"Phantom Networks": The Intangible Shoot-and-Scoot Communication Paradigm For Future Militaries

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***Abstract*—In this work, we put forth a philosophical treatise on a novel paradigm for an intangible, on-demand, and power-free aerial communication relaying, for which we coin the term "Phantom Networks". The proposed Phantom Network aims to temporarily bridge communication gaps between two or more out-of-range communicating devices or infrastructures using aerial nano-nodes suspended in atomized aqueous mists. This proposed on-demand shoot-and-scoot communication enabler is of particular interest to scenarios where there is a need for rapid deployment of temporary communication or relaying infrastructures for enabling higher data volume communication networks, primarily associated with military operations. As the conceptualized aerial network is primarily aqueous, its coverage and lifetime are highly dependent on ensuing atmospheric conditions in the deployment area. The possible future use of this proposed paradigm includes establishing temporary infrastructure-free networks during disaster management and battlefield communications. We discuss the design and implementation challenges posed by the intended on-demand aerial nano-network based communication relaying paradigm, its application horizon, and scope for future works.**

I. Introduction

This paper is a philosophical treatise, which envisions a method, and the challenges thereof, for temporarily bridging communication gaps between two wirelessly communicating network infrastructures or devices by making use of a short-lived and dense network of aerial nano-nodes. The nano-nodes are concentrated and suspended in a water-based solution in the form of an atomized water-based mist. This mist of atomized water is sprayed from the ground-up into the zone in which the network bridging is to be provided. The ensuing mist containing the nano-nodes is temporarily suspended in the air and spreads according to the wind-flow patterns of the deployment area. Due to their intangible nature, we name this network paradigm as – "Phantom Networks". The nano-nodes in the mist broadcast their messages to all nodes in its range in the Terahertz (THz) band, which ensures data rates of several Terabits per second (Tbps). The THz band communication also reduces the chances of undesirable effects of self-jamming owing to the meager communication range of this band. These aerially suspended nano-nodes can provide an end-to-end capture and relay network by bridging the disjoint coverage of the two communication infrastructure/devices. The envisioned technology has immense potential in communications for disaster-hit areas, battlefield communications, and emergency communications in extremely remote areas.

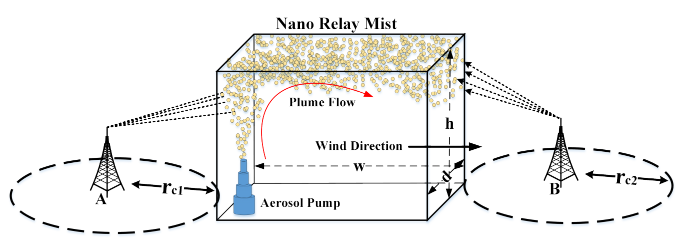

Fig. 1: Aerial nano-node mist-based communication relay implementation scenario.

Fig. 1 shows the use of the envisioned Phantom Networks in bridging communication infrastructures through ground-based spraying of aerial nanorelay nodes suspended in an aqueous mist, which forward messages towards the destination tower in an ad-hoc manner. The high data rates in the mist ensure the lack of transmission lags due to queuing of messages at the nodes. Various existing works towards achieving nanonetworks include addressing challenges pertaining to establishing ad-hoc networks between nanonodes and their powering solutions [1], manufacturing techniques for nano-scale sensing solutions [2], and even securing communications

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between theese nodes in the nanonetwork [3], indicate the general efforts towards achieving nano communication networks, a paradigm quite similar to ours.

Phantom Networks draws motivation from a recently popular paradigm in network communication relaying – Unmanned Aerial Vehicle (UAV) networks. UAVs have been used as aerial base-stations and communication relays for providing coverage in disaster-hit areas, military zones, and civilian areas. However, their use is currently restricted by their limited flight time due to the high energy requirements for keeping UAV platform airborne, their detectable presence on RADARs, and high upkeep cost.

As a significant part of the constituent technologies of this paradigm do not exist yet, we base our vision for the realization of this advanced technology to the recent surge of developments in nano-communication networks [1] and sensing solutions for the Internet of Nano Things (IoNT) [2]. These developments in nano-networks are built heavily upon the principle of molecular absorption loss of signals during sparse deployments and inter-node interference during dense implementations in the $0.1-10$ THz band, in addition to primary considerations of energy harvesting (primarily RF-based) for the operation of the nano-nodes in these networks. Despite the drawback of low transmission range ($\sim$ a few millimeters) in nano-networks operating in the THz band, its main attraction is the significantly high data-rate ($\sim$Tbps) during its operation in an ad-hoc message relaying mode. Table I compares the proposed aerial nano relaying approach with nano-network and UAV network-based message relaying procedures.

