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Challenges and Requirements towards Realizing Internet of Nano Things

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Abstract – The world of IoT has enabled user's to interact with the environment, in order to perform various tasks that best suits their requirements and daily lives. This includes the ability for end users to interact with miniature sensors within the environment, where such sensors can provide vital information (e.g. ECG from on-body sensors). However, extending the IoT to include nanoscale sensors and devices can further expand the application base of IoT. Connectivity of nanosensors can be realized through nano communication, leading to miniaturized nanonetworks. By interconnecting nanoscale networks to the wider Internet, collecting sensed information at microscopic level and in hard-to-access areas will be possible. In this article, we first present an overall vision of Internet of Nano Things (IoNT) before diving deep into two main challenges. These challenges are focused on immediate connection between nanonetworks and the wider Internet, in particular data collection processes and middlewares of devices connecting to nanonetworks. The article also provides a brief outlook on extensions to current pervasive computing environment that could benefit from IoNT, and potential applications of IoNT.

1. Introduction

The vision of Internet of Things (IoT) has transformed the usage of the Internet, as well as interactivity and daily lives of users. Through IoT, users are surrounded by various types of objects, sensors and devices, which can combine and provide effective pervasive environments that can further enhance each user's daily lives as well as their needs. A very good example is in the healthcare domain, where sensors on body (e.g. Body Area Networks) can collect vital information of patients, and feed this information to services operating on medical officer's computing device, allowing more accurate and virtual monitoring of patients. Medical officers, in turn, will be able to monitor large number of patients in a scalable and efficient manner. We have also witnessed, for example, the use of sensors embedded in the living environment that provide ambient assisted living for the elderly.

Parallel to the advancement of the Internet and the sensing world, are also the advances in the field of nanotechnology. Since Richard Feyman's famous Nobel Prize speech in 1959, the field of nanotechnology has advanced tremendously, resulting in sophisticated devices with numerous healthcare applications (e.g. improved sensing at molecular level, accurate and targeted drug delivery). In recent years, the field of nano and molecular communication has emerged, where the objective is to develop new communication paradigms that can enable nanodevices to communicate. Enabling communication between nanodevices will further enhance and improve their capabilities, where these miniature devices can cooperate and possibly lead to new application scenarios [1].

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The communication, however, does not have to be limited to peer nanodevices, but may also extend to the wider Internet. While IoT aims to provide a pervasive presence through the various objects and devices that surround the users, extending this communication to nanodevices will bring a new dimension to IoT. By embedding objects with nanosensors, a new layer is augmented to the architecture of IoT. This augmentation, will lead to discovery of fine grained data within the objects and from hard-to-access areas, that can be collected, analyzed, processed, and delivered to end users. The objects within IoT will continue to provide pervasive support for users. However, the augmentation of nanodevices interconnected through nanonetworks will provide a new level of information that will open opportunities for a new class of services. An example of IoNT could be a user embedded with nanonetworks within the Body providing information from internal of the body (*Body Area NanoNetworks (BAN^2)*), and this could be augmented with environmental sensors that are embedded with nanonetworks collecting chemical information within the living environment. The two source of information could therefore, provide very accurate diagnosis and analysis of a person's condition.

The concept of IoNT was first introduced by Akyildiz and Jornet [2], where a general IoNT architecture for electromagnetic nanodevice communication was introduced, including challenges in terms of channel modeling, information encoding as well as protocols. Akyildiz and Jornet described the communication components that are most suitable for the scale of a nanodevice, and this was particularly focused on graphene-based nano-antennas. The use of graphene-based antennas is most energy efficient when communication is performed in the Terahertz band. However, this leads to very unique and sensitive properties, such as path loss and noise resulting from molecular absorption (molecular absorption affects the attenuation of propagating waves). Akyildiz and Jornet also briefly addressed new forms of routing as well as service discovery that would be required for electromagnetic based nano communication.

However, in this article, we focus on the system aspect of IoNT. The specific challenges we focus on are the mechanisms of collecting data from electromagnetic as well as molecular nanonetworks, and extensions of middlewares needed by micro-gateways to manage nanonetworks (in this article, by micro-gateways we refer to conventional micro-sensors that can connect to nanosensors). This article also provides a brief outlook on extensions that current context and service systems will need to enable pervasive computing environment to support IoNT.

