Carbon Nanotube Sensor Networks

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***Abstract*—The development of carbon nanotube transmitter and receiver circuits operating with radio frequency (RF) allows current wireless technologies to function at nano-scale environments. This vision also enables a very large set of new applications such as coordinated disease detection, drug delivery, and biological and chemical attack defense. Especially, coordinated nano-scale data acquisition is one of the most promising functions in the nanotechnology applications. In this paper, we define the concept of Carbon Nanotube Sensor Networks (CNSN) for future nano-scale data acquisition applications. CNSN can be perceived as the down-scaled version of traditional wireless sensor 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.**

I. Introduction

Recent developments in nano-scale electronics have enabled the fabrication of nano-scale circuitries such as nano-transmitter, nano-receiver, and nano-processor. This envisages that current wireless technologies can be scaled down for plenty of new nanotechnology applications [1].

- In *biomedical field*, a number of communicating nano-scale machines can enable efficient drug delivery systems. For example, the networks of the inorganic nano-tubes can deliver a specific amount of drug to the diseased tissues or tumors arising in a critical part of the body such as brain or heart. This can be achieved based on the acidity-sensitive action potential of the inorganic nanotubes [2].
- In *industry field*, nano-scale machines can allow a lot of new applications from nano-scale vacuum cleaners to the nano-networks providing water and food quality control. For example, using the networks of cooperative nanosorbents, nanocatalysts, and bioactive nanoparticles; water quality control can be efficiently achieved. Moreover, effective water purification process can be performed to completely eliminate all toxic materials in the waste water [3].
- In *military field*, the collective effort of nano-scale sensors can provide accurate detection of infinitesimal changes in the chemical or biological state of the observed environment in the case of a chemical or biological attack [4].

Clearly, sensing and communication are the most fruitful functions for these nanotechnology applications. For the realization of nano-scale sensing, carbon nanotubes are very promising structures due to their unique sensing capabilities. They can provide considerably higher sensitivity and faster response than solid-state sensors [5]. Furthermore, recently developed carbon nanotube based transmitter and receiver circuits facilitate traditional analog RF communications among nano-scale devices [8], [9]. These recent developments in the nano-scale sensing and communication technologies envisage the concept of carbon nanotube sensor networks (CNSN) for frontier nano-scale data acquisition.

The realization of CNSN brings plenty of crucial research challenges to the existing wireless technologies. Although many protocols and algorithms have been proposed for traditional wireless sensor and ad hoc networks [7], they are not well suited to the unique features and application requirements of CNSN. The main differences between traditional wireless networks and CNSN can be given as follows:

- Scale of the communication devices is on the order of micro meter.
- Wireless communication is based on electromechanical vibrations at the nano-scale [8].
- Electromechanical vibrations are severely prone to thermal noise and fading [8].
- Signal power generated by electromechanical vibration in transmitter circuitry is considerably insufficient [9].
- Dense deployment of devices is imperative for network connectivity.
- Nano-scale battery life time is significantly lower than the existing solid-state sensor batteries [10].
- Nano-scale memory and processor are considerably inefficient in data storage and computation [11].

In the literature, there exist several research efforts for the realization of nano-scale sensor networks [12], [13], [14]. In [12], available nanotechology is investigated to enable a nano-scale sensor network architecture. In [13], the impact of current nanotechnology over the existing wireless technologies is manifested. In [14], random deployment of carbon nanotubes are envisaged as a wireless sensor network. However, none of these studies consider the impact of nano-scale electromechanical vibration based communication and network functionalities for the realization of nano-scale sensor networks.

The aim of this paper is to introduce the concept of CNSN and highlight unique research challenges of CNSN for an early development stage of efficient and reliable communication and network algorithms for CNSN.

