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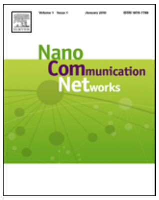

The Internet of Multimedia Nano-Things

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ABSTRACT

Nanotechnology is enabling the development of novel devices which are able to generate, process and transmit multimedia content at the nanoscale. The interconnection of pervasively deployed multimedia nano-devices with existing communication networks and ultimately the Internet defines a novel communication paradigm that is further referred to as the Internet of Multimedia Nano-Things (IoMNT). The IoMNT is a truly cyber–physical system with a plethora of applications in the biomedical, security and defense, environmental and industrial fields, amongst others. This paper discusses the state of the art and major research challenges in the realization of the IoMNT. Fundamental research challenges and future research trends are outlined in terms of multimedia data and signal processing, propagation modeling for communication amongst nano-things in the terahertz band, physical layer solutions for terahertz band communication and protocols for the IoMNT. 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.

1. Introduction

The Internet of Things (IoT) enables the interaction among all types of real-world physical elements (e.g., sensors, actuators, personal electronic devices and home appliances) over the Internet [6,36]. 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, amongst 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 generally 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. Amongst others, graphene [9], a one-atom-thick planar sheet of bonded carbon atoms densely packed in a honeycomb lattice, has been lately referred to as *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 [24,48], nano-batteries [14,42], and nanosensors [41,35], which outperform their microscale counterparts. Moreover, the expected frequency band of operation of novel graphene-based nano-transceivers and nano-antennas points to the terahertz band (0.1–10 THz), which opens the door to ultra-broad-band communications amongst nano-devices [30,16].

Going one step further, nanomaterials are also currently being proposed to develop a new generation of miniature

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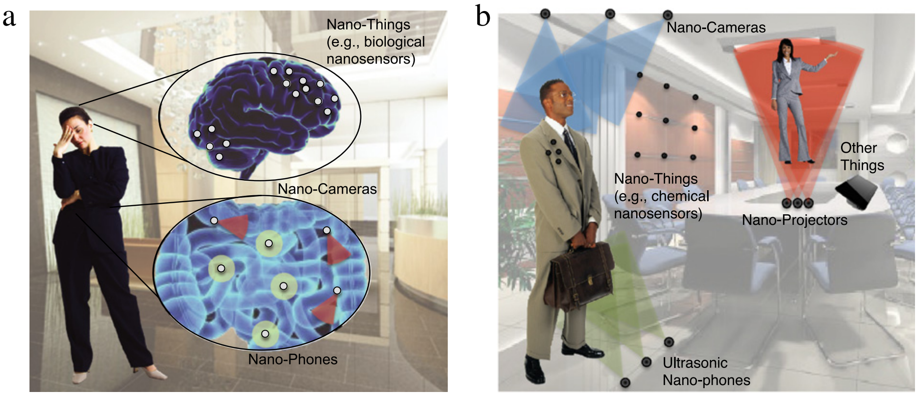

Fig. 1. Applications of the Internet of Multimedia Nano-Things.

photodetectors [27,10] and acoustic nano-transducers [22,39], 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 unprecedented resolution and accuracy, much higher than current micro-cameras and microphones. In addition, the integration of nano-cameras, nano-phones, scalar nanosensors, 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 [4,5] by providing higher quality image and audio sensing capabilities, higher computational and storing capacities, higher energy efficiency and expectedly higher wireless communication data-rates [15,17] than classical multimedia sensors. Nano-things are not necessarily small, but macro-sized nano-things with millions of nano-precise components will be developed too.

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 with the envisioned applications of the IoT [6,36], but it also enables more advanced applications in diverse fields.

