nature. Thus, novel approaches are required to ensure the success of the circular economy concept.

The present work proposes the use of intelligent metamaterials as enforcers of circular economy in a fast-paced product design. Metamaterials are artificial materials with engineered physical properties (such as electromagnetic-EM, acoustic and mechanical behavior). Moreover, they can exhibit properties not found in natural materials, such as negative refraction index, perfect insulation, etc. Additionally, a recent advancement called HyperSurfaces offers metamaterials with software-defined properties [3]. A well-defined programming interface abstracts underlying complexities and allows non-specialists (such as software developers) to incorporate the HyperSurface in applications and products, without caring for their inner physics.

Due to these traits, HyperSurfaces and intelligent metasurfaces in general can act as mitigation agents for partially optimized product designs. We envision metasurfaces as coatings or structural parts of products.

For instance, electromagnetic interference and unwanted emissions can be harvested by HyperSurface-coated walls and be transformed back to usable electrical or mechanical energy [3]–[5]. Mechanical metamaterials can micro-manage emanated heat and vibrations from motors to recycle it as energy while effectively cooling it. Acoustic metamaterials can surround noisy devices or applies on windows to provide a more silent environment, but to also harvest energy which can be added to the household. A notable trait of metamaterials is that they are simple structures and, therefore, their production can easily follow the aforementioned four principles of circular economy. Moreover, their software-defined nature allows for quickly “patching” the non-ecological parts of new or existing products, without much overhead to the industrial pace. The “patching” may also be deferred in the form of “eco-firmware”, distributed via the Internet to ecologically tune a single product or horizontal sets of products.

In the following, we provide a methodology creating ecosystems of intelligent metamaterials and propose the micro-Managed Electromagnetic Environments. We begin by focusing on EM metamaterials (Sections II-III), since they are more well-known to the general audience and, thus, easier to describe. Lastly, we generalize to the case of mechanical and acoustic metamaterials (Section IV).

II. ENABLING TECHNOLOGIES

A. EM Metamaterials and Metasurfaces

This section provides the necessary background knowledge on metamaterials metasurfaces, discussing dimensions and composition, operating principles, programmable metasurfaces and supported functionalities.

A regular metasurface is a planar, artificial structure which comprises a repeated element, the meta-atom, over a substrate. In most usual compositions, the meta-atom is conductive and the substrate is dielectric. Common choices are copper over silicon, printed organic circuits over films, while silver and gold constitute conductors for exotic applications [6]. Other approaches employ graphene, in order to interact with THz -modulated waves [7]. Metasurfaces are able to control EM waves impinging on them, in a frequency span that depends on the overall dimensions. The size of the meta-atom is comparable to the intended interaction wavelength, λ , with $\lambda/2$ constituting a common choice. The thickness of the metasurface is smaller than the interaction wavelength, ranging between $\lambda/10 \rightarrow \lambda/5$ as a rule of a thumb. Metasurfaces usually comprise several hundreds of meta-atoms, which results into fine-grained control

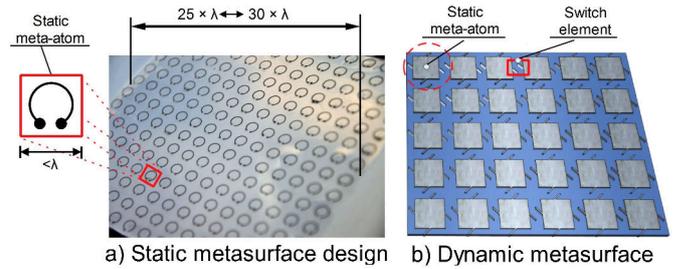


Figure 1. Split ring resonators (left) constituted a very common type of static metasurfaces, with fixed EM behavior. Dynamic designs (right) incorporate switch elements (MEMS, CMOS or other) to offer dynamically tunable EM behavior.

