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Strengthening the Growth of Indian Defence by Harnessing Nanotechnology - A Prospective

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ABSTRACT

Nano-networking is truly interdisciplinary and emerging field including nanotechnology, biotechnology, and ICT. It is a developing research area which consists of identifying, modeling, analyzing and organizing communication protocols between devices in Nanoscale environments. The main goal is to explore beyond the existing capabilities of Nanodevices by cooperating and sharing information between them. Since conventional communication models are not appropriate to represent Nanonetworks, it is necessary to introduce new communication paradigm in the form of suitable protocols and network architectures. Nanotechnology could greatly improve some of the existing technologies and thus create new operational opportunities or, at least, help the military forces to strengthen themselves in the battlefield. The paper presents a brief overview of nanotechnology applications in defence sector and the challenges towards realization of protocols for Nanocommunication. The research is going forward and one can expect more protection rather than damage in the domain of 'Nano-age'.

Keywords: Nanotechnology, molecular communication, simulators, nanosensors

1. INTRODUCTION

In ever developing world, the science and technology is evolving at a fast pace. However, by applying logic and imagination to current technologies, the Future Soldier might be equipped with best facilities. Now a days, a special emphasis is laid on enhancing the cognitive performance to increase the effectiveness of soldiers in the battlefield. Nanotechnology is an area which shows promising prospects for turning fundamental research into successful innovations. According to the Royal Society of the UK (Royal Society, 2004), 'nanoscience is the study of phenomena and manipulation of materials at atomic, molecular, and macromolecular scales, where properties differ significantly from those at a larger scale'. It is an umbrella term that encompasses a vast range of technologies across a number of disciplines and as a result, it has touched almost all aspects of human society like medicine, health, information technology, energy, materials, food, water and the environment, instruments and security in defence sector. Wireless nanosensor networks (WNSN), an interconnection of hundreds or thousands of nanosensors and nanoactuators placed in locations as diverse as inside human body or in the battlefield, are the most promising application of this new communication technology.

The soldier is at the centre stage of the battlefield and combat systems and could largely benefit from nanotechnology in numerous ways. The future war-fighter may use the properties of nanoparticles or nanofibers to create a large surface area (for sensors, absorption) and form a biotic/abiotic interface between body and equipment. For military applications it enables improved group tactics and information intelligence, protected against all kinds of impacts (ballistics, bioagents, chemical agents). In practice such systems result in the ability to participate in a mobile information network, the use of light-weight smart battle-field suits, wearable intelligence such as sensors and displays for situational awareness and health monitoring. Nanotechnology is here crucial. Without miniaturization such functionalities would not have been possible and adaptable to lightweight, wearable systems.

The two alternative means of communication at the nanoscale are nano-electromagnetic communication[1] and molecular communication. While the first is based on electromagnetic radiation from components based on nano-materials, the latter communicates through information coded in molecules. Given the variety of applications and types of nano-networks, different communication media may be present between them. All these implicate the fact that current state-of-the-art protocols need a profound revision and this radically different types of communication necessitate novel communication protocols and channel models.

2. THE RISE OF NANOTECHNOLOGY – GOING SMALL FOR BIG ADVANCES

Nanotechnology is enabling the development of devices in a scale ranging from one to a few hundred nanometers which are able to perform simple tasks such as sensing, computing, data storing, or actuation. At the nanoscale, the physical, chemical and biological properties of novel nanomaterials and nanoparticles differ in fundamental and valuable ways from

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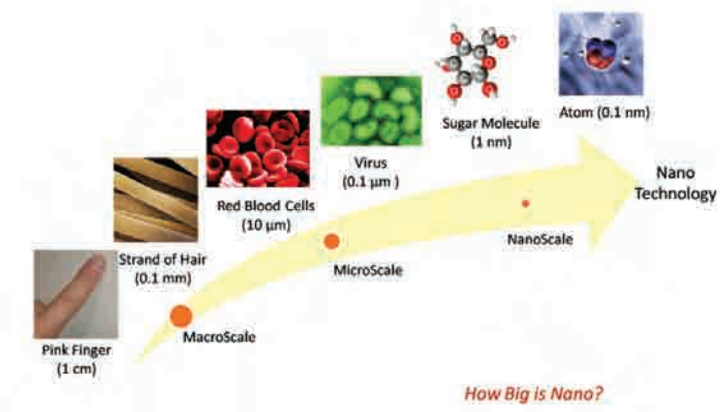

Figure 1. How big is actually 'Nano'.

the properties of those at the microscopic level. Fig. 1 shows the transition of technology from macroscale to nanoscale.