A. *Advantages of the Proposed Technology*

Phantom Networks is technologically similar, yet holistically different from approaches, such as nano-networks and UAV networks (as shown in Table I). The distinct advantages, which makes it quite important as a new, technologically separate, and a highly interdisciplinary branch of study are enumerated as:

1) **Infrastructure**: No need for the establishment of new infrastructure to provide bridging between two communication coverage voids. This feature of the proposed technology additionally translates to lower implementation and maintenance costs required for bridging communication gaps.
2) **Size**: The minuscule size of the nodes in the proposed technology is not fathomable by humans or animals, thereby reducing the risks of physical injuries or obstruction to them. The small form-factor also ensures that the solution is cheap and easy to deploy, and makes it virtually undetectable.

TABLE I: Comparison of the proposed approach with motivating message relaying communication paradigms.

Parameters	Phantom Networks	Nano Networks	UAV Networks
Device	Nano-nodes suspended in air in an aqueous mist	Nano-nodes in intra-body fluid	Electronically controlled aerial mechanical platforms
Lifetime	Hours	Seconds	Minutes
Comm. freq.	THz	THz	GHz
Power	$\sim$ uW	$\sim$ uW	$\sim$ W
Size	$\sim$ um	$\sim$ um	$\sim$ m
Energy	Harvesting	Harvesting	Batteries
Comm. mode	Pulse-based	Pulse-based	Wave/Pulse-based
Pulse width	$10^{-15}s$	$10^{-15}s$	$10^{-3}s$
Loss	FSPL, MAL, SL, FL	FSPL, MAL, SL	FSPL, MAL, FL
Gateway freq.	THz, GHz	THz, GHz	GHz, MHz
Node count	$Nodes/cm^3$	$Nodes/cm^3$	$Nodes$
Network performance	$\propto C$	$\propto C$	$\propto 1/H$
Media Access Control	Possible	Yes	Yes
Routing	Ad-Hoc/ Opportunistic	Ad-Hoc/ Opportunistic/ Externally guided	TCP/IP, Ad-Hoc, Opportunistic
Jamming	$\propto C$	$\propto C$	$\propto f_{comm}$

FSPL, free space path loss; **MAL**, molecular absorption loss; **SL**, scattering loss; **FL**, fading loss; **C**, concentration of nodes; **H**, node hops; f_{comm}, communication frequency

3) **Non-persistent**: The non-persistent and temporary nature of Phantom Networks makes its use in scenarios such as disaster sites and battlefields quite useful and advantageous.
4) **Data-rates**: The high data-rate THz band communication within the nodes in the mist ensures low-latency end-to-end connection, which in turn signifies near real-time transfers between the bridged infrastructures.
5) **Energy**: The self-sustaining nano-nodes do not need additional infrastructure or sources of energy for their operation. The lack of

infrastructure ensures exploitation of their full capabilities in any terrain and under any conditions, making this proposed technology useful under adverse and infrastructure-less conditions.

6) **Resilience**: The use of a huge number of nano-nodes within each connecting relay mists ensures the resilience of this technology against single-point sources of failures.

Table II lists the comparative technological highlights of the proposed "Phantom Networks" and its present-day communication relaying counterparts.

II. System Overview

The constituent nano-nodes of the on-demand aerial communication relay follow the commonly available schematic of the nodes used in nano-networks for electromagnetic communications. These nodes can act as both transmitters and receivers and do not depend on active power sources for their functioning, albeit they make use of energy harvesting techniques for meeting the minuscule energy requirements of their circuit components. This section covers three important aspects of the aerial mist-based relay network:

A. Nano-nodes

The nano-nodes are envisioned to have a spherical shape to ensure minimum surface tension throughout, which ensures better aerodynamics for the nodes, as well as ensures minimum shape-maintaining energy for structural integrity. This shape additionally allows the nodes to mimic the physical behavior of the water particles in the aqueous mist. Fig. 2 shows the envisioned nano-node and its message relaying functionality. The outer surface of these nodes is lined with energy harvesting pads, which can be designed to harvest energy from the surroundings by either exploiting the differences in the thermal behavior of the atmosphere or by making use of EM signals in its surroundings. Each of these nodes internally comprises of basic communication components such as transmitter and receiver modules (transceiver), data storage units, a processor, and energy conversion modules.

