

# Next Generation Connected Materials for Intelligent Energy Propagation in Multiphysics Systems

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**Abstract**—Exerting cyber-control over any natural resource and process has seen explosive growth, yielding technological breakthroughs in recent years. This impressive growth has so far stemmed from a horizontal expansion of control across application sectors, such as industrial, business and household tasks automations. This paper proposes the cyber-control vertically across all application sectors, increasing its penetration to the programmable physics level. First the foundations for a novel architecture for software-defined and interconnected Multiphysics-as-an-app (MaaP) is introduced in this paper. MaaP will allow for programmable control over the flow of electromagnetic, mechanical, thermal and acoustic energy, even in ways not common in the nature. MaaP is leveraged by next generation, interconnected and smart artificial materials which are explained and modeled in this paper. A complete MaaP system architecture is introduced, covering the deployment, software and communication aspects across multiple scales. Further, some research challenges posed by MaaP are presented. Moreover, unique applications such as products with real-time software-augmented physical properties are discussed.

**Index Terms**—Networking, Communications, Propagation, Software-defined, Architecture, Multiphysics, Smart artificial materials.

## I. INTRODUCTION

THE extension of automated control to every aspect of modern life has led to the Internet of Things (IoT) and will, eventually, give form to the Internet of Every-Thing [1]. The resulting huge potential has so far stemmed from cyber-networking expansion across an extremely wide set of application sectors, albeit at a moderate depth. The present work contributes the concept of Multiphysics-as-an-app (MaaP) as an extender of cyber-control from these top-level concerns down to the level of software-defined mechanical, thermal, acoustic (AC) and electromagnetic (EM) energy propagation manipulation.

Multiphysics is defined as the coupled processes or systems involving more than one simultaneously occurring physical field, i.e., thermal, EM, AC and mechanical interactions [2]. As such, in the present study the term multiphysics will denote the joint propagation of energy in any form, and in any real-world system. Common multiphysics systems comprise energy sources and sinks and steady-state objects, i.e., whose material

properties remain constant or cannot change in a controllable manner. In such cases, control over the energy propagation phenomenon can only be exerted by the sources. MaaP introduces a paradigm shift towards transforming all objects in the system space into energy flow control points, resulting into end-to-end, software-defined multiphysics energy propagation phenomenon as a whole.

The methodology of MaaP is based on Artificial Materials (AMs), which are a relatively recent and ground-breaking direction in Physics. AMs are simple structures that offer engineered and tunable physical properties such as EM, AC, mechanical and thermal [3]. MaaP combines AMs with a complete communication platform for conveying control signals, and a programming interface for end-objective-based interaction with AMs, while abstracting the complexities of the underlying physics.

We envision MaaP as a general system orchestrating AMs deployed within multiple scales such as device parts, devices, households and cities: For example, EM interference and unwanted emissions can be harvested by AM-coated walls and be transformed back to usable EM or mechanical energy. Thermoelectric AMs can micro-manage emanated heat and vibrations from motors to recycle it as energy while effectively cooling it. AC AMs can surround noisy devices or be applied on windows to provide a more silent environment, and also to harvest energy which can be added to a system such as a smart-household. MaaP can continuously “patch” the multiphysics behavior of an environment by distributing “eco-firmware” to a single product or horizontal sets of products incorporating AMs.








The present work contributes: i) The MaaP concept and an exploration of its impact potential. ii) A novel model for describing and arbitrarily chaining together existing AMs for joint energy manipulation, paving the way for next-generation of AMs (X-AMs). iii) The control, inter-networking and software architecture for interconnecting and orchestrating AMs within MaaP. iv) The novel potential and challenges introduced by MaaP.

## II. BACKGROUND: ARTIFICIAL MATERIALS BASED ON RESONANT STRUCTURES

AMs are based on the fundamental idea stating that the physical properties of matter stem from its atomic structure [3]. In principle, one can create artificially structured materials

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TABLE I  
INDICATIVE AMS, CLASSIFIED PER TYPE OF BASIC STRUCTURE.