The key metrics for any communication especially with respect to defence sector are Sensitivity, Response time, Probability of correct detection and false positive rate. Nanotechnology has shown an advantage by orders of magnitude and the performance is attributed to its unique properties. Apart from having small dimensions (enabling high speed and high functional density), nanostructures have very large surface area (providing reinforcement and catalytic effects), molecular structures and exhibit quantum effects.

Today, the technology is fast changing the face and nature of electronic warfare. The impact of nanotechnology on future warfare systems or military platforms depends largely on the modernisation requirements of defence forces and military commands. In literature, the following criteria are identified[2,3].

- Highly flexible and fast deployment, mobility (low weight)
- High lethality
- Effective intelligence (acquire data on battlefield)
- Survivability and warfighter protection
- Command, control and communication (C3)
- Endurance (self-supporting soldier)
- Logistics sustainability

It is generally agreed that advances in nanotechnology will drive the next paradigm shift in science and technology. Whilst many commercial applications of nanotechnology remain theoretical, capability exists to manipulate and restructure materials at the nanoscale (typically between 1 and 100 nanometres). The military use of nanotechnology as shown in Fig. 2 will lead to higher protection, more lethality, longer endurance, intelligence and better independent capabilities of future combat soldiers.

3. POTENTIAL MILITARY APPLICATIONS

A wide variety of military applications[4-5-6] (for e.g. in the areas of body armour, camouflage, integrated sensing devices, enhanced body monitoring and care) is conceived as outcomes of R&D in the field of nanotechnology. Furthermore, it is expected that brain-machine interfaces for remote control of military platforms and robotic systems will dominate in the coming 10-20 years. Some of these applications[7] are described below.

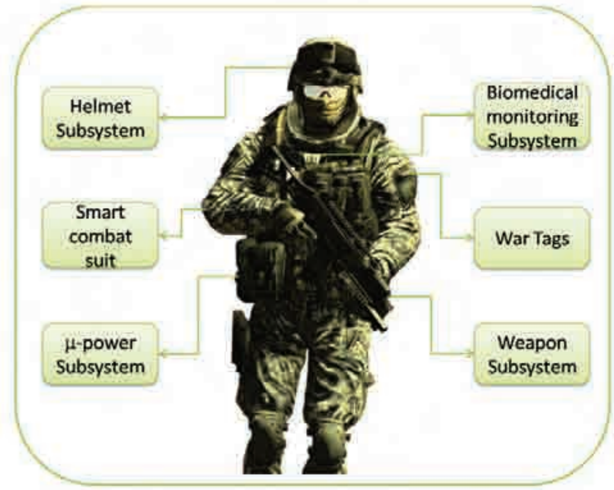

Figure 2. Nanoscience enabled Future Soldier.

3.1 Materials Based

Nanotechnology enables high strength, durable, sensoric and active materials. Nanostructures and nanocomposites are in development for the following functionalities:

- Smart Fabrics – a light-weight, comfortable, water-proof and bullet-proof suits for soldiers. Using chemical vapour deposition (CvD), nanolayers of Teflon are deposited on Kevlar panels which is the base material used to make bullet-proof vests. The hi-tech suits should be adaptable to thermal control and camouflage.
- Sensors – Small nano and micro sensors integrated into smart suits/helmets for environmental and situational awareness.
- Wearable and/or flexible displays for visual feedback information.
- Military platforms – The lighter, stronger and more heat-resistant nano-structured materials like nano-tubes or fullerenes will provide higher speed, light-weight, flexible, more agile and more resistant military platforms, including light armoured vehicles, tanks, fighter jets, man-transportable micro-unmanned air vehicles (MUAV), etc.

3.2 ICT Based

The following ICT technologies will ensure safe and secure communication in network-centric warfare scenario.

Ambient-intelligent networks (AIN) – AIN is used for fitness and health monitoring of soldiers in the battlefield and small devices such as cell phones or receivers are used to collect the information related to heart rate and blood pressure monitors or calorie counters.

- Identification via RFID–identify fellow and enemy soldiers via long-range RFID systems.
- War Tags–Smart nanotech alloy with RFID enabled is proposed as war tag with nanosensor to replace the metallic piece having their name, number and religion engraved on it.
- Nanosensors–easily embedded in combat suit, it emits signal which can be picked by search and rescue operation in the warfare operations.

