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The Internet of Multimedia Nano-Things in the Terahertz Band

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***Abstract*—Nanotechnology is providing the engineering community with a new set of tools to design and manufacture advanced devices which are able to generate, process and transmit multimedia content at the nanoscale. The wireless interconnection of pervasively deployed multimedia nano-devices with existing communication networks and ultimately the Internet defines a truly cyber physical system which is further referred to as the Internet of Multimedia Nano-things (IoMNT). This paper discusses the state of the art and major research challenges in the realization of this novel networking paradigm, which has innumerable applications in the biomedical, defense, environmental and industrial fields. Fundamental research challenges and future research trends are outlined in terms of multimedia data and signal processing, Terahertz channel modeling for communication among nano-things, and protocols for the Internet of Multimedia Nano-Things. These include novel medium access control techniques, addressing schemes, neighbor discovery and routing mechanisms, a novel QoS-aware cross-layer communication module, and novel security solutions for the IoMNT.**

***Index Terms*—Nanonetworks, Terahertz Band, Internet of Things, Multimedia**

I. Introduction

In the Internet of Things (IoT), all types of real-world physical elements (e.g., sensors, actuators, personal electronic devices and home appliances) are able to autonomously interact with each other [5], [30]. The IoT enables many applications in the fields of domotics, e-health, real time monitoring of industrial processes, and intelligent transportation of people and goods, among others. Two main technologies for the IoT are currently being considered, namely, RFID tags and Wireless Sensor Networks (WSNs). On the one hand, *RFID tags* can be easily embedded in all sorts of things due to their small size and their battery-less operation. However, RFID tags do not have processing, data storing or sensing capabilities. On the other hand, *WSNs* can provide the IoT with the necessary computing, data storing, and sensing functionalities, but the size, complexity and energy constraints of existing sensors limit the usefulness of this approach. Therefore, there is a need for *a new communication technology* for the IoT.

Nowadays, nanotechnology is providing the engineering community with a new set of tools to control matter at an atomic and molecular level. At this scale, novel nanomaterials show new properties not observed at the micro level, which enable the development of new devices and applications. For example, graphene [7], a one-atom-thick planar sheet of bonded carbon atoms densely packed in a honeycomb lattice, has been lately referred to as the *the silicon of the 21st century*. The unique optical and electronic properties of this nanomaterial enable the development of a new generation of electronic devices, e.g., nano-transistors for future nano-processors and nano-memories [20], [37], nano-batteries [12], [35], and nano-sensors [34], [29], which outperform their microscale counterparts. In addition, graphene-enabled nano-transceivers and nano-antennas are expected to operate in the Terahertz Band (0.1-10 THz), which opens the door to ultra-broad-band communications among nano-devices [24], [16].

In addition, these same nanomaterials are currently being proposed to develop a new generation of miniature photodetectors [22], [8] and acoustic nano-transducers [18], [32], which can be used to generate multimedia content at the nanoscale. These novel *nano-cameras and nano-phones* will be able to capture visual and acoustic information with higher resolution and accuracy than current micro-cameras and micro-phones. Moreover, the integration of nano-cameras, nano-phones, scalar nano-sensors, with nano-processors, nano-memories, and other nano-components will enable the development of more *advanced multimedia nano-devices*. These advanced nano-devices will overcome the limitations of current multimedia sensor devices [4] by providing higher quality image and audio sensing capabilities, higher computational and data storing capacities, higher energy efficiency and expectedly higher wireless communication data-rates [13], [17].

In our vision, the interconnection of pervasively deployed multimedia nano-devices with existing communication networks and ultimately the Internet defines a truly cyber physical system which we further refer to as *the Internet of Multimedia Nano-Things (IoMNT)*. The IoMNT is not only compliant

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with the envisioned applications of the IoT [5], [30], but it enables new advanced applications in diverse fields such as, i) in the biomedical field, by means of advanced health monitoring systems which combine biological and chemical scalar nanosensors, high-resolution ultra-sensitive nano-cameras and ultrasonic nano-phones, for early cancer detection and treatment of heart or neural diseases; ii) in defense and security applications, by combining imperceptible nano-cameras for remote nanoscale imaging, ultrasonic nano-phones for concealed objects detection, and biological and chemical nanosensors as a countermeasure for novel nanotechnology-enabled attacks; iii) in forensics, for example, for ultra-high resolution imaging of crime scenes; or, iv) in far field imaging, for ultra-high resolution imaging of distant objects.