B. Aerial Mist Nano-Network

The aerial mist consisting of nano-nodes form a network on an ad-hoc basis. Even when the nano-nodes are gradually dispersed away from each other

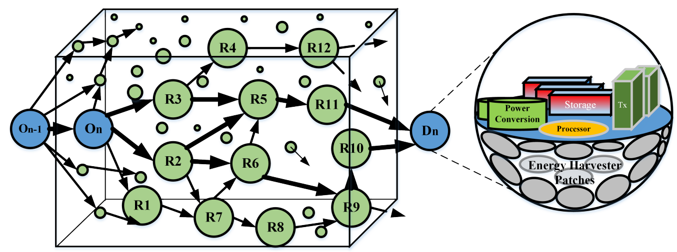

Fig. 2: Message relaying through the nano-nodes in the network.

due to the effects of ambient winds or other sources of kinetic energy, the ad-hoc nature of intra-node communication ensures that the network is maintained within the mist. Fig. 2 shows the network formed and the message relay mechanism within a unit volume of the mist. The nano-nodes represented by **O**, **R** and **D** represent the origin node, relay node and destination node for a message packet. In this scenario, we only consider the forward propagation of packets from **O** to **D**. At any instant of time, a relaying node **R** receives messages broadcasted from its neighboring node and forwards it to the destination node **D** in an ad-hoc manner. Bold arrows denote the possible set of message relay paths representatively established between **O** to **D** in Fig. 2.

C. Network Deployment

The aerial mist-based nano-network is essentially in an atomized aqueous form consisting of water particles along with the nano-nodes in a given volume of space. The spread of the network plume consisting of the nano-nodes, effects of wind, distance covered by the plume, and direction of progression of the plume can be easily estimated using basic calculations. Considering a ground-based atomized water pump with a steady-state concentration of the atomized particles emanating from the pump, terminal velocity of particles, mean horizontal wind velocity at a height, horizontal downwind distance, and the coefficient of Eddy diffusivity at the considered height, a relation between terminal velocity of particles and concentration of particles from a line source can be formulated [12]. Using parameters such as the crosswind standard deviation at a distance from the source, and source strengths for a point source and line source, the concentration of particles at a distance from the source of the

TABLE II: Comparison of the physical communication aspects of the proposed technology with its traditional counterparts for establishing the basic feasibility of our proposed paradigm.

Parameters	**Phantom Networks**	**NLOS UV Communication**	**Ionospheric Scatter**	**Ambient Backscatter**	**WiFi**
Energy Source	Harvesting	Batteries	Batteries	Harvesting	Batteries
Mobility	Yes	Yes	Yes	Yes	Yes
Tx Range	∼10 m	∼100 m	∼1000 Kms.	∼10 Kms.	∼100 m.
Tx Power	∼ μW	∼mW	∼GW	∼MW	∼mW
Bandwidth	10 GHz	1 KHz	-	50 MHz	160 MHz
Device size range	μm	cm	m	cm	cm
Supporting infrastructure	AP, Gt, BN	Ground Tx and Rx required	High power antennae	Transmitted TV signals	AP, Gt, BN
Backward compatibility	Yes	No	No	No	Yes
Interference	M, MA	OzA	IoA	MpF, St	MpF, St, Fol, HDD
Throughput	1.5 Gbps	1 Kbps	120 Kbps	100 bps, 1 Kbps, 10 Kbps	500 Mbps (max.)
Radio spectrum	THz	2.4 GHz	3-30 MHz	539 MHz	2.4 GHz/ 5.8 GHz
Spectrum	-	UV	HF band	UHF TV band	ISM band
Communication mode	D/S	S	S	S	D/S
Operating modes	Reflect, Relay	Reflect	Reflect	Reflect	Source, Relay
Throughput dependency	$\propto Cn$	NA	Channel frequency used.	Being nearer to TV signal source	High-end physical infrastructure
Similar	Nano-networks	IR communication	SW radio, HF Internet Protocol	RFID	Bluetooth, Zigbee, LoRA
References	[4]	[5], [6]	[7], [8]	[9], [10]	[11]

D, Directed; **S**, Scattered; **Cn**, Concentration of nodes; **M**, Metal; **MA**, Molecular absorption; **OzA**, Ozone absorption of UAV rays; **IoA**, Lower ionospheric attenuation; **MpF**, Multipath fading **St**, Structural interference; **Fol**, Interference due to foliage; **HDD**, High density of devices; **Ap**, Access Point; **Gt**, Gateway; **BN**, Backbone Network.

particles, the spread of the plume, and the plume settling time can also be mathematically estimated [12]. The settling time will signify the lifetime of the mist network.

III. Relay Topologies

The proposed technology can be envisioned to have two broad deployment topologies – a) Single mist relay, and b) Multiple mist relay. This section describes the various nuances of both these topologies.

