Function Centric Nano-Networking: Addressing Nano Machines in a Medical Application Scenario

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Abstract

We discuss the combination of in-body nano communication with the Internet of Things (IoT) as the Internet of Nano Things (IoNT). This combination enables a wide range of new applications and opportunities—particularly in the biomedical domain—but it also entails a number of new challenges. One of many research challenges in functional and non-functional aspects is the addressing and naming of nodes in a nano network. Our study in this area not only includes traditional techniques driven from today's IoT, but also new unconventional ideas, originating from molecular level communication. We come up with a summary of either theoretical, simulated or realized ideas to draw conclusions about implementations and performance potential, with a focus on medical in-body communication scenarios, before we present our concept, Function Centric Nano-Networking (FCNN). FCNN allows us to address groups of interchangeable nano machines in a network by using location information and functional capabilities of the machines. This concept does not rely on the durability and uniqueness of individual nodes. We are comparing the novel concept of FCNN with similar ones and highlight elementary differences between them as well advantages and disadvantages.

Key words: addressing, internet of nano things, medical application, nano communication

1. Introduction

Research in the field of communication of wireless micro devices has greatly progressed over the past years and developments in the Internet of Things (IoT) have been integrated into everyday's life [1]. The automobile industry, as an example, interconnects a huge set of car parts in one vehicle (and among vehicles, not to forget) [2], while smart home systems allow users to control features at home with their smartphone [3]. Body Area Networks (BANs), integrated into clothing or used as implants, are able to measure many kinds of body parameters from outside of the body, like physicians can do with tools such as stethoscopes or tongue depressors. Following Moore's Law, extremely resource-constrained micro devices benefit from more complex circuits and may thereby become even smaller and more powerful.

Today the downscaling of device size allows us to think about in-body networks, consisting of nano machines to measure many more parameters from inside the body, e.g., blood and liver characteristics [4]. Instead of visiting medical facilities to take blood samples, we envision nanoscale machines in an in-body network to circulate through the patient's blood while taking measurements whenever necessary and to communicate their results to the outside. Nano machines with acting capabilities may even be able to immediately respond to detected problems such as cancer cells.

In the exploration of in-body nano communication, research is still in a very early stage [4]. It is not just about scaling down from micro to nano in size and apply the same technologies. Additional possibilities inspired by nature arise, such as biological nano machines and molecular communication, e.g., cells communicating through diffusion-based calcium ion concentrations. We are just beginning to discover the potential of nano communication and adapt these new techniques with concepts in computer science.

Nowadays, the nano communication community, with Ian Akyildiz and his group [5] among the first to investigate in-body networks, not only focuses on molecular communication [6] and electromagnetic waves for terahertz radios [7] but also more exotic variants like acoustic ultrasonic communication [8, 9] and neuronal communication [10, 11]. All these concepts gain more and more maturity starting to include channel modulation and medium access control in consideration [12, 13]. Combining the concept of nano communication networks with BANs, we end up in the Internet of Nano Things (IoNT) domain [14, 15].

No matter which medium of communication is chosen, in each of them addressing or naming is an issue that cannot be ignored. Somehow devices have to know which messages to process, to be routed onwards or to be ignored at all.

In this paper, we take a look at what kind of addressing we really need for nano communication systems. This pa-

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per is an extended version of [16], where we proposed our concept for the first time. In the following, we consider additional challenges and possibilities that addressing entails for in-body nano communication regarding medical application scenarios [17]. We start with its challenges in Section 2. With regard to the requirements, we consider related work on addressing and naming for nano communication in Section 3 and then define an addressing concept—which we call Function Centric Nano-Networking (FCNN)—in Section 4, to discuss its properties and compare it to related concepts. Finally, we draw some conclusions in Section 5 and also give an outlook on future work.

2. Challenges and Requirements

Nanoscale communication has its own challenges and requirements we need to deal with, but it also offers a wide range of new possibilities. We start this section with an overview of our motivation from medical application and resulting requirements for nano communication in in-body networks. This part is followed by constraints and challenges from further miniaturization of electronic microsystem devices and electromagnetic communication on one hand and understanding and using new communication concepts on the other hand. Finally, we take a more detailed look at the in-body communication requirements in IoNT architectures.

2.1. Medical application vision

The motivation behind FCNN is the medical application of nano communication [17]. Diseases are an omnipresent topic in everyday life and research. Usually people confronted with diseases, first show symptoms like headache, cough or rash before they suspect anything about their health status. As a consequence, they either apply medicine on possible wrong valuation or consult a physician for a qualified diagnosis and treatment, which may however require time. The majority of the administered medicine has a systemic effect and thus affects the entire body and not only body parts affected by diseases. The consequences of a systemic administration of medications are demonstrated both in antibiotics, which lead to increasingly resistant bacteria, as well as in immunosuppressants, which weaken the entire immune system, making the body more receptive to additional germs.

These are a lot of factors, we like to approach and improve with our vision to provide a mobile monitoring and treatment system. The future patient is not location-bound, but has a communication network, which checks his vital state, reports possible diseases and offers treatment options. As a response, medication by pre-deployed, encapsulated drugs may be applied by nano machines. In contrast to systemic drug administration, this treatment will be applied locally by nano machines in the area. In [15], we proposed our vision of an IoNT architecture integrating in-body nano communication and body area networks. Figure 1 gives an overview of our architecture integrating macro-devices like smartphones acting as central analysis and control stations, micro-sized at-body or implantable devices as information distributors and gateways and nanoscale in-body devices as sensor and actor nodes.

