Carbon Nanotube-Based Nanoscale Ad Hoc Networks

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ABSTRACT

Recent developments in nanoscale electronics allow current wireless technologies to function in nanoscale environments. Especially due to their incredible electrical and electromagnetic properties, carbon nanotubes are promising physical phenomenon that are used for the realization of a nanoscale communication paradigm. This provides a very large set of new promising applications such as collaborative disease detection with communicating in-vivo nanosensor nodes and distributed chemical attack detection with a network of nanorobots. Hence, one of the most challenging subjects for such applications becomes the realization of nanoscale ad hoc networks. In this article, we define the concept of carbon nanotube-based nanoscale ad hoc networks for future nanotechnology applications. Carbon nanotube-based nanoscale Ad hoc NETworks (CANETs) can be perceived as the downscaled version of traditional wireless ad hoc networks without downgrading its main functionalities. The objective of this work is to introduce this novel and interdisciplinary research field and highlight major barriers toward its realization.

INTRODUCTION

Nanotechnology enables the practical realization of very low-end nanomachines that have tiny components to accomplish a simple specific task such as communication, computation, and sensing. Nanomachines can also be interconnected via nanoscale communication links to form a nanonetwork to fulfill complex tasks such as collaborative drug delivery, health monitoring, and biological or chemical attack detection in nanoscale environments [1]. On the other hand, in nanotechnology, one of the most important unsolved problems is how to make electrical contact from nanoelectronic devices to the macroscopic world without any performance degradation. One potential solution is nanoscale communication links, i.e., wireless network-on-chip networks [2]. Hence, nanoscale communication necessitates the integration of nano and communication technologies to develop frontier nanonetwork applications.

In the literature, there are four main nanoscale communication techniques: nanomechanical, acoustic, molecular, and electromagnetic [3]. In nanomechanical communication, the message is transmitted by a mechanical contact between transmitter and receiver. In acoustic communication, acoustic energy such as pressure variation is used for information transmission. Molecular communication provides nanoscale communication using molecules as communication carriers [4]. Among these, due to the availability of many micro or nanoscale communication devices and the high propagation velocity of electromagnetic waves, electromagnetic communication is the most viable and appropriate technique for the realization of nanoscale communication.

The promising potential of nanomaterials for transmission and processing electromagnetic signals has led to a growing interest in their electromagnetic response. A new branch of nanoelectromagnetics is currently emerging to reveal favorable electromagnetic properties of nanoscale materials [5]. In particular, carbon nanotubes (CNT) are of special interest due to their unusual electronic and electromagnetic properties. Recent theoretical and experimental studies have shown that a single CNT can be designed as the four fundamental components of a radio circuitry, i.e., antenna, tuner, modulator, and demodulator, to listen to radio broadcasts [6]. Electromechanical vibrations of nanotubes can also be harnessed to design a nanoscale transmitter circuitry [7]. Moreover, using CNT, it is also possible to fabricate conducting wires to enable nanoscale antennas that have the closest physical realization to dipole antennas [2].

CNT-based nanoscale communication has great potential in its size and capabilities to extremely shift current wireless technologies to radically new applications such as radio controlled tiny devices to operate in the bloodstream, radically simpler, smaller, and cheaper wireless devices [6]. Apparently, all of these frontier communication propositions necessitate the realization of CANETs. However, this brings many new research challenges, which render the current solutions for traditional wireless ad hoc networks inapplicable due to the salient characteristics of CANET, outlined as follows:
- The scale of the communication devices is on the order of micrometers.
- Wireless communication is based on electromechanical vibrations in CNT receivers and transmitters [6].
- Communication signals are severely prone to thermal noise and fading.

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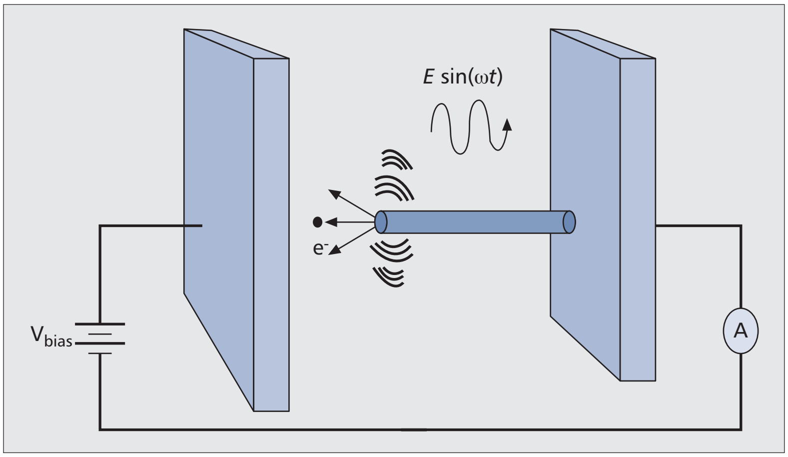