A. Single Mist Relay

The single mist relay topology signifies only one point of mist plume dispersion. The ensuing aerial nanorelay cloud provides continuous coverage to a fixed zone only. Fig. 1 shows a single relay mist deployment. The ensuing atomized water-nano-node mist bridges connection between two disjoint communication towers **A** and **B** only, as shown in Fig. 1. It is technologically too early to speculate/envision the method of handoff between the nanorelay mist and the communication infrastructures (towers). However, drawing motivation from the gradual emergence of the $6G$ paradigm and research in the domain of millimeter (mm) waves, we can safely predict that solutions for integration of THz band infrastructure with other technologies might be possible in the near future.

B. Multiple Mist Relay

The multiple mist relay topology has multiple aerial nanorelays connecting separate disjoint communication infrastructures. The multiple veils of mist get established by separate but simultaneous pumping of the atomized water-nano-node mixtures in separate locations. Considering three disjoint communication infrastructures **A**, **B**, and **C**, the communication bridging requires two separate mists **Relay Mist 1** and **Relay Mist 2**. These two disjoint veils of mist can communicate with each other by a message *Catch-Process-Relay* mechanism. The message signals from **A** or **C** under the coverage of **Mist 1** get caught by **Mist 2** nano-nodes at the plume boundary, are processed to remove errors due to fading, amplified, and finally relayed to **B** via the intra-mist relaying mechanism. This topology requires nano-nodes with better processing and transceiving capabilities than those in a single mist topology. Two simultaneous operations characterize this topology- a) intra-mist relaying, and b) inter-mist relaying. The intra-mist relaying is similar to the relaying mechanism in the single-mist topology. However, the inter-mist relaying operation is envisioned to follow a *Catch-Process-Relay* mechanism for bridging two disjoint veils of mist. The nano-nodes in this topology need to be significantly powerful concerning processing and transceiving capabilities as compared to single mist relay topology. The nodes in this topology need to transmit messages to longer distances than those allowed by THz band communication.

IV. Challenges over the Horizon

The proposed "Phantom Networks" paradigm comes with some unique set of challenges, which are typically not experienced in the domain of communications and relaying. Additionally, these challenges open-up new avenues for research and innovations, which we have broadly grouped into eight categories:

A. Fabrication of Nodes

The fabrication of nano-nodes designed primarily for the proposed paradigm is quite complicated. The considerations of weight and size requirements of these nano-nodes, to enable them to mix with the aqueous mist particles is a primary requirement of this challenge. In addition to this, other challenges include the design of efficient energy harvesting techniques and technologies, designing fast and responsive processors, versatile memories, storage mechanisms and strategies, and high speed, high data-rate, and energy efficient transceivers capable of communication in the THz band. These challenges require novel innovations and research in the domain of electronics, communications, computing, Ultra Large Scale Integration (ULSI), micro and nano-electronics, and nano-fabrication technology.

B. Deployment Strategies

The next challenge deals with the conception and design of various mechanisms and strategies for deployment of the nano-node mist. As the mist is supposed to bridge two or more physically disjoint communication infrastructures, it is impertinent that the mist covers these infrastructures under its spreading area. The concentration of nodes in the ground-based spray, changes in the concentration of nano-nodes per unit volume post-spraying, the design of efficient and versatile sprayers, and selection of liquid spray combinations are some of the prominent problems, which need addressing in this challenge. Addressing these challenges would require interdisciplinary efforts encompassing the domains of electronics, fluid mechanics, nano-fabrication, and chemistry.

C. Environemental Effects

The effect of various environmental factors on the sustainability and survival of the Phantom Network paradigm is a crucial parameter. Different ecological forces such as wind, rain, snow, hail, and moisture are the significant factors threatening the successful deployment and functioning of this proposed paradigm. Unlike regular interference in traditional wireless communication techniques, environmental interference in this paradigm is more of a physical nature. Some of these immediate effects can be blowing away the mist from its intended coverage area, drying-up the supporting atomized water particles due to reduced moisture content, and rapid settling of the aerial network due to rain, snow or hail. Significant planning efforts, keeping instantaneous, and predicted environmental conditions into consideration are required for successfully achieving the Phantom Networks paradigm.

D. Physical Node Lifetime

The individual node's physical lifetime may pose to be an environmental challenge. Design of these nodes considering the degradation/ half-life of these nano-nodes after the disbanding of the bridging network has to be necessarily considered. In case, node fabrication is not carried-out using rapidly degrading materials or bio-materials, this paradigm's repeated use will result in the severe pollution of soil, water, and land. Moreover, non-degradable nano-nodes can find their way into human or animal habitats and also act as allergens if ingested accidentally, leading to severe public health concerns. Some present-day works on biodegradable nano networks [13], [14] hold promise for similar developments towards the ecologically safe realization of this paradigm.

