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Abstract

This paper proposes network centrality as a criterion to designate a gateway or sink in real-time wireless sensor-actuator networks (WSAN). The objective is to improve network schedulability by design, particularly, by means of a centrality-driven gateway designation. To this purpose, four classical centrality metrics taken from social network analysis are explored, namely, (i) degree centrality, (ii) closeness centrality, (iii) betweenness centrality, and (iv) eigenvector centrality. We assume time-synchronized channel-hopping (TSCH) WSANs under centralized shortest-path routing and earliest-deadline-first (EDF) scheduling. Simulation results under varying configurations show that assigning the gateway role based on network centrality is, in general, an effective and promising approach to improve real-time performance in this type of networks. To the best of our knowledge, this work pioneers the use of a centrality-driven gateway designation as a mean to improve schedulability in WSANs

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Impact of network centrality on the gateway designation of real-time TSCH networks

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***Abstract*—This paper proposes network centrality as a criterion to designate a gateway or sink in real-time wireless sensor-actuator networks (WSAN). The objective is to improve network schedulability by design, particularly, by means of a centrality-driven gateway designation. To this purpose, four classical centrality metrics taken from social network analysis are explored, namely, (i) degree centrality, (ii) closeness centrality, (iii) betweenness centrality, and (iv) eigenvector centrality. We assume time-synchronized channel-hopping (TSCH) WSANs under centralized shortest-path routing and earliest-deadline-first (EDF) scheduling. Simulation results under varying configurations show that assigning the gateway role based on network centrality is, in general, an effective and promising approach to improve real-time performance in this type of networks. To the best of our knowledge, this work pioneers the use of a centrality-driven gateway designation as a mean to improve schedulability in WSANs.**

***Index Terms*—Centrality, EDF, TDMA, TSCH, WSAN**

I. Introduction

Wireless sensor-actuator networks (WSAN) are an essential part of industrial monitoring and automation systems [1]. Wireless standards such as WirelessHART, ISA100.11a, WIA-PA, 6TiSCH, are among the most popular, particularly, due to their suitability to support real-time data traffic in WSANs (e.g. control loops or audio streams). TSCH or time-synchronized channel-hopping is an in-built medium-access-control (MAC) layer common to all those standards [2]. Salient features such as time-division multiple-access (TDMA), channel diversity, and centralized network management, have made it adequate for the support of real-time communication within the scope of various industrial domains, e.g. factories and vehicles.

The ability of TSCH-based networks to guarantee a timely delivery of deadline-constrained data flows is a subject widely discussed in prior literature [1]. Theoretical and empirical studies have primarily covered prioritized scheduling and routing, typically focusing on the assessment or enhancement of common real-time properties, e.g., end-to-end delays and schedulability [3]. The relatively vast amount of work on this field has considered both specific and random topological settings, often assuming an arbitrary designation of the gateway (or sink) node. Nevertheless, this rather common assumption has a non-negligible impact on the network real-time performance. More importantly, the problem of how to properly designate a node as gateway in WSANs has not been fully addressed from a real-time perspective, i.e., how can we improve network schedulability by judiciously designating a specific node as gateway.

In this work, we tackle such challenge by proposing the notion of *network centrality* [4] from the social network analysis domain as a criterion for gateway designation in real-time TSCH WSANs. Since centrality is a quantitative measure of how important is a node in relation to others in a given network, we designate as gateway the node with the highest centrality measure. To this purpose, we consider four classical centrality definitions, namely, (i) degree centrality, (ii) closeness centrality, (iii) betweenness centrality, and (iv) eigenvector centrality, and we evaluate their performance against an arbitrary (random) gateway designation. We assume the network is a mesh operating under centralized resource management, particularly, using shortest-path routing and earliest-deadline-first (EDF) scheduling. Simulation results under varying configurations show that using centrality as the only criterion for gateway designation is, in general, an effective and promising approach to improve the real-time performance of TSCH-like WSANs.

II. System Model

A. Network Model

We model a WSAN as an non-directed graph $G = (V, E)$, where V represents the set of vertices or nodes, and E the set of edges or links between those nodes. The set of vertices includes field devices (e.g. sensors and/or actuators), multiple access points and the gateway node (Fig. 1).

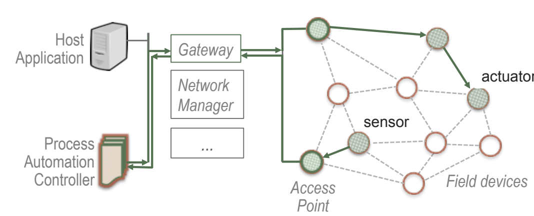

Fig. 1. An illustration of a real-time TSCH WSAN.

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The network is based on TSCH, thus granting a multi-channel TDMA framework with global synchronization. Transmissions are per-slot allocated over $m \in [1, 16]$ channels using fixed slot-length ($\sim$ 10ms). Each time slot corresponds to the interval to allocate a single packet transmission, a number of $w-1$ retransmissions, and their corresponding acknowledgments. All packets are transmitted in a multi-hop and convergecast fashion. A network manager at the gateway is responsible for all routing and scheduling decisions. As in [5], we assume transmissions are scheduled under EDF and routes are pre-defined based on *source routing*. For simplicity, we also assume routes are computed using a classical (hop-count) shortest-path algorithm.