Figure 1. *Illustration of nanotube radio circuit [6].*

- Molecular composition of the communication medium is crucial to model the path loss and noise terms [8].
- Signal power generated by transmitter circuitry is considerably insufficient [7].
- Dense deployment of devices is imperative for network connectivity.
- Nanoscale battery lifetime is significantly lower than existing solid-state batteries.
- Nanoscale memory and processors are considerably inefficient in data storage and computation.
- Nanoscale materials have high manufacturing defect rates and operational uncertainties.
- Mobility of nanoscale ad hoc nodes is governed by the rules of physics in this regime.

In the literature, there exist several research efforts focused on the definition, analysis, modeling, and realization of various nanonetworks [9–12]. However, to the best of our knowledge, an infrastructureless ad hoc nanoscale network composed of nanomachines, its associated challenges, and open research problems have not yet been investigated. The aim of this article is to introduce the concept of CANET and highlight its unique research challenges for an early development stage of efficient and reliable communication and networking techniques for CANET.

Hardware Components of a CANET Nanonode

In CANET, performance of nanoscale communication among network nodes, i.e., nanonode, is affected by the capabilities of four fundamental hardware components, i.e., nanotransceiver, nanopower, nanoprocessor, and nanomemory units, as shown in Fig. 2. Thus, in this section, we give the state-of-the-art of these nanoscale hardware components and discuss their communication, computation, and data storing capabilities for nanoscale communication in CANET.

Nanotransceiver

Here we review the carbon nanotube-based receiver, transmitter, and antenna circuitries, and inspect their communication capabilities.

Carbon Nanotube Radio — The mechanical resonance frequencies of CNT are in the range of 50 MHz–5 GHz, and this range clearly overlaps with the microwave communication spectrum used in traditional wireless communication systems. Hence, this overlapping gives inspiration for developing many innovative nanoelectronic devices [13]. Recently, a single CNT has been designed as the four fundamental components of a radio circuitry, i.e., antenna, tuner, modulator, and demodulator, to receive radio broadcasts [6]. The operation principles of nanotube radio, i.e., CNT radio or CNT receiver, are extremely different from traditional radios since RF signal reception, tuning, amplification, and demodulation are electromechanical processes rather than completely electrical. If an incoming radio wave induces on the nanotube, it causes physical vibrations on the charged tip of the nanotube, as shown in Fig. 1. When the frequency of the incoming wave matches the resonance frequency of the nanotube, the vibrations tune to the incoming wave. Hence, this electromechanical process allows the nanotube to receive the incoming signal.

The resonance frequency of the nanotube, i.e. f, is affected by the length of the nanotube, i.e. L, such that $f \propto 1/L^2$ can be given [6]. To receive a specific radio broadcast, resonance frequency of the nanotube must be initially set by regulating the length of the nanotube. However, the length of the nanotube may be exposed to possible degradation due to the field emission current that traverses in the nanotube. The degradation of the nanotube may also randomly change its resonance frequency, and frequency tuning to the carrier frequency of the incoming wave is no longer possible.

For the amplification and modulation of the incoming signal, DC bias voltage between the electrodes is used, as shown in Fig. 1. The field-emission current generated by the bias voltage is demodulated via the mechanical vibrations. However, degradation of the nanotube would be unavoidable for relatively excessive bias voltage levels, and frequency tuning to the incoming signal would no longer be possible. Hence, the amplification of the incoming signal and the degradation of the nanotube must be jointly considered to efficiently receive the incoming signal. This is one of the most challenging barriers toward the realization of CANET.