2. The Internet of Nano Things

As illustrated in Fig. 1, an envisioned full model of IoNT includes underlying nanoscale networks connecting multitude of nanosensors, devices that interact with the nanonetworks and process their information in a distributed manner, as well as context and service management systems. In this section,

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we will provide a brief background description of solutions that have been proposed for nano communications.

Nano and Molecular Communication

While numerous approaches have been proposed for nano communication (e.g. acoustic), in this paper we will only consider *molecular communications* and *Electromagnetic nanonetworks (EM-nanonets)* [1]. This section will briefly describe some examples, properties and key characteristics of each.

Molecular Communications **-** Molecular communication enables nanodevices to communicate with each other in a biological environment, by overriding the current biological communication system or utilizing biological components specifically for communications. There exist molecular communications within the human body that allow cells and systems to communicate with each other. A number of different solutions have been proposed to artificially create molecular communications that can allow nanodevices to communicate [1] [10]. In this case, information are first converted to biomolecules (e.g. ions, DNAs, peptide) and carried over towards the receiver, which in turn will decode this information for recipient nanodevices. Example solutions proposed include molecular diffusion of biomolecules, calcium signaling [7], bacteria nanonetworks [8], virus nanonetworks [9], and the use of neurons [10]. In the case of bacteria and virus, these can carry genetic information, which are suited for sensors that encode information into DNA form. The vision for nanodevices in molecular communication is synthetic devices constructed from biological components (e.g. re-programming of a biological cell to behave as a sensor) to perform certain functionalities.

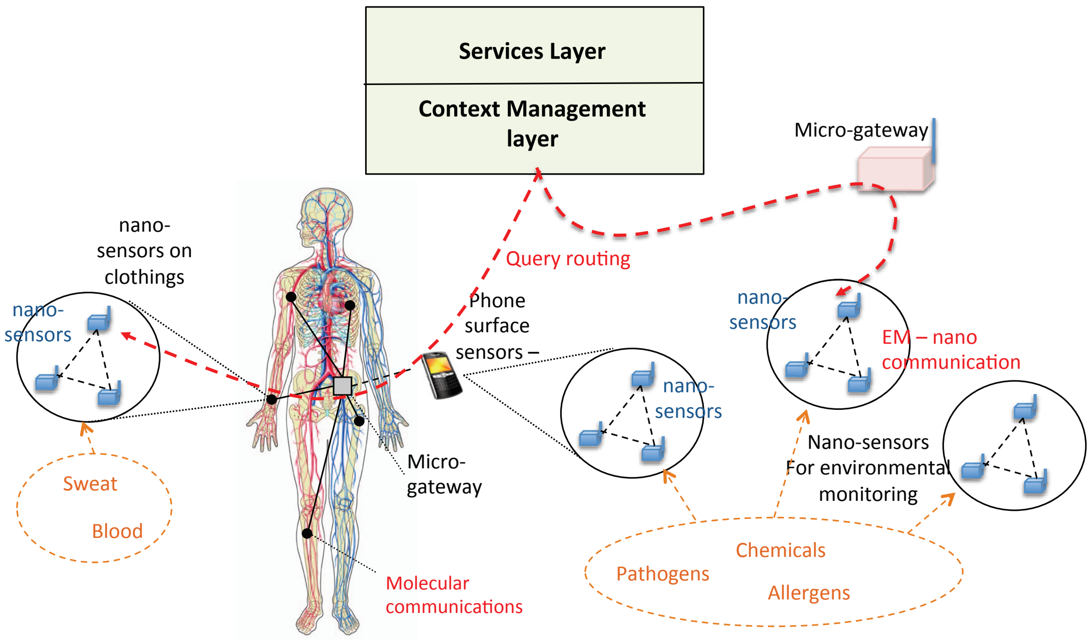

Fig. 1 Vision for Internet of Nano Things

Electromagnetic nanonetworks - EM communication on the other hand is

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slightly more conventional than molecular communications, where each device resembles a micro-sensor (e.g. motes), with a size range of 2μm – 6 μm. Besides the scale, the components used to build the device are at nanoscale, including nano antenna, nano EM transceivers, nano processors, etc. [2]. As described earlier, it is envisioned that the antennas would be built from graphene materials that communicate in the Terahertz band [2].