The remainder of this paper is organized as follows. In Section II, we give the hardware components of a carbon

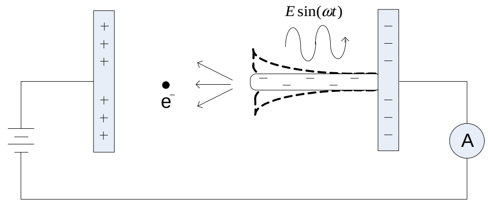

Fig. 1. Illustration of nanotube radio circuit [8].

nanotube sensor node. In Section III, we introduce the concept of carbon nanotube sensor networks. Some fundamental issues in nano-scale communication and networking functionalities in CNSN are presented in Section IV. Finally, we give our concluding remarks in Section V.

II. Hardware Components of a Carbon Nanotube Sensor Node

Many nanodevices are at early stages of their development. To harness their unique features, it can be possible to combine them with a system architecture [16]. The hardware of a CNT sensor node includes four fundamental components, i.e., nano-transciever, nano-power, nano-processor, nano-memory, and nano-sensing units as shown in Fig. 2. Next, we give state of the art these nano-scale hardware components for the realization of CNT sensor node.

A. Nano-transciever

In this section, we review the carbon nanotube based transmitter and receiver circuitries and their operation principles. We also criticize their communication capabilities to assess whether they can provide a reliable communication for CNT sensor nodes.

1) Nano-receiver: Theoretical and experimental studies recently show that a single carbon nanotube can be designed as the four fundamental components of a radio circuitry, i.e., antenna, tuner, modulator, and demodulator, to listen radio broadcast. The nanotube radio has great potential in its size and capabilities to extremely shift current wireless technologies to radically new applications such as radio controlled devices small enough to operate in human's bloodstream, or radically simpler, smaller, and cheaper wireless devices [8].

The operation principles of nanotube radio are extremely different from traditional radios since RF signal reception, tunning, amplification, and demodulation are electromechanical processes rather than completely electrical. A nanotube radio is schematically shown in Fig. 1. If an incoming radio wave impinges upon the nanotube, it causes physical vibrations on the charged tip of nanotube. When the frequency of incoming wave accompanies with the resonance frequency of nanotube, the vibrations tune to the incoming wave and these vibrations become significant. Hence, this electromechanical process enables the nanotube to receive the incoming signal. For this electromechanical signal reception, resonance frequency of the nanotube must be consistent with the carrier frequency of the incoming signal.

Resonance frequency of 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 [8]. This physical dependency severely restricts the resonance frequency of the nano-receiver. To listen a specific radio broadcast, resonance frequency of nanotube must be initially set by regulating the length of the nanotube. However, the length of the nanotube may be exposed to a possible degradation due to the field emission current that traverses in the nanotube [17]. The degradation of the nanotube can also randomly change its resonance frequency and the frequency tunning to carrier frequency of incoming wave can be no longer possible. Nevertheless, it is also possible to avoid the degradation of the nanotube by keeping the field emission current below a specific value. For example, in [18], a stable emission at 0.4 μA has been measured during two months without degradation.

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 and it serves as incoming signal. Furthermore, by regulating the battery power feeding the electrodes, signal amplification can be accomplished. However, this amplification is also subject to the degradation of nanotube because incoming signal must be amplified without degradation of the nanotube. The amplification increases with the bias voltage. After a specific bias voltage, degradation of the nanotube would be unavoidable and the frequency tunning to the incoming signal would be no longer possible. Hence, the amplification of the incoming signal and the degradation of the nanotube must be crossly considered to efficiently receive and amplify the incoming signal. Since the amplification should not cause a possible degradation of the nanotube, incoming signal may not be sufficiently amplified to be stored, processed, and transmitted. This is a major barrier toward the realization of CNSN.