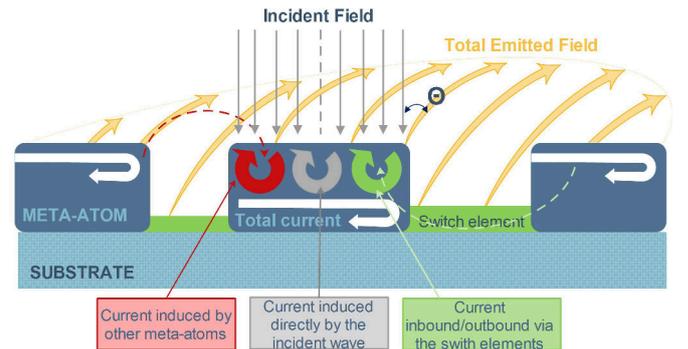


Figure 2. The principle of metasurface functionality. Incident waves create a well-defined EM response to the unit cells. The cell response is crafted in such a way that the aggregate field follows a metasurface-wide design objective, e.g., reflection towards a custom angle Θ .

over the EM interaction control. Metamaterials are the 3D counterpart of the concept, and can be perceived as a stack of metasurfaces.

Figure 1-a illustrates a well-studied metasurface design comprising split-ring resonators as the meta-atom pattern. Such classic designs that rely on a static meta-atom, naturally yield a static interaction with EM waves. The need for dynamic alteration of the EM wave control type has given rise to dynamic, programmable metasurfaces, exemplary illustrated in Fig. 1-b. Dynamic meta-atoms incorporate phase switching components, such as MEMS or CMOS transistors, which can alter the structure of the meta-atom. Thus, dynamic meta-atoms allow for time-variant EM interaction, while meta-atom alterations may give rise to multi-frequency operation [6]. Phase switching components can also be classified into state-preserving or not. For instance, mechanical switches may retain their state and require powering only for state transitions, while semiconductor switches require power to maintain their state.

The operating principle of metasurfaces is given in Fig. 2. The meta-atoms, and their interconnected switch elements in the dynamic case, act as control factors over

the surface currents flowing over the metasurface. The total EM response of the metasurface is then derived as the total emitted field by all surface currents, and can take completely engineered forms, such as the unnatural reflection angle shown in Fig. 2. Engineering the total surface current is a complex process that must account for currents directly induced over the metasurface by the incident wave, the currents induced in a meta-atom wirelessly by other meta-atoms, as well as the currents flowing inwards or outwards from a meta-atom via the switch elements.

A metasurface can support a wide range of EM interactions, i.e., *EM functions*, which are classified as follows [8]:

- Reflection of an impinging wave, with a given direction of arrival, towards a completely custom direction.
- Refraction of EM waves via the metasurface towards any inwards direction. Both the reflection and refraction functions can override the outgoing directions predicted by Snell's law. Reflection and refraction functions will jointly be referred to as wave *steering*. Steering can provide security at physical layer, by bending waves around unwanted users, completely negating eavesdropping [5].
- Wave absorbing, i.e., ensuring minimal reflected and/or refracted power for impinging waves.
- Wave polarizing, i.e., changing the oscillation orientation of the wave's electric and magnetic field.

In general, metasurfaces and metamaterials can fully re-engineer the impinging wave, producing a completely custom response-field [9]. HyperSurfaces are an incorporation-ready approach to metasurfaces [3]–[5], which provide both the hardware and software to control their EM properties. They model the EM functions as a software API, comprising callbacks with the following general form:

```
outcome ← callback(action_type, parameters)
```

where `action_type` defines the type of EM function (such as `STEER`, `ABSORB`, etc.), accompanied by the necessary parameters to completely define the wanted interaction. Thus, the complexities of metasurface Physics are abstracted and hidden, focusing on usability by software developers.

B. The Internet of (Nano)-Things

The Internet of Things (IoT) is a rapidly growing ecosystem of sensory and communication platforms. IoT devices commonly employ inexpensive sensors and microprocessors, tiny power supplies and wireless

transceivers, prioritizing scalability, robust communication and energy efficiency. Via IoT, the number of connected devices increases rapidly and extends to the control over any ordinary object in our environment, such as switches, medical implants, cars, trackers, clothes, lights and door locks. Novel IoT products are being released almost daily, at a trend that is expected to yield 20-30 billion connected IoT devices by 2020 [10]. IoT platforms are promising choices for ambient environmental monitoring and control.