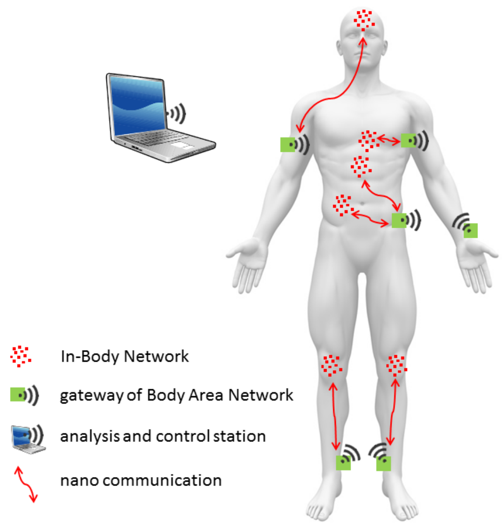

Figure 1: IoNT Network architecture, modified version of [15]

We already addressed some general requirements of nano communication networks [15]. Here we sum up the requirements for nano communication in regards to addressing the medical application scenario. *Location-awareness:* The location is a crucial information for medical application. The position of a disease must be reported as precisely as possible, and treatment must also be carried out at a specific location. Therefore, it is important for nano machines in a network to possess a location-awareness to act accordingly. *Purpose-awareness:* Anticipating one of the later sections, a nano machine may be a single-purpose device, with a narrow set of actions. To make use of nano machines, the machines have to be aware of what they are capable of. *Non-functional requirements:* In addition to functional requirements, non-functional ones also have to be addressed:

- Communication has to be *reliable* enough that successful message transmission can be ensured or is at least highly probable.
- Communication related to medical issues has to happen in *real-time*. Information about diseases have to be transferred from the area of detection to the point of evaluation in an acceptable time frame to be of value. For example, a report on hypertension taking hours for transfer can be useless or even lead to wrong blood pressure control measures.
- Health related data should neither be stolen nor manipulated. Wrong medication leading to life-threatening situations may be a serious consequence. Appro-

priate *security, safety and privacy* precautions must be taken to prevent intrusion.

2.2. Known challenges from scaling down

While IoT microsystem devices suffer from resource constraints, IoNT devices amplify this problem to the extreme in the following aspects [16]:

Energy management: Artificial nano machines need a power source to stay online to measure, act or receive and send data. Large batteries for small nano machines are not a viable option, so these have to decrease in size and accordingly capacity as well to fit the nano machine's size. Zinc oxide high-density nano-wires are an option for nano-sized batteries. Because of their limited size, energy harvesting for renewable long term energy supply, e.g., through movement, is another key feature of this idea [18, 19]. However, as long as there is still no reliable source of energy, which has left the testing stage, we have to assume that we must at least be economical with energy.

Sparse memory and computation power: Wireless sensor devices usually lack memory and processing power for complex implementations, forcing programmers to efficiently use the given resources. At the nanoscale this issue increases. However, many new concepts already arise, mostly involving Carbon Nanotubes (CNTs), formed by atom-thick sheets of graphene. The structural stability and conductivity of CNTs allow the construction of nanoscale field effect transistors (FET), but precise creation and placement are still open issues [20].

Communication distance: Radio communication using electromagnetic waves requires antennas and transceivers. CNT antennas and graphene transceivers with their extremely high conductivity seem to be the best choice here. The resulting wavelength is still so short that the radio waves are in the range of 0.1 to 10 terahertz. At this low wavelength, atmospheric disturbances make communication distances exceeding 10 mm very susceptible to interference [5], especially inside in attenuating human body.

Environment: Destroying nano machines through wind and weather in harsh environment is a problem in a Wireless Sensor Network (WSN). At the nanoscale, the physical condition of a single node is almost impossible to fully control and preserve outside of a laboratory. Simple chemical reactions may destroy vital parts of a nano machine. The environment can not only destroy the nano machines, it may also carry them away. So one may be completely unaware of the machines physical location, while the device cannot be tracked with the human eye. Operating in a human body environment, a lot more elements need to betaken in consideration, therefore we address this topic in more detail in Section 2.4.

2.3. New nano communication techniques

Nanoscale is not just further miniaturization of the IoT. Nano machines are devices in the size of a few hundred nanometers, or a micrometer at most. At this molecule-size, classical paradigms of communication may need to be completely reconsidered as problems and options arise. Instead of using electromagnetic communication principles through cable and radio, bio-inspired molecular communication offers a broad range of propagation principles differing in speed, accuracy, range, reliability and data capacity we need to cope with.

For example, pheromones [21] can be used as a chemical long range communication option either through a fluid or aerial medium. The pheromones spread out via diffusion, a passive transportation process, where the direction of particle movement is not directly influenced by the source or messenger, but dependent on the surrounding environment. Although this process provides a long range for organisms to communicate, the provided concentration for the diffused molecules has to be high enough to provide a sensible concentration at the target, which may require a larger source than a single nano machine may provide. Diffusion is also a highly randomized process, where molecules tend to move to areas with a lower concentration than their own, while they are affected by random movement through collision with other molecules, a process called Brownian Motion. Another passive biological diffusion based communication process is calcium cell signaling through calcium waves [22]. Compared to pheromones, it is a rather short ranged chemical messaging process to coordinate inter- and intra-cell activities. It is also a diffusion based process to distribute calcium ions (Ca^{2+}), but in an aqueous environment. A calcium signal is an increase of calcium ion concentration in a cell, caused by the cells ion reserves or through cell surface reception from external sources. Either way, it triggers a cells reaction, e.g., a muscle contraction.