For example, in Fig. 1, an example application of the IoMNT is shown. In this figure, multimedia nano-things equipped with nano-cameras are used to capture high-quality video for holographic teleconferencing. Similarly, a distributed set of multimedia nano-things equipped with nano-projectors are used to recreate a high quality holographic image in the conference room. In parallel, other nano-things equipped with ultrasonic transducers are used to detect concealed objects. Finally, other nano-things with biological and chemical nanosensors are pervasively deployed in the conference room for early detection of biological and chemical threats.

Nevertheless, the highly heterogeneous capabilities of advanced multimedia nano-devices and the type of applications and scenarios in which they will be used, introduce several research challenges in the realization of the Internet of Multimedia Nano-Things. In this paper, we discuss the state of the art and major research challenges in the realization of this novel networking paradigm. First, we briefly present the state of the art in nano-thing development from the device perspective in Sec. II. In Sec. III, we outline the main research challenges in the IoMNT from the communication perspective, in terms of multimedia and data signal processing, Terahertz Band channel modeling, and protocols for the IoMNT. These include novel medium access control techniques, addressing schemes, neighbor discovery and routing mechanisms, a QoS-aware cross-layer communication module, and security solutions for the IoMNT Finally, we conclude the paper in Sec. IV.

II. Device Components

Many nano-thing components have already been prototyped and tested. However, there are still several challenges from the device perspective that need to be addressed in order to turn existing nano-devices into autonomous machines. In our vision, several nano-components such as a nano-processor, a nano-memory, a power nano-system and a nano-camera, have to be integrated into a device with a total volume *as small as just a few cubic micrometers* [1], [2], [3] (Fig. 2). To date, several solutions have been proposed for each component:

- **Nano-Cameras:** New photodetectors based on novel nano-structures have been demonstrated [22], [8]. Their main properties are i) a reduced size (below 100 nm per pixel, which allows the integration of very dense arrays), ii) higher sensitivity at low energy levels (i.e., better low-light conditions imaging), and iii) reduced power consumption. The fabrication of very dense arrays of nano-photodetectors and nano-lenses, will enable the development of nano-cameras with very high pixel resolution, very high spatial resolution and very high color resolution. Ultimately, the capabilities of a nano-camera will be directly related to its physical dimensions.

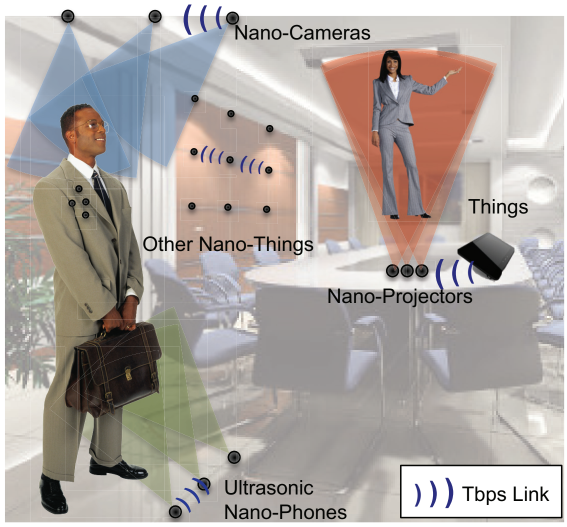

Fig. 1. Application of the Internet of Multimedia Nano-Things.

- **Nano-Phones:** Novel nanoscale acoustic transducers for ultrasonic applications have been prototyped [18], [32]. The integration of nanoscale acoustic transducers into miniaturized arrays will enable the development of novel nano-phones (i.e., nanoscale micro-phones) with i) higher directional resolution (surround audio sensing and recording), and ii) higher frequency resolution (higher quality audio, ultra-sound recording). The final capabilities of the nano-phone will depend on the physical dimensions of the acoustic nano-transducer array.
- **Scalar Nano-Sensors:** Physical, chemical and biological nanosensors have been developed by using graphene and other nanomaterials [9], [38]. A nanosensor is not just a tiny sensor, but a device that makes use of the novel properties of nanomaterials to identify and measure new types of events in the nanoscale, such as the physical characteristics of structures just a few nanometers in size, chemical compounds in concentrations as low as one part per billion, or the presence of biological agents such as virus, bacteria or cancerous cells.
- **Nano-Processors:** These are being enabled by the development of tinier FET transistors in different forms. The smallest transistor that has been experimentally tested to date is based on a thin graphene strip made of just 10 by 1 carbon atoms [27]. These transistors are not only smaller, but also able to operate at higher switching frequencies. The complexity of the operations that a nano-processor will be able to handle will directly depend on the number of integrated transistors in the chip, thus, on its total size.