Cell Type	Domain	Example	Supported Functions $f$				
			Steer	Absorb	Phase	Polariz.	Sense
Resonant structure	EM [4]		✓	✓	✓	✓	✓
	Mech. [5]		✓	✓	✓		✓
	Ac. [6]		✓	✓	✓		✓
	Thermal [7]		✓	✓			✓
			Split			Merge	
Nonreciprocal structure	EM [8]			✓			✓
	Mech. [8]			✓			✓
	Ac. [8]			✓			✓

(comprising sufficiently small elementary *resonating* units of composition and geometry called *cells*) to yield any required energy manipulating behavior including types not found in natural materials [4]. Indicative forms are shown in Table I (top).

EM AMs (also known as metamaterials and metasurfaces) were the first kind to be studied in depth, mainly due to the relative ease of manufacturing as low-complexity printed circuits [4]. Impinging waves create inductive currents within the material, which can be routed by tuning the active elements within it. Notice that the principle of Huygens states that any EM wavefront can be traced back to an EM current distribution over a surface. Thus, in principle, AMs can produce any custom EM function as a response to an impinging wave [4]. The same general principle is followed in other AM types as follows.

The AC AMs can manipulate and re-engineer sound waves in gases, solids and liquids [5]. This control is exerted mainly through the bulk modulus, mass density and chirality. The latter two properties correspond to the EM permittivity and permeability in EM AMs. Related to this are the mechanics of wave propagation in a lattice structure. Additionally, 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 [5].

The mechanical AMs can be seen as a superset of AC AMs [6]. 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 on mechanical waves. The exerted control over vibrations can be customized as required by the application scenario.

The thermal AMs essentially pose structures that restrict the solutions to the heat-conduction equations, thereby attaining controllable heat dissipation and ‘routing’. In specific conditions, it has been shown that parts of AMs in this class can completely avoid thermal energy even under direct heating, essentially attaining thermal cloaking [7].

### III. THE PROPOSED MAAP ARCHITECTURE

The proposed MaaP architecture encompasses: i) AMs based on resonant structures, discussed in Section II. ii) Next generation AMs—denoted as X-AMs—proposed in this paper. iii) A communication and control software platform to orchestrate AMs and X-AMs deployments.

#### A. X-AMs: Next Generation Artificial Material Composites based on Nonreciprocal Structures

The AM types reported so far sought to manipulate an energy wave of a given physical domain, by applying a function over an impinging wave. Thus, for the remainder of this work we denote such AMs as the physical *domain processors*. Domain processors by themselves are immediately reactive: an impinging wave directly and immediately creates a response from the same processor, subject to the chosen cell states. We proceed with a special type of AM which has the potential to route the waves from one domain processor to another, allowing for chaining together the domain processors to obtain composite energy manipulation types.

A common building block across all energy manipulation domains (EM, AC, mechanical) is the concept of non-reciprocal unit/hub, which can be viewed as a special type of an AM cell [8]. A non-reciprocal unit comprises ports through which energy can enter and exit in a hub structure in an asymmetric manner. Indicative implementations are shown in Table. I (bottom) and their operating principle is shown in Fig. 1. In general, an energy wave entering from a port can exit to another port that is selected programmatically. This is accomplished by creating a stationary point in front of undesirable exit ports, with the aid of a separate wave circulating within the device with a tunable phase  $\Delta\phi$ . In the AC regime, the circulating wave is a flow of air, causing a phase shift in the traveling wave. In the mechanical regime, this is accomplished by materials with a carefully designed asymmetric geometry. In the EM regime, the same effect is accomplished via L-C resonators [8]. Notice that a wave following the reverse flow will exit from a port different than the original entry port, thus breaking symmetry and yielding non-reciprocity.

