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An Effective Approach to Discern Leaders in Wireless Sensor Networks

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Abstract: *The influential significance across individual vertices in a Wireless Network raises a concern for the effective evaluation for Centrality metrics. A graph-theoretical comparison between the behaviour of betweenness, closeness and harmonic centrality indices is conducted over a simple, dense wireless network. The authors propose an extended algorithm for harmonic centrality over wireless sensor networks. The inadequacy in the metrics obtained by betweenness and closeness indices are discussed in detail, showing the significance of harmonic centrality in leadership recognition across a network.*

Keywords: *Wireless Sensor Networks, Network Reliability, Centrality, Closeness, Betweenness, Harmonic-influence.*

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I. Introduction

There has been consistent activity in the study and identification of issues in optimally deciding leaders in both wireless sensor networks and mobile ad-hoc networks(MANETS). A wireless sensor network(WSN) is inclusive of ad-hoc connected hosts[1] with the absence a fixed infrastructure. WSN is a fundamental element in pervasive networking[2], which serves as a self-deploying and rapidly executable environment. Hence, they are used extensively in military and communication fields. Several challenges arise in the robustness of practical WSN applications due to the uncertainty in predicting the variations in WSN topology due to environmental factors. This presence of loose control over WSN topology requires constant monitoring and analyses of Critical Nodes or Leaders, knowing which the network can be optimized in accordance with their attributes.

A critical node is as a vertex in a WSN which on removal, will cause dis-connectivity in the network. The term 'centrality' is regarded as a measure of the most important or influential vertices in a graph[3]. Popular examples of centrality applications involve ranking influential users in a social graph and identifying the most visited websites. Through careful consideration between different centrality measures, a harmonic centrality[4] is chosen as an optimal method for critical recognition in a wireless network. In connected graphs, *closeness centrality*[5] introduced by Bavelas of a vertex is a measure of the mean distance between itself and every other vertex in an undirected graph. Closeness may be regarded as the *shortest geodesic* from a given vertex, to every other vertex in a WSN.

$$C_c(v_\omega) = \frac{1}{\sum_{v_\omega}^{\infty} \delta(v_\omega, u)}$$

where $\delta(v_\omega,u)$ is the distance between vertices u and v_ω. In order for this definition to be possible, the graph must be *strongly connected* because, if this is not the case then some distances would tend to infinity, and result in zeros. Intuitively, the greater the central position of a vertex, the closer it is to all other vertices. The *Harmonic Centrality* is obtained by reversing the un-accountability in the definition for closeness[6],

$$C_h = \frac{1}{\sum_{v_\omega \neq u} \delta(v_\omega, u)}$$

The rest of this paper is organized as follows. In section II, related work performed by researchers in related fields is explored. Section III formally introduces required background, equations and definitions that will be necessary for the remaining sections. Section IV is concerned with a carefully structured description of our proposed intuition and implementation. In section V, comments and observations on the comparison of centrality indices over a wireless network are made. Section VI represents a summary of the conclusions that can me made of this work and in section VII, some illustrations and indications for future work that can be carried on are provided.

II. Literature Survey

T The design and deployment of Wireless Sensor Networks for various real-time applications, such as military surveillance and seismic monitoring has been made possible due to rapid advances in wireless communications[7],[8],[9]. A wireless sensor network is a connected-network of low power operable devices, called sensor nodes, with each vertex capable of performing processing or sensing operations. The vertices intercommunicate within the network, relaying relevant information with each other[10]; accordingly, the identification of critical vertices or cut vertices in WSN is a hugely popular field.

Different centralized algorithms have been proposed for detecting cut vertices over the recent decade[11],[12]. Under these schemes, although every vertex is able to determine a cut in the network, this is not usually sufficient because despite the absence of a critical vertex in real-time wireless communications, a source vertex in the disconnected subgraph may still communicate with other connected nodes.

A BFS-based algorithm for *cut-edge* identification is proposed by B. Milic and M. Malek[13]. It should be noted that this algorithm varies greatly from detection of cut-vertices in connected networks. If a vertex is a critical node, the edges incident on it are not cut-edges and conversely, if an edge that is incident on a vertex is a cut-edge, the vertex cannot be a critical vertex.