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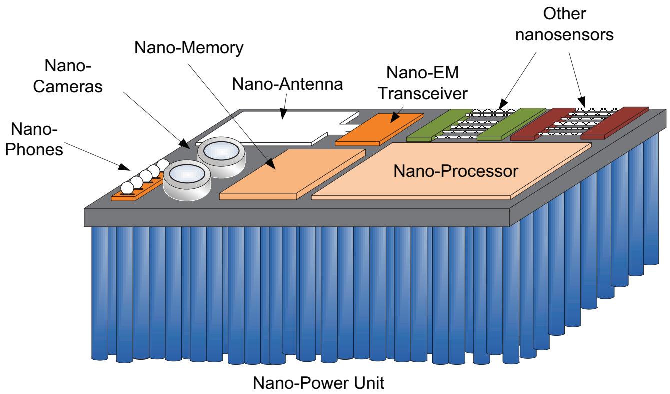

Fig. 2. Conceptual architecture of a multimedia nano-thing.

- **Nano-Memories:** Nanomaterials and new manufacturing processes are enabling the development of single-atom nano-memories, in which the storage of one bit of information requires only one atom [6]. For example, in a magnetic memory [25], atoms are placed over a surface by means of magnetic forces. While these memories are not ready yet for nano-devices, they serve as a starting point. The total amount of information storable in a nano-memory will ultimately depend on its dimensions.
- **Power Nano-Systems:** Powering nano-devices requires new types of nano-batteries [12], [35] as well as nanoscale energy harvesting systems [36]. One of the most promising techniques relies on the piezoelectric effect seen in zinc oxide nanowires, which are used to convert vibrational energy into electricity. This energy can then be stored in a nano-battery and dynamically consumed by the device [14]. The rate at which energy is harvested and the total energy that can be stored in a nano-device depends ultimately on the device size.
- **Nano-Antennas and Nano-Transceivers:** Graphene and its derivatives have also been proposed for the development of novel nano-antennas [16], [39]. Amongst others, in [16] we determined that a 1 μm long graphene-based nano-antenna can only efficiently radiate electromagnetic (EM) waves in the Terahertz Band (0.1-10 THz), due to the unique electron dynamics of this nanomaterial. This frequency range matches the predictions for the operation frequency of graphene-based radio-frequency (RF) transistors [24], [23].

In addition, there are also major challenges in the integration of the different components into a single device. New methods to position and contact different nano-components are currently being developed. Amongst others, *DNA scaffolding* [19] is one of the most promising techniques. In [19], a procedure to arrange DNA synthesized strands on surfaces made of materials compatible with semiconductor manufacturing equipment has been demonstrated. The positioned DNA nano-structures can serve as scaffolds, or miniature circuit boards, for the precise assembly of the nano-components.

Ultimately, the size of the nano-things has a direct impact on the multimedia capabilities, processing power, data storing capacity, energy harvesting rate and energy capacity, and communication abilities of the device. Adaptive communication schemes and networking protocols need to be developed in order to take into account the very high heterogeneity of devices in the Internet of Multimedia Nano-Things.

III. Communication Challenges

A. Multimedia Data Compression and Signal Processing

As a result of the very high pixel density and spectral response of nano-cameras and nano-phones, multimedia nano-things will have a huge amount of information to process and to transmit (e.g., several Terabits of information per second). At the same time, novel faster processing nano-architectures (e.g., Terahertz processors) and higher density nano-memories are expected. For all these, there is a need for novel solutions in data compression and signal processing for the Internet of Multimedia Nano-Things.

