THE INTERNET OF METAMATERIAL THINGS AND THEIR SOFTWARE ENABLERS

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Abstract *– A new paradigm called the Internet of MetaMaterial Things (IoMMT) is introduced in this paper where artificial materials with real-time tunable physical properties can be interconnected to form a network to realize communication through software-controlled electromagnetic, acoustic, and mechanical energy waves. The IoMMT will significantly enrich the Internet of Things ecosystem by connecting anything at any place by optimizing the physical energy propagation between the metamaterial devices during their lifetime, via "eco-firmware" updates. First, the means for abstracting the complex physics behind these materials are explored, showing their integration into the IoT world. Subsequently, two novel software categories for the material things are proposed, namely the metamaterial Application Programming Interface and Metamaterial Middleware, which will be in charge of the application and physical domains, respectively. Regarding the API, the paper provides the data model and workflows for obtaining and setting the physical properties of a material via callbacks. The Metamaterial Middleware is tasked with matching these callbacks to the corresponding material-altering actuations through embedded elements. Furthermore, a full stack implementation of the software for the electromagnetic metamaterial case is presented and evaluated, incorporating all the aforementioned aspects. Finally, interesting extensions and envisioned use cases of the IoMMT concept are discussed.*

Keywords – Internet of Things, metamaterials, programming interface, software-defined networking.

1. INTRODUCTION

Recent years have witnessed the advent of the Internet-of-Things (IoT), denoting the interconnection of every electronic device and the smart, orchestrated automation it entails [1]. Vehicles, smart phones, sensors, home and industrial appliances of any kind expose a functionality interface expressed in software, allowing for developers to create end-to-end workflows. As an upshot, smart buildings and even smart cities that automatically adapt, e.g., power generation, traffic and heat management to the needs of residents, have been devised in recent years. This current IoT potential stems from exposing and controlling a high-level functionality of an electronic device, such as turning on/off lights and air-conditioning units based on the time of day and temperature. This paper proposes the expansion of the IoT to the level of physical material properties, such as electrical and thermal conductivity, mechanical elasticity, and acoustic absorption. This novel direction is denoted as the *Internet of MetaMaterial Things (IoMMT)*, and can have groundbreaking potential across many industrial sectors, as outlined in this paper. There are two key enablers for the proposed IoMMT:

Key Enabler 1:

The first key enabler of the proposed IoMMT are the metamaterials, the outcome of recent research in physics that has enabled the creation of artificial materials with real-time tunable physical properties [2, 3]. Metamaterials are based on the fundamental idea stating that the physical properties of matter stem from its atomic structure. Therefore, one can create artificially structured materials (comprising sufficiently small elementary "units" of composition and geometry) to yield any required energy manipulating behavior, including types not found in natural materials. Metamaterials manipulating electromagnetic (EM) energy were the first kind of metamaterials to be studied in depth, mainly due to the relative ease of manufacturing as low-complexity electronic boards [3].

Going beyond EM waves, the collectively termed elastodynamic metamaterials can manipulate acoustic, mechanical and structural waves, whereas thermodynamic and quantum-mechanic metamaterials have also been postulated [4]. Elastodynamic metamaterials, empowered by recent advances in nano- and micro-fabrication (e.g. additive manufacturing/3D printing), can exhibit effective/macroscopic nonphysical properties such as tunable stiffness and absorption/reflection, extreme mass-volume ratios, negative sonic refraction, etc [5]. Their cell-size spans several length scales, depending on the application: acoustic cloaking/anisotropy/isolation, ultra-lightweight and resilient materials, devices for medical/surgical applications and food/drug administration, MEMS, anti-seismic structures, etc. Tunability of elastodynamic metamaterials can be achieved with electric, magnetic, optical, thermal or chemical stimuli. In a nutshell, their operation is as follows: Impinging EM waves create inductive currents over the material, which can be modified by tuning the actuator elements within it (e.g., simple switches) accordingly. The Huygens principle states that any EM wavefront departing from a surface can be traced back to an equivalent current distribution over a surface [3]. Thus, in principle, metamaterials can produce any custom departing EM wave as a response to any impinging wave, just by tuning the state of embedded switches/actuators. Such EM interactions are shown in Fig. 1 (on the right side). The same principle of operation applies to mechanical, acoustic and thermal metamaterials [6].

