A Bio-inspired Approach to Design Robust and Energy-efficient Communication Network Topologies

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***Abstract*— With the advent of Internet of Things (IoT), sensor networks are being utilized widely for data collection and dissemination. In order to ensure seamless communication, it is imperative to design topologically robust and energy-efficient networks. In this work, we introduce bio-inspired approaches for network topology construction based on the innate graph robustness of a biological network called the Gene Regulatory Network (GRN). We briefly discuss some of the topological properties of GRN, followed by its application in the design of wireless sensor network, disaster response network as well as a distributed event sensing and data collection framework for IoT and smart city applications. Finally, we demonstrate some graph experimental results that suggest that our proposed bio-inspired solutions exhibit greater robustness compared to existing graph topologies.**

I. INTRODUCTION

The Internet of Things (IoT) is a paradigm that has revolutionized modern wireless communication by making sensor devices smart and ubiquitous [1]. Sensors are controlling different facets of human existence such as communication, assisted living, e-health, smart cities, etc. Static and mobile sensor networks, comprising a large number of energy-constrained sensor devices capable of detecting physical phenomena such as light, heat, pressure, etc., have emerged as a key technology for effective data collection, monitoring and dissemination in the domain of IoT [2]. Additionally, sensors embedded in smartphones are utilized in scenarios of natural disasters, where trapped survivors can interact with rescue team and report their position information through the short-range radio (e.g., WiFi) of their smart devices [3].

In order for sensor networks to be effective, it is imperative to guarantee that they are (a) *energy-efficient* so that lifetime of the network can be maximized and (b) *topologically robust* so that the communication among the nodes can be maintained, despite the failure of certain sensor nodes [4]. In order to meet these requirements, we turn to biological networks, which are capable of performing key biochemical processes for sustenance in face of environmental adversities (i.e. robustness) at optimal energy consumption (i.e. energy efficiency) [5]. Our bio-inspired solutions are based on the graphs of *Gene Regulatory Networks (GRNs), which are biological networks formed due to protein interactions among genes and are responsible for controlling specific cell functions* [6]. The most well-studied GRNs belong to microorganisms *E. coli* (Fig. 1(a)) and Yeast [7].

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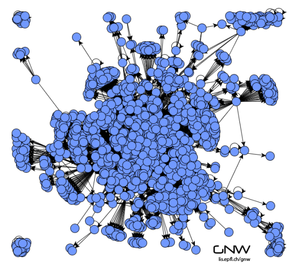
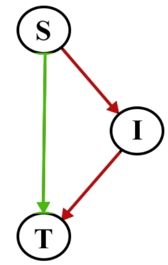
In this paper, we discuss key graph properties of GRN, followed by its application in design of topologically robust Wireless Sensor Network (WSN), energy-efficient disaster response networks (DRNs) and data collection framework for energy-efficient, QoI-aware IoT and smart city applications.

II. TOPOLOGICAL ATTRIBUTES OF GRNS

Here we briefly discuss some of the key graph properties of both *E. coli* GRN and Yeast GRN.



(a)



(b)

Fig. 1: (a) Topology of *E. coli* GRN obtained from GeneNetWeaver [7] (b) Feed Forward Loop motif

1) Abundance of Feed Forward Loop motif: GRN topologies are characterized by the abundance of recurring patterns of subgraphs, called *motifs*. The most abundant 3-node motif in GRN is the acyclic triangle called Feed Forward Loop (FFL). Each FFL motif has a direct path between source S and target T (marked in green Fig. 1(b) and an indirect path via intermediary I (marked in red).

Our studies show that FFL motifs render topological robustness to GRNs by (a) creating vertex-independent paths between source and sink nodes so that the node pairs remain connected despite failure of several intermediate nodes and (b) ensuring that the failure of direct link between S and T causes the shortest path length between S and T to increase only by a single hop [8].

2) Low graph density: Both *E. coli* (1565 nodes and 3758 edges) and Yeast (4441 nodes and 12873 edges) are directed graphs with low graph density 0.0015 and 0.00065.