Moreover, ongoing IoT research now targets the nanoscale, with the target to achieve ultimate levels of minification, scalability and energy-efficiency. Research has started shrinking sensors, antennas transceivers and logic circuits to the nanoscale [11], small enough to circulate within living bodies and to mix into industrial materials, taking medicine, energy efficiency and many construction sectors to a new level. Protocols able to sustain the vast device numbers and sensory data volumes are under active research, with highly promising results [12]–[14]. Due to their minimal size and vast numbers, nanosensors can gather information from a multitude of environmental views. External data aggregators, e.g., in the Cloud, can then generate incredibly detailed snapshots containing the slightest changes in light, vibration, electrical currents and magnetic fields, for uniquely-detailed environmental monitoring.

C. Network Function Virtualization and Software-Defined Networking

Network functions virtualization (NFV) is a novel concept in network design and operation, which seeks to express services offered by a network into building-block components that can be connected (i.e., *chained*) together, to create custom operations on demand.

In essence, NFV is a form of well-structured virtualization that abstracts an offered function from the underlying *material* performing the low-level computations. In its classic form, NFV building blocks—the Virtual Network Function Components—are distributed as well-isolated packages that can be configured, initiated, migrated and destroyed in accordance with a defined workflow or life-cycle. The NFV principles do not specify a strict format for the Components, but rather guidelines on how to effectively structure them to be chain-able in a scalable manner. The Components themselves and the virtualization approach followed to contain and distribute them can be completely custom and heterogeneous. Moreover, the applications of NFV span across domains, and can be employed in a variety of settings [15].

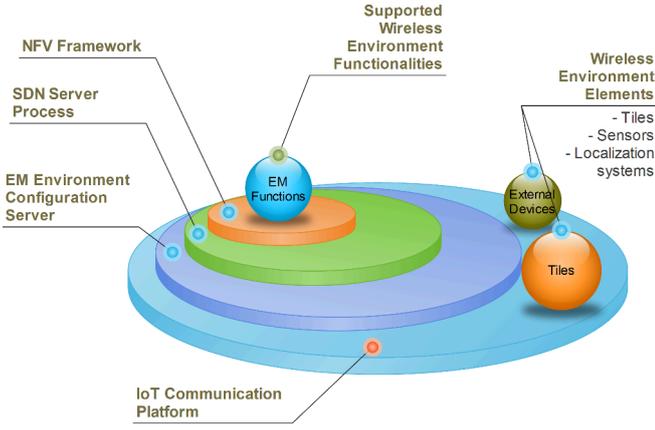


Figure 4. Incorporation schematic of the involved enabling technologies, to form Micro-Managed Electromagnetic Environments.

Software-defined networking (SDN) is a novel way of managing networks that has gained significant traction in the industrial and the academic world [16], [17]. Its core principles are: i) to well-separate the network control from the network data, ii) to provide a clean interface for interacting with the control, and iii) to provide a central view of the various distributed forwarding elements. This is accomplished by delegating network control decisions to a central service, which has a bird’s eye view of the controlled system, and configures its operation in response to policies and events.

In this study, the SDN and NFV are used as abstract approaches for organizing software in general, rather than in their literal use in the narrow field of computer networking.

III. A METHODOLOGY FOR MICRO-MANAGED ELECTROMAGNETIC ENVIRONMENTS

Figures 3 and 4 provide an overview of design methodology for Micro-Managed Electromagnetic Environments (mMEEs). Figure 3 illustrates the envisioned workflow of mMEEs, while Fig. 4 depicts the incorporation scheme of the enabling technologies.

The mMEE design methodology incorporates three core ideas:

- 1) Express the EM functions of tiles within a NFV framework. Exploit the modularity and chaining capabilities of the NFV paradigm, and allow for a well-organized hierarchy of EM functionalities that can be used in a wide application context.
- 2) Implement the expressed EM virtual functions in an SDN-over-IoT platform. Make use of the centralized control offered by SDN, to obtain the requirements of the wireless devices present within

a space. SDN and IoT combined facilitate the interfacing with other systems (e.g., localization) and the control over the numerous tiles within the environment.

- 3) Employ optimization principles to combine and host multiple EM virtual function instances within an mMEE. Express the wireless device requirements in the form of well-defined optimization objectives, facilitating their “compilation” to matching tile configurations.

A driving principle within the methodology is to make mMEE accessible to a broad developer audience, without requiring expertise in Physics, following the paradigm set by HyperSurfaces. Therefore, the envisioned hierarchy of EM functionalities follows the levels shown in Fig. 3.