Therefore, the design of protocols as well as mechanisms of interaction between nanodevices will require a whole new thinking to accommodate the properties of nano communication. For example, in the case of molecular communications, these properties may include slow speed in transmission between nanodevices or high unreliability in message transmission (this could be due to high level of noise in biological environment; slow propagation of molecules or motility of bacteria/virus). In the case of EM based nanonetworks, devices at such small scale must posses the ability to self-power or harvest energy, cater for timing differences between harvesting period and transmission period, as well as cope with molecular absorption found on graphene antennas that can affect transmission reliability.

In this article, we will present important elements that are required to realize the challenges of IoNT system. Table I presents a summary of challenges and proposed solution for IoNT systems. The summary of challenges are organized into three categories, namely Data Collection which focuses on mechanisms of collecting and routing data from nanonetworks, IoNT middleware and its role in interconnecting between nanonetworks and micro-gateways, and future outlook which briefly discusses challenges in context and service management supporting IoNT.

Table I. Challenges and Proposed Solutions for IoNT

	Challenges	**Proposed Solutions**
Data Collection		
System Architecture	High ratio of nanosensors to micro-gateways could lead to swift energy depletion if the micro-gateway has to process information from every single nanosensor.	Distribute the sink architecture and develop a 2-layered hierarchy, which consists of micro-gateways and nanonetworks.
IoNT Routing	Data transmission between nodes in EM-nanonetworks is constrained by limited memory, computational power and energy.	Single - hop transmission to micro-gateway through a star topology. Incorporating unconventional routing techniques (e.g. mobile nodes in Delay Tolerant Network can be used to carry bulk data from nanonetworks).
	Molecular nanonetworks: information that is converted to molecules may move very slowly between network nodes, and face high unreliability (e.g. molecules	Opportunistic routing through multi-hop relays of nanodevices. The topology can be based on random or unstructured graphs.

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	could get lost).	
	Minimize quantity of data transmission from nanosensors.	Incorporate query based routing, where queries are routed between micro-gateways.
IoNT Middleware		
Self - awareness.	Unstable and unreliable environment (e.g. water vapor in the environment for EM-nanonets; molecule diffusion affected by fluid motion in the environment for molecular nanonetworks).	Integrate self-awareness mechanisms at the micro-gateway, where learning of environmental condition could be performed.
Data analysis and processing.	Dynamic changes in the environment can lead to large quantity of data transmitted along the micro-gateway routes. Current approach is limited since it utilizes static trees to collect data from sensors, and passes this to the sink node at the root.	Incorporate a dynamic tree structure, created through interactions between the micro-gateways.
	Timing difference between data propagation from nanonetworks to micro-gateway could lead to disparate timing of transmission between individual nanodevices to micro-gateway.	Integrate time-delayed data fusion process at micro-gateway, by waiting for all messages to arrive before further routing to peer micro-gateways.
Energy conservation through synchronization.	The micro-gateway, as a central point of interface, could deplete its energy swiftly by interfacing with the nanonetworks.	Through awareness of the environment, the micro-gateway could synchronize its sleep pattern to the nanonetwork charging patterns (EM-nanonets) or latency in molecular transmission (molecular networks).
Outlook		
Context Processing for fine granularity of data	Spectrum of heterogeneous data is further expanded when incorporating data collected from nanonetworks.	Integration of specialized ontologies (e.g. Gene ontologies) to enhance reasoning.
Security and Privacy	Information from nanosensors may include molecular and genetic data of individuals.	Incorporation of security for sensitive data collection, as well as privacy for collecting large molecular or genetic sample data of users.
Service Composition and Discovery	Current distributed service architecture, composition, and discovery may not be sufficient to cope with scales of nano and molecular nanonetworks.	Incorporate two layered service models (application services and data collection services), where two layers interact. Each layer can have clustered models for service

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		composition and discovery.

3. Data Collection

An important consideration that is anticipated in the future of IoNT, is the large quantity of data that will result from the number of nanodevices in the environment. This section will present important challenges and possible approaches for data collections in IoNT environment.

