

Design and Development of Software Defined Metamaterials for Nanonetworks

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Abstract

This paper introduces a class of programmable metamaterials, whose electromagnetic properties can be controlled via software. These software defined metamaterials (SDMs) stem from utilizing metamaterials in combination with nanonetworks. Metamaterials are artificial structures with properties that may not be found in nature. Since their initial advent, they have inspired ground-breaking applications to a range of research topics, such as electromagnetic invisibility of objects (cloaking), radiation absorption, filtering of light and sound as well as efficient antennas for sensors and implantable communication devices in recent years. However, existing metamaterial structures are “rigid”, i.e. they cannot be restructured once constructed. This trait limits their fabrication to some well-equipped laboratories worldwide, slows down innovation, and, most importantly, restricts their applicability to static structures only.

The proposed SDMs act as “plastic”

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(reconfigurable) metamaterials, whose attributes can be changed programmatically via a computer interface. This control is achieved by a network of nanomachines, incorporated into the structure of the metamaterial. The nanomachines may receive commands from the user and perform simple, yet geometrically-altering, actions on the metamaterial profile and tuning of its electromagnetic behavior. Architectural aspects, expected features and implementation issues are covered in this paper, while a suitable nanonetworking model is presented along with simulation results on its anticipated performance. The paper concludes by outlining the research challenges pertaining to the analysis, design, prototyping, manufacturing, and initial application scenarios of the proposed SDMs.

I. Introduction

Recently, the field of material science has shifted its focus from studying the properties of new materials to the engineering of the materials. In the realm of electromagnetism, the field of metamaterials (MMs) [1]–[3] has reached significant breakthroughs in correlating the micro- or nano-structure of artificial media to their final properties [4]–[15]. MMs exhibit physical properties not encountered in nature, such as negative refraction index, allowing for electromagnetic cloaking of objects, reflection cancellation from a given surface and electromagnetic energy concentration in as-tight-as-possible spaces [16]–[21]. However, currently the parameters of an MM cannot be altered programmatically, once they are manufactured. Thus, each specific application scenario requires a custom MM design and a manufacturing process, with little-to-no reusability. It is the aim of this paper to address this problem by proposing a new class of real-time reconfigurable MMs, collectively named software defined metamaterials (SDMs). SDMs are the upshot of combining classic MMs with small-scale networked electronic controllers, forming nanonetworks.

The properties of a conventional MM emanate from its structure, which comprises a pattern of a conductive medium, repeated over a 2D surface

(or within a 3D volume). An example is given in Fig. 1 (lower part), where the dimensions of the rectangular split-ring resonators (SRRs) define the refraction angle of an electromagnetic wave impinging on the 2D surface. To understand the impact of this potential, we mention that a carefully designed stack of MMs, each with its own refraction angle, was able to render an object invisible to electromagnetic waves (cloaking) by gradually bending them around it [22]–[25]. The proposed approach allows a dynamic, programmatically controlled formation of custom patterns over an SDM. A network of miniaturized CMOS controllers stitches together patterns by altering the states of a set of switches from conductive to open-circuit mode. These actuations are sent from a standard PC and tunneled inside the SDM through its interface. The scale of the controllers and switches define the granularity of the formable MM patterns.

In this context, SDMs can act as dynamic MMs, incorporating their application pool. Moreover, SDMs offer a set of unique technological capabilities on their own. Particularly, SDMs permit interactivity and interconnectivity. Since SDMs can exchange information with their external environment, they can also sense external effects and adapt their internal patterns according to their goal. For instance, an SDM can function as an adaptive electromagnetic absorber, which may calibrate its absorption pattern to match optimally the time-variant angle of an impinging wave. To this end, SDMs can, also, interconnect with external sensing equipment, forming active components of smart control loops, as shown in Fig. 1.

Consequently, SDMs can be regarded as a timely complement to the software defined networking and radio paradigms, which have revolutionized their respective fields by decoupling system control from the underlying physical equipment [26]–[28]. Both fields have been identified among the future and emerging technologies of IT and communications, in recognition of their potential to reduce the capital

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and operational expenses of a system, while enabling hardware-decoupled innovation. The usual paradigm of software defined systems develops from components (e.g. adaptive antennas) to systems, like software defined radios [29]. In this paper, we propose to follow the opposite direction, i.e. make the very fabric of MMs software defined, reconfigurable, and adaptive. Up to date, the programmability referred to medium access, network, and application layers as well as protocols. The featured SDMs offer programmatic control over their electromagnetic behavior, paving the way not just for reconfigurable physical layers, but for a robust innovation platform aiming at the efficient realization of systems and networking applications.

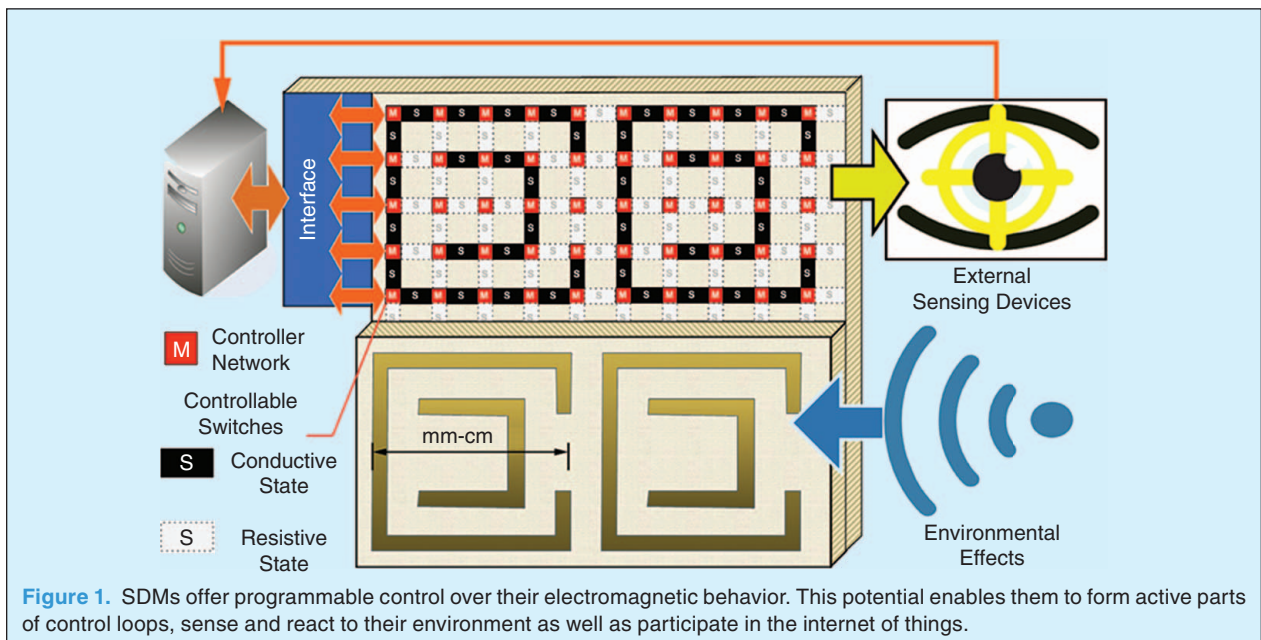
Concerning their uses, SDMs can function as highly controllable media, extending their application pool to encompass adaptivity and reusability. For example, object cloaking could be achieved with a universal SDM coating and be programmatically switchable, partial or spectrum-selective. They could be, also, employed for radars with no moving parts and, thus, for faster alignment. More importantly, SDMs can become a novel research area and serve as a proof-of-principle of: (a) The extension of the internet to the level of materials and their

properties, allowing for remote configuration and control over the electromagnetic behavior of matter. Automation follows, enabling e.g. environment-adaptive cloaking. (b) Cost-effective, accessible and reusable MMs, which by themselves constitute a promising research area.