At the lowest level, we envision wave-front manipulation EM functions, which will allow for custom steering, polarization, absorption and non-linear (e.g., frequency-selective) filtering of waves impinging upon tiles. This basic set of functions will be chained together towards the formation of intermediate-level functionalities. As an example, we propose functions such as *FOCUS* and *FOLLOW*. The former refers to a lens functionality, aimed at gathering ambient energy and directing it towards a wireless device for remote charging. The latter makes an EM function applicable to moving targets. Thus, *FOCUS* and *FOLLOW* could be combined to mitigate path loss for a mobile device within the environment. Additional examples of higher-level functions include the *DISPERSE*, for achieving wireless coverage within a space, *BLOCK* (opposite to *AUTHORIZE*), for absorbing transmissions from malevolent or unauthorized users before they propagate within the environment, and *SET_POWER* to define the total power level carried towards a device or a space, e.g., for wireless power transfer (WPT) tasks.

At the final level, the hierarchy exposes functionality objective templates, which are envisioned as well-defined and parametric optimization goals, organized into four, broad application contexts:

- Communication objectives, which aim to provide advanced QoS to wireless devices, leveraging the mMEE potential. These exemplary include bandwidth maximization, Bit Error Rate minimization, extended high-quality wireless coverage and cross-device interference negation.
- Privacy and Security objectives, which aim at blocking eavesdropping altogether via “private air-paths” and the isolation of unauthorized or malevolent transmissions within a space.

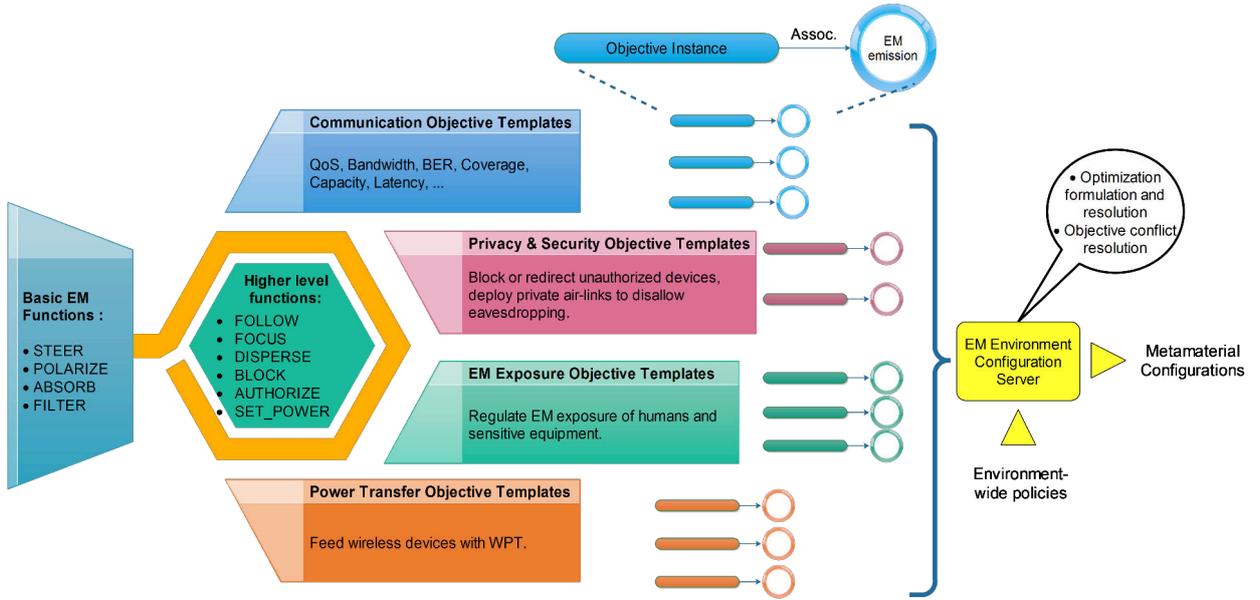


Figure 3. Workflow overview of the proposed Micro-Managed Electromagnetic Environments (mMEEs).

- EM Exposure objectives, which aim at keeping the exposure of humans and sensitive equipment (e.g., medical) within acceptable levels.
- Wireless Power Transfer objectives, aiming at supplying power to properly equipped wireless devices (e.g., supporting energy harvesting).