System architecture: While sensor network architectures in the past have always considered a certain number of sinks to collect data from the sensors, such a solution may not be feasible to support multitude of nanonetworks. Therefore, we believe an intermediate layer of devices is required. In this case, a micro-gateway could act as this intermediate layer. Fig. 2 illustrates the hierarchical structure that enables micro-gateways to interact with nanonetworks. Since each micro-gateway will have dual roles of interfacing to nanosensors and routing between micro-gateways, we assume that each micro-gateway will have dual transceivers (only in the case of EM-nanonets). This dual model will include a transceiver to communicate with nanonetworks at the Terahertz band, and a transceiver at Gigahertz band to communicate with peer micro-gateways.

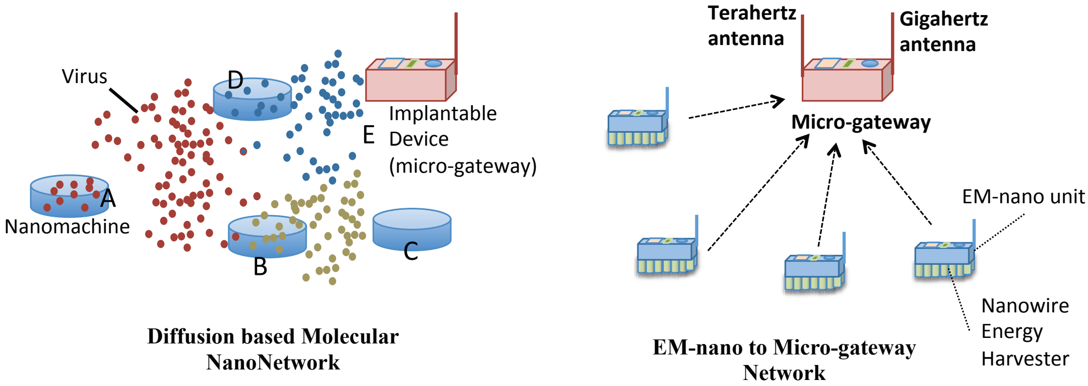

Fig. 2 Examples of Multi-hop molecular and EM-nanonets interfacing to a Micro-gateway

IoNT Routing: Routing has been and will always be a requirement for information transmission through communication networks. In particular routing for sensor networks has been a major research area in the last few years. Majority of sensor network routing algorithms have focused on objectives such as energy-efficiency (or energy harvesting capabilities) as well as scalability. However, before addressing the routing challenges, we will first address the fundamental differences between micro-sensor devices and nanosensor devices, which are as follows:

- Energy of nanosensors is severely limited compared to micro-sensors, where energy harvesting is required to power the device. For example, EM-nanonet devices may use vibrations of nanowires for generating energy, while devices of molecular nanonetworks may use biochemical

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from the environment to fuel the device.

- Nanodevices have very limited memory storage and computational processing capabilities that lead to the devices having limited capability or awareness (e.g. tables of neighboring nodes, topology knowledge) of the communication environment. This blindness by the nanodevices leads to an inability to perform address lookup or calculation of paths.

Routing for EM-nanonets: Although these devices will have dedicated nano-memory, storing protocol code maybe an issue. Therefore, it is expected that these devices will not have the ability to calculate routes to a destination node. This limitation is also extended to the cooperation capability between the devices. Therefore, we expect the architecture to support interaction of EM-nanonet devices to be hierarchical, with an environment of nanodevices communicating single hop to a micro-gateway, i.e. a star topology. We believe that data transmissions between the nanodevice and the micro-gateway will not suffer from packet collision. This is due to the limited memory of the unit being able to only produce packets will small number of bits, and these packets will be transmitted within nano seconds. Due to the limited energy in the nanodevice, the communication protocol will largely be query based, where queries are routed between the micro-gateways, to reach the specific nanodevice.