3) Self-regulation: Genes have expression levels just as sensor nodes have energy levels. Genes can up-regulate or down-regulate the expression of neighbor genes through protein exchange. They are also capable of self-regulation through which it may activate or repress its own activity [9].

III. APPLICATION IN BIO-INSPIRED NETWORKING

We now exploit the above graph properties of GRN in bio-inspired network topology design.

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1) Data collection framework for energy-efficient, QoI-aware smart city applications: We introduce a distributed event sensing and data collection framework, called *bioSmartSense* based on GRNs. *bioSmartSense* makes sensing and reporting tasks energy-efficient through self-modulation of device energy levels, similar to activation or repression of genes by the regulating genes (refer Section II-.3) [10].

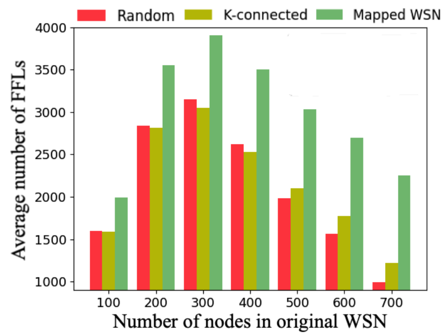

Fig. 2: Number of Feed Forward Loop (FFL) preserved

2) Bio-inspired Disaster Response Network: In the aftermath of a natural calamity, pre-existing communication infrastructures are often damaged, impeding timely interaction between the survivors and rescue workers. Under such circumstances, smart devices, movable base stations, easily deployable WiFi routers, and remaining communication towers are be used to construct makeshift networks, called *disaster response networks* (DRNs). Since such networks are hindered by rapid energy depletion of smart devices as well as node failures, we envision an energy-efficient yet robust DRN topology that replicates the inherent low graph density and robustness of GRN. In the context of such challenged scenarios, *energy efficiency can be quantified by the number of message replica transmissions in the network* [11]. Since the bio-inspired DRN will produce a robust subgraph of DRN topology, the resultant topology promises to exhibit higher energy efficiency compared to the denser original DRN.

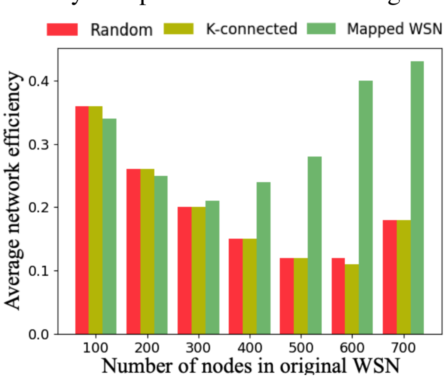

Fig. 3: Average network efficiency

3) Scalable bio-inspired Wireless Sensor Networks (WSNs): We are working on a scalable approach to leverage the similarity between GRNs and input WSNs graphs [12]. The challenge is to preserve the robustness of GRN by mapping the nodes in WSN to GRN graphs. Our initial experiments show that GRN-based WSNs, called *mapped-WSNs*, exhibit higher preservation of FFL motifs[1] and higher average shortest path than k-connected and Erdos-Renyi (ER) graphs of similar density.

IV. Initial results

In this section, we discuss some of initial graph results for our bio-inspired WSNs (i.e.mapped WSNs). We compare the mapped-WSN topology to E-R random graph topology and k-connected topology (of approximately same graph density) based on two metrics: *abundance of FFL motif* and *network efficiency* (which is defined as the average of reciprocal shortest path between all pair of nodes in a graph).

Fig. 2 and 3 show that mapped-WSNs preserve the maximum number of FFL motifs and exhibit the highest network efficiency among the three topologies.

V. Conclusion

In this paper, we discussed how the Gene Regulatory Network (GRN) can be utilized to design robust wireless sensor networks (WSNs), energy-efficient disaster response network and a novel a data collection framework for energy-efficient, QoI-aware smart city applications.

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[1] In Section II-.1 we discuss that FFL motifs render topological robustness to GRNs