Living organisms have evolved to monitor, sense, and respond to activities around them, acting as natural biosensors. Advancements in synthetic biology and bioengineering have allowed us to utilize these naturally occurring, as well as engineered biosensors, in sensing applications such as glucose monitors, water quality monitors, vital sign monitors, and more [1], [2]. Biosensors have the advantages of abundance, natural occurrence, compatibility with their surroundings, sensitivity, and specificity to the bio-system.

Academic and industrial research programs are showing an increased interest in the development of biosensors and the potential presented by this technology [3], [4], [5]. Currently, in the majority of applications, biosensors are operated as independent units whose outputs are either processed off-line (e.g., laboratory blood tests) or are converted to electrical signals by means of transducers. The former approach requires human involvement for post-processing which is time-consuming, expensive, and prone to errors. Electronic signal processing and communication devices, on the other hand, in addition to overcoming the aforementioned limitations, reduce the need for expensive and bulky devices for read-out (I/O device); for example, smart-phone enabled blood tests [6], wearable sensors to monitor health [7]. I plan to focus on the **design of biosensors, their architecture, input/output (reporting methods), and communication mechanisms (between biosensors)** in order to make them practical and efficient for real-time diagnostics and monitoring in domains such as healthcare, food processing, pollution control among others. The latter approach, however, is limited by the existing devices, infrastructure and by the requirement of compatibility of the communication network (wires or electromagnetic (EM) signals) with its surrounding system. Existing communication algorithms are not designed to overcome the challenges and/or exploit the opportunities that arise from a network with biological entities. For example, while energy efficiency is an important aspect in the design of algorithms for an EM network, the abundance and availability of biosensors that can utilize natural sources of energy from their ecosystem provides opportunities for the designer to shift their focus on other aspects of the problem. I plan to identify and explore the unique challenges involved in the design of a communication network of biosensors, and to develop efficient algorithms and protocols for addressing these challenges.

I envision an autonomous network of biosensors that can interact, cooperate, and respond akin to a natural system which would give rise to more opportunities for monitoring, diagnosis, and cure with a high level of accuracy.

My research interests broadly span the areas of biosensor networks, wireless networks, coding theory, and Internet-of-Things (IoT). As part of my PhD research, I have focused on the design of efficient and practical algorithms for networks with transceivers that have extremely high processing delays and very low computational capacity. This work involved close collaboration with a team of synthetic biologists, who engineered *E. Coli* bacteria to behave as transceivers, and a team of mechanical engineers, who designed a microfluidic chip that hosts these bacteria and enables their communication by the transfer of Acyl-Homoserine Lactone (AHL) molecules through a microfluidic channel. I present below an account of my current research work and discuss some of the open challenges involved in the design of an autonomous network of biosensors.

CURRENT RESEARCH

Though the architecture of a bionetwork, consisting of biosensors and biological entities as transmitter and receiver, is similar to that of traditional networks (such as an EM network), the information transmitted, the system or devices used, and the channel/medium of information transfer are fundamentally different in a bionetwork. This entails a rethinking of the design of communication algorithms for a bionetwork. As part of my PhD research, I worked on a pathogen detection system, a bionetwork where genetically engineered bacteria detect and report the presence and intensity of a specific pathogen to the receiver, which conveys the collective information to a server for further processing [8]. Since the topology and function of such a pathogen detection system is typical of other biosensing applications, I believe that the analysis and design of communication algorithms for this system is a significant step towards an autonomous bionetwork.

Time Elapse Communication (TEC)

In traditional communication systems, information is conveyed by modulating the characteristics of a carrier signal (e.g., amplitude, frequency, and phase of an EM signal). Most (if not all) modulation techniques can be categorized as energy-based modulation since information is transmitted in the energy of the carrier signal, and the number of signals transmitted is directly proportional to the number of bits required to encode a message.

In a biolink, such as a bacterial communication link, the processing delays at the transceivers and the propagation delays are of the order of a few minutes to a few hours depending on the environment[1]. Hence, energy-based modulation techniques are not directly applicable to bionetworks due to their extremely high latency and low throughput.

In [9], I developed Time Elapse Communication (TEC), a novel, practical, and non-linear modulation technique that encodes information in the time interval between the transmitted signals. TEC operates by sending a *start* and a *stop* counter that respectively triggers the receiver clock to begin and end counting. For a fixed clock rate at transmitter and receiver, the number of clock cycles elapsed between the two signals conveys the information. TEC reduces the number of signals transmitted in the channel to *two* irrespective of the frame length, by offloading the communication burden to the clocks at

1. In [9], we show that it takes approximately 5 hours for genetically engineered bacteria to receive and respond to a chemical signal.

the transceiver. The data rate improvement of TEC over binary amplitude shift keying (On-Off-Keying(OOK)) is bounded by the achievable clock rates and the channel error rate (which affect the time of arrival of the *start* and *stop* signals).