Key Enabler 2:

The second key enabler of the IoMMT is the concept of networked metamaterials. These will come with an application programming interface (API), an accompanying software middleware and a network integration architecture that enable the hosting of any kind of energy manipulation over a metamaterial in real time (e.g., steering, absorbing, splitting of EM, mechanical, thermal or acoustic waves), via simple software callbacks executed from a standard PC (desktop or laptop), while abstracting the underlying physics. The goal is to constitute the IoMMT directly accessible to the IoT and software development industries, without caring for the intrinsic and potentially complicated physical principles. Regarding the IoMMT potential, large scale deployments of EM metamaterials in indoor setups have introduced the groundbreaking concept of programmable/intelligent wireless environment (Fig. 2) [7]. By coating all major surfaces in a space (e.g., indoors) with EM metamaterials, the wireless propagation can be controlled and customized via software. As detailed in [7] this can enable the mitigation of path loss, fading and Doppler phenomena, while also allowing waves to follow improbable air-routes to avoid eavesdroppers (a type of physical-layer security). In cases where the device beamforming and the EM metamaterials in the space are orchestrated together, intelligent wireless environments can attain previously unattainable communication quality and wireless power transfer [7]. Extending the EM case, we envision the generalized IoMMT deployed as structural parts of products, as shown in Fig. 3:

- EM interference and unwanted emissions can be harvested by IoMM-coated walls and be transformed back to usable EM or mechanical energy.
- Thermoelectric and mechanical metamaterials can micro-manage emanated heat and vibrations from devices, such as any kind of motor, to recycle it as energy while effectively cooling it. The same principle can be applied to a smart household or a noisy factory.

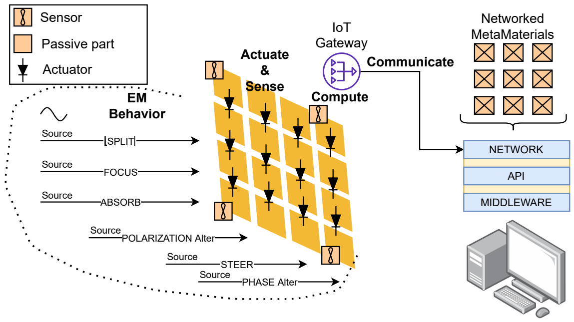


Fig. 1 – Networked metamaterial structure and possible energy wave interactions [8].

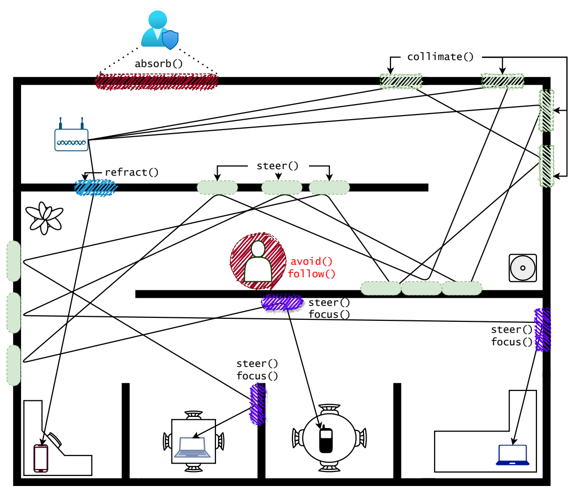


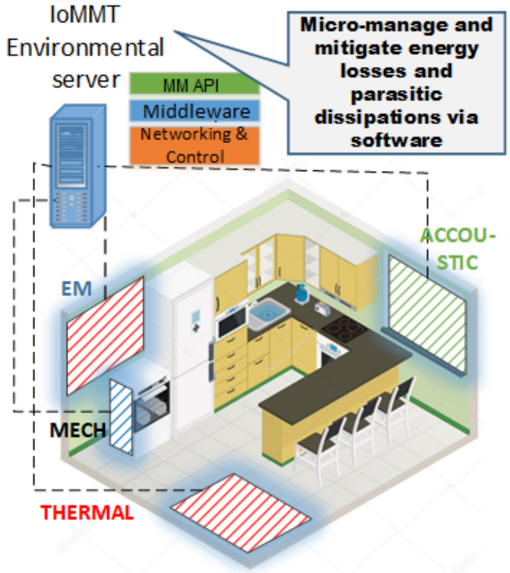
Fig. 2 – The programmable wireless environment introduced in [7], is created by coating walls with networked metamaterials. This allows for customized wireless propagation-as-an-app per communicating device pair, introducing novel potential in data rates, communication quality, security and wireless power transfer.