- Micro-Audio bugs and video recording devices–high capacity data storage devices planted at likely meeting places of terrorists.
- Personal secured access to equipment (biometric id) and information (digital id).

3.3 Energy and Biobased

Light-weight wearable electric power and nano-bio fusion are booming areas with high expectations. The following developments are taking place.

- Flexible solar cells to recharge batteries in the warfare scenario.
- Micropower systems – to power sensor systems in the combat suit, to power unattended sensors and other devices remotely.
- Micro (μ) - nuclear battery for long endurance of various devices in the battlefield.
- Nano-medicine–targeted drug delivery to the soldiers using medically functional nanoparticles for rapid cure without side-effects.
- Smart implants–biocompatible implants that can sense and actuate in order to repair the body function, i.e. monitor a wounded soldier's vital signs, administer basic first aid, and communicate with Headquarters.

3.4 Remote and Unmanned Operation

With nanotechnology, the risk of manned patrol is highly reduced and advanced sensor and wireless communication capabilities are becoming possible, enabling long range guidance, information-gathering and reconnaissance. Especially for military use, continuou s effort is required for development of unmanned and autonomous vehicles e.g. for surveillance. Nanotechnology is crucial here to minimize size, weight and power consumption, important for long range coverage.

- Teleweapons – expanding sensor capabilities and reliable wireless communication enables remotely operated weapons.
- Nano and micro robots – miniaturized, autonomous or remotely controlled robotic systems with firing capability.
- Nano and micro sensors – placed in advance to keep a watch on terrorist hideouts.
- Nuclear, biological and chemical (NBC) defense – Nanosensors can be used to detect the presence of harmful chemicals and biological weapons as they are capable of detecting the concentration of a chemical composite as low as a single molecule.

4. NANO-ELECTROMAGNETIC COMMUNICATION

Nano-electromagnetic communication is defined as the transmission and reception of electromagnetic radiation from components based on nano-materials[1]. The unique properties of nano-materials decide on the communication related parameters such as the bandwidth of emitted radiation or magnitude of emitted power. Although wireless nanosensor networks have a great role to play in strengthening our defence sector, for achieving nanoscale communication, there is a need to study the challenges at nanoscale and redesign the existing communication protocols specifically for distances much below 1m. Some of the research issues associated with wireless nanosensor networks are discussed below.

4.1 Tera-hertz Channel Modeling

There exist many research challenges towards the design of an integrated nanosensor device. Reducing the size of antenna of a classical sensor device to the nanoscale would require the use of extremely high frequencies thus reducing the feasibility of traditional wireless communication among nanosensor nodes. While the novel nano-antennas require communication in the terahertz band, operation in the upper part of the megahertz band could be done by means of an electromechanical nano-transceiver. However, the energy efficiency in the process of communication in MHz band is predictably very low, hence nanosensor devices potentially communicate in the terahertz band (0.1-10.0 THz) and therefore, the terahertz channel needs to be studied and modeled accurately over short distances.

- Path Loss – The spreading loss and molecular absorption loss together account for the total path loss of a travelling wave in terahertz band. The spreading loss indicates the attenuation due to the wave expansion as it propagates through the medium and it depends on signal frequency and transmission distance. The absorption loss is attributed to the attenuation caused when a part of the propagating wave energy is converted into internal kinetic energy of some of the molecules found in the medium. Due to the spreading loss, the total path loss increases with both distance and frequency and is independent of the molecular composition of the channel.
- Noise – The absorption from molecules present in the medium not only attenuates the signal but also introduces molecular noise. This molecular noise neither has Gaussian characteristics nor is it white. Because of the different resonant frequencies of each molecule, the power spectral density is not flat and instead shows several peaks. However, the unique characteristic of this type of noise is that it only appears when transmitting i.e. there will be no noise unless the channel is being used.
- Bandwidth and Channel Capacity - Molecular absorption also determines the usable bandwidth of the terahertz channel. Therefore, the available bandwidth will depend on the molecular composition of the channel and the transmission distance. Single hop transmission within WNSN is only possible upto a distance of few millimetres at which the available bandwidth is extremely high. As a result, the channel capacity in the THz band is expected to be very large, of the order of terabits per second. This large channel capacity can be exploited in a number of ways within Wireless Nano-Sensor Networks (WNSN). Firstly, the amount of information generated by nanosensors is sufficiently large as they transmit information about each and every molecule. Secondly, the density of nanosensors within a WNSN is also very high. Therefore, energy efficient communication protocols are required to exploit these properties to advantage.