In particular, these are the three main challenges and our envisioned possible solutions:

- **To develop novel high efficiency compression algorithms for nano-cameras and nano-phones.** In our vision, there are two main paths to achieve this goal. On the one hand, novel video/audio encoding schemes need to be investigated, which *reverse the traditional balance of complex encoder/simple decoder*. The main reason for this is that we should be more energy efficient at the nano-things side, while increasing the complexity at the final destination of the stream. This is already a problem in current multimedia sensor networks [4]. On the other hand, novel joint compression algorithms for multimedia data, which can exploit the power of novel nano-processor architectures and eliminate the high data redundancy when sensing at the nanoscale are needed. Indeed, in a great number of applications, the high spatial resolution given by nano-cameras is not necessary, and can be removed *by exploiting the spatial correlation among nearby pixels*. A similar concept can be developed for the transmission of correlated audio streams.
- **To develop novel device architectures for nano-cameras and nano-phones.** In our vision, rather than first collecting all the information from very high density arrays of photodetectors or acoustic nano-transducers and then performing compression on them, it is necessary to *move the computation and the complexity towards the pixel or array elements*. This could be achieved in two ways: i) by giving intelligence to each nano-component in the multimedia nano-thing, for example, first, we can create clusters of nano-photodetectors/nano-phones and then each cluster can be controlled by an independent nanomachine with its own nano-processor, nano-memory and nano-transceiver; ii) by creating a multimedia nanonetwork-on-chip, i.e., all the nano-components/nano-clusters are connected for coordination and data exchange purposes. We define this concept as intra-sensor distributed data processing.

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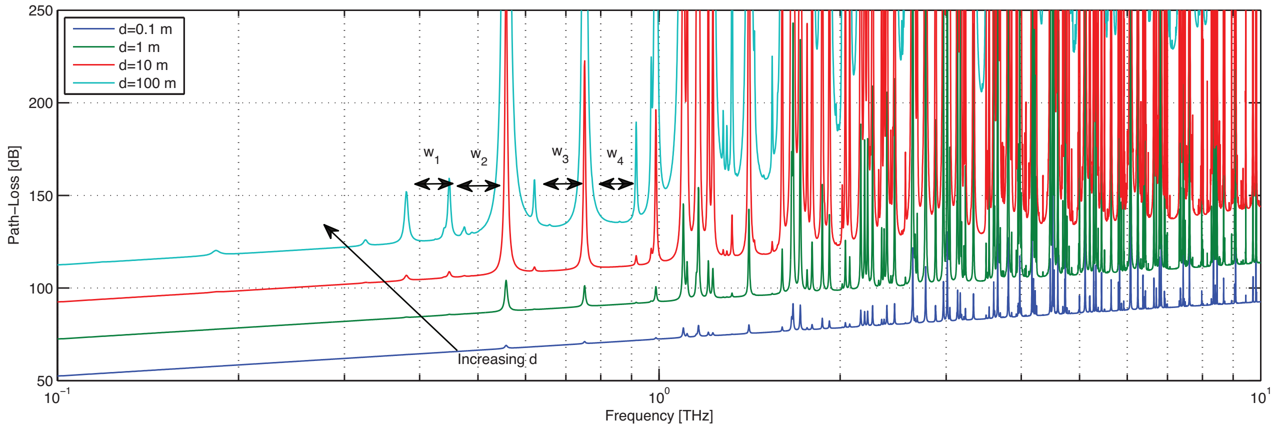

Fig. 3. Path-loss in the Terahertz Band for different transmission distances.

- **To develop faster intra-device communication techniques.** Even in current microscale cameras, reading the value from every single pixel can take some relatively large time. The use of very high density arrays of nanoscale photodetectors will only worsen this problem. To overcome this limitation, new intra-device communication technologies are necessary. In particular, in our vision, there is a need to understand the impact of using internal wired interconnections based on quantum nanoelectronics and quantum transport mechanisms as well as internal wireless communication through graphene plasmonic antennas and optical nano-antennas. This will have an impact not only in nano-cameras and nanophones, but also on current micro-devices.

