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# Dynamic channel allocation in electromagnetic nanonetworks for high resolution monitoring of plants

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ABSTRACT

We investigate techniques to enable communication in the THz band between graphene-based nanoscale devices and microscale network components for agricultural crop-monitoring applications. The properties of THz communications, in particular sensitivity to moisture levels on the communications path and attenuation by obstacles (e.g., leaves) mean that achieving a desired level of throughput of monitoring data can be difficult. Using a simplified model of plant structure and typical plant moisture patterns, we analyze the performance of four frequency selection strategies in terms of throughput and energy utilization for varying numbers of nano and microscale devices, moisture concentration patterns and plant leaf densities. We find that a Two-Phase optimization strategy for frequency selection performs best in a wide range of operational conditions and that leaf density has a significant impact on achievable throughput. Our plant model could serve as a useful basis for planning the necessary concentration of nano and microscale devices to deploy on particular crop types in order to meet given network performance targets.



## 1. Introduction

Plants have been shown to intrinsically possess the ability to communicate with each other through various means in order to control aspects of their biological systems [11]. Understanding and monitoring such communications can provide us with insights into how plants interact with each other and their environment—for example, by accurately detecting the substances that a plant releases into the air, its germination stage and life cycle can be inferred. One inter-plant communication mechanism is chemical signaling, in which plants exchange a range of messages by releasing an extensive set of chemical molecules. These communications meet different objectives, such as activating/strengthening other plants defense systems upon detection of an insect attack, or indicating the presence of available resources in their proximity [11,16]. For example, in the case of detecting an insect attack, plants emit various volatile organic compounds (VOCs) with different concentrations based on the insect type; these emissions can attract the natural predators of the attacking insects [38,15,40]. Furthermore, plants have sophisticated sensing capabilities—for example, a plant can monitor chemical compounds in the soil through its roots and report it to the other plants [34].

Discoveries of plant sensing and communication capabilities have led researchers to argue that high resolution detection of chemical compounds released by plants can provide knowledge of prevailing environmental conditions and plant interaction patterns. Such capabilities would be useful in different scenarios, for example, in plant biology for the development of plants species with enhanced chemical defense systems, or in the use of plants as bio-sensors to retrieve information on underground soil conditions. However, high resolution monitoring of chemical compound emissions from plants remains a significant technical challenge. One promising avenue is to

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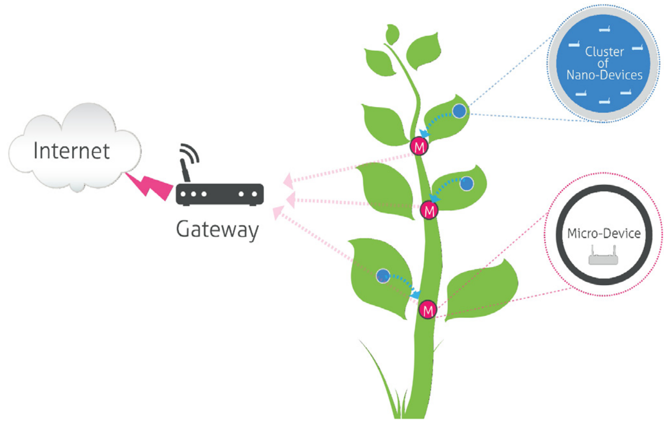


**Fig. 1.** The hierarchical structure of nanonetworks for a plant monitoring application. Chemical nano-devices are miniaturized machines with power limitations that detect chemical compounds emitted by the plant. Micro-devices are considered as control units of larger size and ample power (compared to nano-devices), which manage clusters of nano-devices, e.g., performing data fusion and scheduling. Finally, gateways are the interfaces to relay the collected data from the nanonetwork to the external network, or the Internet.

harness recent advances in nanotechnology to fabricate nano-materials with accurate sensing capabilities. One approach is to fabricate nanoscale transistors from Carbon nano-tubes or Silicon nano-wires, where the presence of different molecules change the functional characteristics of the nano-transistor, enabling it to act as a highly accurate chemical sensor [8,37]. Integrating nanosensors into nanoscale devices, and networking devices together can form a monitoring nanonetwork, which would provide the opportunity to obtain high resolution monitoring data.

Akyildiz and Jornet [2] have proposed a prototypical composition of sensor-based nanonetwork devices. They argue that the most suitable antenna for communication between nanoscale devices would be based on a graphene nano-ribbon, which would radiate electromagnetic waves in the THz band in the range of 0.1–10 THz [22,28]. Such antennae would also be tunable to operate at different frequencies, allowing them to adjust to operational conditions [10]. We can thus envisage deployments of large numbers of nanoscale devices, equipped with chemical nanosensors and THz radio units, which transfer monitoring data to a microscale networking device over a short distance, dynamically selecting a transmission frequency in order to optimize throughput of this information. For a plant monitoring application we would therefore deploy a monitoring system comprising a hierarchical arrangement of nano and microscale network devices, as illustrated in Fig. 1. Large numbers of nanoscale sensing devices could, for example, be situated on the plant through suspension in a spray applied to the plants.

Whilst the high operational frequency of graphene based antennae ("graphennas") provides high bandwidth for communications, it also imposes significant constraints for communications in the terms of signal attenuation and distortion. These constraints, which mostly depend on the transmission frequency and distance and the transmission medium composition, can significantly influence the achievable channel capacity. Adjusting the transmission frequency has the potential to maximize the achievable throughput, although this would need to be coordinated across clusters of nano-devices. In this paper, we present and analyze a set of solutions to optimize frequency selection and assignment to nanonetwork nodes deployed for plant monitoring. Our contributions include a model for THz communications for plant monitoring applications that takes into account the probability of signal attenuation due to obstacles (leaves) being present in the path between nano and microscale devices, a suite of frequency selection strategies, and an analysis of the performance of the latter under a range of moisture concentration and plant structure conditions. Our plant model could serve as a useful basis for planning the necessary concentration of nano and microscale devices to deploy on particular crop types in order to meet given network performance targets. An earlier version of the paper was published in [1]: that version contained a simple analysis of the operation of the frequency selection strategies under varying moisture concentrations; here we additionally introduce our plant model and present a complete analysis of the frequency selection strategies for a broad range of operational conditions.

The paper is structured as follows: Section 2 reviews the existing literature in the area of electromagnetic nanonetwork communications and constraints. Section 3 presents our system model in terms of a plant monitoring nanonetwork and the related plant structure parameters; also included is our proposed performance measurement model. Section 4 describes the proposed frequency selection strategies, whilst Section 5 contains the analysis of their performance. Finally, Section 6 summarizes our main conclusions.

## 2. Related work

As outlined above, we envisage nanoscale devices that transmit data using the THz band. THz Transmissions offer very high bandwidth at ultra low latency. However, THz propagation is prone to very high attenuation, distortion, phase-shift and variations in angle of arrival due to the high path-loss, noise, scattering and reflections [39]. Piesiewicz et al. [39] and Jornet and Akyildiz [23] show that water