In addition to the electromechanical vibrations, thermal vibrations may also be imposed on the nanotube tip. When the nanotube tip experiences some thermal vibrations, amplitude of the minimum detectable electric field, i.e., E, can be written as [8]

$$E = \frac{1}{q}\sqrt{\frac{4k_B T m \omega_0 B}{Q}} \tag{1}$$

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, ω_0 is the fundamental vibration frequency of carbon nanotube, and T is the temperature [8]. Clearly, (1) may be used to derive a signal detection mechanism for the nano-scale communication among CNT sensor nodes. Similarly, it can be possible to extract some analytical and theoretical issues from the concepts of Physics and Chemistry to derive theoretical models for CNT sensor communications. For example, channel and noise models can clearly follow some statistical distributions observed in some electromechanical reactions that have been

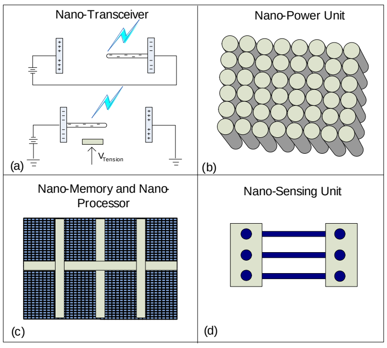

Fig. 2. Illustration of integrated CNT sensor hardware including nano-transceiver, nano-power, nano-memory, nano-processor, and nano-sensing units.

experimentally and theoretically modeled and analysed [31].

2) Nano-transmitter: Similar to the carbon nanotube based receiver unit, electromechanical vibrations of nanotubes can be harnessed to design a nano-scale transmitter circuitry. In [9], using a single carbon nanotube, 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 single carbon nanotube. Frequency modulation (FM) in the nanotube transmitter is realized by modulating mechanical resonance frequency of the nanotube. This mechanical modulation can be performed by an external electrode fed by another power source $(V_{Tension})$ as shown in Fig. 2(a). Information signal can be applied to this electrode for the modulation. After the modulation of the information signal via self-oscillation of carbon nanotube, the nanotube acts as an antenna to enable 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 of an array of nanotubes [9].

Similar to the nano-receiver, nano-transmitter is also prone to the degradation of nanotube. When a nanotube transmitter degrades, its resonance frequency also randomly changes. By applying low bias voltage, it may be possible to avoid the degradation of the nanotube. However, in this case, power of the radiated wave cannot be sufficiently amplified and transmission range of the nano-transmitter becomes extremely small and information signal cannot be reliably transmitted along the network. Therefore, the degradation of nanotube and the amplification of the radiated power must be crossly considered to efficiently amplify and transmit the information signal. This is also another major barrier on the realization of CNSN.

B. Nano-battery

Power supply at nano-scale is one of the most critical challenges to realize far future nanodevices. Energy obtained from a power source is proportional to the amount of electroactive material in the power source. However, in addition to quantity of the electroactive material, energy level is affected by some additional factors, e.g., surface-to-volume ratio and shape of the material. Therefore, the fabrication and implementation of nano-scale batteries necessitate the investigation of their macroscopic counterparts [10].

TABLE I
SOME MICRO-BATTERY CONFIGURATIONS [22]

Process	**Sputtering, Thermal Evaporation**	**Pulsed Laser Deposition**	**Sputtering, Electroplating**
Cathode	V_2O_5	$LiCoO_2$	NiOOH
Anode	Li	Li	Zn
Electrolyte	LIPON	$LiClO_4$	KOH-ZnO
Nominal volt. (V)	3.75	$3.2 - 3.6$	$1.7 - 1.8$
Area (cm^2)	1.21	3.0	$0.007 - 0.02$
Capacity (μAh)	$13.5 - 18.5$	216	$1.9 - 6.74$

The traditional approach to obtain micro-scale power source is the downsizing of macroscopic power sources. In [19], for autonomous micro systems, nickel-zinc batteries are manufactured using a fabrication method as in the microelectronic industry. They have 0.02 cm^2 of footprint and approximately generates 0.555 mWh/cm^2 of energy and the open circuit voltage of cells ranges from 1.7 V to 1.8 V. To further scale down the micro-batteries, lithium-based and silicon-based batteries are also developed [20]. In [21], micro-battery arrays with nano-scale anodes and cathodes are introduced using commercially available nano-materials that can scale on the order of nanometers in diameter. The capacity of these battery arrays range from 3 mAh/g to 18 mAh/g with $1.5 - 2V$ nominal voltage. In Table I, some micro-battery configurations are briefly presented [22].