To the best of our knowledge, the interdisciplinary merge of computer networking and MMs is new and unique. Thus, in Section II we provide the necessary background on these two disciplines and present the SDM architecture in Section III. Actually, the SDM is decomposed to an *active, networked* control layer and a *passive* substrate, which are then studied separately. Subsequently, a simple network model for SDMs is given in Section IV, while key challenges for future SDM research and proposed solutions are discussed in Section V. Finally, the paper concludes in Section VI with some interesting deductions and future perspectives.

II. Background and Related Work

We initiate our analysis via a brief insight into: (a) the operational principles of traditional MMs and (b) the nanonetworks. Generally, MMs are composed of periodically placed building blocks. In most of the cases, these blocks comprise metallic elements on a silicon substrate,



as shown in Fig. 2 (left). The achievable MM property depends on the geometry of these building blocks, e.g. the ring diameters and gap sizes in Fig. 2 (top-left). In essence, one forms repeated patterns on a substrate surface and the result as a whole yields the required electromagnetic behavior (see Fig. 2 (right)). According to Snell's law, any material refracts an electromagnetic wave, altering its angle from θ to θ' . However, no natural medium has ever been observed to yield negative refraction angles. An SRR-based MM can offer any angle, either negative or positive, as a function of its building block geometry. This property has been exploited to construct electromagnetic invisibility cloaks, by carefully stacking MMs with different refraction angles [22]–[25]. A beam is bent around an object, as if it never interacted with it.

Furthermore, the adjustable refraction angle is not the only property that can be attained by MMs. Different building blocks lead to different physical properties, such as high electromagnetic absorbance, near zero permittivity and permeability, peculiar anisotropic response leading, e.g. to hyperbolic dispersion relation, giant chirality, negative phase and energy velocity, negative Doppler effect, etc. These traits can be beneficially utilized in a variety of applications, like wide-band communications, highly efficient energy harvesting photovoltaics, and thermophotovoltaics, ultra-high resolution medical imaging, sensing, and military applications [16]–[21].

Nonetheless, a critical limitation of MMs is their rigidity. Their properties stem directly from the geometry of their building blocks which, obviously cannot be altered after their construction. As a result, classic MMs do not allow for point-to-point or programmatic control, automation and formal programming [30]. For example, changing the radius of the cylindrical object in Fig. 2 or the frequency of the incident wave, requires the design of a completely new MM coating. Presently, the related research acknowledges the need to attain tunable, switchable, nonlinear and sensing functionalities at the MM level [11], [19], [31]. However, till now, no concrete proposals for programmatic control or equivalent have been reported. Actually, there are many techniques to tune regular MMs, such as changing the properties of the substrates, modifying the lattice of the medium, and altering the geometry of the unit elements (e.g. when their temperature rises). Equivalent solutions may be pursued through the incorporation of phase-change media, graphene, carbon nanotubes, and liquid crystals [14], [32]. There is, also, an effort to design MMs with optically switchable parts; merging the phase-change technology of semiconductors with MMs leads to high-contrast, near-infrared, optical switching, albeit at an increased manufacturing cost, considering that precise

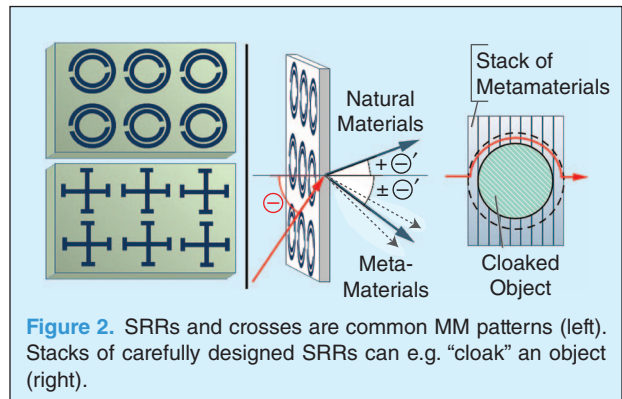


Figure 2. SRRs and crosses are common MM patterns (left). Stacks of carefully designed SRRs can e.g. “cloak” an object (right).

fabrication at the nano scale is required throughout the structure [33]. Furthermore, MMs produced by hybridizing metal nanostructures with nonlinear lumped parts and controlled by optical pulses are expected to yield fast switching/tunability when they reach a manufacturing stage [34]. Despite these important efforts, “tunability” has lately obtained a very lax meaning in the relevant literature [31], referring, essentially, to MMs whose performance changes mildly throughout the medium, e.g. in response to heat.

On the other hand, the proposed SDMs can offer true point-to-point programmatic control of the electromagnetic properties of a medium, allowing even for interconnection to smart control loops in real-time. This control is imposed by a network of miniaturized electronic controllers, carefully placed within the SDM structure. The smaller and denser the nodes, the more granular the *spatial* control over electromagnetic properties of a material. Furthermore, the more powerful the nodes (higher clock frequency), the more granular the *temporal* electromagnetic control. Therefore, the most fine-grained spatiotemporal control of SDMs could be accomplished though the use of nanonetworks [35]. It is clarified that SDMs do not change in terms of shape or appearance. Their programmability refers exclusively to their electromagnetic properties. This fundamental goal differentiates SDMs from the Claytronics project, which employs the term *programmable matter* to describe swarms of nanorobots which cooperate to form certain physical shapes. Claytronics is intended as a long-term research direction (up to 50 years) and related work on this topic can be pursued in [36]. In contrast, SDMs can be tuned programmatically via standard semiconductor technology. The tuning refers to electromagnetic behavior and not to mechanical or physical-form-associated attributes. Moreover, SDMs are feasible even with larger-than-nanoscale controllers. However, nanonetworking is expected to yield the theoretical bounds of their potential.

Each specific application scenario requires a custom metamaterial design and a manufacturing process, with little-to-no reusability.

The nanonetworking technology applicable to SDMs refers to large, dense networks with extreme limitations in available node energy, connectivity, CPU power, and storage [37]. Due to these restrictions, the nanonetworking paradigm needs new algorithms and communication protocols [38], [39]. Initial studies on nanonetworks showed that these networks can operate in the THz regime for high performance [35]. Explicitly, related wireless channel models for nanomachines dispersed in a material have been proposed in [40], taking into account the molecular electromagnetic absorption. Also, point-to-point node communication is discussed at a higher level in [37], [41], considering the rate division time spread on-off keying (RD TS-OOK). Alternative approaches follow hierarchical nanonetworking, namely the clustering of nanonodes into groups, delegating communication abilities only to more powerful cluster masters [42]. Another theoretical approach for ideal networking within an SDM is the network-on-chip paradigm [43], which assumes more sizeable, wired, yet very powerful nodes, able to even support a full IP protocol stack [44].