B. *Terahertz Band Channel Modeling*

Despite efficient data processing solutions, multimedia nano-things will still have to transmit a very large amount of data in a timely and reliable fashion. Fortunately, graphene-based nano-transceivers [21], [24], [23] and nano-antennas [16], [39], [31] are expected to implicitly operate in the Terahertz Band (0.1-10 THz). The Terahertz Band supports the transmission of information at very high bit-rates, up to several Terabit/second (Tbps). However, this frequency band is also one of the least explored frequency ranges in the EM spectrum. Existing channel models for the Megahertz and the Gigahertz frequency bands cannot be reused for the Terahertz Band, because they do not capture several effects such as the attenuation and noise introduced by molecular absorption, the scattering from particles which are comparable in size to the very small wavelength of Terahertz waves, or the scintillation of Terahertz radiation. Due to the very high attenuation created by molecular absorption, current standardization efforts by the IGthz group [10] are focused on device development and channel characterization at the absorption-defined window at 300 GHz [28], [33]. However, we envision that either a higher frequency window, more than one window at the same time, or even the entire band will be needed to achieve stable Tbps links the IoMNT.

For this, we have recently developed a new channel model for Terahertz Band communications [17], [13]. In particular, we used radiative transfer theory to analyze the impact of molecular absorption on the path-loss and noise:

- The **path-loss** for a traveling wave in the Terahertz Band is defined as the addition of the spreading loss and the molecular absorption loss. The *spreading loss* accounts for the attenuation due to the expansion of the wave as it propagates through the medium. The *absorption loss* accounts for the attenuation that a propagating wave suffers because of molecular absorption and depends on the concentration and the particular mixture of molecules encountered along the path. As a result, the Terahertz channel is very frequency selective.
- The **molecular absorption noise** is the main noise source in the Terahertz channel. The absorption from molecules present in the medium does not only attenuate the transmitted signal, but it also introduces noise. The equivalent noise temperature at the receiver location is determined by the number and the particular mixture of molecules found along the path. The molecular absorption noise is not white, i.e., its power spectral density of noise is not flat, but has several peaks. In addition, this type of noise appears only when transmitting, i.e., there will be no noise unless the molecules are excited.

In Fig. 3, the total path-loss is shown as a function of the frequency and for different transmission distances (0.1m, 1m, 10m and 100m), for a medium containing a 10% of water vapor molecules. This figure has been obtained with the model given in [17], [13]. The path-loss can easily go above 100 dB even for transmission distances in the order of just a few meters. Due to the limitations in the transmitted power of Terahertz transceivers, very high directivity antennas are required to still be able to use the channel. In addition, the molecular absorption defines several transmission windows, whose position and width depend on the transmission distance. For very short distances, e.g., a few centimeters, the Terahertz Band can be seen as a single transmission window almost 10 THz wide. For longer transmission distances, more resonances become significant and the transmission windows

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become narrower. Several transmission windows, w1, w2, w3 and w4, have been marked in the figure.

In light of these results, these are additional research challenges in terms of Terahertz Band channel modeling:

- **To locate the *best* transmission windows in terms of channel capacity and achievable information rates** for a given transmission power and as a function of the transmission distance. By starting from the path-loss and molecular absorption noise model, the center frequency and its associated 3dB bandwidth of each transmission window can be computed. Different windows suffer from different path-loss and noise and have different 3dB bandwidth. With these, the maximum achievable information rate or channel capacity can be computed. In order to make an accurate analysis and to determine feasible values for the achievable bit rates, it will be necessary to account for the transmitter and receiver antenna directivity as well as for the gain and electronic thermal noise factor of the receiver.
- **To investigate the impact of multi-path propagation on the capacity and achievable information rates** in the IoMNT for different transmission windows, for a given transmission power and as a function of the transmission distance. In many scenarios, multi-path propagation will be present. The amplitude of the multiple reflections that the EM wave can suffer depends mainly on the material, the shape and the roughness of the surface on which it has been reflected. Many of the standard materials found in Terahertz networks scenarios are currently being characterized [11], [26]. Based on this, it is necessary to obtain the channel impulse response in the presence of multi-path in different scenarios as well as a model of the resulting channel fading and its temporal correlation (first and second order statistics).