Centrality measures in social networks have been studied extensively since the early 20^{th} century to determine various influence and importance measures in society. Bavelas[5] introduced *closeness* for undirected, connected networks as the reciprocal of the summation of the geodesic distances from a specific vertex to every other vertex, extended by Lin in his algorithm(1976), who optimizes this definition so to make it applicable on directed graphs.

Among other popular definitions for centrality; degree centrality, node betweenness and closeness centrality are noted, as reviewed in [14] by L. C Freeman, as well as the page rank algorithm. These measures have been found useful in a range of applications, including influence identification under social networks. However, neither are these measures universally appropriate, nor have they been applied successfully in optimally discerning cut vertices in wireless sensor networks[10]. The frequency of shortest geodesics that a vertex appears on, attributes to its betweenness[15]; It is also evident that the larger the distance between a pair of vertices, the less they tend to influence each other. This scheme however, is not applicable in real-time wireless networks.

Boldi and Vigna in [16] suggest an *axiomatic* approach to study centrality comparatively and describe the application of harmonic-centrality measures in social networks. They evaluate the behaviour of centrality measures over changes in size, density and arc-attachments. However, their analogy is restricted to centrality predictions in social networks, and did not include any indications or operations toward critical analysis in wireless social networks.

III. Definitions And Equations

This section briefly recalls some notation and a few basic definitions of graph theory that will be used throughout this paper.

A WSN is a un-directed connected graph defined by $S = (V,E,\lambda)$ where V is the set of sensor vertices, and E represents the set of edges between the vertices in V. λ is the transmission range which is same network-wide.

There exists a link between vertices a and b ($a,b \in V$) if and only if they are in operable transmission range of each other.

In Fig.1, a representation of an undirected, connected graph with 11 sensor vertices, and 22 communication links is displayed.

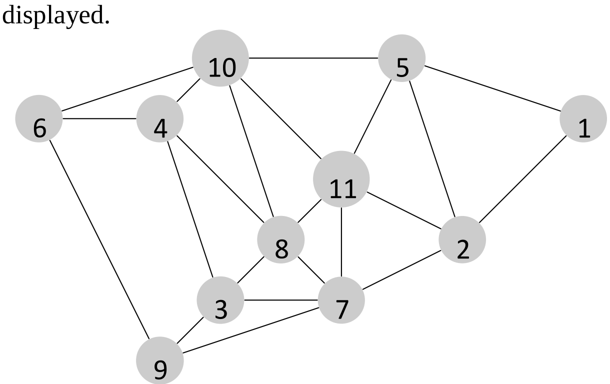

Fig. 1. Connected Network with 11 Sensor Vertices

Connected component of a graph, also referred to *strongly connected* component, is a maximal subset in which there is a path between every respective vertex pair. *Components* are derivatives of *partitioning* the network; thus a graph is *strongly connected* if there is a connected component, that is, for every vertex $k, v_\omega\ v_\omega \in$ V there is a path between k and v_ω.

Closeness of a vertex $v_\omega \in$ V normalised to $N - 1$ with $\delta(v_\omega,k)$ representing the *geodesic* between vertices v_ω and k is defined by:

$$C(v_\omega) = (N-1)^{-1}\sum_{v_\omega}^{N} \frac{1}{\delta(v_\omega, k)} \tag{1}$$

Intuitively, the vertices toward the center possess considerably larger centrality values. Note that in order for this definition by Bavelas be applicable, the graph must be strongly connected.

The *Betweenness*, proposed by U.Brandes[17] of a vertex v_ω is the sum of the geodesic paths for vertex-pairs $(k,p) \neq v \in V$ that pass through v_ω:

$$B(k \to v_\omega \to p) = \frac{2}{(N-1)*(N-2)} \sum_{k,p\neq v_\omega}^{N} \frac{\delta(k,p|v_\omega)}{\delta(k,p)} \tag{2}$$