III. Software Defined Materials

An SDM is, primarily, a 2D surface which supports the programmatic creation of custom MM building blocks and their offset over it. Specifically, it consists of passive parts, called *substrates* and active, ultra-low-power electronic components, operating as *control agents*. In the ideal scenario, the control agent is a nanonetwork, since it provides the finest spatiotemporal control granularity.

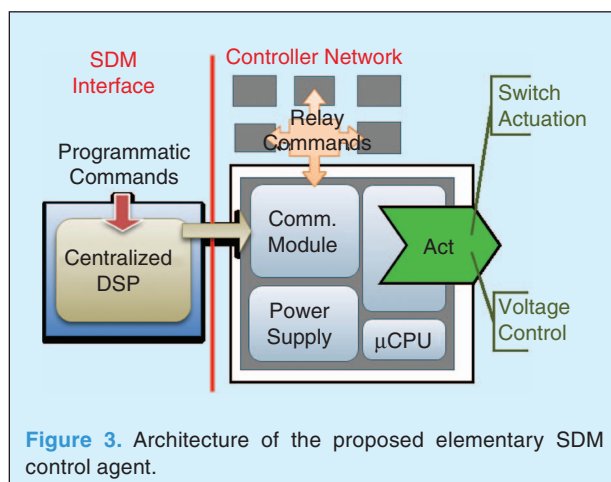


Figure 3. Architecture of the proposed elementary SDM control agent.

The control agents receive programmatic commands, relay them through their network and act upon the SDM substrate, stitching together typical MM patterns. The origin of the commands can be either internal or external to the SDM. In the former case, a standard computer can interface and interact with the SDM, while in the latter we assume that the control agents can operate more autonomously. For instance, they could sense their environment and react automatically in a collaborative fashion.

Based on the above aspects, the core architecture of the control agents is expected to follow the paradigm of Figs 1 and 3. To this goal, the control module comprises an external hardware interface and the network control agent. In particular, the SDM interface has two distinct roles:

- Relay data between the external world and the SDM control agents. These include programmatic commands or sensor readings.
- Handles centrally all deferrable, computational intensive tasks, thus offloading the network of control agents when possible. An example is the manipulation of digital signal processing tasks, which are computationally laborious and require precise floating point calculations.

It should be stressed that massively parallel computing architectures are strong candidates for implementing the SDM interfaces, given that: (a) the number of control agents is anticipated to be high and (ii) they perform a small set of identical functions. Toward this direction, general-purpose graphical processing units (GPUs), such as CUDA-enabled video cards, for illustration, can handle thousands of threads, conveniently organized in kernels, batches, and grids [45].

Therefore, a single control agent will consist of a communication module, a rudimentary CPU and a proper “actuator” per SDM substrate approach, as shown in Fig. 3. When designing a specific SDM, a rational choice should be made early regarding the wired or wireless nature of the communication module and its power supply. The wireless approach has the benefit of avoiding the need for a conductive network to reside behind the SDM surface, especially in the case of dense control agent networks. Nonetheless, it adds a supplementary level of complexity, i.e. transmitting/receiving commands through radio waves or infra-red optical links, as well as harvesting energy through induction [46] or photogeneration [47]. The wired approach, in principle, is simpler, but may require time-multiplexed methods

to circumvent a large continuous mesh and submicron routing to reduce electromagnetic interference that will affect the SDM's performance. The wireless networking paradigm may, also, be simplified from bidirectional to unidirectional, depending on the application scenario (or due to technical feasibility reasons). In such a case, the programmatic commands are broadcast from an external antenna to all the controller nodes, which are, now, passive receptors. Bidirectional communication is certainly preferred, since it extends the SDM application pool, allowing for network-and SDM-monitoring as well as node-collaborative sensing and actuation over the substrates. The actuator module can vary per SDM substrate approach. Note that in the substrates proposed in this paper, the actuator has either the form of a binary switch or a controllable voltage source, as discussed below.

A Building the SDM Substrate

The SDM substrate can be readily implemented as a “switch-fabric”, illustrated in Fig. 4. The depicted electronic semiconductor switches change programmatically from ON to OFF states, altering the basic geometry of an MM in an impactful manner. The conventional SRR-based pattern is described as a representative example, but similar approaches can be followed for potentially any other building block, as well. The controllers can effectively handle the connection between adjacent metallic patches, resulting in ring openings with parametric dimensions. Since the position of the gaps in conjunction with the angle and polarization of incidence are responsible for the overall SDM response, the proposed combination is able to modify the orientation of the device depending on the impinging wave. Additionally, the controller network may dynamically determine the suitable geometry for each case and implement it by properly connecting/disconnecting the metal patches. In this manner, an SDM can yield a refraction angle chosen from a set of positive and negative values. To this extent, it is possible to set a different refraction angle at each point of the SDM. Thus, one can achieve, for example, a spatially-varying electrical permittivity and magnetic permeability response, ranging from large positive to negative values. At the application level, these physical attributes enable diverse new electromagnetic devices, including controllable waveguides, absorbers, and wavefront shapers.

The key characteristic of the switch-fabric approach is the discreteness of their end-behavior. Not every refraction angle is possible (discrete set of choices), since it is not possible to freely alter the geometry of the building blocks. However, in this case the control agents can be quite sizeable (e.g. 1 mm × 1 mm), comparable to the metallic patches they interconnect.

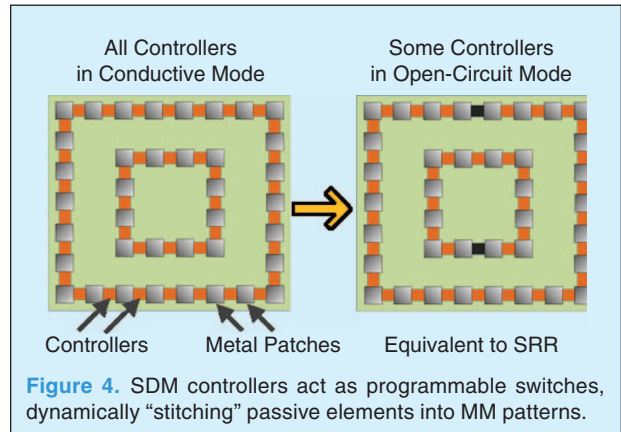


Figure 4. SDM controllers act as programmable switches, dynamically “stitching” passive elements into MM patterns.

Therefore, the switch-fabric approach can favor ease of SDM implementation further, like the micro-electro-mechanical systems [48]. These act as tiny bimetallic strips that may bend once a voltage has been applied to their ends. They offer the advantage of persistent, wide-band switching actuations. However, the MEMS technology is not mature for large-scale applications and cannot easily be incorporated within the hardware controller design. Furthermore, high voltages, e.g. 30 V, are required for proper operation [48]. Nonetheless, the MEMS technology is rapidly evolving and these drawbacks may be eliminated very soon.