In addition to the electromechanical vibrations, thermal vibrations may also be imposed on the nanotube tip. When the nanotube tip experiences some thermal vibrations, the amplitude of the minimum detectable electric field, i.e., E, can be written as [6]:

$$E = \frac{1}{q}\sqrt{\frac{4k_B T m f_0 B}{Q}} \quad (1)$$

where q is the charge on the nanotube tip, m is the effective mass of the nanotube, Q is the quality factor, B is the achieved bandwidth, k_B is the Boltztmann constant, f_0 is the fundamental vibration frequency of the carbon nanotube, and T is the temperature [6]. Clearly, Eq. 1 may be used to derive a signal detection mechanism for nanoscale communication in CANETs. Similarly,

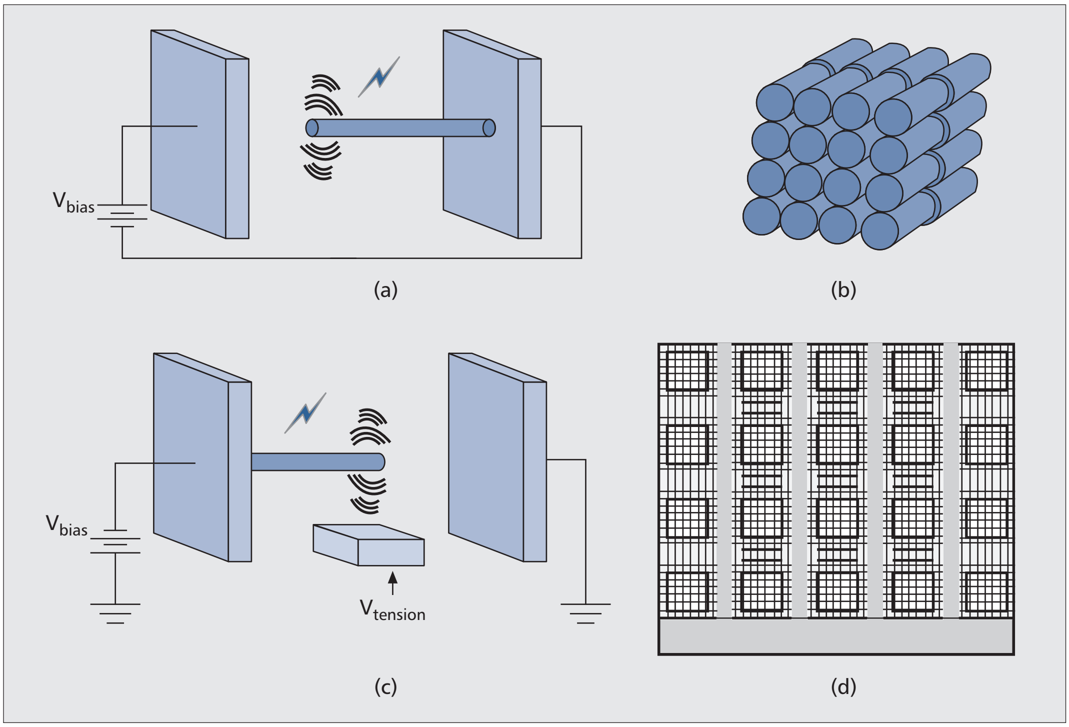

Figure 2. *Illustration of integrated hardware required for nanoscale communication in CANETs, including nanotransceiver, nanopower, nanoprocessor, and nanomemory units.*

Based on the electrostatic actuation of the nanotube with another gate electrode, nanotube radio can be tuned using the entire FM and AM bands. Tunneling nanotube radio is promising to provide nanoscale communication with a relatively low power level and more extensive spectrum range.

it may be possible to extract some analytical and theoretical issues from the field of physics and chemistry to derive theoretical models for nanoscale communication.

Tunneling Nanotube Radio — Beside its efficacy as a nanoscale receiver circuitry, the present form of CNT radio also has severe restrictions, outlined as follows [13]:

- It needs 200 V of power supply to operate.
- It can only tune to 4 MHz, which is five times lower than the FM bandwidth of 88–108 MHz.

Tunneling nanotube radio is proposed to address the above challenges [13]. To reduce the required power level, a tunneling detection mechanism is proposed instead of field emission obtained from the vibrating charged tip of CNT as in [6]. Based on quantum tunneling, the bias voltage of the nanotube radio is decreased on the order of 10 V. Moreover, based on the electrostatic actuation of the nanotube with another gate electrode, a nanotube radio can be tuned using the entire FM and AM bands. Tunneling nanotube radio is promising to provide nanoscale communication with a relatively low power level and more extensive spectrum range.