A different option is the use of the optoacoustic effect [8]. An area may be excited by optical means to cause acoustic wave generation. Ultrasonic waves may be an alternative to radio frequency by means of reduced attenuation at lower frequencies and therefore increased range [23].

An active transport technique inside the body are molecular motors [6] riding along rails like microfilaments and microtubules. A railroad infrastructure between the nano machines would be required to communicate like this. Another alternative are railless motors like flagellated bacteria, they have flagella to control their movement in aqueous environment.

Some of these new techniques may inspire or lead to new communication paradigms.

With regards to nanoscale size, molecular communication options and the need for bio-compatibility the idea of using biological vessels as nano machines comes to mind [24]. A cell itself is a very basic structure but quite similar to an autonomous robot. It has a nucleus as memory and processor, needs AdenosineTriPhosphate (ATP) as a power supply, actuators and senors like gap junctions to transfer ressources in and out and also allow cell signaling as a kind of communication. For this reason ways to make cells usable as nanomachines are also currently explored [25]

At the latest when biological nano machines in the in-body network using molecular communication have to communicate with classical electronic microsystems in the BAN using electromagnetic communication, the need for biological and electronic hybrid hardware arises to cope with this challenge.

2.4. Environment challenges

Particularly noteworthy is the area of deployment. In the context of medical application scenarios, nano machines are located inside the human body. The environment does not only affect the lifetime of the machine, but also the passive movement as well as the communication options and range.

Just because of the nanoscale size classical mechanics fail to properly describe the applicable physical effects, the nano machine—and its communication—now depends on quantum mechanical effects [26]. Additional phenomenons like Brownian motion influence molecule sized objects in a liquid medium. The floating molecules of the fluid collide with the object and create a random movement. The consequence for nano machines is additional random movement in the bloodstream or the lymphatic vessels on top of the direction of the flow. As these vessels are the main ways for transport in the human body—to distribute oxygen, nutrients and medicine—we can strongly consider these as the whereabouts for the nano machines inside the human body and thus have to anticipate passive movement and mobility of the machines. A particle in the bloodstream needs approximately a minute for a whole cycle, while the flow speeds differentiate drastically between venes and arteries as well as big and small vessels. The ever changing location of the nano machine is a problem to be aware of for achieving the important location awareness. Without location-awareness localized measurement and treatment cannot be possible.

With hundreds, thousands or even millions of nano machines present in the human body it is not only about how the environment influences the nano machines but also about how the nano machines influence the environment. The machines are intruders in a highly complex biological system, which is designed to isolate potential threats. The machines need to be properly designed to be tolerated by the immune system. It does also require the machines to be biodegradeable or at least removeable to not cause harm to the environment after they've fulfilled their task. These are constraints for the materials and their composition.

Considering medical applications many more factors need future consideration. To accomplish monitoring and medical observation, the whole IoNT needs to be able to run diagnostic procedures either as single Lab-on-Chip solutions for each nano machine or as combined swarm intelligence. To avoid physical examinations by a doctor and provide autonomous functionality, sensors and procedures for nanoscale laboratory analysis or image processing have to be developed. While—for example—qualitative methods only generate positive or negative confirmations for the existence of particles, the more common quantitative diagnostics measure relative degrees of particles for more precise statements. The consequence for communication to successfully monitor the human body can be a high demand for communicative interaction between the nano machines for cooperative measurement and majority vote procedures. Also coordinated actuation has to be taken in consideration when it comes to releasing a specific amount of medicine in order to avoid over- or underdosing.

2.5. In-body networking challenges

The combination of body area networks and in-body networking leads to even more challenges to overcome in nano communication. When speaking of in-body communication, we cannot ignore the fact that this will be an invasive operation within the human body. We need biocompatible communication, as the communication itself should not harm or disturb the biological balance in the human body. This includes not only medical and ethical, but also legal issues to be considered. However, we want to focus on the technical part in this paper.

Furthermore, the traditional electromagnetic communication suffers from additional attenuation through body substances in comparison to air transmission.

As mentioned before (cf. Figure 1), the body area network to in-body network communication delivers messages through different levels of device-size: macro, micro and nano. This creates a demand to deal with heterogeneity of nodes and communication principles. Here we take a closer look at what the communication between the different layers is used for:

- Communication between macro- and micro-sized devices has already been researched and is out of the focus. Existing solutions like IP, Zigbee or 6LoWPAN could be used for communication. Here, orders are routed towards the in-body nano network and sensor data from the nano network received by the body area network is routed outwards to the analysis and control station.

- A direct communication between the macro-sized analysis and control station and the nanoscale devices inside the body seems very unlikely. It may be rather possible for the large device to use wireless communication types like radio waves with a wavelength and signalstrengh able to penetrate the body and reach every nano machine in the body, but the nano machines on the other hand may not be able to perceive lower frequency signals than terahertz, not to mention that signals from the nano machines have to somehow be perceived by the macro-sized device. For molecular communication the device needs to have a direct connection to the same medium the nano machines are using—for example the blood stream—to send and receive messages. This requires the device to be an implant or at least posses a connection port as a gateway. Therefore—and to achieve location awareness in the future—we intend to use multiple well distributed micro-sized devices as gateways between the in-body nano network and the outer world.