- Multipath Fading and Scattering – Since a large number of nanosensors are usually deployed in the battlefield, multiple copies of transmitted signals are received. These multiple signals together create oscillation of power at the receiver. The multipath propagation effects will depend on the distance being travelled, and the type of material, shape and roughness of the surface on which it has been reflected. Also, the molecules and other particles in the medium can create scattering effects which can sometimes drastically affect the communication performance.

4.2 Information Encoding and Modulation

Wireless nanosensor networks require novel encoding and modulation techniques to exploit the high bandwidth available in the terahertz band. Keeping in mind the hardware and processing limitations at the nanoscale, sub-picosecond-long pulses are suitable for communication among nanosensor devices. The power of a sub-picosecond-long pulse is contained within the terahertz frequency band and it can be obtained by simple combination of graphene delay lines and a nanocapacitor. However, conventional modulation techniques like PAM, PPM, and PWM are ineffective with the use of these kinds of pulses. Therefore, design of novel modulation techniques is a challenging task with hardware limitations and frequency selective as well as random nature of terahertz channel.

4.3 Reliability

End-to-end reliability in WNSN is of serious concern in the military applications as wrong or untimely information might be disruptive. There might be several reasons affecting the reliability of nodes like device failure, molecular interference and collision. One of the easiest ways to deal with device failure is to increase the density of nanosensor devices. However, this might not be a practical solution to the problem. Also, with respect to molecular interference, new cognitive protocols need to be designed to enhance the reliability.

5. MOLECULAR COMMUNICATION

Molecular communication[9] is another promising communication paradigm for nanonetworks where the transmission and reception of information take place through molecules. Owing to small size and domain of operation, molecular transceivers are easy to be integrated in nano-transceivers. In the molecular communication process, during particle emission, the particle concentration rate in the environment is increased or decreased according to the modulating signal. The propagation from transmitter to the receiver takes place using particle diffusion and underlying laws of physics. At the receiver, the particle concentration value is sensed and decoded. Although the sequence seems to be simpler, state-of-the-art architectures and protocols need significant revision for realizing molecular communication in nanonetworks. Defining and realization of molecular channel model and encoding/decoding mechanisms is another big challenge to the system designer.

Depending on the type of propagation through the medium, there are three main nanonetwork architectures as shown in Fig. 3. The walkway architecture is based on pre-defined pathways through which the propagation takes place from transmitter to the receiver using carrier substances such as molecular motors. The second architecture is flow based. Here, the propagation takes place through diffusion in a fluidic medium whose flow and turbulence are guided and predictable. In diffusion based architectures, the molecules propagate through spontaneous diffusion in a fluidic medium. It is ruled solely by the laws of diffusion and sometimes affected by the unpredictable turbulence in the diffusion medium. We limit our scope to diffusion based particle communication in this paper.

A key research question in the design of nano-communication networks is the process followed to encode/decode the information. The task of the particle emission process is to modulate the particle concentration rate at the transmitter according to the information signal. The particle receiver model is developed by using the ligand-receptor binding mechanism[10]. However, an interesting work has been done for decoding frequency coded signals in the context of molecular communication[8]. The key design issues in these types of decoders are as follows:

- First, the decoder must exhibit frequency selective behaviour which means that encoder symbol of a specific frequency causes a bigger response at the decoder than symbols of other frequencies.
- Second, the decoder must take into account inter-symbol interference which turns out to be a major performance issue.

The diffusive channel produces serious inter-symbol interference due to the spreading of encoder symbols. Also, when there are more than one transmitting pairs trying to

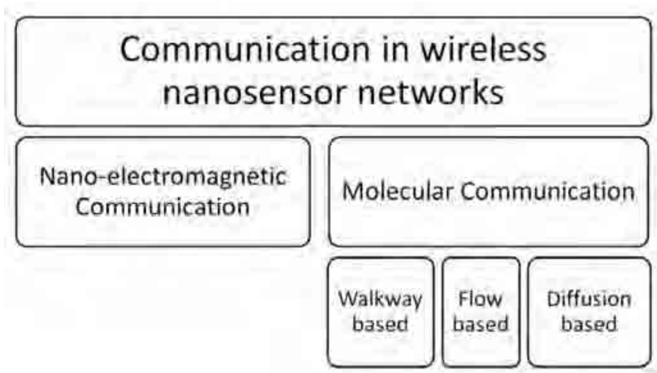

Figure 3. Communication options in WNSN.