C. Medium Access Control

Existing Medium Access Control (MAC) protocols cannot be used in IoMNT because they do not capture the peculiarities of the physical layer and the very high heterogenous capabilities of all sorts of nano-things. In particular, the three main particularities of the Terahertz Band and their impact on the MAC protocol design are:

- **The Terahertz Band supports the transmission at very high bit-rates, i.e., up to a few Tbps, which is several orders of magnitude over that of the current state-of-the-art wireless technologies.** Existing MAC protocols have been mainly designed for narrow-band channels and, thus, cannot exploit the transmission at these very high bit-rates. Even existing MAC protocols for networks at 60 GHz target much lower transmission rates.
- **The Terahertz Band has a unique relation between the available transmission windows, the 3dB bandwidth for each window and the transmission distance.** Shorter transmission links benefit not only from a much lower path-loss, but also from much wider transmission windows. As a result, dynamic band selection schemes, intelligent modulations, advanced ways to allocate the power within the transmission band, and novel channel access schemes can be developed to capture this distance dependence, unique to networks in this frequency band.
- **The Terahertz Band requires the use of very highly directional antennas in transmission and in reception in order to overcome the very high path-loss.** In addition, the very small size of a Terahertz antenna (just a few millimeters), allows the development of high density antenna arrays. Several MAC protocols for devices with directional antennas have been developed already. However, first, the directivity of Terahertz antennas is much higher than in the considered scenarios (more than one order of magnitude), and, second, these solutions do not capture any of the other two peculiarities above.

To address these fundamental differences, we envision that major contributions are needed along these two main research directions:

- **To develop novel transmission schemes which exploit the unique relation between the transmission 3dB bandwidth and the transmission distance.** Nano-things should be able to adapt their transmission window and the modulation scheme based on the distance between them as well as their hardware capabilities. For example, for very short transmission distances (below one meter), very low complexity modulation and communication schemes based on the transmission of femtosecond-long pulses could be used, such as the schemes we proposed in [15]. As the transmission distance increases, nano-things should focus their transmission power in a specific window, which can be jointly selected by the transmitting and the receiving nano-things, and make use of novel bandwidth adaptive modulations.
- **To develop a MAC protocol which dynamically selects the modulation scheme and, at the same time, which guarantees that the transmitter and the receiver are properly aligned before the transmission of a data packet.** For this, contrary to conventional transmitter-initiated communication, we believe that novel *receiver-initiated transmission schemes* will be more suited for this paradigm. In particular, we consider that a nano-thing periodically switches between three operation modes: sleeping mode, transmitting mode and receiving mode A nano-thing in *transmitting mode*, just waits for its intended receiver or relaying candidate to be available. A nano-thing in *receiving mode* scans its neighborhood by steering its antenna beam at a fixed speed and in a predefined pattern. During this process, the receiver announces its availability to receive a packet.

D. Addressing

In the IoMNT, assigning a different address to every nano-thing is not a simple task, mainly due to the fact that this would require either to individually assign these addresses at the manufacturing stage, or to use complex synchronization and coordination protocols between nano-devices. Moreover,

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taking into account that the IoMNT can contain extremely large numbers of nano-things, very long addresses would be needed if classical addressing schemes were followed.

Some envisioned solutions for the addressing challenges in the IoMNT are as follows:

- **To develop novel addressing schemes that capture and exploit the network hierarchy in the IoMNT.** In our vision, we can avoid the use of very long addresses among nano-things by taking into account the hierarchical network architecture of the Internet of Things and Nano-Things [5], [2]. In the majority of cases, only those nano-things coordinated by the same *nano-router* need different addresses. The global identifier of the nano-things will be established based on the gateway and the nano-router to which each nano-thing is connected.
- **To explore specific applications in which it is not necessary to have information from a specific nano-thing, but just from any nano-thing of a specific type.** For example, chemical nanosensor devices with different types of sensing unit can be jointly deployed in the same network. If information regarding the concentration or the level of a given substance in the air is necessary, there is no need to ask for a particular nano-thing, but the query can be satisfied by any nano-thing which can sense this substance. At the same time, different nodes will react in the same way depending on the information that is being sensed or their internal state. This can relax the coordination requirements among nano-nodes, while still supporting interesting applications.