Nanotransmitter — Electromechanical vibrations of nanotubes can also be harnessed to design a nanoscale transmitter circuitry. In [7], using a CNT, an electromechanical transmitter circuitry is devised. The four fundamental components of a transmitter circuitry, i.e., modulator, oscillator, antenna, and amplifier, are implemented using a CNT. Frequency modulation (FM) in the nanotube transmitter is realized by modulating the mechanical resonance frequency of the CNT. This mechanical modulation can be performed by an external electrode fed by another power source ($V_{Tension}$), as shown in Fig. 2c. The information signal can be applied to this electrode for the modulation. The nanotube also acts as an antenna to allow the radiation of the modulated information signal. Finally, the power of the radiated information signal can be regulated by changing the oscillation amplitude of the nanotube, or increasing the charge in the nanotube, or using an array of nanotubes [7]. Similar to the nanoreceiver, the nanotransmitter is also subject to the degradation of the nanotube and a considerably low power source of nanopower unit. Hence, the degradation of the nanotube and the amplification of the radiated power must be jointly considered to efficiently amplify and transmit the information signal.

Carbon Nanotube Antenna

Due to their promising electromagnetic characteristics, CNT-based antennas are favorable in different frequency regimes ranging from microwave to visible. One of the important parameters of a CNT is its quantum resistance, which is much smaller than the normal metal wire with the same geometry in nanometer scale. The skin effect in CNT can also be ignored when the operating frequency reaches terahertz. Therefore, the power dissipation of a CNT antenna is low, and this also leads to high antenna efficiency with respect to a metal wire with the same size [14]. However, theoretical estimates in [2, 15] show that due to the estimated –90 dB of losses imposed by ohmic currents, the radiation efficiency of a single-walled CNT antenna, i.e., $\eta = P_r/P_r + P_t$, is very low, i.e., on the order of 10^{-4} and 10^{-5}, where P_r is the radiated power and P_t is the power of the thermal losses. Thus, CNT bundles are used to provide higher efficiency [14].

Radio	Circuit size	Antenna size	System size
Hitachi	1E-14	1E-08	1E-08
France-Telecom	1E-09	1E-09	1E-09
Smart Dust	3.125E-09	1E-06	1E-06
Single-chip radio	—	—	1E-14
Nanotube radio	—	—	1E-21
Volume of living cell	—	—	1E-18

Table 1. *Estimated circuit, antenna, and system size (m^3) for various radios complied from the literature [17].*

When a CNT antenna carries several microamperes of current under an applied voltage of a few volts, it emits the maximum of a few microwatts of power to its surrounding environment. As the required communication range increases, it may be possible to amplify the transmission power using a number of nanotubes in parallel. In addition to amplifying the power, an antenna array also enables directionality properties of transmission, which leads to less power consumption when point-to-point communication is needed [16].

CNT antennas may be incorporated into available micro or nanoradio circuitries to provide greater efficiency in the size of the overall system volume. In Table 1, radio systems in the literature are compared with respect to their circuit, antenna, and entire radio system size. The aim of this comparison is to illustrate the relative importance of antenna volume in total system size. The comparison clearly reveals that the small circuit size is possible; however, having small antenna size is more challenging [17]. Hence, due to the availability of a CNT antenna that is on the order of 100 times smaller than a classic dipole antenna, CNT antennas are clearly a promising alternative for nanoscale communication requirements in frontier nanotechnology applications of CANETs. In Table 1, the system sizes of the given radios are also compared with the volume of a single living cell. This also reveals that carbon nanotube radio and tunneling nanotube radio [6, 13] with 1E-21 m^3 of average system volume are feasible alternatives for nanoscale communication in envisioned biomedical nanotechnology applications in a living cell [17].

Nanobattery

Power supply at nanoscale is one of the most critical challenges to realizing future CANET nodes. In [18], nickel-zinc batteries having a footprint of 0.02 cm^2 and 0.555 mW h/cm^2 of energy supply are manufactured, and their open circuit voltage ranges from 1.7 V to 1.8 V. In [19], micro-battery arrays with nanoscale anodes and cathodes are introduced using commercially available nanomaterials with extremely small diameter size on the order of nanometers. The capacity of these battery arrays ranges from 3 mAh/g to 18 mAh/g, with 1.5–2 V nominal voltage. Consequently, current technologies may support nanoscale power sources for the realization of nanoscale communication in CANETs. However, overall power budget analysis, including the energy consumption in the transceiver, memory, and processor units, must be performed. This analysis can be critical to assessing whether the existing nanobattery technologies can enable both point-to-point and multi-hop nanoscale communication.