In addition to the realization of the nano power unit, the distribution of the generated power along all interconnections is also a critical challenge. Copper wires are not an appropriate alternative for efficient power distribution due to their high resistivity. Instead of copper wires, carbon nanotubes are also feasible alternative for these interconnections [10].

Consequently, current technologies may support nano-scale power source for the development of CNT sensor nodes. However, overall power budget analysis including the energy consumption in transceiver, sensing, memory, and processor units must be performed. This analysis can be critical to assess whether the existing nano-battery technologies allows the CNT sensor communication or not. For example, due to their insufficient capacities, nano-power units may not sufficiently feed the nano-transceiver circuitry to amplify the received and transmitted signal. This may severely restrict the transmission radius of CNT sensor nodes and may also hinder reliable transmission and reception of the information signal.

C. Nano-memory and Nano-processor

Memory unit is one of the most critical components in sensor hardware to provide a reliable store-and-forward mechanism in data acquisition. At the nano-scale, some memory systems have been previously designed for the development of memorized nanodevices such as nano-processors and molecular computers. In [24], nano-wire crossbar circuit is used to design a nano-scale memory system that operates with $0.5V - 3.5V$. By switching and setting the resistance of the crossbars, each cross point is used as an active memory cell. Crossbar circuits are configured as multiplexer and demultiplexer circuits. An 8×8 crossbar circuit can be inserted into an area of $1\ \mu m^2$ with a density of $64Gbits/cm^2$. In [23], another addressable nano-memory is designed using aligned carbon nanotubes with crossed geometry. Moreover, in [25] and [26], similar nano-memory systems are designed to enable future nanodevices with memory. With this regard of the existing nano-memory hardware, current technologies may clearly allow the development of CNT sensor node with memory system.

For the realization of CNSN, nano-processor is imperative for the integrated operations of CNT sensor nodes such as synchronized transmission and simple computations. To this end, some nano-processor designs can be found in the current literature and involved in the hardware structure of CNT sensor node. In [27], using semiconductor nano-wire blocks, functional nano-device components are constructed. Nano-wire junction arrays are configured to build OR, AND, and NOR logic-gates and to enable simple computations. In [28], a bottom-up design approach for Programmable Logic Arrays (PLAs) is introduced using molecular-scale nano-wires. In [29], sequential nano-memory and processor with clocked operations are devised.

Consequently, nano-memory and nano-processor are feasible to realize CNT sensor nodes with extremely limited data-storage, computations, and synchronization capabilities. However, these limited capabilities also severely restrict CNT sensor communication in terms of power consumption and computational complexity. They also radically shift the conventional network functionalities to extremely unobservable, uncontrollable, and resource-constrained domain. In Fig. 2(c), nano-power, nano-memory and nano-processor units are illustrated.

D. Nano-sensing Unit

Due to their fast response capabilities and substantially higher sensitivities, carbon nanotubes are promising to enable future nano-scale sensor nodes [5]. Here, we assume a carbon nanotube based sensing unit as shown in Fig. 2(d). Carbon nanotubes have been previously researched for plenty of nano-scale sensing applications. In [30], using single-walled carbon nanotubes (SWNTs), the fabrication and characterization of pressure sensors with circular radius range of 50-100μm are introduced. In [32], for infrared (IR) applications, physical features and electronic properties of carbon nanotube arrays are investigated. Theoretical and experimental studies have shown that carbon nanotube arrays provide significant response toward IR signals having very broad wavelength range $(1 - 15\mu m)$. In [5], based on extreme changes in carbon nanotube resistance as a response to molecule capturing,

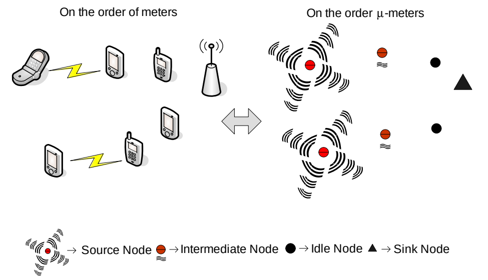

Fig. 3. Illustration of a CNSN environment with the comparison of a simple wireless ad hoc network.

chemical sensor is introduced to detect gaseous molecules using an individual SWNT.