Table 1. Traditional communication *vs* molecular communication

Communication	Electromagnetic	Molecular
Carriers	Electrical Signal	Chemical Signals
Environment	Wires	Aqueous Fluids
Velocity	High-Speed	Slow Velocity
Range	[m – Km]	[nm – m]
Energy Consumption	High Requirements	Energy Efficient
Transmission Accuracy	High Accuracy	Low Accuracy, Stochastic Effects

communicate through the same modulation technique and same type of messenger molecules, their signals affect each other and the effects of interference (ISI, ACI, CCI) either degrade/enhance the signal quality thereby decreasing/increasing the overall signal to noise and interference ratio (SINR) of all nearby transmissions.

6. N3SIM - SIMULATOR

There are several diffusion-based simulators in the literature, most of them implement diffusion but do not include the effects of communication metrics. Hence, they are not useful to explore the molecular communication process. The simulator developed by Michael Moore[16] models two communication techniques: diffusion-based and walkway-based. The diffusion-based technique is implemented for the diffusion of single molecule; it does not allow the simulation of diffusion of a set of particles. Besides, it models diffusion based only on Brownian motion ignoring the other effects of inertia and electrostatic forces. Another advanced simulator, NanoNS[14], is available for the modeling of molecular nanonetworks where nodes communicate through diffusion. It is an open-source discrete event-driven network simulator built as a module of NS-2 (Network Simulator)[17] which will facilitate the future study of higher layers of the molecular communication model. However, there are three drawbacks towards using this simulator. First, it models diffusion but not collective diffusion. Second, it uses Fick's laws of diffusion. It is not possible to observe the noise inherent to molecular communication using Fick's laws. Thirdly, NanoNS combines the diffusion and reception processes in one equation thus making the simulator less flexible in making changes. Therefore, N3Sim simulator is considered for studying molecular communication characteristics.

N3Sim is a simulation framework for diffusion-based molecular communication in nanonetworks, a bio-inspired paradigm based on the use of molecules to encode and transmit information. Each transmitter is modeled as a nanomachine with a fixed location. Transmitters encode the information by releasing molecules into the medium with a user-specified pattern. The emitted molecules move according to Brownian motion, as a result of collisions with the smaller fluid molecules. Finally, receivers are modeled as spherical nanomachines which are able to count the number of molecules in a surrounding volume, thus estimating the local concentration. From this measurement, the transmitted information can be decoded. The main output of N3Sim is the concentration as a function of time measured by each of the receivers. The interested reader can find more details about N3Sim in the website of the NaNoNetworking center in Catalunya[11].

The benefits of N3Sim with respect to other diffusion-based molecular communication simulators comes from the fact that it simulates the motion of every single molecule independently, which allows for the observation of the effect of the molecules interactions and the uncertainty introduced by the Brownian motion. Moreover, N3Sim[12,13] allows the simulation of scenarios having virtually any number of transmitters and receivers. This feature enables simulations where the molecular information is broadcast from one transmitter to many receivers, or where more than one transmitter accesses the channel at the same time.

The simulator is highly configurable in terms of parameter settings. The user can edit multiple parameters, such as the number of transmitters/receivers (as well as their locations), the radius of emitted molecules, the emission pattern for each transmitter, the fluid viscosity and the diffusion coefficient, and a bounded/unbounded space, amongst others. This extensive simulator will help the researchers to analyze the new designs and protocols for molecular communication. To illustrate the effect of some of the parameters like diffusion Constant (D) and the particle radius, simulations were done and Figs. 4, 5, and 6 show the performance[15].

The simulation space contains the particles, emitters and receivers. Particles are modeled as spheres and its radius is set with the parameter sphereRadius. Fig. 4 shows the receiver concentration obtained by varying the sphere radius. As the radius increases, the concentration decreases significantly due to the restricted movement in bounded space. The pulse based propagation can be modeled analytically by Fick's laws of diffusion. If the transmitter releases Q molecules at the instant t=0, the

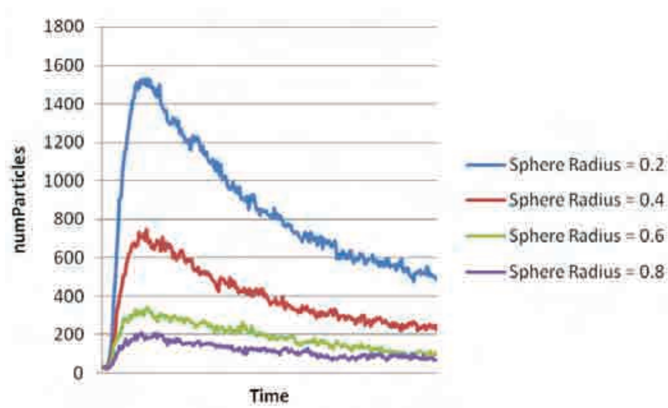

Figure 4. Impact of sphere radius.