Finally, an alternative approach for implementing SDM substrates adopts a graphene layer [49], [50], whose local conductivity changes controllably, forming MM patterns. A remarkable property of graphene is its variable transparency to electromagnetic waves by applying a capacitive bias (electrostatic field) [12], [51]–[56]. The design of a graphene-oriented SDM is given in Fig. 5, where the controller network can act by setting the proper electric bias to the graphene segments. Essentially, the SDM surface

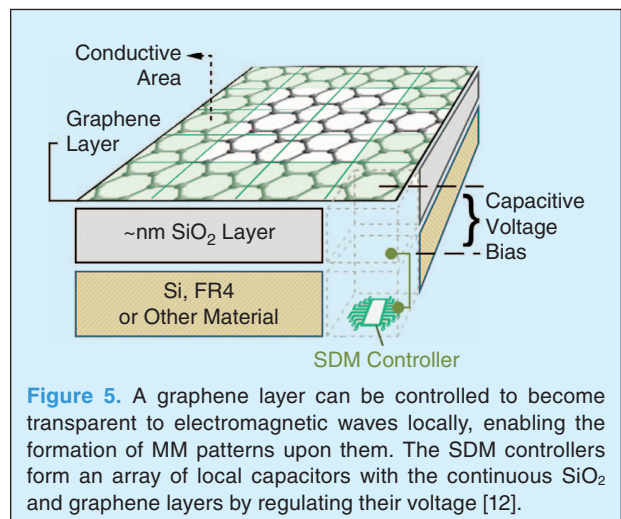


Figure 5. A graphene layer can be controlled to become transparent to electromagnetic waves locally, enabling the formation of MM patterns upon them. The SDM controllers form an array of local capacitors with the continuous SiO₂ and graphene layers by regulating their voltage [12].

Due to the significant degree of interdisciplinarity, software defined metamaterials should, also, be modeled abstractedly from a networking point of view in order to study the data communication issues at an appropriately high level.

becomes a controlled matrix, whereupon a programmer can form custom MM building blocks at any point. Qualitatively, the concept is tantamount to drawing any custom shape on a bitmap. Hence, the SDM can exhibit a diverse repertoire of spatially-varying electromagnetic behavior on-demand. Nevertheless, drawing patterns with good resolution requires a rapidly escalating number of controllers, accentuating manufacturing cost and networking efficiency considerations. Furthermore, graphene interacts only with electromagnetic waves traveling along its surface [12]. This can restrict the use of such SDMs, since they e.g. cannot be used for cloaking objects. However, planar MMs have an application repertoire of their own. For example, this kind of SDMs can pave the way for a new class of graphene-tailored electronic circuits. A programmer could form custom MM patterns performing certain tasks on the SDM surface, including antennas, then erase them and form completely different patterns at any given time.

IV. SDM Nanonetworking Model

The previous sections provided the necessary low-level SDM specifications. Nevertheless, due to the significant degree of interdisciplinarity, SDMs should, also, be modeled abstractedly from a networking point of view in order to study the data communication issues at an appropriately high level. Standard network attributes that must be defined are the topology, the connectivity and data channel models as well as the agent-to-agent SDM-to-interface data exchange protocols. In the light of these aspects, the major SDM-specific networking challenges are:

- The efficient addressing of a vast number of control agents.
- Linking the agent addresses to specific positions within the SDM.
- The low computational complexity requirements of the data exchange protocols.
- The resilience against frequent network errors, attributed to noise, interference, and hardware failures.
- Making sure that the control agent networking and SDM operation functions are sufficiently disjoint.

It should be mentioned, herein, that the present section is not to be considered as a concise treaty of all challenges, but rather as a tutorial and an initial step towards their resolution in subsequent studies.

A. Abstracting the Physics: Higher-Level Connectivity, CPU and RAM Modeling

The topology of an SDM nanonetwork follows that of controlled patches. In line with the presented implementation approaches, nanonodes may be assumed to form a square grid of several vertices (thousands to millions), comprising {1 square patch – 1 control agent} pairs. From the SDM substrate dimensions (input), one derives the node arrangement in rows and columns ($N = m \times n$). The connectivity of each node in the grid can be deemed circular, as explained in [39]. Moreover, the connectivity radius is derived in a manner straightforward for wireless communications, from the transmission power and reception sensitivity of the agent, assuming a fitting path attenuation model [40]. The operating frequency can range within $10^2 - 10^3$ GHz, making for ≈ 10 nsec-long data packets that carry $\propto 10^1$ bytes [41]. Related studies on nanonetworking have converged to simplistic modulation schemes (typically a direct representation of logical “1”s with very short pulses and silence for “0”s) and no error correction capabilities [37], [39], [40], [41]. Such choices are attributed to power conservation and manufacturing costs. Given the vast nanonode number in an SDM, it is obvious that each node should be as weak (and thus cheap) as possible. In this spirit, the present study assumes: (a) the total absence of queuing capabilities in general, (b) a total memory capacity of ≈ 100 bytes, and (c) a lightweight CPU, able to perform integer calculations only¹ Finally, all nodes are considered uniform.

B. Quasi-p2p Communications Paradigm

Networking a vast number of the outlined extremely weak nanonodes requires special approaches regarding their addressing, the type of relayed data, and their reachability via programmatic directives. To efficiently treat this situation, a quasi-p2p communications paradigm is proposed, as a starting point. At first, we assume that all nodes have an embedded SDM-wide unique serial number by manufacture, which takes the form of a hardwired integer number. This initial approach can be achieved by machines similar to the automatic Siemens Sipplace assembler, which can place sequentially 40,000

¹Namely, int counter increase/decrease, modulo operations and evaluation of simple Boolean conditions.

electronic chips per hour on a given substrate [57]. For the sake of simplicity, we presume that the control agents are placed based on their serial numbers incrementally from left to right and up to down on the 2D SDM substrate. For example, in a 5×5 configuration, if node at (1, 1) has a serial number of 1, then the serial number of the node placed at (2, 1) is 6. Next, we proceed to launch a special data exchange format.

According to the featured concept, every single packet originates from an external programming entity (Fig. 1) and needs to be relayed to all agents. However, each agent translates it differently, depending on its serial number. Two data packet types are defined, the *config* and the *setup* packet, depending on the nature of the information they carry. The *config* packet conveys data on the nanonetwork topology, such as informing all agents about the total number of rows and columns, $m \times n$. A node reads this information and derives its personal row-column indices, i, j , using simple integer division and modulo arithmetic on its serial number, SN :

$$\begin{pmatrix} i \\ j \end{pmatrix} = \begin{pmatrix} \lfloor \frac{SN-1}{n} \rfloor + 1 \\ (SN-1) \bmod n + 1 \end{pmatrix}.$$

For illustration, in the previous 5×5 example, the node with serial number 6 understands that it is in position (2, 1).

The *setup* packet, on the other hand, carries the directives for the formation of MM patterns on the SDM surface. In fact, the quasi-p2p scheme proposes the exchange of programmatic functions, rather than plain raw data. A node receives a *function* and evaluates it for its personal serial number. This function returns a simple Boolean value and each node sets its status accordingly (true:actuate or false:do nothing). Observe that a few bytes of information can describe the complete SDM form, exploiting the repetitive nature of the MM patterns and the periodicity of the building blocks. An example is given in Fig. 6 (top inset). The depicted SRR building block, comprises periodically-repeated line segments and gaps. These are expressed in integer modulo-based conditions, as functions of the i, j nanonode indices. Each nanonode receives these conditions in the form of a *setup* packet. It then applies its personal i, j indices and derives its intended, programmatic status. Notice that several line segments are symmetric, compacting the packet size further, not requiring extra formulations. Thus, the new quasi-p2p combines the inherent reachability and packet exchange minimization benefits of broadcasting with the granularity of p2p commands, *without* explicit reference to any node. This results in minimal-sized SDM directives, as shown in Fig. 6. It is stressed that a sole setup packet of roughly 100 bytes describes the complete SDM.