AMs comprising arrays of reciprocity-breaking cells have been shown to operate as tunable topological insulators across energy domains, i.e., materials that can be dynamically tuned

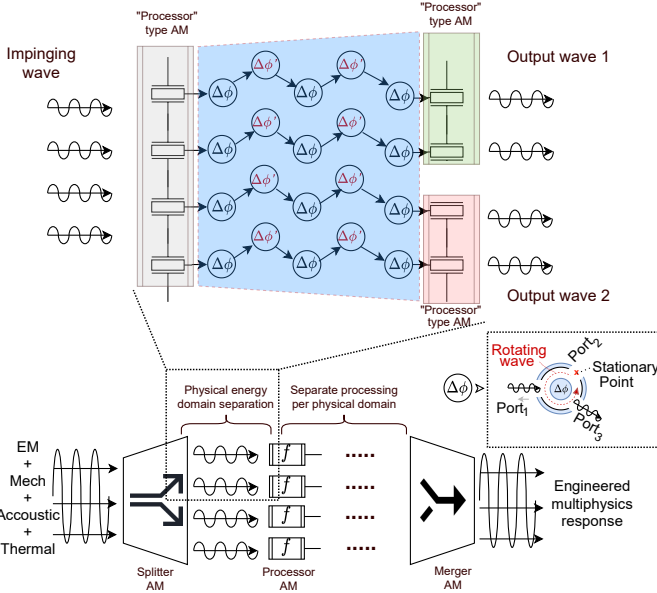


Fig. 1. Progressive breakdown of the structure of X-AMs, encompassing the use of energy flow splitter/mergers (AMs comprising nonreciprocal cells) as energy routers between stacks of energy flow processors (AMs comprising plain resonant cells).

to route energy flows over their surface while insulating their internal parts [8]. Extending this principle, a combination of resonators and nonreciprocal cells could be used to route energy within an AM, as shown in Fig. 1 (middle). Ideally, this could enable the separation of multiphysics flows per domain: an energy wave can be separated to its physical domain components, each of which can be routed and processed as required. We denote such AMs as *physical domain splitter/mergers*.

With the introduction of the splitter/mergers, we can model complex combinations with AM processors, creating the X-AMs. As shown in Fig. 1(bottom), X-AMs can comprise stacks of processors and splitter/mergers of any physical domain. For instance, a first layer of processor AM can absorb an impinging multiphysics energy wave. Subsequent stacks of domain-specific splitter AMs can separate the impinging wave per domain. Additional stacks of domain-specific processor AMs can manipulate the separated energy flows, and a final stack-up of merger AMs can combine the processed flows into an engineered multiphysics response, which is the final output of the X-AM.

X-AMs inherit the interconnectivity paradigm of the recently developed Software-Defined Metamaterials (SDMs) and include an *IoT gateway* [9], [10], i.e., an on-board computer, whose main tasks are to control (get/set) the state of the tunable blocks embedded in the domain splitter/mergers comprising the X-AM, inter-operate with embedded sensors to detect incoming waves, and interconnect with the outside world. The workflow is illustrated in Fig. 2 for the EM domain. Different physical domains support different end-functionalities, as previously shown in Table I, but the gateway logic remains the same. Any external device can interact with an X-AM by implementing a software programming interface (META-API) and a middleware service, in a user-friendly

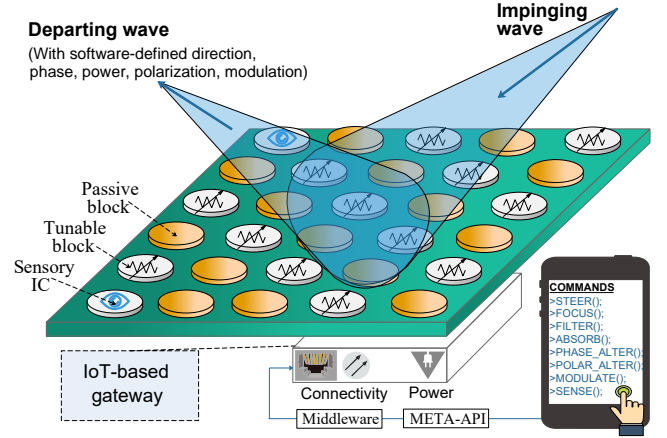


Fig. 2. Block-based illustration of the interconnectivity model for AMs and X-AMs. Control over EM domain is used as example.

manner that abstracts the underlying physics [9]. The API allows to establish the X-AM state and sets its function while abstracting the underlying physics.