- The acoustic metamaterials can surround noisy devices or be applied on windows to provide a more silent environment, but to also harvest energy which can be added to a system such as a smart-household.

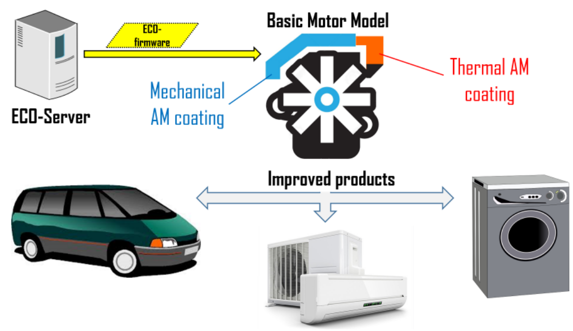
Assuming a central controller to optimize a given IoMMT deployment allows for further potential. For instance, one can allow for quickly "patching" of overlooked physical aspects (e.g., poor ecological performance) of IoMM-enabled products during operation, without overburdening the product design phase with such concerns. 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 this context, the principal contributions of the paper are as follows:

- We propose the concept of the IoMMT and discuss



(a) Conceptual IoMMT deployment within a smart home.



(b) Conceptual IoMMT deployment within single products.

Fig. 3 – Envisioned applications of the IoMMT in smart houses and products.

its architecture and interoperability with existing network infrastructures.

- We define two novel categories of software: the *Metamaterial API* and the *Metamaterial Middleware*, which enable any software developer to interact with a set of networked metamaterials, in a physics-agnostic manner. We establish the data models, workflows, and test bed processes required for profiling and, subsequently, componetizing metamaterials.
- We present an implemented and experimentally verified version of the metamaterial API and the Metamaterial Middleware for the EM case.
- We highlight promising, new applications empowered by the featured IoMMT concept.

In this aspect, the potential of our IoMMT paradigm is the first to offer true control over the energy propagation within a space, in every physical domain, i.e., for any physical material property and corresponding information-carrying wave. For instance, control over the equivalent RLC parameters of an electric load controls the power that can be delivered to it by an EM wave. Moreover, the presented software is a mature prototype platform for the development of IoMMT applications. This constitutes a major leap towards a new research direction. On the other hand, other research directions have proposed and explored the Internet of NanoThings [9]. Although similarly named, these directions are not related to the IoMMT, as they are about embedding nano-sized computers into materials in order to augment the penetration level of applications (e.g., sense structural, temperature, humidity changes within a material, rather than just over it, etc.), and not to control the energy propagation within them.

The remainder of this paper is organized as follows, devoting a section to each of the principal contributions of our work. In Section 2 we provide the related work overview and the necessary prerequisite knowledge for networked metamaterial. In Section 3 we present the architecture for integrating the IoMMT in existing Software-Defined Networks (SDNs) and systems. In Section 4 we present the novel metamaterial API, and Section 5 follows with the description of the Metamaterial Middleware and its assorted workflows. In Section 6 we present the implemented version of the software for the EM metamaterial case, along with a description of the employed evaluation test bed. Finally, novel realistic applications enabled with our new paradigm are discussed in Section 7, and we conclude the paper in Section 8.

2. PREREQUISITES AND RELATED WORK

Metamaterials are simple structures that are created by periodically repeating a basic structure, called a *cell* or a *meta-atom* [3]. Some examples across physical domains are shown in Fig. 4. The planar (2D) assemblies of meta-atoms, known as *metasurfaces*, are of particular interest currently [10, 11]. For instance, EM are currently heavily investigated by the electromagnetic/high-frequency community, for novel communications, sensing and energy applications. [12–14].

A notable trait of metamaterials is that they are simple structures and, therefore, there exists a variety of techniques for generally low-cost and scalable production [3]. The techniques such as printed circuit broads, flexible materials such as Kapton, 3D printing, Large Area Electronics, bio-skins and microfluidics have been successfully employed for manufacturing [3].