E. Physical Network Lifetime

Considering that the network infrastructure in this paradigm is semi-gaseous and of negligible mass, they are highly prone to the effects of wind. Effects of speeded-up diffusion due to strong winds over the implementation area, and due to the semi-gaseous nature of this network, may manifest itself in the form of short-lived networks, frequent disruptions in network connectivity, and even failure to establish the network altogether. Additionally, accounting for wind direction is also a major challenge in this paradigm as it may affect the mist's plume formation. Additionally, another interesting phenomenon can be associated with this paradigm – increased loss of connectivity and packet error rates at the extreme plume boundaries of the mist. We predictively attribute this behavior to the effects of diffusion and temporal drift of the constituent particles in the aerial mist. The particles towards the center of the atomized water flow are denser and closer to each other as compared to the particles/nodes at the boundaries. The spatiotemporal variations in network performance are yet another exciting challenge that needs addressing for ensuring reliable communication under this paradigm.

F. Network Security and Privacy

The open broadcast and relay scheme followed by this network paradigm makes it vulnerable to eavesdropping, jamming, and hijacking. This problem is akin to the present-day security issues in low-power IoT devices, which are mostly unprotected at the Edge layer. Initially, focusing only on the content authenticity and confidentiality aspects, there is a definite need for the development of advanced protocol stack components, which can handle security measures in this paradigm, and yet be small and efficient enough to adjust itself to the constraints of this paradigm. Possible solutions for ensuring content authenticity might include the use of hardware embedded Physically Unclonable Functions (PUFs) and the use of channel hopping at the physical layer itself for confidentiality. In terms of infrastructure-based security vulnerabilities, some of the immediately foreseeable threats could be flooding of excessive packets in the network and path/segment overloading in the network. Other aspects include network breakdown at various points due to environmental effects such as wind and rain, change of network deployment direction due to the effect of sudden winds, and highjacking/ forcible jamming of the network by pumping extra nodes into the aerial mist. The envisioned effects of the environment, the concentration of nodes, and other such phenomena on the security of the proposed Phantom Networks will be unique to this paradigm only.

G. Communication Challenges

Much work is under active research which can be directly mapped to address the challenges in communication for the "Phantom Networks". The main challenge under this category is the enablement of communication between two separated infrastructure by increasing the probability of contact between the randomly floating aerial nano-nodes. We can visualize this problem as, whenever the nodes are in range, transmission begins; however, the receiving nodes relocate due to their motion model even before they can receive all the packets. The randomness in their motion makes the transmission an even more challenging task. However, increasing the concentration of nodes provides a better end-to-end packet relaying probability, but may also induce self-jamming of the network. Additionally, the challenge of interfacing THz-based nano communication with regular GHz/MHz-based communication infrastructures may also be a problem as of now. However, we are hopeful that works on THz-band communication and the upcoming $6G$ paradigm might be able to address this predicament over time.

H. Networking Challenges

The establishment of reliable networking among the nano nodes and between the aerial mist and in-place infrastructure is purported to be considerably challenging. The development of a Media Access Control (MAC) layer within each nano node can be quite complicated. Additionally, at present, the technology to handle massive amounts of simultaneous packet transmissions through multiplexing is also absent. However, approaches such as the one by Mohrehkesh *et al.* [15] and Atakan *et al.* [1] indicate the possibility of various routing solutions to incorporate reliable networking in such a paradigm.

V. Conclusions

The "Phantom Network" paradigm opens up vast new avenues for studies, innovation, and implementation of path-breaking technologies in communication, networking, and nano-device fabrication, especially focused for military operations. This paradigm, with its own unique set of challenges, requires highly inter-disciplinary approaches for physical realization, which, as per current technologies, are immediately not possible. However, the trends in technological advancements do support its physical realization within a decade or so. We envision that the "Phantom Networks" will be able to provide economical and readily deployable solutions owing to the on-demand nature of this paradigm and its lack of dependence on tangible infrastructure and energy sources for communication. The physical realization of this paradigm and its implementation would revolutionize not only niche domains of disaster management and military communications, but will be readily adaptable for use in general applications such as precision agriculture, remote healthcare, and even short-range cellular communications.

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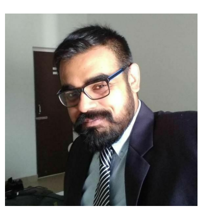

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