- With micro-to-nano communication, we enter the area of nano communication. In this direction of messaging, the network intends to forward messages from the control station to the receiver side in the in-body nano network. These messages mostly contain commands to actuators or requests for data. Thinking far ahead, it could also be used for on-the-fly (re)programming of nano nodes.

- To report (requested) sensor data, nano nodes may use nano-to-micro communication to send collected data from the assigned task. The communication may also be used to send alive-messages to keep track of the sensor and actuator nodes.

- We also have a possible nano-to-nano communication. While very simple single-task nano machines will probably have not many topics to communicate about, this way of communication can be used to forward messages in the in-body nano network, the devices thus act as repeaters. Another scenario would be communication between self-organizing nano machines. Okaie et al. [27] describe a scenario where nodes are attracted or repelled by one another through different gradients of signaling molecules to spread out in a uniform distribution.

3. Existing Concepts

The global addressing standard is based on IP and MAC addresses. However, there are alternative options with different objectives than end-to-end communication like Named Data Networking (NDN) with a focus on addressing the data itself. Some of the concepts for addressing and naming even rely on a specific type of communication as mentioned above and specific types of nano machines, e.g., completely man-made consisting of CNTs [28] or application-specific mutated cells.

Also worth mentioning are alternatives to the concept of addressing. To reach a destination it is not always necessary to know the address, sometimes it may suffice just to be pointed in the right direction, there is only one possible option or even any destination is suitable.

To be able to distinguish between these approaches, we devide the concepts into three categories: *Addressing concepts* are about classical communication ideas, before nano communication came up, which might be scaled down to nano-size solutions and also new and unconventional addressing schemes that are only made possible through nanoscale communication and architecture or ways of molecular communication. *Guidance concepts* are solutions to reach a target without an address used in packets. Instead the data is guided to their distination by—physical—paths, a specific direction or distance. Concepts from these two categories have the chance to be combined for more precise addressing. The last two concepts from the category *communication alternatives* are not based on the concept of classical communication at all but offer options to circumvent the idea of needing communication.

3.1. Addressing concepts

MAC-Address: A hardware MAC-Address scheme is used for local addressing. It traditionally consists of 48 combined manufacturer and individual unique address bits. An equivalent with hardware encoded address information for a nano machine is required. On a biological basis, it could also be adapted by a unique cell information like individual DNA strands. The messenger molecule could wield a complementary DNA-strand to specifically connect at the desired location through DNA scaffolding. At the moment, this idea is intensely analyzed for self-assembly procedures [29, 30] to combine nanoparticles and nano machines into larger constructions. As it can provide unique addresses for nano machines, a reuse of these strands needs helicase enzyme activity to separate the complementary strands lossless after message delivery for the next reception.

IP: A protocol addressing scheme like IPv4 (32 bit) / IPv6 (128bit) would yield too much overhead if directly transferred to the nanoscale, as it already does in the IoT. The feasibility of overhead reduced standardized protocols, e.g., the IEEE 802.15.4 standard with either Zigbee [31] or 6LoWPAN [32], for efficient transmission in resource constraint networks for man-made nano machines has to be evaluated and is a matter of available memory size, processing power, and applicable message size.

CCN/NDN: Addressing the endpoints in the traditional packet-switched IP network is a very host-centric approach, designed for telecommunication networks. Nowadays the communication is mostly data oriented. Data is to be procured independently of where exactly it is found. A content delivery network is an example for a distributed server structure for IP to provide information at different locations. The redundancy of the data on several geographically distributed servers is intended to enable a better scaling of the communication process and shorter distances. Content Centric Networking (CCN) also known as NDN [33] is an alternative to the IP. Data—not the host—is directly addressed as an *interest* and routers keep tables for pending interests. The interests are forwarded until matching data is found. This is subsequently returned to the source of the request, while a content store temporarily caches packets to satisfy similar future interests. In Section 4, we will discuss CCN/NDN in relation to FCNN.

Hierarchical Addressing: Hierarchical addressing can be used to group nodes—based on location—into bigger and bigger segments to build an addressing scheme for the nodes [14, 34]. An address could look like this: 'Node 2' in 'sensor group 4' assigned to 'gateway 7'. This concept allows to easily address different groups and group sizes, while nano machines only need local unique addresses. The global address can be established by the whole path.

However, in a mobile context the group information may change fluently as the nodes move and addresses have to be maintained. Therefore, we need a possibility to adapt to these changes. In Section 4 we will discuss hierarchical addressing in relation to FCNN.

Broadcasting: Broadcasting is always viable as a option to more or less address a target. Instead of choosing the receiver, possible receivers have to decide themselves whether or not they are interested in the data. It can be used in many new ways of communication. Using calcium signaling in molecular communication, by passive transportation to transmit data for example, calcium ions diffuse from a cell in all possible directions relying on a random walk, called Brownian motion. Collisions with atoms and molecules let the involved particles move in seemingly randomly changing motion. Therefore data spreads like a broadcast in the network. Of course, this will also work with known classical radio frequency communication as far as the communication distance will allow it. The result however is a fairly coarse grained message distribution in the network.

Molecular coordinates: Instead of directly addressing the receiver nano machine or a type of nano machine, we can address a location itself like in a coordinate system [35]. In a biological triangulation-like system, a set of beacons (three or more) with fixed positions is needed to dispense different substance concentrations into the surrounding environment. Messenger molecules can seek out a specified concentration level of each substance to position themselves through molecular movement (e.g., chemotaxis) at the desired address to deliver the message in the target area. The nano machines can use this principle to position themselves. On the downside, this way of addressing requires reliable beacons in known and stable positions, where each address needs at least three beacons in communication distance.