In each physical domain, a properly configured metamaterial has the capacity to steer and focus an incoming energy wave towards an arbitrary direction or even completely absorb the impinging power. In the EM case this capability can be exploited for advanced wireless communications [7, 15–19], offering substantially increased

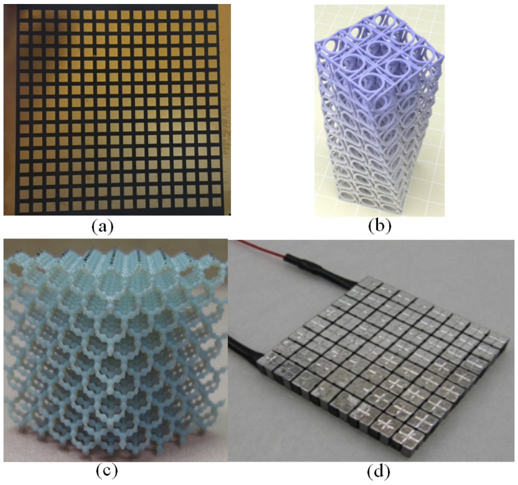


Fig. 4 – Energy manipulation domains of artificial materials: (a) Electromagnetic [20] (b) Mechanical [21] (c) Acoustic [22] (d) Thermoelectric [23].

bandwidth and security between two communicating parties.

The potential stemming from interconnected metamaterials has begun to be studied only recently [8]. The perspective networking architecture and protocols [7,8], metamaterial control latency models [24], and smart environment orchestration issues have been recently studied for the EM case [25,26].

Notably, a similarly named concept, i.e., the Internet of NanoThings [9], was recently proposed to refer to materials with embedded, nano-sized computing and communicating elements. In general, these materials are derived from miniaturizing electronic elements and placing them over or embedding them into fabrics and gadgets, to increase their application-layer capabilities. For instance, this could make a glass window become a giant, self-powered touchpad for another IoT device. Originally. the concept of software-defined metasurfaces wa based on the nano-IoT as the actuation/control enabler [17]. Nano-devices can indeed act as the controllers governing the state of the active cells, offering manufacturing versatility and extreme energy efficiency. Nonetheless, until nano-IoT becomes a mainstream technology, other approaches can be adopted for manufacturing software-defined metasurfaces, as reported in the related physics-oriented literature [6]. It is also noted that nano-IoT as a general concept is about embedding nano-sized computers into materials in order to augment the penetration level of applications (e.g., sense structural, temperature, humidity changes within a material, rather than just over it, etc.), and not specifically to control the energy propagation within them.

In contrast, our work refers specifically to the case of metamaterials and the capabilities they offer for the manipulation of energy across physical domains. Moreover, our paper introduces the software enablers for this direction, which has not been proposed before. Additionally, our paper focuses more on the networking approaches for metamaterials, which has only been treated in our previous work [8], and only for the EM case. Finally, the work of Chen et al. [27] also advocates for the use of metamaterial in any physical domain for distributed energy harvesting, e.g., in a smart house or a city. However, software enablers and networking considerations are not discussed or solved in [27]. Moreover, the energy manipulation type is restricted to harvesting which can be viewed as a subset of our proposed IoMMT potential.

Metamaterials: Principles of Operation, Classification and Supported Functionalities

A conceptual metamaterial is illustrated in Fig. 5 [3]. Basically, a metamaterial consists of periodically repeated meta-atoms arranged in a 3D grid layout, with the metasurfaces being a sub-case. In particular, unit cells comprise passive and tunable parts, required in reconfigurable metamaterials as well as optional integrated sensory circuits, which can extract information of the incident energy wave. Furthermore, tunable parts are crucial for metamaterials, as they enable reconfigurability and switching between different functions. For illustration, in EM metamaterials at microwave frequencies, the tunable parts embedded inside the unit cells can be voltage-controlled resistors (varistors) and/or capacitors (varactors), micro-electromechanical switches (MEMS), to name a few [3,19].

On the other hand, in mechanical and acoustic metamaterials, the tunable parts can be micro-springs with a tunable elasticity rate [28,29]. The meta-atoms may also form larger groups, called *super-atoms* or *supercells*, repeated in specific patterns that can serve more complex functionalities, as discussed later in this paper. Lastly, the software-defined metamaterials include a *gateway* [7], i.e., an on-board computer, whose main tasks are to: i) power the whole device and ii) control (get/set) the state of the embedded tunable elements, iii) interoperate with the embedded sensors, and iv) interconnect with the outside world, using well-known legacy networks and protocol stacks (e.g. Ethernet).