Routing for Molecular nanonetworks: The information transmitted in molecular nanonetworks can be represented in two forms. This includes information stored within a DNA component (this resembles an IP packet representation) or in binary representation. The binary representation is usually a concentration of molecules that are transmitted between the nodes (e.g. binary 1 is represented as a specific concentration compared to 0 which is represented as no molecular transmission). However, unlike the EM-nanonets, the routing within molecular nanonetworks can be multi-hop. This is required due to the limited range that molecules or organism carrying the message can travel. However, similar to the EM-nanonet device, a relay nanodevice will not have a routing table that can compute routes to a destination point. Therefore, the routing mechanism will largely be opportunistic. The routing process in the molecular nanonetworks can take on two forms, which are query based as well as polling at the micro-gateway to collect data. Since multi-hop routing can be performed in molecular nanonetworks, we anticipate that topologies deployed for molecular nanonetworks, can take on various shapes and forms (e.g. scale-free, grid). In [6], an example of multi-hop routing using bacteria as carrier for DNA based messages was simulated for various simple topologies. Although multi-hop routing could be performed in molecular nanonetworks, the probability of information loss along the path is very high. For example, diffusion of information molecules could get lost due to environmental fluid motion, or viruses or bacteria may get killed due to external chemical agents (e.g. antibiotics).

Unconventional Routing: Since the ratio of one micro-gateway to nanonetwork

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can be large, the bulk data may be difficult to be routed along the micro-gateway infrastructure. An alternative is to possibly combine this with other unconventional routing approaches. A good example is incorporating mobile Delay Tolerant Networking (DTN) as information carriers of data from nanonetworks. We have seen the emergence of DTN networks, where human carriers are used to transport data and opportunistically route between mobile devices to get to a destination point. Therefore, in this scenario each mobile device maybe equipped with a transceiver that can receive signals from EM-nanosensors (at terahertz band), and could in turn collect information directly as they come within close proximity. However, in the case of molecular communications, an intermediate micro-gateway is required to fuse and collect data before transmitting to the mobile carrier. Through mobility (either human or vehicular), the information can be carried opportunistically to various locations. This is similar to data mules that move around the environment, collecting data from the sensors.

4. Micro-gateway Middleware

While the previous section concentrated on data collection mechanisms for IoNT environment, this section will concentrate on the middleware architectures for IoNT. A number of different middlewares for sensor networks have been proposed in recent years [5]. These middlewares are designed to abstract the underlying network functionalities from the services that utilize the sensor information. However, there are a number of challenges that current middlewares will need to address in order to support IoNTs. Fig. 3 illustrates a system architecture that is envisioned for distributed middlewares that can support IoNT. Within the micro-gateways we have a middleware that contains two main modules which are the System Management module for the gateway unit, and the Data Analysis module.

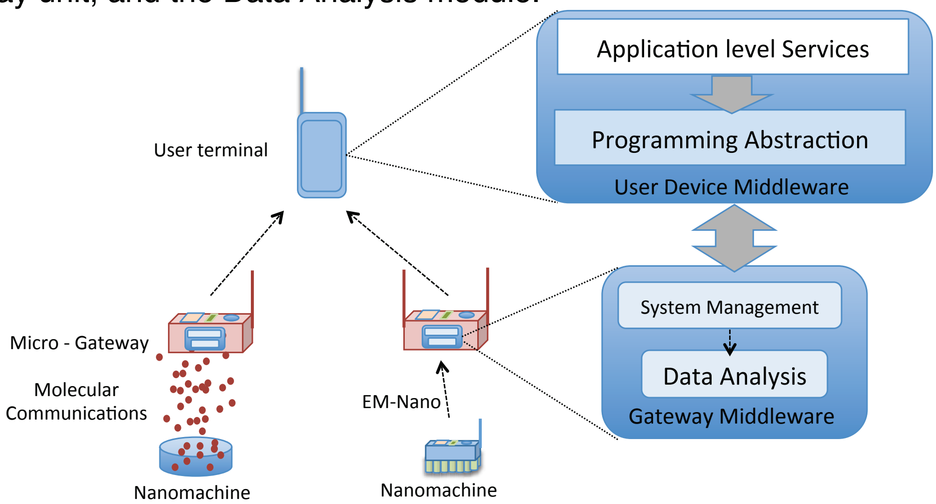

Fig. 3 System Architecture for IoNT Middleware

On the user side, there are the programming abstractions that link to the micro-gateway middleware and the application services that will make use of the information from the nanonetworks. We will, however, only concentrate on

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the middleware of the micro-gateway, since this links closely to the nanonetworks in the environment.