We proceed to present the MaaP communication and control platform, in charge of orchestrating vast deployments of X-AM-enabled products and systems.

### B. The MaaP Communication and Control Platform

The MaaP communication and control platform comprises three horizontal application scales, and three vertical separation of concerns, as shown in Fig. 3.

The horizontal application scales are: i) the *product component scale* which is the core of the MaaP system. It comprises X-AMs embedded within product components, thereby constituting their physical operation tunable overall. ii) The *local system scale*, which refers to deployments of two or more X-AM units within a space, with each X-AM gateway being connected to a *local hub* for control/data exchange between the X-AMs and the external world. The hub itself is a MaaP-aware IoT hub. The deployment space can, e.g., be a floorplan or car where multiple X-AMs need to co-operate to optimize multiphysics for a given objective of this scale. iii) The *wide area* (WA) MaaP application scale, which refers to the horizontal multiphysics orchestration of two or more local scale systems, up to a smart city level. One or more WA servers provide interconnectivity among the local hubs at the local scale of the hierarchy.

The vertical concerns cover the aspects of secure control, inter-networking, and the MaaP Cloud services and middleware:

1) *Secure Control and Inter-networking*: MaaP proposes a general control infrastructure, which offers secure and assured control over massive IoT deployments. The infrastructure is built upon techniques and methodologies to enable assured and accountable control, employing sophisticated multi-party analytics.

Its functionality is organized into three levels which correspond to the MaaP application scales, as shown in Fig. 3.