In a practical channel with processing and propagation time errors, information encoded in the time is corrupted. In [10], I developed TEC-SMART to correct for the timing error in a non-ideal channel. TEC-SMART introduces redundancy by increasing the minimum distance (time interval) between the individual messages, and uses differential encoding to minimize the overall time required to transmit a message. The feasibility of TEC-SMART was experimentally validated in a bacterial communication system, and it was demonstrated that TEC-SMART approaches the maximum achievable data rate of timing based modulation techniques while also providing reliability to the information transmitted.

Amplitude Division Multiple Access (ADMA)

By introducing more than one sensor, a pathogen detection system can be designed to detect a variety of pathogens. As multiple transmitters report to a single receiver, a mechanism to identify and decode information from each transmitter is required. In traditional networks, the sender and receiver addresses are included as address fields (IP address, MAC address) which are part of the message. In a bacterial network with very high processing delays, using additional bits for addressing would be inefficient and wasteful of resources. To address this problem, I designed ADMA, an embedded addressing mechanism wherein the transmitter address is embedded in the amplitude of the transmitted signal, eliminating the need for address fields [11]. Note that increasing amplitudes does not affect the energy efficiency of the system as the energy consumed by a bacterial transceiver remains constant for different amplitude levels. When multiple transmitters communicate to the receiver simultaneously, the sum of amplitudes of the transmitted signals is received at each instant of time. The receiver decodes the individual amplitudes (and the transmitted bits) from the received signal based on its prior knowledge of the amplitudes assigned to the transmitters. Such an embedded addressing mechanism implicitly and efficiently solves the medium access control (MAC) problem.

One of the challenges of ADMA is that, as the number of transmitters increases, the number of collisions in the channel increases, which in turn increases the bit error rate. To correct for such collision errors, I developed a decoder whose error rate approaches the minimum achievable bit error rate. The bit error rate achieved by ADMA under the low signal collision scenario is of the order of 10^{-1} [11], [12]. In order to improve the error correction performance of ADMA when there are a large number of transmitters, I designed Embedded Error Correction (EEC), a simple and efficient Forward Error Correction (FEC) mechanism that can be implemented using bio-circuits. EEC introduces redundancy by varying the on-period of the signal transmitted and uniquely identifies each transmitter using the tuple $\langle$amplitude, on-period$\rangle$. While the number of unique amplitudes and on-periods available are limited by the system, EEC effectively allocates and reuses them in order to assign a unique id to each transmitter. I implemented EEC in nano-ns3 [13], a bacterial network simulator built on top of ns-3 [14], that simulates bacterial transceivers communicating through a microfluidic channel. It was shown that bit error rates of the order of 10^{-2} can be achieved using EEC even in a high-density network. I plan to continue and extend my work on single-hop bacterial networks to multi-hop scenario.

Future Research

As part of my doctoral research, I considered a bionetwork with genetically engineered bacteria as the sensor, the transmitter and the receiver, and developed algorithms to build a single-hop bionetwork. There are a number of open challenges and problems to be addressed to realize my vision of an autonomous network of bio-sensors. Working towards my vision, I classify bionetworks further into three categories 1) Bio-Electronic Networks 2) Bio-Electronic Systems, and 3) Bio-only Networks, based on the sensor, the transmitter, and the receiver used. Each of these classes have applications on their own while also advancing us towards my vision of an autonomous bionetwork. My expertise in bionetworks combined with a strong background in communication systems places me in a strong position to address the challenges in each of these classes. I briefly discuss each of these classes and their challenges in the following sections.

Bio-Electronic Networks

A bio-electronic network consists of a biosensor, an electronic transmitter, and an electronic receiver. Examples include wearable sensors with a wireless network card [7], fitness trackers, and vital sign monitors [4]. Research programs on environmental sensing, wearable sensors, and healthcare connectivity funded by agencies such as the National Science Foundation (NSF) and the National Institutes of Health (NIH) are indicative of the growing need and interest in the research community towards bio-electronic networks [15], [16], [5], [17]. Currently, bio-electronic networks utilize the existing wireless (Bluetooth, WiFi) infrastructure for data transmission. However, data transmission in applications involving biosensors present unique challenges and opportunities for the design of practical and efficient communication algorithms. Such algorithms developed for resource constrained nodes are also applicable to other domains such as IoT, ad-hoc networks, and vehicular networks.

Asymmetric Communication: In existing communication systems, signal processing, storage, and data transmission are all handled at the transmitter end. This creates an asymmetry in the work done in the system; transmitter being at the heavy end and the receiver at the light end. In a bio-electronic network, the transmitter is attached to a biosensor and has limited battery power, computational resources, and storage, making it the weaker end. Such a work load and resource asymmetry with the weaker node carrying out the heavy lifting is inefficient. Limited memory at the transmitter also leads to a knowledge asymmetry. For example, in an environmental monitoring system, the receiver collects information from multiple transmitters and it also has access to past data, which allows it to predict future measurements. Communication algorithms designed to address and leverage such asymmetries will improve the durability and performance of the transmitter as well as the overall system. Receiver initiated communication is one of the approaches that I plan to explore for solving this asymmetry problem.