- *Biomedical applications*: e.g., advanced health monitoring and treatment 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 diseases [44,45].
- *Defense and security applications*: e.g., imperceptible nano-cameras for remote nanoscale imaging, ultrasonic nano-phones for concealed objects detection, and biological and chemical nanosensors [49] as a countermeasure for unprecedented nanotechnology-enabled attacks.
- *Advanced multimedia applications*: e.g., ultra-high-resolution imaging, for example, of crime scenes (application in forensics); ultra-high-resolution imaging of distant objects, for example, in far-field aerial or satellite imaging; and high-definition holographic videoconferencing.

For example, in Fig. 1, two sample applications of the IoMNT are shown. In Fig. 1(a), a biomedical application is illustrated. In particular, biological nanosensors are used to monitor the brain activity, specific chemical substances or the intracranial pressure. Similarly, nano-cameras are used to monitor the digestive system. The use of imperceptible multimedia nano-things is much less invasive than current techniques which rely on microscale technologies [8,25]. In Fig. 1(b), 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 is 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 threats.

Nevertheless, the high heterogeneity in the capabilities of multimedia nano-things, and the communication requirements of the scenarios in which they will be used, introduce several research challenges in the realization of the IoMNT. 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 Section 2. In Section 3, we outline the main research challenges in the IoMNT from the communication perspective, in terms of multimedia and data signal processing, terahertz band propagation modeling, physical layer implementation 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 Section 4.

2. Device components

Many nano-thing components have already been prototyped and tested. However, several challenges remain from the device perspective that need to be addressed in order to turn existing nano-devices into autonomous machines.

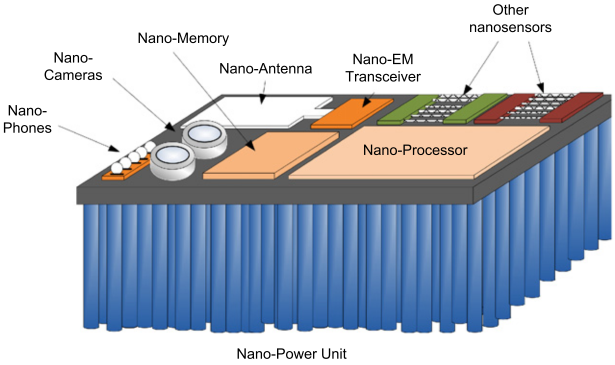

Fig. 2. Conceptual architecture of a multimedia nano-thing.

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* [1–3] (Fig. 2). To date, several solutions have been proposed for each component.

- *Nano-cameras*: New photodetectors based on novel nano-structures have been demonstrated [27,10]. Their main properties are as follows.
  - Very small size (below 100 nm per pixel, which allows the integration of very dense arrays).
  - Very high sensitivity at low energy levels (i.e., better low-light conditions imaging).
  - Very low 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.
- *Nano-phones*: Novel nanoscale acoustic transducers for ultrasonic applications have been prototyped [22,39]. The integration of nanoscale acoustic transducers into miniaturized arrays will enable the development of novel nano-phones (i.e., nanoscale micro-phones) with the following features.
  - Higher directional resolution (surround audio sensing and recording).
  - Better 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 nanosensors*: Physical, chemical and biological nanosensors have been developed by using graphene and other nanomaterials [11,49]. 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 [33]. 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 directly depend on the number of integrated transistors in the chip, and thus on its total size.
- *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 [7]. For example, in a magnetic memory [31], 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 [14,42] as well as nanoscale energy harvesting systems [46]. One of the most studied 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 [20,21]. Alternatively, graphene has been also used to enhance the absorption of light in novel organic photovoltaic cells [28]. 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 [16,50,37]. Amongst others, in [16] we determined that a 1 μm long graphene-based nano-antenna can efficiently radiate electromagnetic (EM) waves in the terahertz band (0.1–10 THz), due to the unique propagation characteristics of surface plasmon polariton waves in this nano-material. This frequency range matches the predictions for the operation frequency of graphene-based radio-frequency (RF) transistors [30,29]. Given the very small antenna size, very large antenna arrays can be created, with a total number of active elements at least one order of magnitude above current systems.