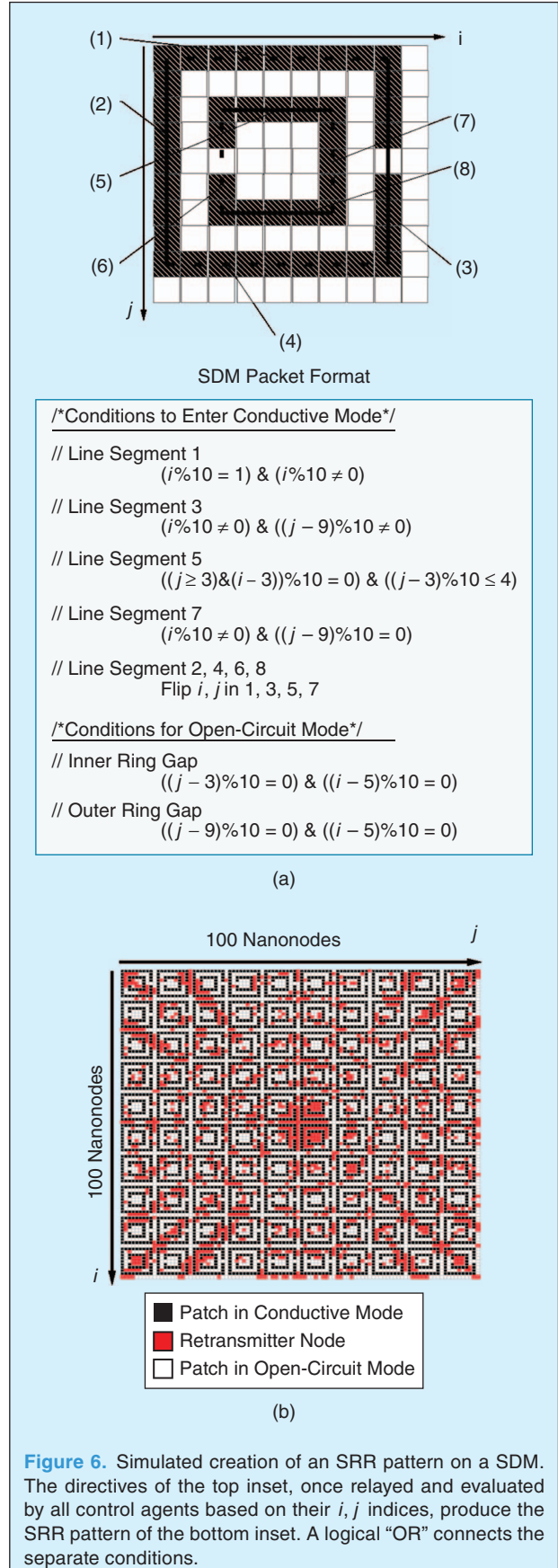


Figure 6. Simulated creation of an SRR pattern on a SDM. The directives of the top inset, once relayed and evaluated by all control agents based on their i, j indices, produce the SRR pattern of the bottom inset. A logical “OR” connects the separate conditions.

Apart from advancing the theory and verifying it through simulations, it is essential to take into account the state-of-the-art manufacturing capabilities, both in terms of metamaterials and the integrated circuit technology.

C. Role-Centric Networking

In traditional communications, well-defined medium access, routing and application layers receive, alter, and encapsulate a packet separately. However, in these cases, packet queuing capabilities, fast RAM and powerful CPUs are considered a given. Actually, the SDM agent networking protocols require a much more lightweight approach and out-of-the-box thinking. Then, what is the role of a MAC layer? The key answer is that *it limits interferences*. Why do we need a routing layer? Primarily to ensure *fast packet delivery* via e.g. a short path. We, therefore, demonstrate a simple *layer-less* communication scheme that offers interference limitation and fast packet delivery. Moreover, it is claimed that the role-centric networking proposed in [39] is a good (although not restricting) candidate for SDM agent networking.

To this purpose, we define a role-based operation. A node starts off in “neutral” role, during which it acts as packet retransmitter and also keeps separate count of packets it received successfully or not. After a certain number of total packet receptions, a node assumes a “passive auditor” or a “blind retransmitter” role, depending on the aforementioned counter values. Essentially, role-centric networking defines no MAC protocol and yet surpasses queuing-enabled handshake-based, and flood-based approaches in successful packet reception/transmission rate. Note that most nodes turn into “passive auditors”, conserving energy. Moreover, “blind retransmitters” have been analytically proven to form predictable well-defined symmetric patterns, as demonstrated in Fig. 6 (lower inset). This symmetry ensures

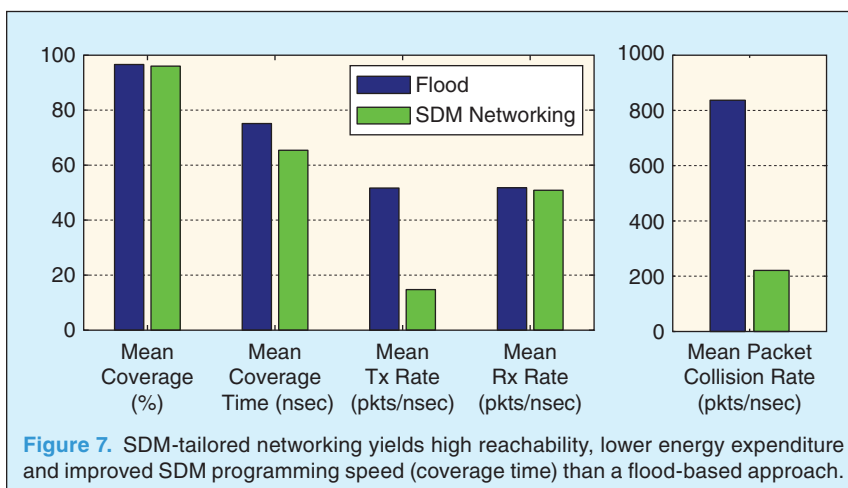
that packets travel over straight lines, yielding shortest-path routing benefits, as well. Finally, it has been shown that the described traits are actually accentuated when the number of nodes increases.

In the case of a MEMS switch-fabric SDM, the role-centric approach can be employed as is, considering that the switching actuation is almost instantaneous and persistent. However, graphene and semiconductor-based SDM substrates introduce an interesting implication. A node may not assume the role of “retransmitter” and apply voltage to a graphene patch or power a semiconductor switch (“actuator” role) at the same time, due to power restrictions. In other words, the “actuator” and “retransmitter” roles are mutually exclusive. Thus, a node instructed to “actuate” discards immediately the “retransmitter” role it may have assumed. An open issue is whether the described properties of [39] continue to hold under these circumstances.