3.2. Guidance techniques

Cable wiring: The connection between nodes could be wired by CNTs to directly link the data from one nano machine to another. This would definitely limit the mobility of the nodes and the assembly of a whole network inside a body would be quite difficult to create and maintain.

Natural wires: A wired connection between nano machines does not mean it has to be a classical cable (e.g., with CNTs). Microtubules are biological wires to stabilize cells and provide platforms for transportation. These platforms can be used by molecular motors, like kinesin and dynein proteins, to chemically bind and transport data like other proteins along the microtubules [4]. It is obvious that a wired connection implies restrictions in movement and relative distance of the nodes as it is already intended as a short range communication type. However, it offers direct message exchange between communication participants.

Electromagnetic fields: The direction of electromagnetic communication can be steered by creating electromagnetic fields around the communication participants. This way, the receiver is not explicitly addressed but indicated by the direction of communication.

Directional antennas: Rotating around its axis, a nano machine could also control the direction of communication with a highly directional antenna for electromagnetic radio wave communication [34]—to determine relative positioning. The antenna would target a designated direction until it receives a ready signal from another directional antenna, which was rotating in a receiving state and is now in the right position to start message delivery. So awareness of a node's relative position in the network is a crucial aspect and could prove especially difficult in a mobile scenario.

Bio-circuits: Teuscher et al. [36] describe synthetic bio-circuits, where the cell's behavior is adapted and used to identify concentration levels from different substances to correctly react to the measured value. To achieve the desired results, they use libraries of biological parts for biological circuit assembly. Using this idea, we can estimate a communication range by the initial concentration of a chemical substance before diffusion and the reaction of a cell at a specific concentration range when receiving the chemical substance.

3.3. Communication alternatives

Target tracking: As a very basic functional unit—performing only simple tasks—a very specialized and simple communication may already suffice. If the task for a nano machine is to seek and destroy a special type of cells (e.g., cancer cells), Okaie et al. [27] describe the principle of repellent and attractant biological nano machines similar to the idea of molecular coordinates: To distribute themselves across the body or the desired area, they use one type of signaling molecules to repel one another by moving to areas with lower concentration through chemotaxis. Moreover, biological nano machines can be attracted by other types of signaling molecules and move towards the source of the molecules (e.g., to enclose and therefore destroy it). This principle of swarm intelligence-like movement appears to be suitable for clearly structured simple tasks defined by a few repellents and attractants.

Cell programming: Instead of or in addition to addressing nano machines to fulfill a task, we can reprogram cells in the target area to fit our purpose on the fly by altering a cells behavior itself. This may be possible by means of gene-delivery [37]. The message information gets encoded in DNA and is released by a micro or macro device to the target area by any means of active or passive transportation. To prevent degradation of the DNA message content while in the medium, it needs to be embedded into safeguarding complexes [38] functioning like a network layer packet frame. By reaching the desired cell or any cell that can bind the packet at a matching receptor, it will retrieve the content of the packet. At the destination the DNA alters the cells nucleus and therefore the behavior of the cell, changing the protein production lines until the cell resets through mitosis [37]. Compared to the previous scheme, this may provide a solution for more complex scenarios, but mutation of existing cells is a serious intervention in their biological environment. They may fail to reproduce in mitosis and be eliminated by the immune system as a potential threat, which limits their lifetime.

4. Function Centric Nano-Networking

As seen in the last section, addressing a single nano machine does not seem to be an attractive concept. It may be theoretically possible to provide an artificial nano machine with a hard-coded address, or a biological machine with a seemingly unique DNA strand identifier, but this may already prove to be a challenging task to handle individual machines. Checking the status of each individual – most probably mobile – nano machine with presumably short range communication to maintain an intact network of known nodes, is a costly process. As mentioned before, environmental effects influence the machines status, position and overall lifetime, while the whole network of nodes is visually untraceable. Consequently, discovering the status of a single machine is not an easy task.

4.1. Concept introduction

We propose an addressing concept without the focus on individual nodes, but on the function of the nano machines, where nano machines can be replaced by any other machines on the fly, relying on their redundancy. Instead of addressing the communication endpoints, we address the location and function of the machines, forming a principle we coin the term Function Centric Nano-Networking (FCNN). Figure 2 shows the three general communication participant types in our IoNT network. The control station is the central processing unit in the body area network with sufficient resources to send requests to and analyze data from the in-body network. The gateways are micro system devices similar to WSN devices with resource constraints. They are spread over the body as wearable devices or implants, being part of the body area network, as well as the in-body network. The magnitude of distribution of the gateways depends on the networking performance of the communication types used, in order to cover the desired communication areas. The gateway's job is the message handling between the control station and the nano machines—the third communication participants. Keep in mind that the gateways and especially the nano machines can be biological, artificial, or hybrid.

The communication between the control station and the gateways, as well as between the gateways themselves can rely on known protocols like IPv6 or overhead-reduced variants like 6LoWPAN. For communication between gateways and nano machines or between nano machines themselves, we propose addressing using a *FCNN address*.

Different sensor nodes may monitor various physical or chemical properties. While we do not care which sensor exactly is responsible for the measurement data, we still need context attached to the information, such as the approximate origin area of the data. It could, for instance, be useful to detect increased concentrations of C-reactive protein and/or white blood cells as a marker of inflammation somewhere in the human body. It would be even better to know the location of the inflammation. Messages sent from the nano machines with information about the location and measurements would address a gateway to forward the information for an external analysis of the situation. In comparison of the different increased concentration levels, messages from the location with the highest raise in white blood cells is likely to be the origin of the inflammation.