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* [23] is one of the most promising techniques. In [23], 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.

3. Communication challenges

In this section, we highlight the main communication challenges and future research trends in the IoMNT. As emphasized in the previous sections, the high heterogeneity in the capabilities of the nano-things (tightly related to their size and the application for which they have been developed) requires the development of highly adaptive solutions.

3.1. 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 IoMNT.

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 amongst 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.
- *To develop faster intra-device communication techniques*. Even in current microscale cameras, reading the value from every single pixel can take a relatively long 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 nano-phones, but also on current micro-devices.

3.2. 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 [26,30,29] and nano-antennas [16,50,37] 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 terabits per second (Tbps). However, this frequency band is also one of the least explored frequency ranges in the EM spectrum.

Existing channel models for lower 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 [12] are focused on device development and channel characterization at the absorption-defined window at 300 GHz [34,40]. 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 to the IoMNT.

For this, we have recently developed a new channel model for terahertz band communications [15,17]. In particular, we used radiative transfer theory to analyze the impact of molecular absorption on the path-loss and noise.

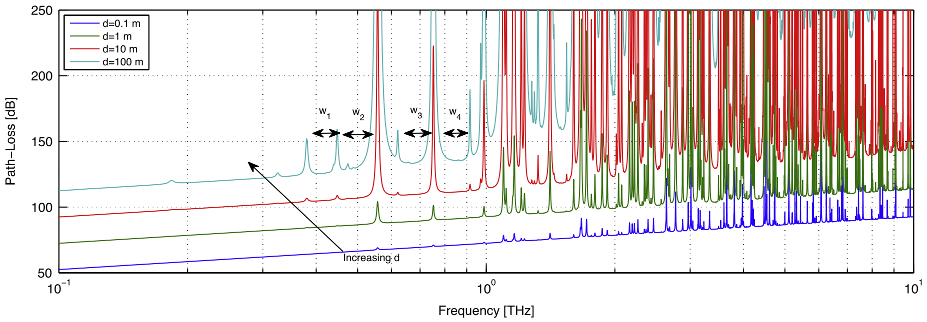

Fig. 3. Path-loss in the terahertz band for different transmission distances.

- 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; 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 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 (0.1, 1, 10 and 100 m), for a medium containing 10% of water vapor molecules. This figure has been obtained with the model given in [15,17]. 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 become narrower. Several windows, w_1, w_2, w_3 and w_4, 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 3 dB bandwidth of each transmission window can be computed. Different windows suffer from different path-loss and noise and have different 3 dB 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 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 [13,32]. Based on this, it is necessary to obtain the channel impulse response in the presence of multi-path propagation in different scenarios as well as a model of the resulting channel fading and its temporal correlation.
- *To analyze the effect of terahertz radiation on biological entities*. Nano-devices might be placed over or even inside the human body in the long term, and their effects on the human body need to be analyzed. First of all, note that terahertz radiation is not ionizing and, thus, it cannot break molecules or biological entities. Second, despite some initial results pointing to the mechanical resonances in DNA molecules induced by terahertz radiation, which could further result in mutations, the latest research works have shown that those initial results were inaccurate [43,47]. For this, it is necessary to investigate the different types of resonance that terahertz waves can create in different biological entities starting from bipolar molecules, macromolecules, amino acids, proteins, organelles and cells.

3.3. Physical layer

Existing modulations and coding schemes are not suitable for the IoMNT because they do not capture the peculiarities of the terahertz band and the capabilities of the multimedia nano-things. In particular, these are the main particularities of terahertz band communication in the IoMNT when compared to classical wireless communication in microscale networks, which affect the design of modulation and coding schemes.