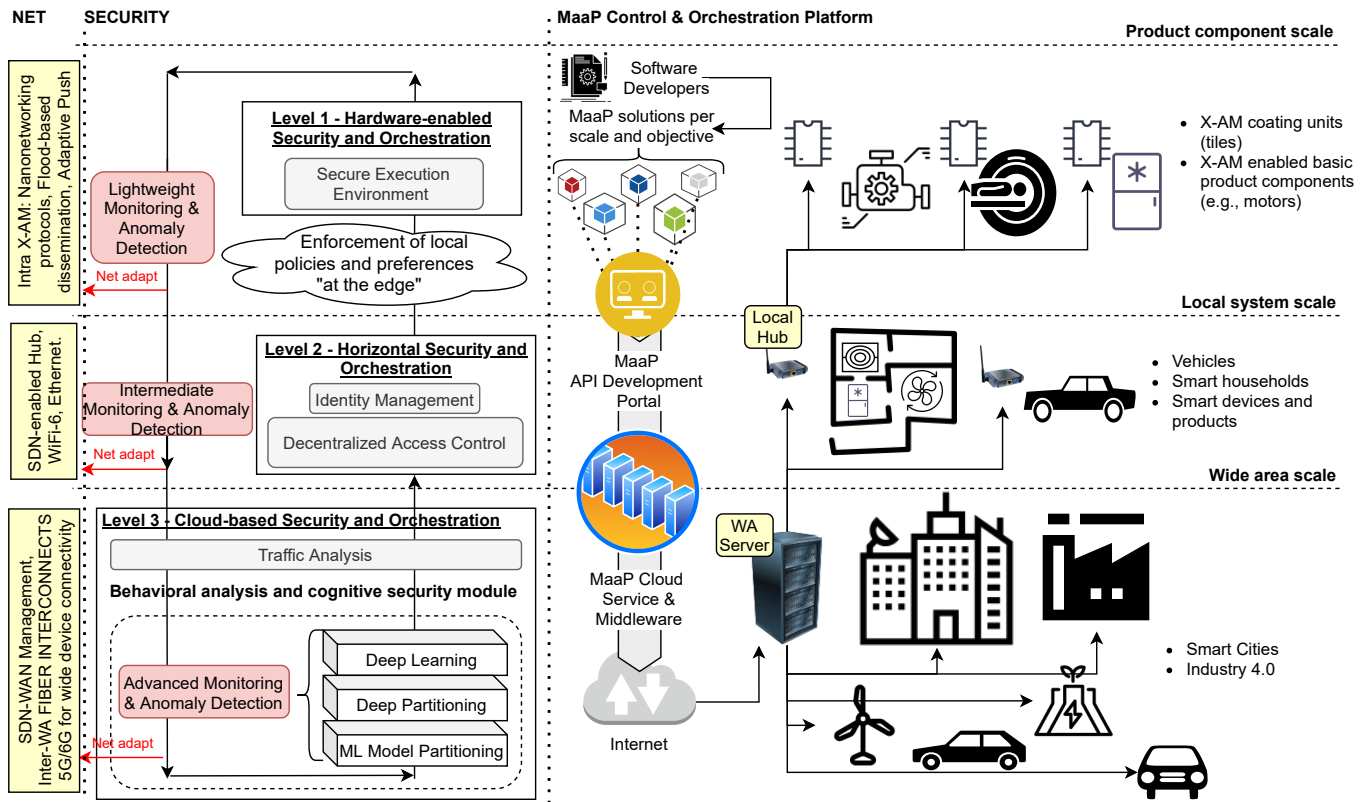


Fig. 3. Overview of the Multiphysics-as-an-App control and communication platform (left); envisioned applications and research objectives per scale (right).

Level 1 secures and controls edge nodes, e.g., X-AM product components, Level 2 operates at the local hub scale, while Level 3 refers to the WA scale while also coordinating Levels 1 and 2. All three levels operate on the principle of differential security, comparing running machine learning (ML) outcomes on traffic and component behavior data to: i) operational policies set, or ii) calibration data, i.e., ML data derived during X-AM controlled MaaP system operation in a training-at-the-edge fashion. It is noted that the detection system uniformly encompasses both malfunctions of any scale, as well as security incidents and malevolent attacks.

At Level 1, the X-AM gateways assume the role of lightweight anomaly detection based on their local running behavior only. The anomaly detection refers to the patterns (frequency and consistency) of external commands arriving to the X-AMs from a hub, as well as the status of the X-AM-internal set of embedded tunable blocks. A secure execution environment enforces access rights at this level. The partitioned ML model to accomplish this task is provided by Level 3. In case of a detection event, the X-AM gateway can perform reactive countermeasures (e.g., activate another X-AM gateway for load balancing, or filter incoming commands). In any event, the event data are hierarchically sent to Levels 2 and 3 for further processing.

Level 2 hubs assume the additional role of performing decentralized identity management and access control to X-AM products. A blockchain deployment in conjunction with smart contracts distributed via Level 3 are employed to ensure the timely deployment of X-AM product operation modes,

protect against tampering, and activate failover strategies automatically to ensure a minimum level of combined X-AM performance in the deployed space. Moreover, this level binds energy waves to corresponding identities (i.e., to the user devices or products that emit them). This is accomplished via sensory equipment that track the wave propagation paths and correlates them to user device locations. Following this identity management, decentralized access control ensures that each user accesses X-AMs per the local policies and preferences. In the simplest case, an X-AM will serve wave emissions from the device of a user that owns the X-AM, and ignore them in any other case.

Level 3 inherits the tasks of the previous levels, and also acts as a central point of traffic analysis and ML model training update and distribution. The inherent complexity of monitoring and grooming multiphysics energy flows in real-time necessitates the use of ML automation, instead of analytical or semi-analytical models. Thus, Level 3 aggregates flow monitoring data in all scales and X-AM deployment circumstances, continuously training ML models. In this manner, Level 3 can deploy anomaly countermeasures beyond the reactive ones executed at Levels 1 and 2, in order to mitigate: i) large scale attacks, and ii) large scale system failures at the WA level, by performing network-level adaptations for traffic engineering and firewall rule updates.