Hence, carbon nanotube based sensing unit is feasible and can be incorporated in a possible CNT sensor hardware. Due to their high sensitivity and fast response capabilities, carbon nanotube based sensing unit may also support significant sensing coverage [6] and considerably robust response toward the observed phenomenon for CNSN applications.

III. Carbon Nanotube Sensor Network

In conventional sensor network applications, an environment is assumed to be covered by low-end communicating sensor nodes for data monitoring [7]. Similarly, to envisage the concept of CNSN, we assume that CNT sensor nodes are deployed in an environment to gather nano-scale mechanical, optical, or chemical phenomena. In Fig. 3, a CNSN environment is illustrated comparing with a simple wireless ad hoc network. As will be detailed in Section II, CNT sensor nodes are assumed to have the capability of environmental sensing, storage, processing, and analog RF signal transmission and reception. By means of these capabilities, CNT sensor nodes can store-and-forward the sensed information toward the sink node. The sink node has also the capability of RF signal reception from the sensor nodes. In Fig. 3, three phases in which each CNT sensor may involve are illustrated.

- If a CNT sensor detects a phenomenon such as some molecules or some photons via its sensing unit, it is in the *gathering phase* and acts as *source node*. In this phase, it converts the sensing information into RF signal and transmits to its surrounding environment. The details of this operation are introduced in Section II.
- If a CNT sensor node receives an RF signal from another CNT sensor node, it is in *forwarding phase* and acts as *intermediate node* to amplify and transmit the received RF signal. Here, we also assume that each CNT sensor node can be concurrently act as source and intermediate node.
- If a CNT sensor node neither detects a phenomenon nor receives a RF signal, it is in *idle phase* and in this phase, CNT sensor node only senses its environment.

Main challenges for the realization of CNSN include intelligently controlling these three phases in terms of energy consumption, reliability, and robustness. This mandates some intelligent and synchronized scheduling mechanisms on CNT sensor communication. Due to extremely limited storage, synchronization, and processing capabilities of CNT sensor nodes, simple communication and network algorithms must be developed to alleviate computation and synchronization requirements of CNT sensor communication. Moreover, due to extremely low nano-scale battery life time, the gathering and forwarding phases must be crossly controlled to minimize energy consumption required for data transmission, reception, storage, and processing. For these ultimate goals, some fundamental communication and networking functionalities in CNSN should be first investigated.

IV. Fundamental Communication and Networking Issues in CNSN

In CNSN, communication and networking functionalities aim to allow carbon nanotube sensor nodes to reliably and efficiently monitor the environment. Due to extreme sizes and hardware inefficiencies of CNT sensor nodes, traditional communication and networking functionalities radically shift to an absolutely random, uncontrollable domain for the realization of CNSN. In the following, we discuss research challenges and open issues in the fundamental communication and networking functionalities in CNSN.

A. Communication Medium

All communication paradigms are subject to physical properties of the communication medium in terms of propagation speed of communication signal, path loss, and noise. There may be two alternative communication medium for CNT sensor communication, i.e., airborne medium and aqueous medium. In airborne medium, radiation of electromagnetic wave generated by nanotube transmitter is similar to the well-known radio wave radiation. However, in aqueous medium, high transmission power is needed to propagate the electromagnetic wave between CNT sensor nodes due to more intensive nature of the aqueous medium [33]. High transmission power also needs high field emission current. High field emission current may also severely cause degradation of nanotube transmitter and this prevents frequency tunning of the nanotube transmitter. Moreover, high field emission current results in quick depletion of nano-power sources. Therefore, aqueous medium may not be suitable for CNT sensor communication. However, molecular communication[1] is a viable nano-scale communication paradigm to allow nano-scale communication in aqueous environment using molecules as communication carrier [34].