The relative size of a meta-atom compared to the wavelength of the excitation (impinging wave) defines the energy manipulation precision and efficiency of a metamaterial. For example, EM metasurfaces share many common attributes with classic antenna-arrays and reflect-arrays. Antenna arrays can be viewed as independently operating antennas, being very effective for coarse beam steering as a whole. Reflect-arrays typically consist of smaller elements (still subwavelength), permitting more fine-grained beam steering and a very coarse polarization control. Metamaterials comprise orders of magnitude smaller meta-atoms, and may also include tunable elements and sensors. Their meta-atoms are generally considered tiny with regard to the exciting wavelength, hence allowing full control over the form of the departing energy wave.

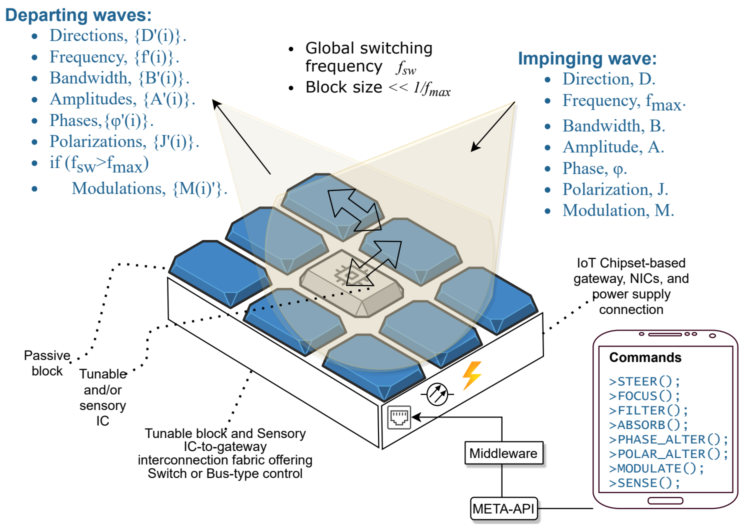


Fig. 5 – Overview of the metasurface/metamaterial structure and operating principles.

Regardless of their geometry and composition, the operating principle of metamaterials remains the same. As depicted in Fig. 5, an impinging wave of any physical nature (e.g., EM, mechanical, acoustic, thermal) excites the surface elements of a metamaterial, initiating a spatial distribution of energy over and within it. We will call this distribution "exciting-source". On the other hand, well-known and cross-domain principles state that any energy wavefront, which we demand to be emitted by the metamaterial as a response to the excitation, can be traced back to a corresponding surface energy distribution denoted as "producing-source" [3, 6]. Therefore, a metamaterial configures its tunable elements to create a circuit that morphs the exciting-source into the producing-source. In this way, a metamaterial with high meta-atom density can perform any kind of energy wave manipulation that respects the energy preservation principle. Arguably, the electromagnetism constitutes a very complex energy type to describe and, as a consequence, manipulate in this manner, as it is described by two dependent vectors (electric and magnetic field) as well as their relative orientation in space, i.e. polarization (mechanical, acoustic and thermal waves can be described by a single scalar field in space). As such, incoming EM waves can be treated in more ways than other energy types. The common types of EM wave manipulation via metamaterials, reported in the literature [3], can designate a set of high-level functionality types as follows:

- Amplitude: Filtering (band-stop, -pass), absorption.
- Polarization: Waveplates (polarization conversion, modulation).
- Wavefront: Steering (reflecting or refracting), splitting, focusing, collimating, beamforming, scattering.
- Bandwidth: Filtering.
- Modulation: Requires embedded actuators that can switch states fast enough to yield the targeted modulation type [30].
- Frequency: Filtering, channel conversion.
- Doppler effect mitigation and non-linear effects [8].

Additionally, sensing impinging waves may be considered one of the above functionalities and, as an outcome, the embedded sensors can extract information of any of the above parameters related to the incident wave.

In this aspect, the role of the contributed metamaterial API is to model these manipulation types into a library of software callbacks with appropriate parameters. Then, for each callback and assorted parameters, the Metamaterial Middleware produces the corresponding states of the embedded tunable elements that indeed yield the required energy manipulation type. In other words, a metamaterial coupled with an API and a Metamaterial Middleware *can be viewed as a hypervisor that can host metamaterial functionalities* upon user request [8].