For the prior scenario, a set of initial simulation results is provided. We assume a topology of 100×100 nodes over a 10×10 mm area, each with a connectivity radius of 8 nodes (Fig. 6). Each node operates, as previously described, with the following physical parameters: 100 GHz carrier frequency, 10 nW transmission power, and 10 nsec packet duration. The SDM directives enter at the middle of the surface and propagate over it, following the simulation setup of [39]. So, we require the creation of an SRR-based SDM, as shown in the top inset of Fig. 6. In this context, we measure:

- The percentage of nodes that successfully receive (Rx) a given packet with directives.
- The time required to reach this percentage (SDM programming speed).
- The induced energy consumption rate measured by the network-wide packet transmission rate (Tx).

Furthermore, we observe the formation of patterns of retransmitters. The SDM-tailored networking is compared to a flood-based approach, which makes no differentiation between “retransmitter” and “auditor” nodes (see Fig. 7). Results refer to mean values over 1000 SDM setup trials. Both approaches yield



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almost a 100% coverage. Nevertheless, this proposed one achieves so with the $\approx 1/3$ of the energy expenditure of the flood solution, as exhibited by the respective packet transmission rates. Additionally, it offers better SDM programming speed at the same time. By assigning retransmitter roles to nodes with good overall reception, the SDM-tailored approach limits the interference events considerably, while retaining the same rate of successful packet receptions network-wide. In this manner, the retransmitters form symmetric patterns, despite the intervention of SDM-specific node roles.

V. Key Challenges

The successful introduction of the novel SDM class implies three specific objectives:

1. *The theoretical foundation of SDMs*, comprising analytical modeling, design, and simulation techniques. Emphasis should be placed on deriving SDM design processes that yield wide tunability in high-level electromagnetic traits, such as the absorption potential per given angle of impinging waves, as depicted in Fig. 8. The MM and networking aspects of SDMs could be studied via a mutual abstractive modeling, at first.

Concentrating on the MM aspect, well-known computational algorithms, such as effective medium theories [58], the finite-difference time-domain (FDTD) method [59], the finite element method (FEM) [60], and the finite integration technique (FIT) [61], can be successfully employed or combined to optimally assess the SDM electromagnetic properties. A critical issue is to ensure that these characteristics are not noticeably affected by the presence of controllers/nanomachines and their communication network. To this aim, all electromagnetic compatibility/interference (EMC/EMI) issues should be thoroughly assessed, deriving separate operating spectrums for the SDM, as a whole, and for the controlling component.

For the networking aspect and complementing the challenges, presented in Section IV, SDM topologies need to focus on the minimization of the nanomachines number, while still providing both a diverse set of programmable MM patterns and a reduced SDM fabrication cost. Also, SDM-specific nanonetworking protocols are expected to antagonize over programming speed, i.e. the time required to reconfigure an SDM for new electromagnetic properties. Note that rapidly-programmable SDMs may unlock new performance profiles stemming from

spatial and temporal variations. *Reliability* covers *security* and *error-resilience* notions, since SDMs can connect matter to the internet, implying authorization concerns. A lightweight security mechanism to enable SDM programming to authorized users only can potentially rely on the quasi-random scrambling of node IDs during the manufacturing phase. Thus, SDM programming will be viable only to programmers that know the location of the node IDs. Nonetheless, extra restrictions will be required to describe the SDM setup, creating a trade-off between packet size and security. In addition, nanomachines are generally error-prone, due to the absence of serious error-correction schemes. Strict binary formats for packet directives and SDM-tailored codebooks may guarantee that faulty packets are detected and invalidated with high probability, prior to causing unplanned alterations to the SDM geometry. Finally, measurement-based mechanisms for detecting nanomachine failures can offer a more programmer-friendly SDM interface, offering SDM “debugging” and real-time monitoring capabilities.

2. *The manufacturing and testing of SDM prototype(s)* which will serve as proof of the SDM concept. Apart from advancing the theory and verifying it through simulations, it is essential to take into account the state-of-the-art manufacturing capabilities, both in terms of MMs and the integrated circuit technology. The metric of success of this goal is the outcome of physical measurements, a procedure known as “MM electromagnetic

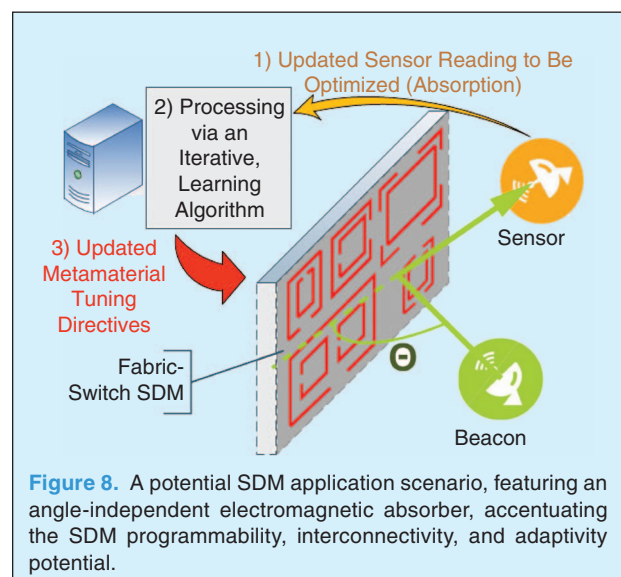


Figure 8. A potential SDM application scenario, featuring an angle-independent electromagnetic absorber, accentuating the SDM programmability, interconnectivity, and adaptivity potential.

characterization” [62]. In particular, if a programmed SDM prototype behaves as the intended MM, this objective will have been clearly met.

3. *The demonstration of the SDM potential* through motivating and promising application scenarios. SDM demonstrators, simulation or experiment-based, should accentuate the offered *programmability, interconnectivity, and adaptivity* potential. A possible scenario is illustrated in Fig. 8, where a switch-fabric SDM is used as an angle-dependent absorber of electromagnetic waves. This proof-of-concept scenario can in principle be extended to cloaking applications, in the future, by absorbing all the impinging electromagnetic radiation on an object, e.g. increasing the quality of medical imaging by canceling all unwanted reflections. The setup of Fig. 8 assumes a beacon which emits waves that illuminate the SDM surface at an angle that may vary during the experiment. An array of sensors reads the reflected energy from the SDM and then feeds the measurements to an algorithm running on a standard computer, which fine-tunes the SDM in order to minimize future readings. The algorithm can be selected from any family of learning heuristics, such as neural networks, genetic algorithms or learning automata. Its inputs are the readings of the sensor array and its outputs the specific SDM programming directives fed to the SDM external interface. The directives can refer to e.g. changing the rotation, gap size and dimensions of SRRs, according to the sensor readings.

VI. Conclusion

In this paper, a novel class of systems which allow for programmatic control over the electromagnetic behavior of matter, has been presented. This is achieved by means of the proposed SDMs, an innovative combination of nanonetworks and MMs. The latter are artificially designed materials, with unnatural, geometry-dependent electromagnetic properties. A network of nanomachines receives external programmatic commands and performs geometry-altering actions, yielding tunable or adaptive behavior. The present paper abstracted a fitting networking model from the physical underpinnings of MMs and outlined its challenges. Finally, it systematically outlined the foundations and realizability clarifications, required to spur research on this new field of research.