Nanomemory and Nanoprocessor

The memory unit is one of the most critical hardware components to provide an efficient store-and-forward mechanism in CANETs. In [20], a nanowire crossbar circuit is used to design a nanoscale memory that operates with 0.5–3.5 V. By switching and setting the resistance of the crossbars, each cross point is used as an active memory cell. Crossbar circuits are also configured as multiplexer and demultiplexer circuits. An 8 × 8 crossbar circuit is inserted into an area of 1 μm^2 with a density of 64 $Gbits/cm^2$. In [21], another addressable nanomemory is designed using aligned carbon nanotubes with cross geometry. Some nanoprocessor designs can also be found in the current literature. In [22], using semiconductor nanowire blocks, functional processor components are constructed. Nanowire junction arrays are configured to build OR, AND, and NOR logic-gates and to enable simple computations. In [23], sequential nanomemory and processor with clocked operations are devised.

Consequently, nanomemory, nanoprocessor, and nanopower units are feasible to enable required nanoscale communication functionalities in CANETs. However, their extremely limited power, computation, and storing capabilities also severely restrict nanoscale communication in terms of transmission power, communication range, data storage, and computational complexity. This also radically shifts the conventional network functionalities to an extremely resource-constrained and uncontrolled domain. In Fig. 2, nanopower, nanomemory, and nanoprocessor units are illustrated.

Fundamental Communication Issues in CANET

Here, we discuss the fundamental research challenges and open issues of nanoscale communication in CANETs.

Operating Frequency Band

In nanoscale communication, it may be possible to use a frequency band selected from a large range of electromagnetic spectrum, i.e., from megahertz (MHz) to terahertz (THz). The MHz frequency range may be used with CNT receivers and transmitters, whereas THz ranges require CNT antennas. Clearly, if the operating frequency is selected from the megahertz range, it may be feasible to provide higher communication range than with CNT antennas. However, as introduced in the previous section, CNT receivers and transmitters need on the order of 100 V of power. Therefore, CNT antennas with an applied voltage of a few volts may be a more feasible alternative for nanoscale communication. In fact, tunneling nanotube radio reduces the power need of CNT receiver and transmitter circuitry to on the order of 10V, and rapidly developing nanotechnology might be expected to further decrease this power need, which may make CNT receivers and transmitters more feasible.

PATH LOSS AND NOISE

Due to the extremely low transmission power level in nanoscale communication, signal propagation is severely prone to spreading and molecular absorption loss that constitute the path loss term. The spreading loss stems from the expansion of the electromagnetic wave as it propagates through the medium. The molecular absorption loss is an environmental phenomenon by which a part of the wave energy is absorbed by some of the molecules in the medium [24]. Each molecule type has different absorption characteristics in frequency and amplitude. This imposes an ambiguity on the received signal and may severely reduce the achievable communication rate in nanoscale communication [8].

The molecules also disperse electromagnetic energy that is captured from the medium [24], which incurs an ambient noise. Each molecule type in the medium has different characteristics of electromagnetic energy dispersion. This also imposes a critical irregularity on the characteristics of noise power whose statistical properties may completely differ from traditional wireless communication. Hence, in order to comprehensively analyze a nanoscale communication channel, the electromagnetic energy absorption and dispersion characteristics of molecules found in the medium should be carefully taken into account.

Nanoscale communication is also prone to some environmental factors such as thermal noise and interference from other wireless systems. If CNT receivers and transmitters that operate in the MHz range are used, it may be more likely to be exposed to a higher interference level compared to other wireless systems using the MHz range. However, CNT antennas that operate in the THz range, which is still an unlicensed band, might be a better choice to avoid high interference level.

COMMUNICATION RATE AND RANGE

In nanoscale communication, communication rate and range are functions of molecular composition in the medium, the upper bound of transmission power, and the operating frequency. Among them, the molecular composition of the medium may vary according to the molecular mixture of the medium. Thus, the achievable communication rate and range also differ from one medium to another. For a medium with a high level of molecular absorption loss, achievable communication rate and range may be improved by increasing the upper bound of the transmission power.

Due to the lack of precise analytical models to determine the upper bound of transmission power provided by CNT transmitters and antennas, it may not be possible to estimate achievable communication rate and range even if some environmental assumptions on molecular composition of the medium are made. Actually, the analysis of them is an important open research issue that must be addressed. However, recently, in the terahertz nanoscale communication channel, communication ranges from 10 μm to 10 m and 10^{10}–10^{14} (bits/s) of communication rate are shown to be possible under a set of certain assumptions such as the upper bound on transmission power [8].