In the following, we focus on EM metamaterials which, as described, yield the richest API and most complex Metamaterial Middleware. The expansion to other energy domains is discussed via derivation in Section 7.

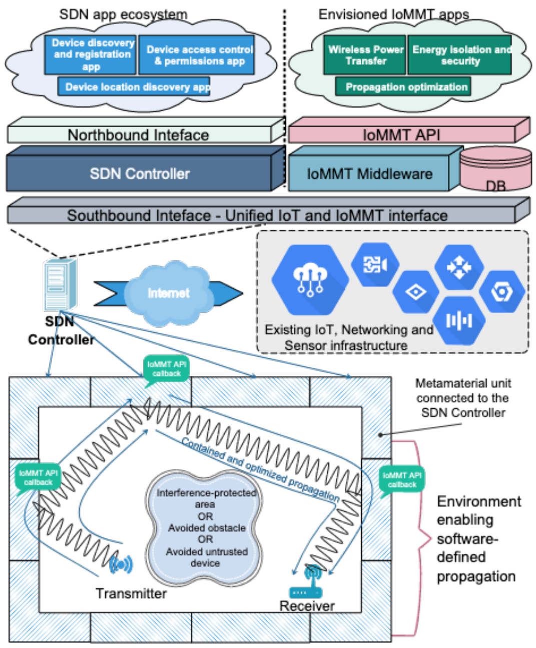


Fig. 6 – SDN schematic display of the system model and the entire workflow abstraction.

3. NETWORKED METAMATERIALS AND SDN WORKFLOWS

Many metamaterials deployed within an environment can be networked through their gateways. This means that they may become centrally monitored and configured via a server/access point in order to serve a particular end objective.

An example is given in Fig. 6, where a set of metamaterials is designed with the proper commands for energy wave steering and focusing, in order to route the energy waves exchanged between two wireless users, thus avoiding obstacles or eavesdroppers. Other applications include wireless power transfer and wireless channel customization for an advanced quality of service (QoS) [7, 13]. Such a space, where energy propagation becomes software defined via metamaterials is called a programmable wireless environment (PWE) [8].

As shown in [7], the PWE architecture is based on the software-defined networking (SDN) principles. The PWE server is implemented within an SDN controller [31]; the southbound interface abstracts the metamaterial hardware, treating metamaterial devices as networking equipment that can route energy waves (e.g. similar to a router, albeit with a more extended and unique parameterization). Thus, the metamaterial API constitutes a part of the northbound SDN interface, atop of which the security, QoS and power transfer concepts can be implemented as SDN controller applications. On the other hand, the Metamaterial Middleware is part of the SDN middleware, translating metamaterial API callbacks into metamaterial hardware directives.

A notable trait of the Metamaterial Middleware is that it is divided into *two parts,* in terms of system deployment [32]:

1. The metamaterial manufacturing stage component, a complex, offline process requiring special metamaterial measurement and evaluation setups (discussed in Section 5), and

2. The metamaterial operation stage component, which operates in real time based on a codebook. This codebook is a database populated once by the manufacturing stage component and contains a comprehensive set of configurations for all metamaterial API callbacks, supported by a given metamaterial.

The operation stage component simply retrieves configurations from the codebook and optionally combines them as needed, using an interleaving process described in Section 5.

Notably, other studies propose the use of online machine learning as a one-shot process, which can be more practical when response time is not a major concern [33]. However, in this work we propose the aforementioned separation in deployment, to ensure the fastest operation possible overall, thus covering even the most demanding cases.

It is noted that SDN is not a choice due to restrictions, but rather a choice due to compatibility. In the software-defined metasurfaces presented in this paper, a key point is the abstraction of physics via an API that allows networking logic to be reused in PWEs, without requiring a deep understanding of physics. SDN has (among other things) already introduced this separation of control logic from the underlying hardware and its administrative peculiarities. Therefore, we propose an integration of PWE within SDN to better convey the logical alignment of the two concepts.

4. APPLICATION PROGRAMMING INTERFACE FOR METAMATERIALS

In the following, we consider a metamaterial in the form of a rectangular *tile.* The term tile is used to refer to a practical metamaterial product unit, which can be used to cover large objects such as walls and ceilings in a floorplan.

A software process can be initiated for any metamaterial tile supporting a unique, one-to-one correspondence between its available switch element configurations and a large number of metamaterial functionalities. The metamaterial tiles in this work incorporate tunable switch elements, which dictate the response of each individual cell, locally. In this way, providing an arrangement of all the tile cells allows the tuning of the "concerted" metamaterial response of the entire tile.