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References

- [1] V. Veselago, “The electrodynamics of substances with simultaneously negative values of ϵ and μ ,” *Sov. Phys. Usp.*, vol. 10, no. 4, pp. 509–514, 1968.
- [2] J. B. Pendry, A. J. Holden, D. J. Robbins, and W. J. Stewart, “Magnetism from conductors, and enhanced non-linear phenomena,” *IEEE Trans. Microw. Theory Tech.*, vol. 47, no. 11, pp. 2075–2084, Nov. 1999.
- [3] D. R. Smith, D. Schurig, and J. B. Pendry, “Negative refraction of modulated electromagnetic waves,” *Appl. Phys. Lett.*, vol. 81, no. 15, pp. 2713–2715, 2002.
- [4] A. Lai, T. Itoh, and C. Caloz, “Composite right/left-handed transmission line metamaterials,” *IEEE Microw. Mag.*, vol. 5, no. 1, pp. 34–50, 2004.
- [5] A. Grbic and G. V. Eleftheriades, “Practical limitations of subwavelength resolution using negative-refractive-index transmission-line lenses,” *IEEE Trans. Antennas Propag.*, vol. 53, no. 10, pp. 3201–3209, Oct. 2005.
- [6] C. R. Simovski and S. A. Tretyakov, “Local constitutive parameters of metamaterials from an effective-medium perspective,” *Phys. Rev. B*, vol. 75, no. 19, 2007.
- [7] V. M. Shalaev, “Optical negative-index metamaterials,” *Nat. Photonics*, vol. 1, no. 1, pp. 41–48, 2007.
- [8] A. Alù, N. Engheta, A. Erentok, and R. W. Ziolkowski, “Single-negative, double-negative and low-index metamaterials and their electromagnetic applications,” *IEEE Antennas Propag. Mag.*, vol. 49, no. 1, pp. 23–36, Feb. 2007.
- [9] M. G. Silveirinha, “Metamaterial homogenization approach with application to the characterization of microstructured composites with negative parameters,” *Phys. Rev. B*, vol. 75, no. 11, 2007.
- [10] R. S. Penciu, K. Aydin, M. Kafesaki, T. Koschny, E. Ozbay, E. N. Economou, and C. M. Soukoulis, “Multi-gap individual and coupled split-ring resonator structures,” *Opt. Express*, vol. 16, no. 22, pp. 18131–18144, 2008.
- [11] N. I. Zheludev, “Applied physics: the road ahead for metamaterials,” *Science*, vol. 328, no. 5978, pp. 582–583, 2010.
- [12] A. Vakil and N. Engheta, “Transformation optics using graphene,” *Science*, vol. 332, no. 6035, pp. 1291–1294, 2011.
- [13] C. Holloway, E. Kuester, and A. Dienstfrey, “Characterizing metasurfaces/metafilms: the connection between surface susceptibilities and effective material properties,” *IEEE Antennas Wirel. Propag. Lett.*, vol. 10, pp. 1507–1511, 2011.
- [14] N. I. Zheludev and Y. S. Kivshar, “From metamaterials to metadevices,” *Nat. Mater.*, vol. 11, no. 11, pp. 917–924, 2012.
- [15] M. Liu, D. A. Powell, I. V. Shadrivov, M. Lapine, and Y. S. Kivshar, “Spontaneous chiral symmetry breaking in metamaterials,” *Nat. Commun.*, vol. 5, pp. 5441–5449, 2014.
- [16] G. V. Eleftheriades and K. G. Balmain, *Negative-Refraction Metamaterials: Fundamental Principles and Applications*. Hoboken, NJ: Wiley-IEEE Press, 2005.
- [17] N. Engheta and R. W. Ziolkowski, *Metamaterials: Physics and Engineering Explorations*. Hoboken, NJ: Wiley-IEEE Press, 2006.
- [18] C. Caloz and T. Itoh, *Electromagnetic Metamaterials: Transmission Line Theory and Microwave Applications: The Engineering Approach*. New York: John Wiley & Sons, 2006.
- [19] A. K. Sarychev and V. M. Shalaev, *Electrodynamics of Metamaterials*. Singapore: World Scientific, 2007.
- [20] R. Marqués, F. Martín, and M. Sorolla, *Metamaterials with Negative Parameters: Theory, Design, and Microwave Applications*. New York: John Wiley & Sons, 2008.
- [21] T. J. Cui, D. R. Smith, and R. Liu, *Metamaterials: Theory, Design, and Applications*. New York, NY: Springer Verlag, 2010.
- [22] D. Schurig, J. J. Mock, B. J. Justice, S. A. Cummer, J. B. Pendry, A. F. Starr, and D. R. Smith, “Demonstration of a metamaterial electromagnetic cloak at microwave frequencies,” *Science*, vol. 314, no. 5801, pp. 977–980, 2006.
- [23] K. Iwaszczuk, A. C. Strikwerda, K. Fan, X. Zhang, R. D. Averitt, and P. U. Jepsen, “Flexible metamaterial absorbers for stealth applications at terahertz frequencies,” *Opt. Express*, vol. 20, no. 1, pp. 635–643, 2012.