The harmonic-mean is regarded as one of an average metric. It is defined as the reciprocal of the total arithmetic mean in an observation. It is calculated by dividing the number of observations by their reciprocals in the observed set, and is always found to be smaller than the arithmetic mean for a given observation, as it tends to give less relevance to large outliers and more relevance to small values[19]. A de-normalised definition of the harmonic index for a vertex is obtained as the inverse of the summation of *mean*-harmonic *geodesics* $\forall\ v_\omega \in$ V. This approach, expresses the harmonic centrality measure for a pair of vertices k and v_ω as the function of the separation between them respectively. In general, this scheme is proposed under social-network analysis and if the harmonic mean for a pair of nodes in wireless networks is to be considered, it is natural to extend this definition to include the Euclidean distance between vertices k and v_ω. The harmonic centrality of a vertex v_ω is obtained as:

$$H(v_\omega) = \sum_{v_\omega\neq k}^{\infty} \frac{1}{\delta(v_\omega, k)} \tag{3}$$

$$\Rightarrow \sum_{v_\omega\neq k}^{N} \frac{(N-1)^{-1}}{\delta(v_\omega, k)} \tag{4}$$

where $\delta(v_\omega,k)$ is the Euclidean distance between vertices v and k.

IV. Proposed Approach

This section introduces our network model and illustrates relevant approaches that share our intuition and discusses preliminary assumptions for *harmonic-influence centrality* in wireless networks. The network topology consists of varying number of sensor nodes. The sensor nodes are randomly deployed in an 800m x 800m region to construct the network model. Each node is restricted to a 250m transmission range.(λ).

The results are averaged over 20 trials whilst simultaneously varying λ between individual experiments.

The simulations were performed on a network simulator, NS2 where λ ranges from 20 to 150m. Assuming strong connection within the network, the observations are discussed.

A. Intuition

This paper proposes a *harmonic* index as a method to ascertain *leaders* (critical nodes) in wireless networks, which is inspired from the works in [16]; three main axioms for comparatively classifying and categorizing centrality indices, based on their behavior and effectiveness are suggested. A summary of their work is shown in Table 1. As suggested, only the harmonic-influence index is shown to satisfy all the three axioms and is expressed for a pair of vertices v_ω and k as the function of the distance between respectively.

Index	Size	Density	Arc-attachment
Katz	only k	✓	✓
Betweenness	only p	×	×
Degree	only k	✓	✓
Closeness	×	×	×
Lin	only k	×	×
PageRank	×	✓	✓
Harmonic	✓	✓	✓

Table 1

A comparison for *leadership recognition in* wireless-networks across centrality measures is included. A wireless-network topology with 100 sensor vertices are *densely* arranged in a *finite field*. The network is assumed as an undirected, connected simple graph. A single link between a vertex-pair is determined by the euclidean separation across them, λ. There exists a link in the graph if they lie within *ad hoc* communicable range of each other,

$$S = (V,E,\lambda) \text{ and } \lambda = \{20,50,100,150\},\ \forall\ v_\omega \in V$$

Sensor vertices are assumed to operate under equal communication ranges and constant energy consumption rates.

B. Algorithms

The algorithm proposed for harmonic centrality(Algorithm 1) is mentioned in detail.

Algorithm 1 Input: Un-directed, connected graph $S = [V, E, \lambda]$ with no loops and number of vertices N
Output: List of vertex *harmonic* values

Require: N>1
  $norm\_value \leftarrow \frac{1}{N-1}$
  $shortest\_path \leftarrow array[N]$
  $harmonic\_values \leftarrow array[N]$
  for each vertex $v_\omega \in V$ **do**
    $shortest\_path[v_\omega] \leftarrow 0.0$
    $harmonic\_values[v_\omega] \leftarrow 0.0$
  end for
  for each vertex $v_\omega \in V$ **do**
    $shortest\_path[v_\omega] \leftarrow do\_BFS(v_\omega)$
    for each vertex $w \neq v_\omega \in V$ **do**
      $shortest\_path[v_\omega] \leftarrow shortest\_path[v_\omega] + \lambda$
    end for
    $harmonic\_values[v_\omega] \leftarrow norm\_value * \frac{1}{shortest\_path[v_\omega]}$
  end for
  return list: $harmonic\_values$

V. Observations And Comments

The previous section dealt with algorithm derived from relevant intuitions for a harmonic-centrality index in undirected networks.

This section discusses the observations made by the various algorithms implemented on a connected, wireless sensor network $S = (V,E,\lambda)$ where V is a set of 100 sensor vertices, $\forall v_\omega \in V$; and E is the link set between the vertex pairs in V.

By convention, the paper neglects *equal* λ values for all v $\in$ to V so as to make the graph undirected; Consequently, $S = (100,542)$.