B. Analog vs. digital communication

In CNT sensor communication, the carrier frequency of information signal is absolutely specific to the length of the nanotube. It is imperative for CNT sensor nodes to tune the same frequency to communicate with each other. Therefore, half-duplex communication is only feasible and available bandwidth for CNT sensor communication is severely inefficient and static. This static frequency tunning causes also considerably high interference among CNT sensor nodes. Moreover, the existing CNT based transmitter circuits allow only frequency modulation (FM) for data transmission [9].

Electromechanical vibrations are also prone to some environmental factors such as thermal noise and interference from other wireless system. Due to the extremely small size of carbon nanotube, these factors can be one of the most crucial barriers on the reliable CNT sensor communication. Especially, the interference from other wireless systems such as cellular system or radio broadcast must be carefully considered when the carrier frequency of CNT sensor nodes are selected. For example, if the carrier frequency of CNT sensor nodes is overlapped with the radio broadcast, CNT sensor communication would be exposed to high interference from the radio broadcast.

C. Channel access and encoding

Due to the uncoded analog data transmission with a common frequency tunning, FDMA and CDMA are not feasible for CNSN. Instead, a TDMA based scheduling mechanism may be feasible to enable CNT sensor nodes to synchronously transmit and receive. Due to extremely lower life time of nano-power sources, it is imperative for a possible scheduling mechanism to crossly control transmission and reception to minimize energy consumption in CNSN. This scheduling mechanism also necessitates coordinated and synchronized operations among carbon nanotube sensor nodes to enable network-wide reliable communication. Therefore, a possible nano-processor hardware must support the clocked and synchronized operations [29].

Since CNT sensor communication is completely analog and nano-processors have considerably low computational complexity, none of the digital error detection and correction mechanisms are achievable. Hence, a proactive error compensation mechanism may be feasible, that can anticipate and compensate some errors before errors do not result in significant performance degradation.

D. Multi-hop reliability

Upon the transmission of FM signal, some additional functionalities and challenges should be also overcome to route the modulated signal among CNT sensor nodes. Due to the naive FM signal generation of nanotubes, the modulated transmissions are radiated along the network. Therefore, a possible routing scheme may be also similar to flooding-based routing mechanisms. A simple store-and-forward mechanism may be attainable for low-end CNT sensor nodes. However, due to extremely low life time of nano-power source, power consumption required by data storage and computation can be harshly burden to the network life time. Therefore, an efficient store-and-forward scheme should also take into account the power consumption in data storage and computation.

E. Deployment and Topology

Deployment of CNT sensor nodes and CNSN topology are also critical to provide reliable multi-hop communication.

[1]Molecular communication is not in scope of this paper

Because of severely energy constrained nano-batteries, transmission power generated by nano-transmitter is significantly low and therefore, CNT sensor nodes have very limited radio range. This necessitates the dense deployment of CNT sensor nodes for a network-wide connectivity. In fact, the transmission power and communication range of CNT sensor nodes may be regulated by changing the oscillation amplitude of the nanotube, or increasing the charge in the tip of the nanotube, or using an array of nanotubes [9]. However, all of these methods incur also higher power consumption and may cause degradation of nanotube transmitter. Therefore, dense deployment of carbon nanotube sensor nodes may be reasonable to provide network-wide connectivity with smaller energy consumption. Due to the considerably small radio range of CNT sensor nodes, CNSN must also have a robust topology to maintain normal network operations despite some node failures or mobilities.

V. Conclusion

In this paper, we introduce the concept of Carbon Nanotube Sensor Networks (CNSN). By investigating some existing nano-transceiver, power, memory, processor, and sensing circuitries, we first introduce a hardware components of a carbon nanotube (CNT) sensor node. After discussing the feasibility of a CNT sensor node with the nano-scale sensing, data storage, processing, and communication capabilities, we introduce fundamental communication and networking issues and research challenges in CNSN. Our investigations reveal that CNSN significantly shift the traditional wireless communication and networking paradigms to an unobservable, uncontrollable, and extremely resource-constrained domain. However, CNSN is also promising to enable future nano-scale data acquisition mechanisms for plenty of new applications.

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