We proceed to discuss the control and networking approaches per Level. At Level 1, the primary task of a component gateway is to set the state of all tunable blocks. The gateway needs high reachability and low-latency in the

downstream direction, i.e., sending state control data to the AM cells. Broadcast and diffusion-based networking from the discipline of nano/IoT are selected for this task [11].

At the local area scale, the hub needs to control multiple component gateways in a robust manner, and support versatile networking, monitoring and anomaly detection tasks described above. WiFi 6 is chosen as the connectivity protocol standard, to support a high number of X-AM products within a space with high-bandwidth and low latency. Finally, multiple hub deployments are network-orchestrated following the Software Defined Networking (SDN) paradigm.

At the WA level, multiple WA servers are needed to cover a smart city, either for fail-over or spatial coverage under latency minimization requirements. WAs are ideally interconnected in a mesh using high-bandwidth, low-latency optical fibers. For the downstream connectivity, fiber to the home can serve the communication objectives, while 5G can ensure reachability for vehicles and moving X-AM systems.

2) *The MaaP Cloud Service and Middleware:* The MaaP Cloud service is the central portal that allows: i) AM manufacturers to register a new AM or product incorporating AMs for use in the MaaP architecture, and ii) MaaP developers to propose and distribute new solutions, i.e., MaaP algorithms for configuring local and WA MaaP deployments in order to meet one or more energy flow objectives.

The registration of an AM product comprises:

- Its structural characteristics and material composition, in order to enable its integration to larger systems.
- The listing of all supported energy flow manipulation functions, their allowed parameter sets and the function efficiency for each combination of parameter values. As an AC regime example, an X-AM could list that it supports sound wave steering and absorption. For the steering case, it should specify the wavefront types supported (e.g., planar, spherical, etc.), the direction or arrival-direction of departure pairs supported, as well the steering efficiency for each.
- A complete set of lookup tables matching every functionality listed above to the corresponding AM cell states that yield it. It is worth noting that state interpolation can be employed to obtain functionalities not explicitly listed in the lookup tables [9], [12].
- A full profile describing the flow manipulation effects when the X-AM receives unintended input. For instance, in the EM regime consider an AM tuned for planar wave absorption for a given direction of arrival. The profile would describe how the same X-AM and under the same configuration would affect an impinging EM wave incoming from any different direction of arrival.

Such processes have already been defined and experimentally validated for the EM domain [9]. The methodology for completing the aforementioned steps relies on multiphysics simulations [13], whose efficiency has been boosted by recent advances in parallel computing hardware and data processing techniques.

#### IV. EVALUATION

The goal of the evaluation is to provide comparative signal-to-interference (S/I) gains, expected from employing AMs

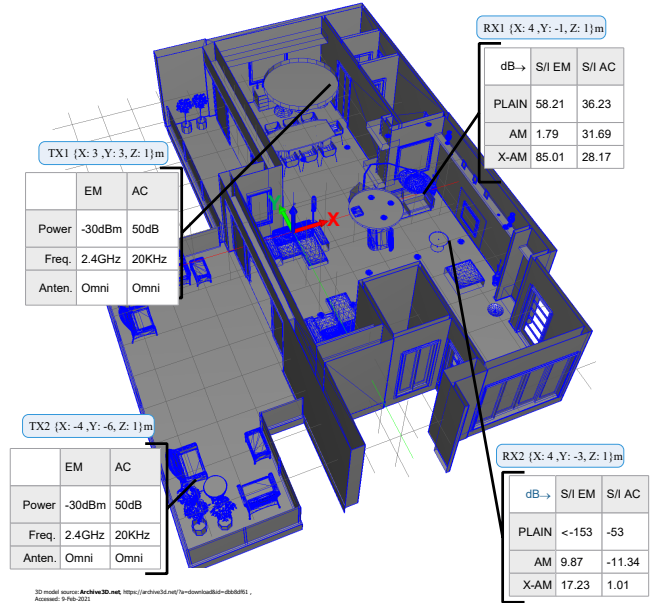


Fig. 4. Evaluation setup and results for the electromagnetic (EM) and acoustic (AC) domains, in the plain, AM, and X-AM environment cases.