System Management: Similar to the middlewares of wireless sensor networks today, the system management module of the micro-gateway is used to manage the internal operation of the gateway. The roles within the system management includes self-awareness, resource management process, as well as QoS management (in this paper we will only touch on the self-awareness, since other processes have already been investigated extensively in sensor middlewares).

Self-awareness – Since processing is an issue in nanonetworks, a certain degree of self-awareness is required on behalf of the nanonetworks by the micro-gateway. For example, nanodevices within the nanonetworks may not have topology knowledge (largely due to the fact that these topologies may be random and dynamic depending on the environment conditions). Secondly, the environments of the nanonetworks, as described earlier, are known to be harsh, sensitive, and unreliable. For both the *EM-nanonet* and *molecular nanonetworks*, the relationship between the micro-gateway and the nanonetwork will be a *master-slave* relationship, rather than cooperative. This means that full knowledge of the network and environment will be controlled by the micro-gateway. Therefore, efficient and reliable management of data collection from the nanonetworks by the micro-gateways will be required in order to enable the micro-gateway to have a high degree of awareness. The self-awareness process should infer the topology of nanonetworks that are interfaced with the micro-gateway, determine the condition of the environment (which could vary with time) and degree of fluctuations that could affect the reliability of message transmission. This would then allow the micro-gateway, which acts as a master, to reconfigure and control the behavior of the nanonetworks.

Data analysis and processing: In normal static sensor networks today, the data collection is usually performed through an optimal data collection tree. Each node along the tree senses the data and then passes this along the tree to the sink. However, since each micro-gateway now interfaces to a large number of nanosensors, the dynamic tree could lead to large data traffic, in particular, if a periodic sensing process is required by the nanosensors. Therefore, a dynamic data collection tree will be required, but such trees should only be constructed through node-to-node interactions and in a distributed manner. The dynamic data collection tree could be constructed as a response to nanosensor activities. We anticipate that the communication between the nanonetworks and the micro-gateway will only be performed when an event is triggered by the nanosensors. This is applicable to both EM-nanonets and molecular nanonets. The micro-gateway will require processing and analyzing of data from the various nanonetworks before transmitting this up the data tree. However, there are a number of constraints and trade-offs that each micro-gateway must encounter during data processing. This trade-off is the waiting time to collect all incoming data from the nanonetworks and

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fusing it together, which could result in long delays before messages are sent to the sink. On the other hand, the micro-sensor could transmit all data it receives immediately and have a short waiting time, which leads to higher traffic as well as energy consumption. This effect is attributed to the properties of the nanonetworks. In the case of EM-nanonets, the energy-harvesting period is a major constraint, where harvesting process can take up to a minute before transmission can be performed. For molecular nanonetworks, the transmission of information along the network could take a large amount of time, in particular, when queries are sent down the nanonetworks and a feedback is expected. Therefore, an optimal time-delayed data fusion process is required for the micro-gateway to process all information before further transmission along the data collection tree.

Energy conservation through Synchronization – The self-awareness process of the micro-gateway to infer and learn the environmental condition of the nanonetworks, could be used to accurately determine periods that the micro-gateways could be put to sleep in order to conserve energy. This can possibly lead to dynamic timing synchronization between the micro-gateways and the nanonetworks. For example, EM-nanonet devices that use nanowires for energy harvesting may lead to fluctuations in energy production depending on the amount of vibrations on the nanowires. If the micro-gateway could infer this accurately, then the micro-gateway could be put to sleep during the period that the nanodevices are harvesting energy. In the case of diffusion based molecular nanonetworks, if the conditions are currently harsh due to high quantity of foreign fluids or unexpected waves leading to potential delays in molecules arriving at the destination, the micro-gateway could be put to sleep and be woken once the molecules are estimated to arrive.

5. Outlook

Context Management for IoNT

The data collection and IoNT middleware requirements described in the previous two sections, could lead to new pervasive applications of the future. Data collected from the environment can be reduced to fine-grained microscopic levels, which could provide opportunities for a new class of services, as well as context models to support these services. Inherent to all Internet of Things architecture are context systems [3] [8]. Context models usually have to deal with information from variety of sources. While numerous models have been developed for context information, and modeling of semantic representations of different context models – the requirements of IoNT will require further extensions to current context management approaches. The wide spectrum of data heterogeneity found in IoNT, will require cross-domain reasoning that spans various specialized ontologies, as shown in Fig. 4(a). Fig. 4(b) illustrates an example of a context model that is processed from different ontology domains, which includes smart space ontologies and gene ontologies (to process data from molecular nanonetworks).