- *The terahertz band provides nano-things with a very large transmission bandwidth, several orders of magnitude above classical wireless systems*. In contrast, existing modulations and coding schemes have been primarily designed for band-limited channels (a few tens of megahertz wide at most).
- *The terahertz band has a unique relation between the available transmission windows, the 3 dB bandwidth for each window and the transmission distance*. Shorter transmission links benefit not only from a much lower path-loss, but also from wider transmission windows.
- *The very small size of a terahertz antenna (just a few millimeters with classical metals, just a few micrometers when using graphene) allows the development of very large antenna arrays*. Many mobile wireless communication systems take advantage of antenna arrays, but usually the number of active elements is low.

Resulting from these properties, extensive research is needed in the following two directions.

- *To develop novel transmission schemes which exploit the unique relation between the transmission* 3 dB *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 [18]. As the transmission distance increases, the nano-things should focus their transmission power in a specific window and make use of novel bandwidth adaptive modulations. In addition, new *ultra-broad-band very large-scale MIMO systems* need to be investigated for more advanced nano-things with very large antenna arrays [38].
- *To develop new channel coding schemes suited to the capabilities of nano-things and tailored to the nature of transmission errors in the terahertz band*. For example, in [19], we proposed novel *low-weight channel codes* for error prevention in terahertz band communications. By simply reducing the coding weight of any existing coding scheme, the number of channel errors due to noise and interference in the terahertz band can be reduced. In addition, joint source and channel coding schemes suitable for multimedia data transmission need to be investigated. Moreover, new *frequency–space–time codes* built on top of very large MIMO will be required for more advanced nano-things (e.g., nano-routers) with higher capabilities.

3.4. Medium access control

Existing medium access control (MAC) protocols cannot be used in the IoMNT because they do not capture the peculiarities of the physical layer and the high heterogeneity in the nano-things' capabilities. In particular, the peculiarities of the terahertz band and their impact on the MAC protocol design are as follows.

- *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. In addition, as a result of the very large transmission bit-rate, interference is only a problem in very high node density applications.
- *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*. 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. Note that this also diminishes the chances of having multi-user interference.

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

- *To develop new interference models for terahertz band communications, which take into account the propagation peculiarities of the terahertz channel, the use of very high directivity antennas, and the specific type of modulation in use*. For example, in [18,19], we developed novel stochastic models for the interference under different network topology assumptions. These models are useful, first, to understand what the main characteristics of multi-user interference in the terahertz band are, and, second, to analytically model the performance of novel protocols for IoMNT.
- *To develop MAC protocols which dynamically select the modulation scheme and, at the same time, which guarantee 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 in a predefined pattern. During this process, the receiver announces its availability to receive a packet. In addition, in the case of very resource-limited nano-things, new MAC protocols that *shift the complexity to more advanced devices in the network hierarchy* (e.g., nano-routers) should be investigated.

3.5. 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 one either to individually assign these addresses at the manufacturing stage, or to use complex synchronization and coordination protocols between nano-devices. Moreover, 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 amongst nano-things by taking into account the hierarchical network architecture of the Internet of Things and Nano-Things [6,2]. 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 amongst nano-nodes, while still supporting interesting applications.

3.6. 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 3 dB 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 amongst nano-things*. For example, in addition to the transmitting mode and receiving mode mentioned before, a nano-thing can go into 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 3 dB 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 which it can then transmit faster and with lower interference (by using a lateral modulation scheme), rather than transmitting to the first coming candidate if the available 3 dB window is narrower.

3.7. 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 amongst the transmission distance, the transmission windows, the 3 dB bandwidth of each transmission window and the antenna directivity. In addition, due to the nature of the IoMNT, 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 3 dB 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 Sections 3.4 and 3.6.
- *To select data paths compliant with the envisioned application requirements and QoS*, in terms of maximum 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. Some examples are as follows.

- *To develop a new rate-energy-distortion theory for the IoMNT*. QoS-aware 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 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.

3.8. 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. In its turn, despite the information being 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.

4. 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 amongst 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 band channel model, modulation and coding, 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.

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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