Not only for the data origin, but especially for the data destination we want to have information about the target area and function of the nano machines. For example, after an inflammation in a body area (caused by a bacterial infection) was detected through analysis in the control station, actuator nodes in the specified area can be notified to release their encapsulated antibiotics. On one hand, this would stop infections in an early stage at the designated location, and on the other hand, the body parts without inflammation would not be negatively affected by the antibiotics, killing harmless or useful bacteria.

4.2. FCNN structure

To address nodes using FCNN, we propose the following parts for a packet header [16]:

- *Domain*: This is the most general area or system definition. A body area network and an in-body network are part of a unique person or more general 'system' we call domain. It may not be necessary to include domain information in a closed system, but other systems may be close to each other with overlapping communication ranges (e.g., radio). This address part is optional.

- *Location*: By location, we mean an explicitly nameable part of the body or system. Medical/anatomical standards seem to be well suitable here. The granularity of the information in this part should just be precise enough to fit the purpose and render the message meaningful. Information on locations may help to only use nearby gateways for inbound messages. If the location of the receiver does not matter, this information can be left out. This address part is optional.

- *Function*: The function addresses the desired type of nano machine. It can either indicate simple parameters like sensor or actuator or more complex ones such as blood pressure detection or insulin release. The function name depends on the complexity of nano machines used in the network and helps to address nano machines, which are able to fulfill the message request. If the function of the receiver doesn't matter, this address part is also optional.

- *TTL*: A time to live hop limit number for differentiation between old and new messages and to indicate

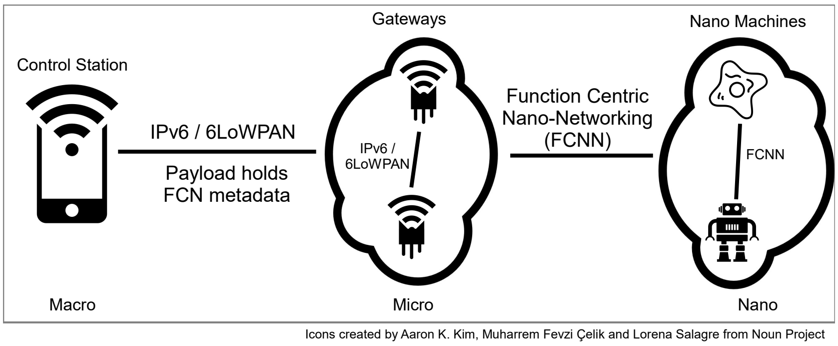

Figure 2: Address areas in the IoNT Network [16].

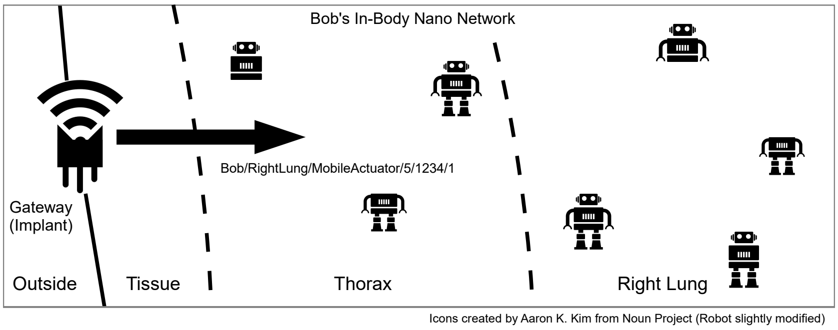

Figure 3: Address example with an FCNN header: The gateway releases a packet into a medium with different nodes regarding functions and locations.

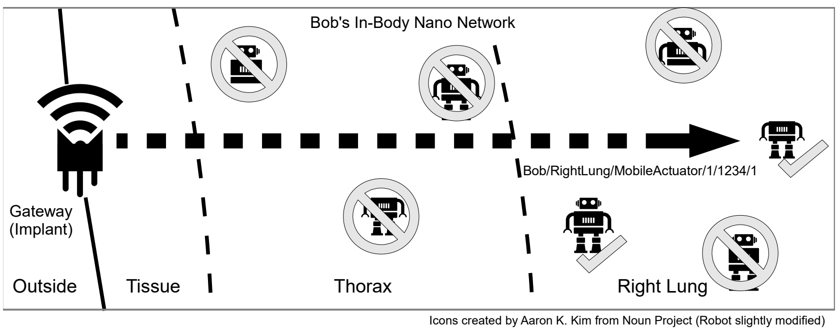

Figure 4: Address example with an FCNN header: Only packets with the addressed function in the correct location accepted the packet.

when to stop routing these messages through the domain.

- *ID*: A unique ID serves as message identifier and is created by the request. It has to be determined how this number will be defined.
- *Segment*: If the message is too long to be sent in one part, the segment holds information about the incrementally growing packet number.

The address parts of the header work like pattern matching, because a gateway or nano machine receiving a message with an FCNN header compares domain, location and function information with its own specifications. If the receiver is part of the right domain and location and can fulfill the function, it will accept the message and its content for further processing. The pattern does not need to be fully used, fields can be left empty. In a sealed-off system, the domain does not need to be set. Not setting a location would address nano machines in every body part. Not setting a function would lead to address all nodes in an area. Finally, setting neither location nor function creates a broadcast in the in-body nano network.