E. Neighbor Discovery and Routing

The peculiarities of the Terahertz Band channel also affect the way in which network layer solutions should be developed for the IoMNT. Existing neighbor discovery and routing protocols cannot be used in the IoMNT because they do not capture the properties of the physical layer, such as, the capability to transmit at very high bit-rates, the use of very highly directional antennas, and, more importantly, the unique relation between the transmission distance and the available 3dB bandwidth, which does not occur in lower frequency bands of the EM spectrum. In addition, the capabilities of nano-things change drastically between devices and thus, there is a need to account for the heterogeneity in the nano-things by means of resource dynamic protocols.

In particular, these are two of the main research directions that require novel solutions:

- **To investigate novel neighbor discovery strategies that exploit the high directivity of Terahertz antennas to simultaneously determine the relative location and orientation among nano-things.** For example, in addition to the transmitting mode and receiving mode mentioned before, a nano-thing can go in discovery mode. The *discovery mode* of a nano-thing is similar to the receiving mode, but rather than just looking for incoming information, the device is actively looking for its neighbors. When a node receives a packet from a node in discovery mode, it quickly replies back with its ID. By this short control packet exchange, the two nodes can determine their relative position and orientation. In particular, first, the use of very highly directional antennas, allows a node to accurately estimate the Angle of Arrival (AoA) of the EM signal. With the AoA, the relative orientation between the nodes is approximately set. The spectral shape of the transmitted packets can be used to infer the available 3dB bandwidth, and, thus, the distance between them.
- **To develop novel routing protocols by starting from the proposed neighbor discovery mechanism, and by taking into account as a metric the expected waiting time for the transmitter and next hop relay antenna beams to be aligned as well as the available transmission bandwidth between the two nodes.** In addition to classical routing metrics, a node can decide the next hop in the route by taking into account the estimated meeting time with the relaying candidates (whose antenna beam is periodically swiping the space looking for awaiting transmitters) as well as the best modulation scheme based on the distance between the nodes as well as the overall network interference. Based on this, a node may decide to wait longer for a node to whom then he can transmit faster and with lower interference (by using a lateral modulation scheme), rather than transmitting to the first coming candidate if the available 3dB window is narrower.

F. QoS-Aware Cross-Layer Module

Many of the functionalities in the envisioned MAC and Routing solutions are closely related and heavily depend upon the Terahertz channel peculiarities, such as the unique relation among the transmission distance, the transmission windows, the 3dB bandwidth of each transmission window and the antenna directivity. In addition, due to the nature of the Internet of Multimedia Nano-Things, a very high heterogeneity in the capabilities of the nano-things is expected. Moreover, the transmission of multimedia content usually imposes strict requirements in terms of Quality of Service (QoS), e.g., maximum packet delay or maximum packet error rate. A joint optimization of all these network functionalities (e.g., physical layer, MAC, routing) is required in order to achieve the highest possible performance under different network metrics.

For this, we envision a cross-layer communication framework for the IoMNT. The main performance objectives of this framework should be as follows:

- **To efficiently exploit the Terahertz Band channel,** by choosing the best modulation that exploits the available 3dB bandwidth in light of the specific capabilities of the nano-things involved in each link.
- **To jointly overcome the limitations of highly directional Terahertz antennas,** by combining the dynamic neighbor discovery, the receiver-initiated transmissions and the routing functionalities, as described in Sec. III-C and Sec. III-E above.
- **To select data paths compliant with the envisioned application requirements and QoS,** in terms of max-

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imum acceptable end-to-end packet delay or end-to-end successful packet delivery probability.

This cross-layer framework can be then utilized to explore and develop new fundamental results on the performance of very large scale multimedia networks. For example,

- **To develop a new rate-energy-distortion theory for the Internet of Multimedia Nano-Things.** QoS and distortion aware protocols have been developed for classical multimedia sensor networks. However, the fundamental limits of these techniques have not been explored. In particular, it is necessary to investigate i) the minimum distortion that can be achieved for a given energy budget and given bandwidth in a very large-scale network (trillions of nano-things), or ii) the trade-offs between distortion, bandwidth and network lifetime.
- **To investigate the impact of several physical layer, MAC and Routing parameters in the overall network performance in terms of end-to-end packet delay, end-to-end energy per bit consumption, end-to-end successful packet delivery probability, or network throughput.** For example, the chosen transmission window, the transmission and reception antenna beam shapes and steering patterns, the type of modulations, the error correcting schemes or the packet size, have a direct impact on the network performance, and can be optimized in a cross-layer fashion.