Coexistence and Cooperation A variety of bio-electronic systems have been used in health care [6] and precision farming [18] for monitoring and diagnostics. Typically, in such kind of monitoring applications, the number of sensors deployed is large while the amount of information transmitted by each of them is small. In such high-density environments with resource constrained transmitters, solutions to address radio resource management and medium access control are required. I plan to focus on scheduling-based algorithms to achieve energy-efficient, spectrum-efficient, and scalable coexistence of biosensors [19]. In a typical bio-electronic network, information from multiple sensors can be highly correlated as the sensors are deployed in close proximity of each other. I plan to focus on practical, scalable, and resource-efficient cooperative communication algorithms that can reduce such kind of information redundancy.

Bio-Electronic Systems

A bio-electronic system consists of a biosensor, a biotransmitter, and an I/O device for electronic read-out. Examples include a wearable sensor with genetically engineered bacteria [20] that emit fluorescence in response to chemical stimuli from the human body and blood tests using lab-on-chip [6] that makes use of biochemical reactions to monitor for nutrient deficiency. The output, which depends upon the sensor design, is captured by a suitable device such as a phone's camera or a microscope and processed to extract information. The efficiency of a bio-electronic system thus depends not only on the biosensor, but also on the read-out mechanism, the architecture, shape, and location of the sensor.

I plan to focus on the sensor architecture and response mechanism of biotransmitter in order to obtain information more quickly, accurately and efficiently. Though the design of a biosensor depends strongly on the specific application, the response (reporting) methods of the transmitter can be designed to improve the overall efficiency of communication. A number of ongoing research programs funded by the NSF and the NIH reveal a promising trend towards the development of programmable biomarkers and read-out mechanisms [21], [22], [23]. My work on TEC [10], which proposes a response technique that minimizes the number of signals broadcast in order to convey a message, can be applicable in such scenarios. The response of the biotransmitter to a sensor signal conveys information to the receiver. Biotransmitter design is analogous to modulation technique in a traditional communication system. I plan to explore and develop alternate response mechanisms for biotransmitters such as the color of fluorescence (convey different messages as a function of the fluorescence response), varying the densities of molecules in response to a stimuli, which can then tracked using post-processing techniques such as image processing. I plan to develop reporting techniques to maximize the throughput via the biotransmitter design. In applications such as healthcare and food and water quality monitoring, accuracy of the information sensed and reported is crucial. Designing biosensors that can accurately detect a stimuli is the first step towards achieving this. In a bio-electronic system, the response of the biotransmitter to the output of the biosensor also affects the overall accuracy of the system accuracy, and this response can be (indirectly) affected by cross-talk between the transmitters as well as interference from other stimuli in the surroundings.

Information fidelity can be improved by introducing redundancy in the transmitter response with the help of multiple biotransmitters and a spatial arrangement of sensors that can minimize cross-talk and noise from the surroundings. While, in principle, reliability algorithms in traditional networks have the same goal of improving signal fidelity, existing reliability solutions rely on redundancy in the bits transmitted. I plan to improve signal fidelity in bio-electronic systems by embedding reliability mechanisms in the design and architecture of the sensor and the transmitter, thus reducing the computational burden on the biological circuits of the transmitter. In practice, multiple biotransmitters can be used to broadcast multiple signals at the same time. Read-out mechanisms and transmitter architecture that can process this parallel information broadcast are needed. In ADMA, a unique amplitude was assigned to each transmitter and used by the receiver to identify the transmitters. I plan to focus on alternate, novel read-out mechanisms that will allow for faster and parallel reporting. Bio-electronic systems will further the scope for collaboration with teams from information security (to securely broadcast data) and data science (to process and understand the received data).

Bio-Only Networks

A bio-only network is a network of biosensors that communicate with each other using biotransmitters and bioreceivers. A proof-of-concept bio-only network was designed in my PhD work [10], [8], where the sensor, transmitter, and receiver are all genetically engineered bacteria. Bio-only networks can foray into domains that would otherwise remain partially or completely inaccessible due to various challenges including compatibility, safety, and lack of infrastructure. For example, real-time monitoring of the functioning of the human body with minimally invasive techniques, learning and understanding the interaction between disease-causing pathogens and their surroundings, autonomous targeted drug-delivery and therapeutics. Recent advancements in synthetic biology have led to the design of logic gates, storage devices and computing units using live biological entities such as bacteria [24], [25], [26], [27]. However, in its current design, biological computing devices have very high processing delays, and their computational capacity is much lower than that of electronic processors. Therefore, existing communication algorithms cannot be applied directly to bio-only networks. Also, genetically engineered biological devices tend to evolve and adapt to their surroundings, deviating from their original design. Therefore, algorithms designed for bio-only networks must be robust to frequent device repairs and should have the capability to adapt and handle device changes. Communication algorithms designed to overcome extremely high processing delays are required to improve the throughput efficiency. In fluidic channels such as blood stream, or water bodies, the sensor and transmitter can be expected to be mobile and dynamic. Message delivery techniques that take into account this mobility of sensors will be a focus of my future work. Feasibility of implementation of algorithms using biological circuits will be an important practical constraint for every solution. I plan to identify a variety of bio-only networks, understand their unique challenges and opportunities, and develop communication algorithms that can leverage these opportunities and handle these challenges.

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