Domain, location, function, TTL and ID are specified by the initial creator of the message. The segment number is set as soon as the message enters the FCNN-based network, resulting in, e.g., `JohnDoe/RhomboidRight/RelAntibiot/7/3424/1`.

This means that the message is within the system of John Doe and addressing a nano machine sensor node, containing information for the right rhomboid muscle section, capable of an antibiotics release. Any node in the John Doe in-body network receiving this message would forward the message towards the designated nano machines based on the information 'John Doe', 'RhomboidRight', 'ReleaseAntibiotics' and eventually a time to live information to prevent message flooding lifelocks.

The creation of an FCNN header is as follows: A message originating at the control station carries information about domain, location, function, TTL and ID as metadata. It does not directly address nano machines, but instead it addresses the gateways as a middleman using IPv6/6LoWPAN. Upon receiving the message, the gateway uses the metadata to create the new FCNN header. If the payload of the message does not fit into one packet, it fragments the payload into appropriate sizes and adds a segment number to each new packet's header. With the new header, the packets are sent into the in-body nano network. Nano machines that receive a packet and do not match the desired domain, location and function will only decrement the TTL field of the packet and forward the packet. Nano machines matching all three address parts will accept the packet and it's contents. They store the information on domain, location, function and ID in a ring buffer as a message blacklist to not accept these multiple times. They will act like not matching the address, decrement the TTL and forward the packet.

Figure 3 shows a communication example, where a gateway located on the thorax in domain `Bob` inserts the packet `Bob/RightLung/MobileActuator/5/1234/2` into the in-body nano network. The message addresses all nano machines in the `right lung`, which are `mobile` (depicted by legs) and have `actuator capabilities` (depicted by arms), with a `hop limit of 5`, a message `ID of 1234` and `segment number 1`. After traversing through domain Bob, the TTL decreases each time the message gets forwarded. Figure 4 shows two of the nano machines in the example provide the requested location and function in the correct domain to accept the message.

A message does not always have to originate at the control station and target a nano machine. The addressing works similar with messages originating from a nano machine and the receiver being another nano machine or a control station. To address a control station, a nano machine just needs to address the function 'gateway' without location information to reach any—probably the nearest—gateway. At the gateway, the packets are reassembled and the payload will be forwarded to the control station.

We do not include source information in the header, as we aim to keep the header lightweight and with this concept, we do not identify individual nano machines. However, if the source is still important (for the desired receiver), it can still be included in the payload. E.g., a request from a control station may need a response from the targeted nano machines. Therefore, the request payload needs to deliver metadata for the response message.

In case not all the address parts are needed (e.g., an ingoing message is broadcast) or cannot be provided (e.g., a position is unknown), the header can be used partially. For example, `./nanomachines/./10/2345/.` addresses all reachable nano machines, given a hop limit of 10.

4.3. Related architectures comparison

The concept behind FCNN is quite similar to the concepts for hierarchical addressing and CCN/NDN from Section 3, but it also has some elementary differences. In the following section, we discuss the architectures and explain why we have made other design decisions at FCNN.

FCNN involves a hierarchical structure similar to the principle of hierarchical addressing. To the same degree the hierarchy offers the possibility to use different broadly or precisely defined addresses. However, in the concept proposed by the authors [14, 34] hierarchical addressing confers to the hierarchical network architecture for grouping nano machines to allow group-addressing and to provide short addresses for nano machines in a group. A node's ID for example is only unique in the current designated local group of nano machines. This kind of addressing is a problem for mobile nano machines, as the group membership changes continuously. In FCNN, we hierarchically address regions of the human body—with regard to different precision—as these regions are in a quite static position. This way nano machines in the desired region can be addressed regardless of where individual nano machines are located.

As with CCN or NDN, the connection between two endpoints is not the focus of the interest, but the exchange of data. Here both principles have the same motivation. Since the network in FCNN is not the Internet backbone, but a strongly resource-limited in-body network, the structure must be as light as possible. Thus, the provision of data and the maintenance of tables at the nodes must be minimized so to reduce memory waste. Due to the potentially high mobility of the nano machines, routing tables are quickly outdated. Furthermore, the communication in CCN/NDN is mainly PULL-based. Communication participants use interests to retrieve data from the network. In the medical scenario, however, we envision the communication to be mainly PUSH-based. Sensors report critical measurements and gateways send commands to actuators as actions and not reactions. Of course the gateways should also have the possibility to send requests and receive responses but in order to ensure fast and lightweight communication, abusing interests for PUSH-based messages should be avoided.

4.4. Location-awareness

The nano machines need to be *location-aware* to include this information in their messages respectively accept messages addressing them. As a nano machine moves through the body and changes its location either willingly or unwillingly, the address of this machine has to change too and adapt to the new position. Location-awareness can either be achieved by giving static positions to the nodes, routing them to the desired locations or providing regular location updates. Static positions can be achieved by installing nano machines manually in the desired location, which may be possible, but seems like a rather impractical solution for replaceable nodes. Routing nano machines to locations using their own locomotion possibilities requires less strong direct intervention and control. The aforementioned chemotaxis [27] or more specifically triangulation through beacons [35] provide means for biological guidance of nano machines in the body. Wang [39] offers an overview of man-made guided micro and nanoscale locomotion engines as an artificial alternative. However, if a nano machine does not have absolute control over its position (or none at all), it is necessary to allow the nano machine to determine its position itself. In this case, the nano machines could be enabled, by the provision of molecular or radio signal generators, to determine their position by using the signal strength for estimation. It has to be evaluated if the gateways are able to provide this functionality with a satisfactory reliability.