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ANALOG VS. DIGITAL COMMUNICATION

In CNT receiver and transmitter circuitry, transmission and reception of information signal are purely analog. The carrier frequency of the information signal is absolutely specific to the length of the nanotube. By using CNT receiver and transmitter circuitry, nanonodes that are in close proximity to each other can communicate if they tune in the same frequency. Therefore, only half-duplex communication is feasible, and available communication bandwidth is inefficient and static for CNT receivers and transmitters. This static frequency tuning also causes considerably higher interference among nanonodes. However, CNT antennas that are integrated with a sufficiently small radio system can allow nanonodes to use more than one communication channel, thus providing full-duplex digital nanoscale communication [16]. This can also provide higher communication bandwidth.

ENCODING OF INFORMATION

None of the available encoding mechanisms in digital communication may be feasible if CNT receivers and transmitters are used in CANET nodes. Coded transmission of information may be possible if a CNT antenna is integrated with a sufficiently small radio system. However, due to considerably lower computational power in a nanoprocessor, available encoding mechanisms may not be practical for nanoscale communication in CANETs. Similarly, none of the digital error detection and correction mechanisms may be applicable. Instead, novel encoding and error detection and correction mechanisms with considerably lower computational complexity must be developed.

FUNDAMENTAL NETWORKING ISSUES IN CANETS

In this section we consider an application example of CANETs, i.e., a nanoscale bio-sensor network (NBSN) to detect hazardous antigen concentration as an immune system support, and then highlight the corresponding networking challenges and open issues to be addressed. In addition to the hardware components given earlier, we assume that nanonodes in NBSNs also have a sensing unit [25] to detect the presence of antigen molecules, as shown in Fig. 3.

In NBSNs we assume that nanonodes are deployed to detect a concentration of antigens and to forward the concentration information to a central entity who makes decisions such as the dosage of the taken drug or the type of detected antigen to fire an action potential. During the network operation of NBSNs, there might be

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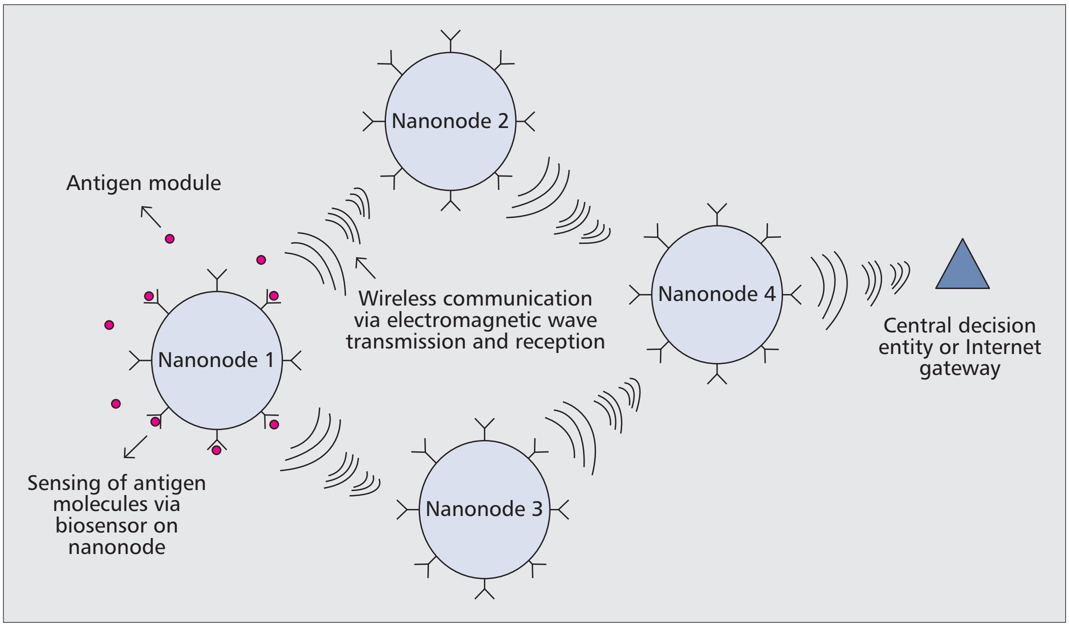

Figure 3. *Illustration of a CANET application example, i.e., nanoscale bio-sensor network.*

three operational phases for nanonodes, as follows:

- If a nanonode detects a concentration of antigens, it measures, encodes, and transmits the concentration information to its surrounding environment. This phase is called the *transmitter phase* of nanonodes. In Fig. 3, nanonode 1 is in the transmitter phase.
- If a nanonode receives a communication signal from another nanonode, it is in *forwarder phase* and it amplifies and forwards the received transmission. Nanonodes 2, 3, and 4 are in the forwarder phase, as seen in Fig. 3.
- If a nanonode has no information to transmit and does not receive a communication signal from its surrounding environment, it is in *idle phase*.