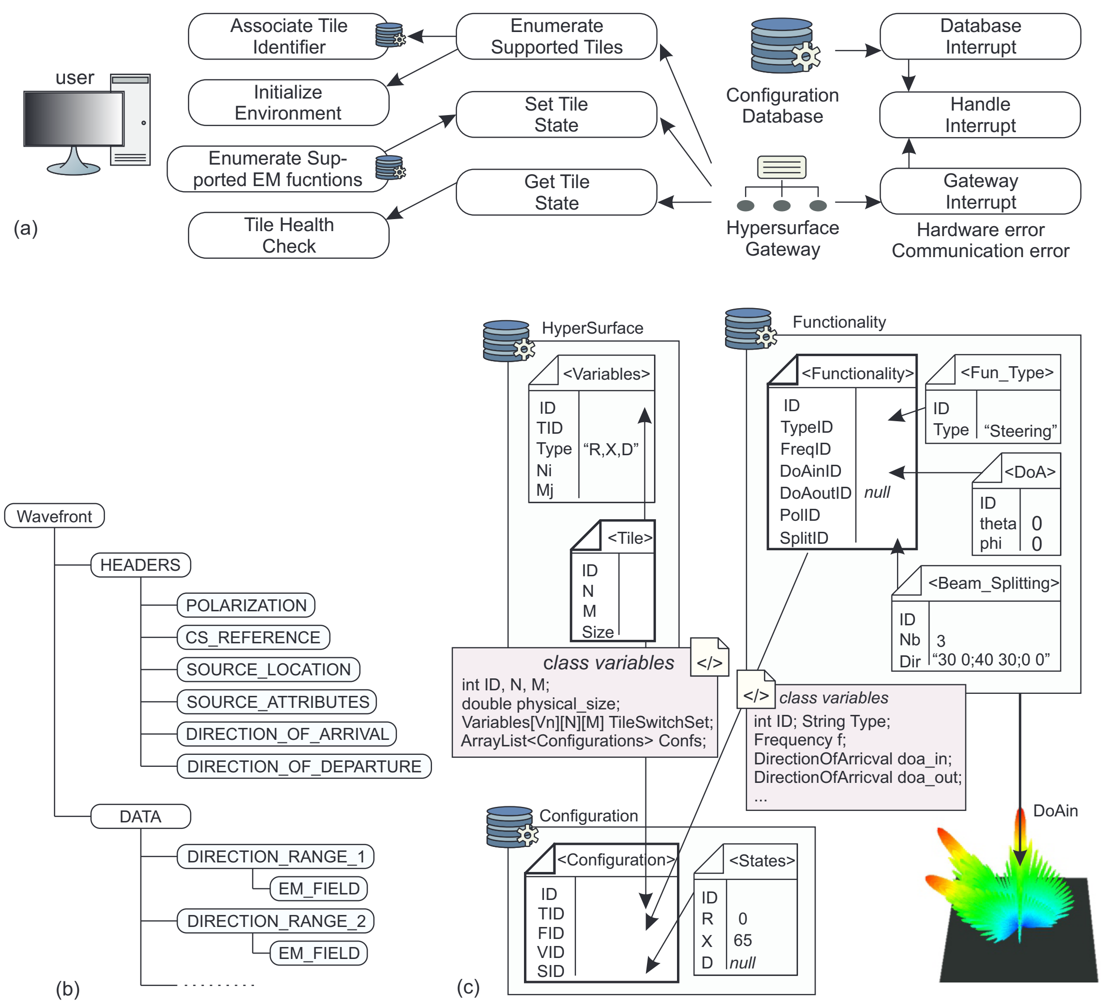


Fig. 7 – (a) Case diagram of the main functions supported by the three basic entities. Tasks highlighted with the database icon indicate that a set of data is to be retrieved from the Configuration Database. (b) Wavefront description in data object format. (c) A simplified overview of the structure of the Configuration Database. The <Tile> table hosts all information regarding a tile's physical implementation. The <Functionality> table combines a set of metamaterial parameters to define new functionalities. Both tables are combined in the <Configuration> table with a set of entries from the <States> table to compose a new configuration that supports the functionality FID on tile TID (VID refers to an entry in the table <Variables>).