4.5. Concept summary

Function Centric Nano-Networking is a concept for addressing and naming in wireless and mobile nanoscale networks. The field of application is the medical monitoring and treatment of persons by a combination of an in-body communication network and a BAN. In the in-body network, the unambiguous addressability of the communication users is not the focus. Instead, the address of the nano machines is determined by their current function and location. Function and location are important properties of the nano machines. They have to be determined to successfully assign the correct task to the nano machines and to provide important location information for measurements. Since an address is taken over by a nano machine, an individual machine is not relevant in this concept and is thus easily replaceable. As long as machines fulfill the same purpose and are in the same body segment, they are basically equally addressed and treated.

On the downside, a lack of individual addressing can also lead to problems. If a command is to be given to nano machines at a target site, e.g., to release drugs from a number of x machines, this is not trivial to accomplish. All nano machines on site receive the command, which can be none or a multiple of x. Possibilities have to be found to enable quantity control. If the number of nano machines in the body and a distribution model are known, probabilistic methods could be used for this purpose to only activate a node by a certain chance.

In Section 2, we mentioned challenges and requirements for the development of a fitting address scheme. Not all technical challenges and new opportunities for communication techniques have been discussed in the course of development yet. Choosing a nano machine platform, either biological, artificial or even hybrid as well as choosing a communication type, e.g., molecular or terahertz, has a lot of complex implications. Amongst other things, the choices have an impact on communication distance, communication reliability, nano machine lifespan, processing power, memory size, power supply and not at least, an influence on the human health. The options have to be investigated in the future development of FCNN and require test results from simulations of communication in the various prerequisites.

5. Next Steps / Future Work

The very different addressing and guidance concepts as well as the communication alternatives showed that we are not bound to the classical internet communication process and protocols. Sparse resource options are expected for devices at nanoscale sizes, so efficient but still effective communication methods are needed. With FCNN we proposed a first concept to handle these conditions but have a lot of future work.

5.1. Implementation and evaluation

While this proposal was intended as an overview of existing addressing schemes and an introduction to a new concept to handle in-body communication for medical application scenarios, FCNN needs a more detailed concept regarding implementation. Thus the computational requirements need to be defined and categorized in order to assess the problem complexity. This can have significant impact on the nano machine design [40]. One aim of FCNN is to minimize memory requirements by combining crucial information of the nano machine with routing information, i.e. data about location and function. The combination with fitting routing algorithms for mobile and heavily resource constrained devices has to prove the feasibility of this approach. Resulting from communication, processing and memory usage, we will also need to assess the energy usage of the system.

The implementation of this concept also depends on the nano machine type used (artificial, biological, or hybrid) and the communication type (molecular or radio). It is easy to imagine this concept being used on artificial nano machines with wireless radio communication, using scaled down processor and memory components. Here bit sequences can be used after optimizing the address size through the encoding of address parts, analogous to IPv6. For using biological means to implement this address concept, we propose the use of DNA encoded information and molecular coordinates, as presented in the gene delivery example [37]. Receptor binding would allow the addressing of nano machine cells, consisting of the desired domain and function. Only cells matching these message requirements would accept the delivered message for further inspection of the content. The DNA itself holds the remaining information encoded in base pairs to be processed in the cells nucleus.

The most important future work part is an accompanying concept evaluation. We plan to implement our concept as simulators like NanoSim [41] or NanoNS [42] to learn from experience in the field and to create and implement routing protocols. They are based on ns-2 and ns-3[1], the most commonly used open source discrete-event simulation frameworks for nano simulation. While ns-2 is a well advanced network simulator, ns-3 is the emerging new generation to improve the core architecture. As simulations like NanoSim prove, ns-3 is already mature enough to be build upon. Hence we aim to build our simulation on top of ns-3.

Another significant factor to implement FCNN is to ensure location-awareness. We will test how many BAN gateways are required and where they have to be distributed so that the nano machines present in the body can reliably achieve a correct position determination. In the first step, this is carried out with electromagnetic communication using a body model from medical imaging for correct dielectric properties. For a signal in the range of 0.1 to 10 terahertz, strong disturbances of the signal are to be expected. Accordingly, we will orient our modulation scheme at current research results [43].

5.2. Concept progression

We need to enhance our concept to address further needs and use cases for medical application scenarios [17]. For example, telling all actuator nano machine nodes in an area to release their freight into the body may cause an unwanted overdose reaction. So we may need to address only a reduced amount or percentage of the nodes in the area.

We will also further investigate and elaborate our FCNN concept. There are several important topics for successful nano communication, related to addressing that need to be visited in future work. As these have been generally discussed in [15, 44] they need to be integrated in this concept as it evolves. *Health and Ethics:* While communication concepts may be feasible to accomplish given tasks, in-body communication is a critical intervention to the human body. We must ensure that we do not cause unintended alterations in the biological balance of the human body and study risks of nano machines and communication in extreme detail. *Security:* We also need to investigate the applicability of established security solutions in this context and their influence on the users privacy requirements. Access to monitoring and control functions has to be deniable to intruding third parties. *Reliability:* We will need to come up with insights on Quality of Service (QoS) impact of the interconnection of In-Body Nano Communication Networks with Body Area Networks. *Real-Time:* On one hand it needs to be evaluated on which topic real-time can be a thing and how it is defined and on the other hand: Which communication types do even allow message transfer in time?

[1] ns-2 and ns-3 network simulators available at https://www.nsnam.org

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