Bio-Inspired Disaster Response Networks

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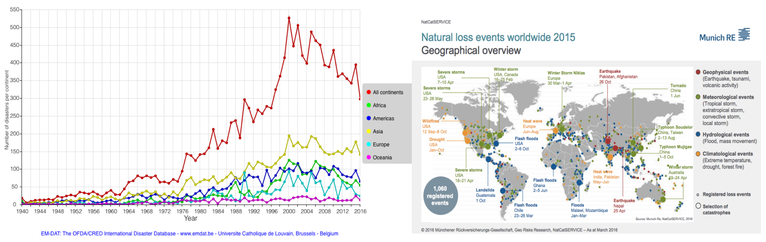
Background

- Large-scale natural disasters (e.g., Earthquake, Hurricane) –
  - **Three times** as many disasters between 1980 and 2016 compared to 1940-1980. (*EM-DAT – The International Disaster Database*)
  - Since 1990, 217 million people affected each year. (The *New England Journal of Medicine*)



- Aftermath a disaster,
  - Loss of human lives and property
  - Lack of food, clean drinking water, shelter etc.
  - **Disruption of infrastructure networks** (e.g. cellular towers) and other public infrastructures (e.g. power sources) – Our focus !

- After Nepal Earthquake 2015,
  - *Communication breakdown*: Approx. 800 out of 2600 cellular sites were down across Nepal. 300 out of 500 in KTM (worst affected district)
  - *Power outage*: 12 out of 15 hydropower facilities were non-functional

Fig. (a) Hurricane Irma, USA 2017

(b) Earthquake, Nepal 2015

Motivation

- Construct a temporary network, termed ***Disaster Response Network*** (DRN) using *smart devices*, *movable base stations* and *easily deployable antennas*- for timely information exchange between between survivors and responders

- State-of-the art literature addressed **high packet delivery** and **energy efficiency** through intelligent **routing protocols**.
- However, no work addresses the network robustness, which is a primary requirement for DRN.

- Robustness is extremely crucial, given that DRNs are subject to –
  - *intermittent connectivity* (due to irregular survivor mobility),
  - *defunct smart devices* (due to battery depletion), and
  - *component failures* (due to environmental adversities)

❖ **Network Robustness:** *the ability of the network to ensure steady information flow between survivors and the intended coordination center, despite component failures.*

❖ **Proposed Approach: Propose a robust and energy-efficient DRN, termed Bio-DRN that mimics the inherent robustness of a biological network of living organisms, called *gene regulatory networks* (GRNs)**

Gene Regulatory Network (GRN)

- A network of interaction between *DNA* segments, called ***genes***, that regulate protein synthesis within living cells.

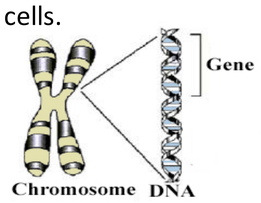


Fig. GRN: Chromosome, DNA and gene

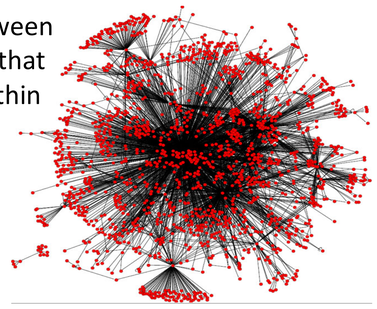


Fig. *E. Coli* GRN.

- GRNs of unicellular organisms like *E. coli* and *yeast* have been widely studied for their ***biological robustness***, proven to be a consequence of their graph properties particularly
  - ***Motif abundance*** - **Robustness** !
  - *Low graph density* – **Energy-efficiency** !

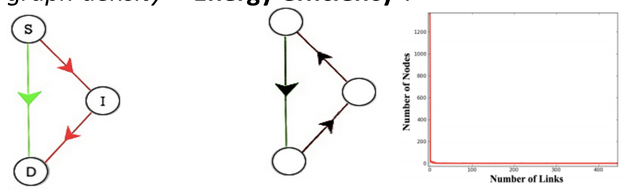


Fig. Motifs: (a) Feed forward loop (FFL) – Acyclic triangles (b) Feed back loop (FBL) – Cyclic triangles, and **Yeast GRN**: (c) Scale-free out-degree distribution

Graph	Nodes	Edges	Density	Diameter	Motif Centrality
GRN (Yeast)	4441	12873	0.00065	6	4115
Random	4441	12992	0.00065	10	20

Table: Comparison between Yeast GRN and **Erdös - Rényi** Random Graph

Problem Formulation

- **Problem Statement**: *Given a GRN $G_g(V_g, E_g)$ and DRN $G_d(V_d, E_d)$, we want to determine a subgraph, bio-DRN $G_d^{bio}(V_d^{bio}, E_d^{bio})$ such that* (i) $|V_d^{bio}| = |V_d|$ (ii) $E_d^{bio} = \max(E_d \cap E_g)$

- Formulate an ILP optimization problem

$$\text{Maximize } x_{ij}$$ — Maximize edge cardinality

$$\sum_{v_i \in V_d} y_{ik} = |V_d|, \ v_k \in V_g$$ — Bio-DRN must have $|V_d|$ nodes

$$\sum_{v_k \in V_d} y_{ik} \leq 1, \ v_i \in V_g, \ \sum_{v_i \in V_g} y_{ik} \leq 1, \ v_k \in V_d$$ — One-to-one node mapping between GRN and DRN nodes

$$x_{ij} + y_{ik} \leq 1 + \sum_{l \in N(k)} y_{jl}, \ e_{ij} \in E_g, \ v_k \in V_d$$ — If $y_{ik} = 1$ (i.e., $v_i \rightarrow v_k$) and $x_{ij} = 1$, there must exist a neighbor v_l of v_j s.t. $v_j \rightarrow v_l$.