versus X-AMs in an indoors setting shown in Fig. 4. (The link to the 3D model file is given at the bottom of the Figure). All planar surfaces (walls, ceiling, floor) are segmented into  $1 \times 1$  m square tiles. All tiles can be either AMs or X-AMs altogether. Two pair of users,  $\{TX1 \rightarrow RX1\}$  and  $\{TX2 \rightarrow RX2\}$ , seek to communicate via EM and AC messages independently. The transmission power, TX and RX positions, single frequencies and antenna characteristics are shown in Fig. 4. The  $\{TX1 \rightarrow RX2\}$  and  $\{TX2 \rightarrow RX1\}$  directions are considered as interference.  $S$  denotes the received power of useful signals and  $I$  the power of interference plus noise. We seek to optimize the performance metrics  $\max \min \left\{ (S/I)_{RX1}^{EM}, (S/I)_{RX2}^{EM} \right\}$  and  $\max \min \left\{ (S/I)_{RX1}^{AC}, (S/I)_{RX2}^{AC} \right\}$  for the EM and AC domains respectively, and in the presence of 3 dB noise for both domains. The AC environmental properties are 101, 325 Pa atmospheric pressure, 50% relative humidity and 20°C temperature [14]. The furniture is considered to be transparent in both physical domains.

In the case where all tiles are AMs, we consider a checkerboard differentiation per tile, resulting into 50% EM AM and 50% AC AM tiles in total within the environment. Notably, an AC AM behaves as a plain material from EM aspect and vice-versa. In case where all tiles are X-AMs, the same tile can interact with EM and AM waves independently and at the same time.

From the tile functionality optimization aspect, for the EM case we employ the PWE simulation software presented in [12], coupled with the accompanying `KpConfig` handling the EM optimization metric. Each EM AM tile can freely focus, redirect, re-polarize, partially absorb and/or modify the phase of impinging waves. For the AC case, I-SIMPA is the employed AC simulation engine [14]. In order to handle the AC optimization metric we employ the genetic algorithm presented in [10], but modified as follows. Each

AC AM tile has a tunable reflection coefficient expressed by a variable surface normal vector (i.e., with tunable azimuth and elevation), and an absorption coefficient which can be either 0% or 100%. This triplet of values per tile is a gene, and a collection of genes for all tiles is treated as a genome (i.e., a complete candidate solution to the optimization problem).

The results are shown in Fig. 4. In a plain environment, RX2 is generally unreachable from the intended TX2. Especially in the EM aspect, the non line of sight leads to almost total disconnection ( $\approx -150 \text{ dB S/I}$ ). In the AC domain, the S/I drop is large, but less so, owed to the low frequency of the studied AC signals ( $\approx -53 \text{ dB S/I}$ ). Moreover, RX2 naturally receives strong interference from TX1 due to their respective positions, in both the EM and AC cases.

We proceed to study the AM-coated environment case. Notably, the TX2→RX2 connectivity is restored in the EM domain ( $\approx 10 \text{ dB S/I}$ ), while the AC performance is improved significantly (i.e. by  $\approx +42 \text{ dB}$ , reaching  $\approx -11 \text{ dB S/I}$ ). Notice that the TX1→RX1 S/I decreases at the same time, due to the close proximity of RX1 to RX2. Note that in the AM-case, half of the tiles are strictly AC AMs, and half of them are strictly EM tiles. This means that the AM deployment can be considered as partial for each physical domain. This generally results into improved performance (over the non-AM case), albeit with limited spatial granularity, reducing the interference mitigation capabilities.