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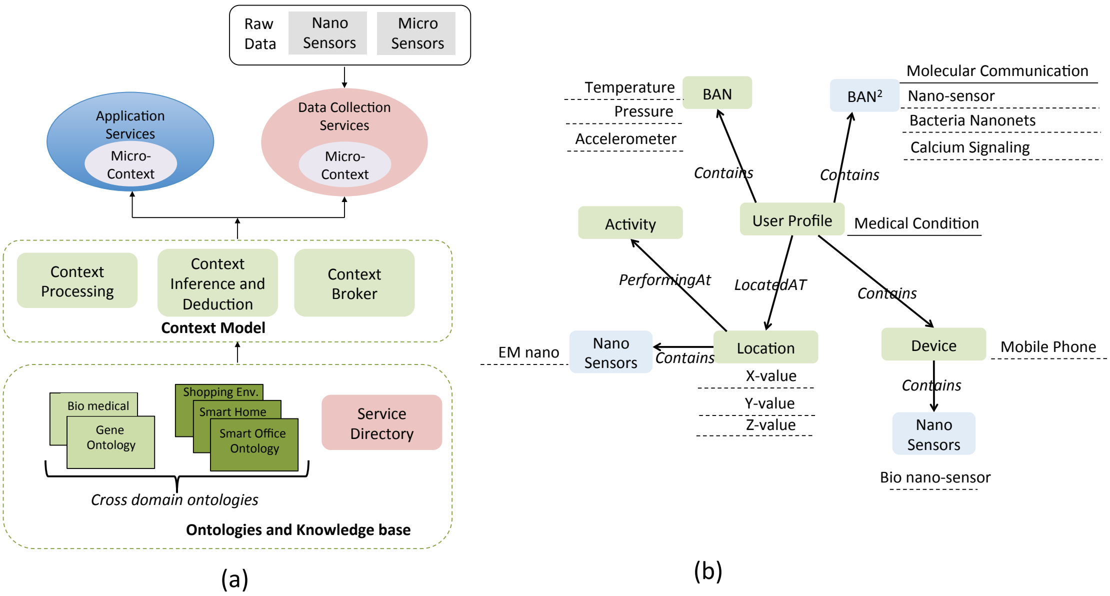

Fig. 4 (a) Context Management for IoNT, (b) An example definition of IoNT ontology

Besides extending context models to support information from nanonetworks, new mechanisms would be required to support security and privacy of context information. In particular, since the context information can involve detailed chemical and biological samples of individual users. An example of such analysis is when a specific location is suspected of harmful virus within the air, then molecular information of users who have passed that particular location maybe required to understand who have been infected, and how severe was their infection.

Services for IoNT

Typical to the design paradigm of IoT, services are also an essential part of IoNT. In particular, services bridge the gap between the requirements of the end user's application and the information provided from the context model. This is usually represented through a Service Oriented Architecture model, which are mostly used for developing the services. Due to the large number of data, beyond what is available in IoT, we define a hierarchical structure of services, where efficient service composition and discovery will be a major requirement for scalable IoNT. As shown in Fig. 4 (a), the services could be subdivided into two layers, *Application Based Services* and *Data Collection Services*. An example of this interaction between the Application and Data Collection services is illustrated in Fig. 5.