- [24] B.-X. Wang, L.-L. Wang, G.-Z. Wang, W.-Q. Huang, X.-F. Li, and X. Zhai, "Frequency continuous tunable terahertz metamaterial absorber," *J. Lightwave Technol.*, vol. 32, no. 6, pp. 1183–1189, June 2014.
- [25] D. L. Sounas and A. Alù, "Extinction symmetry for reciprocal objects and its implications on cloaking and scattering manipulation," *Opt. Lett.*, vol. 39, no. 13, pp. 4053–4056, 2014.
- [26] K. Tan, H. Liu, J. Zhang, Y. Zhang, J. Fang, and G. M. Voelker, "Sora: high-performance software radio using general-purpose multi-core processors," *Commun. ACM*, vol. 54, no. 1, pp. 99–107, 2011.
- [27] G. Kolumban, T. I. Krebesz, and F. C. M. Lau, "Theory and application of software defined electronics: design concepts for the next generation of telecommunications and measurement systems," *IEEE Circuits Syst. Mag.*, vol. 12, no. 2, pp. 8–34, 2012.
- [28] M. Kaminsky, M. Dahlin, E. Thereska, H. Ballani, G. O'Shea, T. Karagiannis, A. Rowstron, T. Talpey, et al., "IOFlow: a software-defined storage architecture," in *Proc. 24th ACM Symp.*, Nov. 3–6, 2013, pp. 182–196.
- [29] K. Rawat, M. S. Hashmi, and F. M. Ghannouchi, "Dual-band RF circuits and components for multi-standard software defined radios," *IEEE Circuits Syst. Mag.*, vol. 12, no. 1, pp. 12–32, 2012.
- [30] E. Ozbay, K. Guven, and K. Aydin, "Metamaterials with negative permeability and negative refractive index: Experiments and simulations," *J. Opt. A: Pure Appl. Opt.*, vol. 9, no. 9, pp. S301–S307, 2007.
- [31] A. Q. Liu, W. M. Zhu, D. P. Tsai, and N. I. Zheludev, "Micromachined tunable metamaterials: A review," *J. Opt.*, vol. 14, no. 11, 2012.
- [32] Y. Liu and X. Zhang, "Metamaterials: a new frontier of science and technology," *Chem. Soc. Rev.*, vol. 40, no. 5, pp. 2494–2507, 2011.
- [33] M. Kafesaki, N. H. Shen, S. Tzortzakos, and C. M. Soukoulis, "Optically switchable and tunable terahertz metamaterials through photoconductivity," *J. Opt.*, vol. 14, no. 11, 2012.
- [34] K. Fan, X. Zhao, J. Zhang, K. Geng, G. R. Keiser, H. R. Seren, G. D. Metcalfe, M. Wraback, et al., "Optically tunable terahertz metamaterials on highly flexible substrates," *IEEE Trans. Terahertz Sci. Technol.*, vol. 3, no. 6, pp. 702–708, Nov. 2013.
- [35] I. F. Akyildiz, F. Brunetti, and C. Blázquez, "Nanonetworks: A new communication paradigm," *Comput. Netw.*, vol. 52, no. 12, pp. 2260–2279, 2008.
- [36] (2005). Claytronics project. [Online]. Available: <http://www.cs.cmu.edu/claytronics/>
- [37] P. Wang, J. M. Jornet, M. A. Malik, E. Fadel, and I. F. Akyildiz, "Energy and spectrum-aware MAC protocol for perpetual wireless nanosensor networks in the terahertz band," *Ad Hoc Netw.*, vol. 11, no. 8, pp. 2541–2555, 2013.
- [38] M. Pierobon and I. F. Akyildiz, "Diffusion-based noise analysis for molecular communication in nanonetworks," *IEEE Trans. Signal Process.*, vol. 59, no. 6, pp. 2532–2547, June 2011.
- [39] C. K. Liaskos and A. N. Tsioliaridou, "A promise of realizable, ultra-scalable communications at nano-scale: a multi-modal nano-machine architecture," *IEEE Trans. Comput.*, 2014, doi: 10.1109/TC.2014.2329684.
- [40] J. M. Jornet and I. F. Akyildiz, "Channel modeling and capacity analysis for electromagnetic wireless nanonetworks in the terahertz band," *IEEE Trans. Wirel. Commun.*, vol. 10, no. 10, pp. 3211–3221, Oct. 2011.
- [41] J. M. Jornet, J. C. Pujol, and J. Sole-Pareta, "PHLAME: a physical layer aware MAC protocol for electromagnetic nanonetworks in the terahertz band," *Nano Commun. Netw.*, vol. 3, no. 1, pp. 74–81, 2012.
- [42] V. Srikanth, S. Chaluvadi, P. Sandeep, M. Vani, and R. Venkatesh, "Energy efficient, scalable and reliable MAC protocol for electromagnetic communication among nano devices," *Int. J. Distrib. Parallel Syst.*, vol. 3, no. 1, pp. 249–256, Jan. 2012.
- [43] S. Abadal, M. Iannazzo, M. Nemirovsky, A. Cabellos-Aparicio, H. Lee, and E. Alarcón, "On the area and energy scalability of wireless network-on-chip: a model-based benchmarked design space exploration," *IEEE/ACM Trans. Netw.*, 2014, doi: 10.1109/TNET.2014.2332271.
- [44] S. Milner, J. Llorca, and C. Davis, "Autonomous reconfiguration and control in directional mobile ad hoc networks," *IEEE Circuits Syst. Mag.*, vol. 9, no. 2, pp. 10–26, 2009.
- [45] D. Donno, A. Esposito, L. Tarricone, and L. Catarinucci, "Introduction to GPU computing and CUDA programming: a case study on FDTD," *IEEE Antennas Propag. Mag.*, vol. 52, no. 3, pp. 116–122, 2010.
- [46] G. Dolmans. (2013). iMEC range wireless projects. [Online]. Available: <http://www.hightechcampus.com/viewfile.php/633>
- [47] P. Theilmann, Wireless power transfer for scaled electronic biomedical implants. Ph.D. dissertation, University of California, San Diego, 2012.
- [48] H. Tao, A. C. Strikwerda, K. Fan, W. J. Padilla, X. Zhang, and R. D. Averitt, "MEMS based structurally tunable metamaterials at terahertz frequencies," *J. Infrared Millimeter Terahz Waves*, vol. 32, no. 5, pp. 580–595, 2011.
- [49] A. K. Geim and K. S. Novoselov, "The rise of graphene," *Nat. Mater.*, vol. 6, pp. 183–191, 2007.
- [50] H.-S. Wong and D. Akinwande, *Carbon Nanotube and Graphene Device Physics*. Cambridge, UK: Cambridge University Press, 2011.
- [51] G. Deligeorgis, M. Dragoman, D. Neculoiu, D. Dragoman, G. Konstantinidis, A. Cismaru, and R. Plana, "Microwave propagation in graphene," *Appl. Phys. Lett.*, vol. 95, no. 7, 2009.
- [52] F. Bonaccorso, Z. Sun, T. Hasan, and A. C. Ferrari, "Graphene photonics and optoelectronics," *Nat. Photonics*, vol. 6, no. 9, pp. 611–622, 2010.
- [53] S. Srikanth, I. E. Alarcon, A. Cabellos-Aparicio, M. Lemme, and M. Nemirovsky, "Graphene-enabled wireless communication for massive multicore architectures," *IEEE Commun. Mag.*, vol. 51, no. 11, pp. 137–143, Nov. 2013.
- [54] H. Alcalde, J. de la Fuente, B. Kamp, and A. Zurutuza, "Market uptake potential of graphene as a disruptive material," in *Proc. IEEE*, vol. 101, no. 7, pp. 1793–1800, 2013.
- [55] B. K. Kaushik, M. K. Majumder, and V. R. Kumar, "Carbon nanotube based 3-D interconnects: a reality or a distant dream," *IEEE Circuits Syst. Mag.*, vol. 14, no. 4, pp. 16–35, 2014.
- [56] A. A. Sagade, D. Neumaier, D. Schall, M. Otto, A. Pesquera, A. Centeno, A. Z. Elorzab, and H. Kurza, "Highly air stable passivation of graphene based field effect devices," *Nanoscale*, vol. 7, no. 8, pp. 3558–3564, 2015.
- [57] SIPLACE. (2014). The placement solution for high-mix SMT production environments. [Online]. Available: <http://www.siplace.com/sg/placement-systems/sx-series>
- [58] J. G. Van Bladel, *Electromagnetic Fields*. New York, NY: IEEE Press and Wiley Interscience, 2007.
- [59] A. Taflove and S. C. Hagness, *Computational Electrodynamics: The Finite-Difference Time-Domain Method*, 3rd ed. Norwood, MA: Artech House, 2005.
- [60] J. M. Jin, *The Finite Element Method in Electromagnetics*, 2nd ed. New York, NY: John Wiley and Sons, 2002.
- [61] T. Weiland, "A discretization method for the solution of Maxwell's equations for six-component fields," *Electron. Commun. (AEÜ)*, vol. 31, no. 3, pp. 116–120, 1977.
- [62] D. R. Smith, S. Schultz, P. Markoš, and C. M. Soukoulis, "Determination of effective permittivity and permeability of metamaterials from reflection and transmission coefficients," *Phys. Rev. B*, vol. 65, no. 19, 2002.