Finally, we study the performance under X-AM deployment in the same space. This case corresponds to the maximal wave control granularity, since an X-AM tile can control both AC and EM waves independently and simultaneously. X-AMs yield the best S/I results under both domains. The TX2→RX2 connectivity is optimized, with both domains yielding positive S/I. Regarding RX1, a minor drop is noted in the AC S/I only, compared to the plain case. This is attributed to the X-AM tiles resorting to impinging wave absorption in the vicinity of TX1, in order to limit the interference to RX2. This unavoidably incurs a small drop on the RX1 received AC power, in order to optimize the chosen EM and AC performance metrics as a whole.

## V. ENVISIONED APPLICATIONS AND RESEARCH OBJECTIVES

An overview of MaaP-enabled applications and open research objectives across deployment scale levels is given in Fig. 5, showing examples of product component scale applications. Motors with X-AM coatings can become able to absorb or energy-harvest induced mechanical vibrations and noise. The internal parts of imaging devices (e.g., magnetic resonance imaging devices) can receive X-AM coating to augment the imaging precision and overcome possible design shortcomings. Home appliances can selectively harvest thermal waves and convert them to usable energy, or revert to normal operation depending on the ambient temperature and the end-objective.

Moving to the local system scale, in the indoors case multiple X-AM-enabled products ranging from smart wall insulation X-AMs, home appliances and air-conditioning units

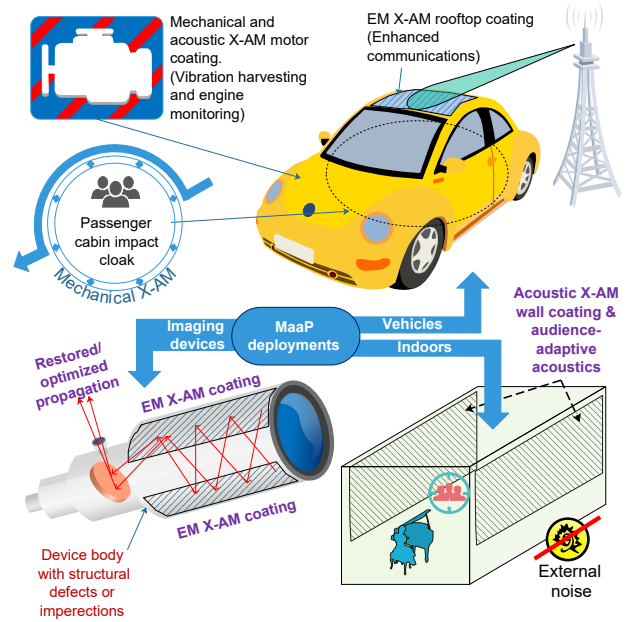


Fig. 5. MaaP deployment examples in various scales, such as within vehicles, building indoors and within imaging devices.

can be orchestrated to optimize key-performance indices such as extreme power efficiency, long-range multiphysics power transfer (heat, AC, EM), even at places far off from line-of-sight from the energy sources.

Exemplary objectives of the WA scale can include: Ecologic cloak, referring to the nullification of the resource footprint of the WA as a whole; Seismic cloak can ensure that seismic waves bypass the WA, minimizing or nullifying structural damages to buildings; Noise cloaking can ensure that the environment surrounding the WA receives little to null noise pollution from its controllable activities; Entropy-reduction expresses the cross-cutting concern of routing all parasitic and unintended energy flows within the WA towards corresponding energy harvesting devices, thereby maximizing their output; Finally, the manipulation of multiphysics energy flows via MaaP can be scheduled in tandem with the energy production at power plants, to ensure minimal path losses and waste.

## VI. CONCLUSION

This paper proposed the Multiphysics-as-an-app (MaaP) concept. Leveraging recent advances in artificial material design and manufacturing, MaaP is envisioned to enable the software-defined control over the propagation of energy waves in the electromagnetic, mechanical, acoustic and thermal domains. The study introduced and specified a next generation of smart artificial materials as the MaaP enablers, which acts a general framework for arbitrarily combining existing artificial materials and yielding complex energy processing workflows. Moreover, a hierarchical MaaP architecture was defined, outlining the necessary software services and communication approaches for this task. Multiple MaaP deployment scales were outlined, along with corresponding performance objectives and promising envisioned applications.

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