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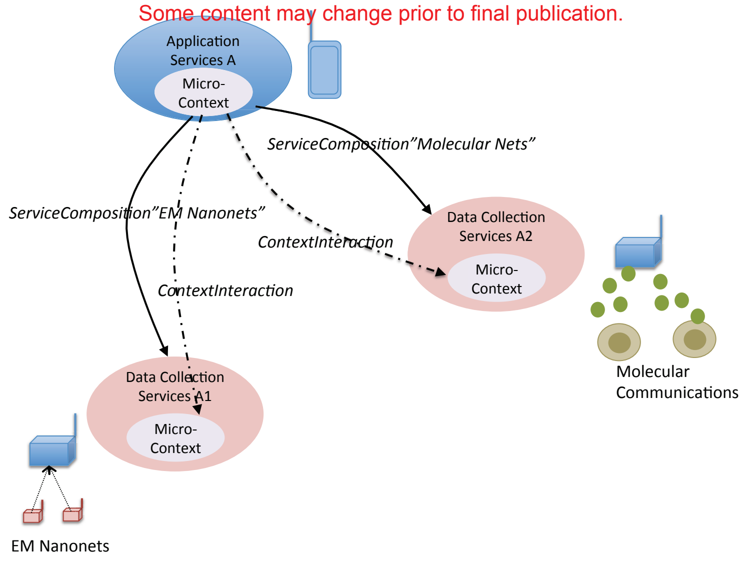

Fig. 5 Distributed Service and Context Interaction

6. Applications

The major question now is what will IoNT bring to the table, and how this will extend and provide new applications that are limited or unavailable in IoT. The obvious answer is the incorporation of nanonetworks that interconnect nanoscale devices to the Internet world. We envision that the IoNT will bring to each domain, access of this information, and potentially enable an on-going process of testing and analyzing harmful molecules. This section will provide some example use of future IoNT from the perspective of healthcare, as well as environmental and agricultural monitoring scenarios.

Healthcare

The most obvious applications of IoNT would be in the healthcare domain. From an in-body perspective, nanosensors would be networked within a body through a BAN[2], collecting and monitoring vital changes in molecular contents or harmful viral infections. The nanosensors will provide a close to real time monitoring process that allows users to obtain information on changes in molecular contents or infections, where these information could be transmitted to an on-body micro-gateway and onto the mobile device. Through the in-body nanonetworks, patients will not be required to go to pathologists to receive any lab tests, as the tests will already be done within the body, and these readings could be provided to doctors from the patient's mobile device.

Another possible application is in public locations, which is where people contract numerous diseases, either through close contacts or through viral propagation via the air. The nanosensors can be placed in public locations such as hospitals, airports, restaurants, etc., and other high-density locations to collect this information and pass to individual user's services. This could also provide opportunities for healthcare authorities to analyze and trace to locations that infected people may have passed, whereby better

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understanding can be developed on viral propagation and methods of infection for different groups of individuals.

Environmental Monitoring and agriculture

The networked nanosensors will also have tremendous benefits in environmental monitoring. Obvious applications are in pollution monitoring; in particular as green environment is currently a pressing agenda for numerous countries. The agricultural sector can also benefit from networked nanosensors, which can help detect harmful diseases that may infect livestock or crops. Recent examples in Europe of such harmful disease are the outbreak of *E.Coli* on vegetables and *mad cow disease*. Therefore, services can be developed by the environmental and agricultural sector to monitor specific disease that may frequently be found in specific locations.

Cross-domain Applications

Besides individual domains, cross-domain IoNT can also be created to allow users to access wide range of information that maybe beneficial to their specific needs. For example, a cross-domain link could be formed between the manufacturing domain and the healthcare domain. An example could be that dairy product manufacturers may produce milk in certain range of conditions, where certain conditions of production may affect specific people with certain types of allergies.

The example applications above bear many similarities to typical examples where IoNT could be applied. However, the key difference between IoT and IoNT is the granularity at which sensors operate. In IoNT, sensors will operate at the microscopic level and thus enable services, which traditional IoT would not be able to realize, e.g., the in-body monitoring or agricultural applications. These differences set IoNT apart from traditional IoT and require addressing the challenges we have outlined in this paper.

7. Future Direction

The nanotechnology industry has transformed and changed traditional approaches that have been used to solve various pressing problems. A good evidence of this has been from a healthcare perspective, where we are witnessing new nanotechnology driven solutions. However, to date little attention has been placed on how nanodevices could be brought closer to support computing for end-users. The concept of IoNT, can provide new directions and opportunities in end user computing that utilizes nanosensors embedded in their environment. This vision could be realized when we incorporate new communication paradigm between nanodevices, as well as between nano and micro-devices that we utilize on a daily basis. This is the right time to bridge the world of nanotechnology, as well as computing, in order to develop a living environment that can better support and serve mankind.

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