An SDN control service is the focal point for the mMEE operation. In collaboration with localization and environmental sensing systems, it gathers information on the present wireless devices, their configurations and connectivity intentions. Subsequently, it expresses these intentions to corresponding objective instances, i.e., a parameterized association between an objective template and a set of wireless emissions.

We envision environment-wide policies, apart from device-specific objectives. These policies will allow for the expression of:

- 1) General limits that should be respected within the wireless environment. For instance, a maximum allowed value of wireless power throughout the environment. We note that this is an additional feature enabled by mMEEs, which cannot be supported by plain environments.
- 2) mMEE resource reservations, e.g., the “air-paths” that should be kept spare as slack reserve, ensuring the proper and timely handling of emergency requests for EM micro-management.
- 3) Sub-space optimizations, such as offering a specific EM micro-management type within a sub-space only.
- 4) Priorities for the resolution of conflicting user

requirements. For instance, a user may require WPT within an area of strict EM silence.

The SDN controller passes the knowledge of: i) the needs of the wireless devices present, and ii) the environment policies, to an optimization service. This service deduces the mMEE configuration that best fit the objectives, subject to the policy restrictions. The SDN controller and the optimization service will be engaged in an online control loop, constantly matching the currently gathered knowledge to the optimal mMEE response.

We note that the nature of the mMEE objectives and policies is mathematical, as they correspond to EM profiles (e.g., desired ranges of EM field values) that should be present at points within a space (device locations). On the other hand, the “inputs” to the optimization problem are the supported EM functions that can be deployed to each tile, which can be viewed as “discrete variables”. Therefore, optimization techniques based on Mixed-Integer Programming [18] can constitute a promising resolution direction. Metaheuristic optimization approaches, e.g., Swarm-based or Genetic algorithms, offer an alternative direction, with multiple success stories across disciplines [19]. Finally, we highlight the research direction of artificial intelligence-controlled mMEEs, where Neural Networks can be trained for a given space, i.e., learning the necessary tile EM profiles that correspond to time-variant user needs [20]. This direction could exemplify the mMEE configuration for filtering WiFi signals by high-level attributes such as their SSID, deliberately scrambling signals and making them readable only within a given room, and more.

IV. EXTENDING TO MICRO-MANAGEMENT OF MECHANICAL PROPERTIES

EM metamaterials were the first kind of metamaterials to be proposed and studied, mainly due to the relative ease of manufacturing. However, the same principles have been applied to control sound (acoustic metamaterials [21]) and mechanical waves (mechanical metamaterials [22]). With the advent of 3D printing, acoustic and mechanical metamaterials have become easier to manufacture boosting the related research.

Acoustic metamaterials can manipulate and re-engineer sound waves in gases, solids and liquids. This control is exerted mainly through the bulk modulus, mass density and chirality. The latter two properties correspond to the electromagnetic permittivity and permeability in EM metamaterials. Related to this are the mechanics of wave propagation in a lattice structure. Also materials have mass, and intrinsic degrees of stiffness. Together these form a resonant system, and the sonic resonance is excited by sonic frequencies (e.g., pulses at audio frequencies). Controlling sonic waves has been extended to unnatural properties, including negative refraction.

Mechanical metamaterials can be seen as a superset of acoustic metamaterials. They too can be designed to exhibit properties which cannot be found in nature. Popular mechanical properties that have been controlled in academic studies include compressibility, contractivity and focusing of mechanical waves. However, the exerted control over vibrations can be customized as required by the application scenario.

The functionalities of acoustic and mechanical metamaterials can be exposed in software, following the HyperSurface example. Subsequently, and due to the identical principles of operation, they can be incorporated to a micro-management environment. The later can be derived by generalizing the presented mMEE.

V. CONCLUSION

The present paper introduced the use of intelligent metasurfaces and metamaterials, as enforcers of circular economy principles in the life-cycle of products. The study exploits the fact that intelligent metamaterials can change the electromagnetic, mechanical or acoustic properties following software directives. These artificial materials can be incorporated within products, objects and spaces and micro-manage electrical and mechanical energy. Thus, they can mitigate on-the-fly the ecologic discrepancies of the original product design. The study presented a methodology for organizing, controlling and orchestrating intelligent materials, while discussing their potential in circular economics.

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