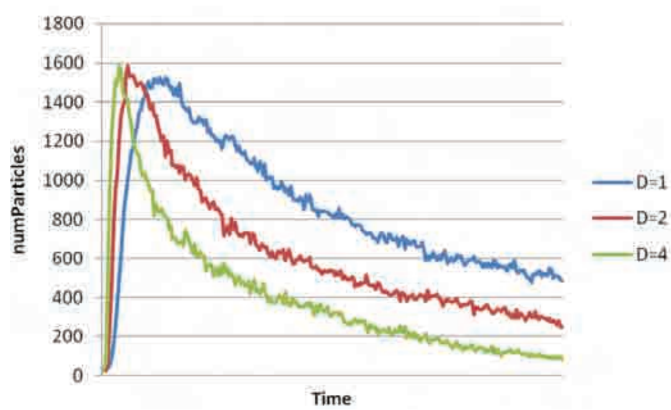

Figure 5. Effect of diffusion constant, D.

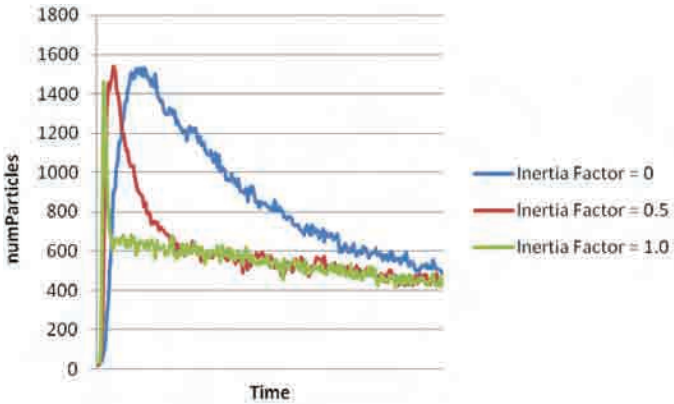

Figure 6. Effect of inertia factor.

molecular concentration at any point in space at time t is given by

$$c(r,t)=\frac{Q}{(4\pi Dt)^{3/2}}e^{-r^2/4Dt}$$

Figure 5 illustrates the effect of increasing diffusion constant, D. As the parameter D increases, the concentration falls down quickly. Inertia Factor (0 to 1) controls the amount of inertia of the emitted particles. If set to zero, particles have no inertia. Otherwise, at every time step, N3Sim adds a displacement equal to the velocity of the previous time step multiplied by this factor. The effect of increasing inertia factor is shown in Fig. 6, which supports the fact that an increase in inertia factor decreases the randomness of the motion by adding interia to the displacement of each particle.

7. CONCLUSIONS

The keywords for military applications are: smart structures, smart skin, smart uniform, smart textiles etc. For the war-fighter to be smart enough in the future combat system, nano-technology enabled systems are a necessity. Soldier capabilities can be enhanced by nanotechnology with strong, lightweight materials for different systems and novel detection and protection schemes for bio/chemical warfare threats and identification of friend or foe.

To realize nanonetworks, significant research work is required to design and analyze the communication protocols. For nano-electromagnetic communication, different modulation techniques like OOK, FSK, and PPM have been explored and compared in the literature. However, challenge remains in minimizing the overall energy consumption while allowing for correct reception of the transmitted signal. The transmitter nanomachines should be able to adjust the energy and the duration of the transmitter pulses adaptively.

Some amount of studies with reference to molecular communication also has already been done and has shown promising simulation results. Although decoding of frequency coded signals have been evaluated in molecular communication networks using enzymatic circuits, more realistic encoder signals and frequency selective behaviour needs to be characterized. Diffusion based molecular communication also poses several challenges in terms of modulation techniques and collision/interference issues between molecules. The two transmitting couple simulation topology is evaluated for interference issues. However, the CCI effect becomes prominent in denser topology when there are more than one interfering communicating pairs in the network. With heterogeneous and complex topologies of nanosensors, relaying and network coding could be highly beneficial for reliable communication.

Ultimately, the future technological progress is directed towards nano, and we need to study and analyze these effects and apply them.

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