Fig.2 presents the behaviour of three centrality indices on connected, wireless sensor network, averaged over 20 trials. The graph displays the study of betweenness, closeness and harmonic-influence indices using the

previously obtained definitions.
Fig.4 displays the behaviour of the network under the application of our algorithm. on the previously stated network is displayed. The resulting graph is obtained by normalizing colour gradients in harmonic measures for each vertex.A comparison between the behaviour of closeness and harmonic centrality indices in discerning leaders is shown in Table 2; the Spearman's rank coefficient is applied to correlate between the two indices.
$\tilde{h}$ is a *set* of all HIC values obtained in Fig.2,

$$\tilde{h} = \{ h_0, h_1, h_2,..., h_{99}\} \in [0.0039,0.0181] \forall v \in V$$

The infelicity in the results obtained from the betweenness index is discussed briefly. An important intuition in betweenness centrality is that vertices possessing a greater centrality value, appear on more geodesic(shortest) paths in the network. Taking *influence − recognition* into consideration, it is also evident that the larger the separation between a pair of nodes, the lesser is the *mutual influence* between them.[18] However, a concerning limitation is observed. The betweenness index is shown to perform extremely poorly over large, densely connected, wireless-networks, resulting in *zero − inflated* measures. Another limitation to be noted is the inability of closeness to account for unreachable nodes properly (Fig.3). As the size of the network increases, the influence of the vertices that are distant from the center cannot be determined precisely and correspondingly *zeros* are obtained,

$$\tilde{b} = \{ b_0, b_1, b_2,..., b_{99}\} \in [0,0.15907] \forall v \in V$$

Similarly a range of closeness values is defined as,

$$\tilde{c} = \{ c_0, c_1, c_2,..., c_{99}\} \in [0.00452,0.01810] \forall v \in V$$

Notably, although betweenness appears to exhibit worst behaviour over the network, an important restriction involving the closeness index is also observed; vertices of known tendency further away from the center, are suggested to more likely influence the closeness measure, *suppressing* the contribution of interior nodes; the presence of interior vertices is much more correlated to the *local density* in a network[5]; hence, closeness is bound to behave counter-intuitively, failing to satisfy all three *axioms for centrality*. Fig.2 displays the ineffectiveness of the closeness and betweenness indices, despite the latter producing mildly correlated results against the harmonic index; for example, the betweenness index ranks vertex 23 to be more influential than vertex 2 as shown in Table 2, despite the latter bearing greater edge-linkage, and being present in a denser region of the topology. Vertex 23 is edge-connected to 9 other vertices whereas vertex 2 is connected to 18 vertices in the network.

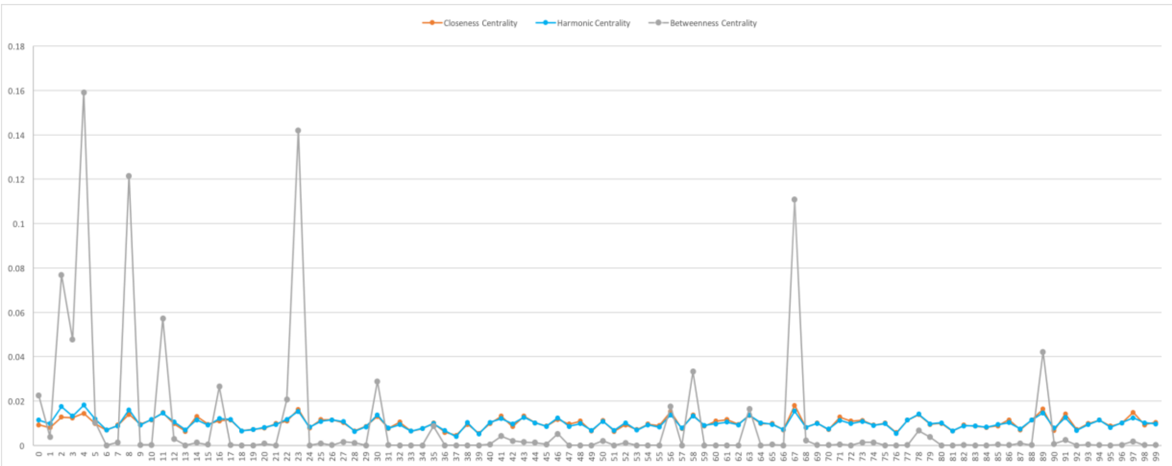

Fig.2 Comparison of centrality measures over WSN

In addition, the influence of vertices such as 18 and 19 are ranked equally irrelevant(zero-inflated) by betweenness despite the evident rise in the influence value as shown by the harmonic index in Fig.2. The steady rise in the influence values under the harmonic index is not shared by the drop to zero under the betweenness scheme. Similarly, vertices 26 and 38, etc. are ranked as zero-influence while the contrary is shown by harmonic analysis. Evidently, the mutual *influence* between a pair of vertices is inversely affected by the geodesic separation between them.