G. Security

Nano-things are vulnerable to all sorts of physical and wireless attacks. On the one hand, nano-things will be unattended most of the time and, thus, it is easy to physically attack them. In addition, due to their almost imperceptible size, involuntary physical damage is also likely to occur. On the other hand, both classical and novel types of wireless attacks to nano-things are possible and relatively simple, despite the fact that the nano-devices communicate at ultra- high transmission rates and over very short transmission distances.

Existing security solutions cannot be directly used in the IoMNT because they do not capture the peculiarities of the Terahertz Band physical layer and the heterogeneity in the capabilities of diverse nano-things. For this, future research trends should be along these three main directions:

- **To develop new authentication mechanisms for nano-things.** In many of the envisioned applications, it is crucial to certify the identity of the transmitting or receiving nano-device. Due to the very large number of nano-devices in the IoMNT, classical solutions based on complex authentication infrastructures and servers are not feasible. For this, in our vision, new authentication mechanisms that exploit the network hierarchical structure of the IoMNT is needed. For example, nano-things might need to only authenticate themselves to the closer nano-router or nano-to-micro interface [2]. This can be done by means of a unique EM signature, which is a well-established property of Terahertz radiation.
- **To develop novel mechanisms to guarantee the data integrity in the IoMNT.** As in any communication network, it is necessary to guarantee that an adversary cannot modify the information in a transmission without the system detecting the change. Data can be altered either when stored or when being transmitted. Due to the expectedly very limited memory of miniature nano-things, the first type of attack is unlikely. However, new techniques to protect the information in nano-memories will be developed by exploiting the quantum properties of single-atom memories to implement practical solutions from the realm of quantum encryption. On its turn, despite the information is transmitted at very high bit-rates, guaranteeing the data integrity while the information is being transmitted requires the development of new secure communication techniques for IoMNT.
- **To develop new mechanisms to guarantee the new user privacy in the IoMNT.** Nano-things can be used to detect, measure and transmit very sensitive and confidential information, which in any case should be available to non-intended addressees. Moreover, due to their miniature size, nano-things will be usually imperceptible and omnipresent. In our vision, new mechanisms to guarantee the privacy in the IoMNT are needed. Amongst others, techniques to guarantee that a user can determine and limit the type of information that nano-things can collect and transmit are needed in our vision. Moreover, physical-layer security mechanisms need to be explored to prevent the eavesdropping problem.

IV. CONCLUSIONS

Nanotechnology is enabling the development of advanced nano-devices which are able to generate, process and transmit multimedia content at the nanoscale. The wireless interconnection of pervasively deployed nano-devices with all sorts of devices and ultimately the Internet will enable the Internet of Multimedia Nano-Things. The IoMNT is a truly cyber-physical system with applications in many diverse fields, e.g., in advanced health-monitoring systems; as a countermeasure for novel biological and chemical attacks at the nanoscale; for monitoring and control of industrial processes that require atomic and molecular precision; or in forensic science.

In this paper, we have described the state of the art in the development of nano-things from the device perspective. In particular, we have shown that future nano-cameras and nano-phones will be able to generate a huge amount of visual and acoustic content with very high accuracy and resolution. The need to process and compress this very large amount of data motivates the development of new multimedia data compression and signal processing techniques. In any case, and despite those, very large amounts of data will need to be transferred among nano-things in a reliable and timely manner. This introduces many communication and networking challenges in the realization of this novel paradigm.

In particular, we have outlined the main research trends and possible solutions to novel challenges in terms of Terahertz

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Band channel model, medium access control mechanisms for nano-things, addressing schemes, and neighbor discovery and routing techniques for the IoMNT. In addition, we have motivated and proposed a novel cross-layer communication framework which can capture the peculiarities of the Terahertz Band physical layer as well as the very heterogenous capabilities of diverse nano-things. While the division of network functionalities in separate layers can simplify the design of each task individually, the optimal network performance can only be achieved within a cross-layer communication framework. Finally, the security challenges in terms of authentication, privacy and data integrity have been discussed.

We acknowledge that there is still a long way to go before having integrated multimedia nano-devices, but we believe that hardware-oriented research and communication-focused investigations will benefit from being conducted in parallel from an early stage.

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