$$y_{ik} \in \{0,1\} \, \forall v_i \in V_d, v_k \in V_g$$

$$x_{ij} \in \{0,1\}, \ \forall e_{ij} \in E_g$$

- **NP-Complete, reduced to K-CLIQUE problem**

Conclusion

- Proposed an **energy-efficient** yet **robust** DRN topology, termed ***bio-DRN***, inspired from a biological network of living organisms.
- Formulated an *ILP optimization problem* and showed that it is NP-complete by reducing it to K-CLIQUE problem.
- Proposed a novel two-step mapping algorithm for the construction of bio-DRN topology.
- Performance evaluations showed that the bio-DRN achieves both energy efficiency and robustness against component failures.

Bio-DRN Topology

Key Observation: GRN and DRN communication structures are **very similar**

DRN

- Certain well-connected entities, such as **CCs and PoIs** (such as schools, evacuation centers etc.), that are central to its information flow.
- A large portion of the network is made up of **survivors** that communicate with few PoIs (or CCs).

GRN

- Few well-connected genes, called ***Transcription Factors*** (TFs), that control the bulk of protein interactions within the network.
- Large fraction of GRN nodes constitute **regulated genes** that are loosely connected to the TFs

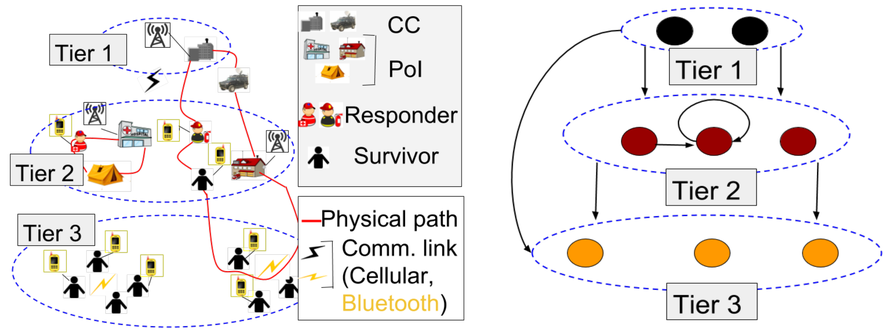


Fig. DRN: (a) Three tier network structure, (b) GRN: Three tier topology (degree distribution)

Two-step Mapping Algorithm:

Inputs: (i) Original Yeast GRN (with edge directions reversed) and input DRN

Step 1: ***Generation of Reference GRN***

- ***Greedy approach:*** *maximize* ***motif centrality*** *while preserving* ***degree distribution***

Step 2: ***Construction of Bio-DRN topology***

- Calculate **similarity** between each pair of DRN and ref. GRN node using Blondel's Similarity metric (*neighbor-based similarity)*
- ***Hungarian algorithm:*** *Maximum similarity bipartite matching*

Performance Evaluations

- *Disaster area:* 10 x 10 sq. km *Number of nodes:* 250
- PoIs (*18-20%)* and CC (*2-3%)* - randomly placed, Survivors are located in the vicinity of PoIs
- Comparison with (i) **Input original DRN**, (ii) **Random-DRN**: sparse DRN (constructed by random edge selection from original DRN), and (ii) **DT-DRN:** DRN with directed tree topology

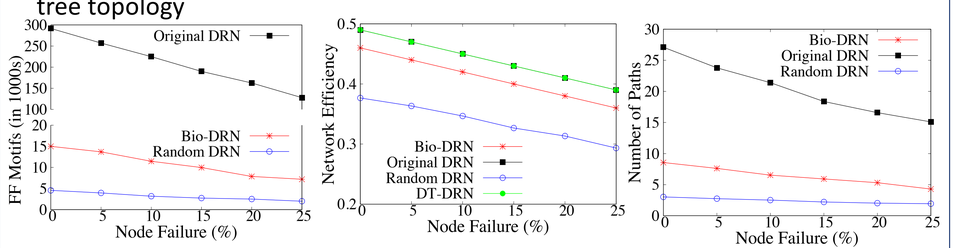


Fig. Robustness: (a) FF Motifs, (b) Network Efficiency, (c) Number of Paths

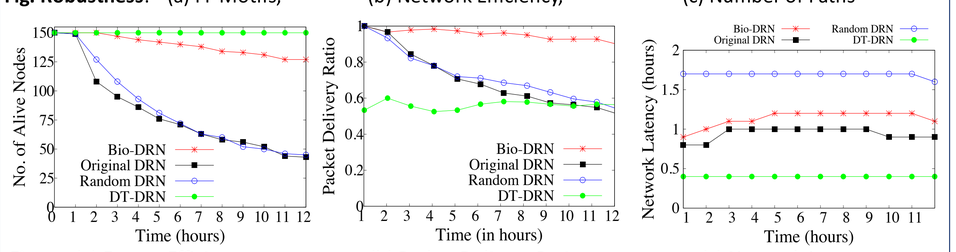


Fig. (a) Energy Efficiency, (b) Packet Delivery Ratio, (c) Network Latency

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