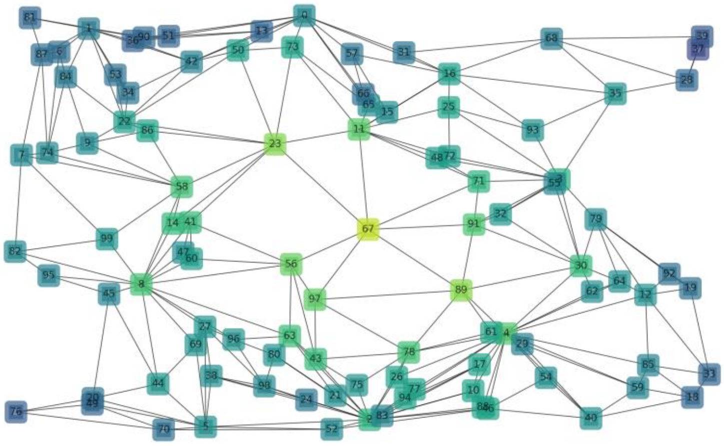

Fig.3 Behaviour of closeness centrality over WSN

A comparative summary of the top 5 leaders, as described by the three indices is shown in Table 2. Both *betweenness* and *harmonic* indices recognize the influence of *Vertex* 4 as the greatest in the network; It is also determined that closeness is unable to intelligently discern leaders in larger, connected networks;

Index	I	II	III	IV	V
Closeness	67	89	23	56	97
Betweenness	4	23	8	67	2
Harmonic	4	2	8	67	23

Table 2

Fig.3 and Fig.4 provide a topological indication of *leadership recognition* by the closeness and harmonic influence measures respectively.

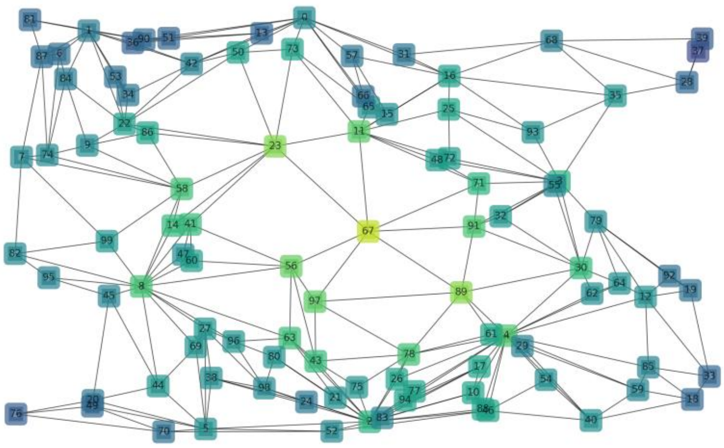

Fig.4 Behaviour of harmonic centrality over WSN

VI. Conclusions

The veracity of three centrality measures, and their precision in discerning leaders in real-time wireless networks is indicated. With regard to recognition of leaders, the paper also describes the application of the *harmonic−influence* index and compares its effectiveness against other centrality metrics. Results tabulated describe the inadequacy in betweenness and closeness indices, bound by certain inherent limitations in their definitions. Evidently, vertex 4 is discerned as the most influential vertex (most critical node) with a normalized HIC value of 0.018108. The least influential vertex, 37 bears a HIC value of 0.0039605.

VII. Future Work

The future direction of this research can be foreseen as follows; on the one hand, the impact of centrality measures over a real-time wireless network bearing varying energy parameters can be described in more detail. On the other hand, a more rigorous analysis of influence dissemination in wireless networks can be conducted; a more *intricate* and dense network with one or more *cross − links* may be considered; their performance metrics over such topology may be intriguing as areas of research.

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