Clearly, all of the communication challenges and open issues previously outlined must be addressed as the prerequisite for the deployment of CANETs toward the realization of this sample NBSN application. Furthermore, the realization of NBSN necessitates intelligent control of these three phases in terms of energy consumption, reliability, and robustness. This mandates the development of novel communication and networking techniques for CANETs, which addresses the challenges outlined next.

Deployment and Topology

Because of severely energy constrained nanobatteries, transmission power generated by the nanotransmitter is significantly lower, and therefore nanonodes have very limited radio range. This necessitates the dense deployment of nanonodes for network-wide connectivity with smaller energy consumption. Due to high manufacturing defect rates and operational uncertainties in CNT, CANETs must also have a resilient topology to maintain normal network operations despite node failures or mobility.

Multi-Hop Reliability

Upon the transmission of the information signal, additional functionalities and challenges should be overcome to route the signal among CANET nodes. A possible routing scheme may be similar to flooding-based routing mechanisms if CNT receivers and transmitters are used in nanotransceiver circuitry since they naively generate analog signals that radiate along the network. However, CNT antennas provide the capability of directivity for nanonode transmission [16]. This may enable a spatial routing scheme in which each nanonode can forward its transmission toward the direction of its destination.

A simple store-and-forward mechanism may be attainable for CANET nodes. However, power consumption required by data storage and computation may seriously reduce network lifetime. Therefore, an efficient store-and-forward scheme should also take into account the power consumption required by data storage and computation.

Medium Access Control

Due to uncoded analog data transmission, code-division multiple access (CDMA) is not feasible for CANETs with CNT receivers and transmitters. Similarly, due to their high computation complexity requirement, CDMA mechanism may also not be appropriate for the configuration with CNT antennas. Instead, a much simpler form of frequency-division multiple access (FDMA)-based or time-division multiple access (TDMA)-based approaches might be suitable to efficiently access the communication medium. Using more than one CNT receiver and transmitter in each nanonode, each of which having different CNT resonance frequency, nanonodes might use different frequency channels that do not interfere with each other. This might provide a simple form of FDMA mechanism in which each nanonode selects a frequency to transmit and some of its neighbors receive its transmission if there is no other simultaneous transmission on the same frequency channel. The realization of such an access mechanism clearly entails the efficient selection of transmission frequencies. However, it might be feasible to initially select and set the transmission frequency of all nanonodes to provide the minimum level of interference among nanonodes.

Moreover, a TDMA-based mechanism might also be possible as long as the nanoprocessor provides synchronized operations [23]. However, these clocked and synchronized operations are subject to some synchronization errors due to the low computational power of the nanoprocessor. For this type of asynchronous channel access, it might also be feasible to use the pulse-width of the nanonode transmissions to provide an efficient collision detection mechanism. Let us assume that every nanonode located in the same collision domain uses a different pulse-width, which is an integer multiple of a predefined minimum pulse-width. If the transmissions of more than one nanonodes collide and the pulse-width of these transmissions overlap, then it is highly likely that the pulse-width of the received signal is not an integer multiple of the predefined minimum pulse-width and this pulse-width cannot be identified at the receiver side. This mechanism may clearly lead to a collision detection mechanism.

Conclusion

In this article we introduced the concept of CANETs. By investigating existing nano-transceivers, power, memory, and processor circuitries, we first explored hardware components required for nanoscale communication. After discussing the suitability of these hardware components, we presented fundamental communication and networking issues and research challenges in CANETs. Our investigations reveal that CANETs significantly shift the traditional wireless communication and networking paradigms to an unobservable, uncontrollable, and extremely challenged domain.

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Our investigations reveal that CANET significantly shifts the traditional wireless communication and networking paradigms to an unobservable, uncontrollable, and extremely challenged domain.