B. Flow Model

Consider a subset of $n \in \mathbb{N}$ field devices that are sensor nodes, each transmitting one periodic deadline-constrained data flow towards the gateway, while the rest $|V|-n-1$ nodes act as relays. This results in a set of n real-time network flows denoted as $F \stackrel{\text{def}}{=} \{f_1, f_2, \ldots, f_n\}$. Each f_i is characterized by a 4-tuple (C_i, D_i, T_i, ϕ_i), where C_i denotes the effective transmission time between source and destination, T_i is the period or sampling rate of sensors, D_i the relative deadline, and ϕ_i the routing path. We assume that each f_i releases a potentially infinite number of transmissions. The γ^{th} of these instances denoted as $f_{i,\gamma}$ is released at time $r_{i,\gamma}$ such that $r_{i,\gamma+1} - r_{i,\gamma} \stackrel{\text{def}}{=} T_i$. Then, in accordance with EDF, $f_{i,\gamma}$ is constrained to reach its destination before its absolute deadline, i.e., $d_{i,\gamma} \stackrel{\text{def}}{=} r_{i,\gamma} + D_i$.

C. Performance Model

Consider the supply/demand-bound based schedulability analysis proposed in [6], which offers a state-of-the-art schedulability test for TSCH WSANs under EDF [7]. In short it is defined as the relationship between the so-called *forced-forward demand-bound function* [8] (FF-DBF) when adapted to WSANs and the *supply-bound function* (sbf) as defined in [9]. Formally, it checks if the minimal transmission capacity offered by a TSCH-based WSAN with m channels ($m > 0 \in \mathbb{N}$) is greater than or equal to the upper-bound on the maximum possible demand of a set of n real-time flows F (as defined in Section II-B), when evaluated in any time interval of length ℓ. For completeness, we revisit the primary expressions of this analysis. The schedulability test is given by Eq. 1, in which $\text{sbf}(\ell)$ is such that fulfils the condition in Eq. 2 and FF-DBF-WSAN is given by Eq. 3.

$$\text{FF-DBF-WSAN}(\ell) \leq \text{sbf}(\ell),\ \forall \ell \geq 0 \tag{1}$$

$$\text{sbf}(0) = 0 \wedge \text{sbf}(\ell + k) - \text{sbf}(\ell) \leq m \times k, \forall \ell, k \geq 0 \tag{2}$$

$$\begin{aligned} \text{FF-DBF-WSAN}(\ell) = \quad & \frac{1}{m} \sum_{i=1}^{n} \text{FF-DBF}(f_i, \ell) \quad + \\ & \sum_{i,j=1}^{n} \left(\Delta_{i,j} \max\left\{ \left\lceil \frac{\ell}{T_i} \right\rceil, \left\lceil \frac{\ell}{T_j} \right\rceil \right\} \right) \end{aligned} \tag{3}$$

FF-DBF-WSAN is the sum of two main terms, the first of which corresponds to the channel contention contribution to the total demand (as defined in [6]) and the second term represents the transmission conflict component of network demand, where $\Delta_{i,j}$ is a path overlapping factor between any pair of flows f_i and $f_j \in F$ (with $i \neq j$) whose respective transmission periods are T_i and T_j.

We highlight that both terms, channel contention and transmission conflicts, are the two dominating factors of the worst-case workload dynamics, thus have a direct influence on network schedulability.

III. Problem Overview

Given the network, flow and performance models presented in the previous section, we consider the problem of how to properly designate a node as gateway (or sink) in order to improve network schedulability. To this purpose, we introduce the notion of *network centrality* [4] as an effective criterion for gateway designation in real-time TSCH WSANs.

Specifically, we assess 4 of the most common centrality measures in social network analysis, namely, (i) degree centrality, (ii) closeness centrality, (iii) betweenness centrality and (iv) eigenvector centrality, and we evaluate their performance against a random gateway designation. For completeness, we revisit the definitions of these 4 centrality measures:

(i) **Degree centrality (DC)**: represents the number of one-hop neighbours of a specific network node. For a given node $v_q \in V$, it is formally expressed as in Eq. 4, where $degree(v_q)$ is the number of links or edges of v_q directly connected to other nodes and $N = |V|$.

$$DC(v_q) = \frac{degree(v_q)}{N-1}. \tag{4}$$

(ii) **Closeness centrality (CC)**: quantifies the "closeness" or "proximity" of a specific node to all the other nodes in the network. For a given node $v_q \in V$, it is defined as the inverse of the sum of the geodesic distances from v_q to the other nodes in the network. This is shown in Eq. 5, where $distance(v_p, v_q)$ is the shortest path distance between the nodes v_p and v_q, with $p \neq q$, $\forall\ v_p \in V$. Note that, for simplicity, we only consider hop-count-based shortest paths.

$$CC(v_p) = \frac{1}{\sum_{p \neq q} distance(v_p, v_q)} \tag{5}$$

(iii) **Betweenness centrality (BC)**: measures how many shortest paths in the network pass through a specific node. For a given node $v_q \in V$, it can be expressed as the fraction between the number of shortest paths of any pair v_r and v_s ($\forall$ $v_r, v_s \in V \wedge r \neq s \neq q$) passing through node v_q, and the total number of shortest paths in the network. This is expressed in Eq. 6, where $sp_{r,s}$ is the total number of shortest paths between any pair of nodes v_r and v_s, and $sp_{r,s}(v_q)$ is the number of those paths passing through the node v_q.

$$BC(v_q) = \sum_{q \neq r} \frac{sp_{r,s}(v_q)}{sp_{r,s}} \tag{6}$$

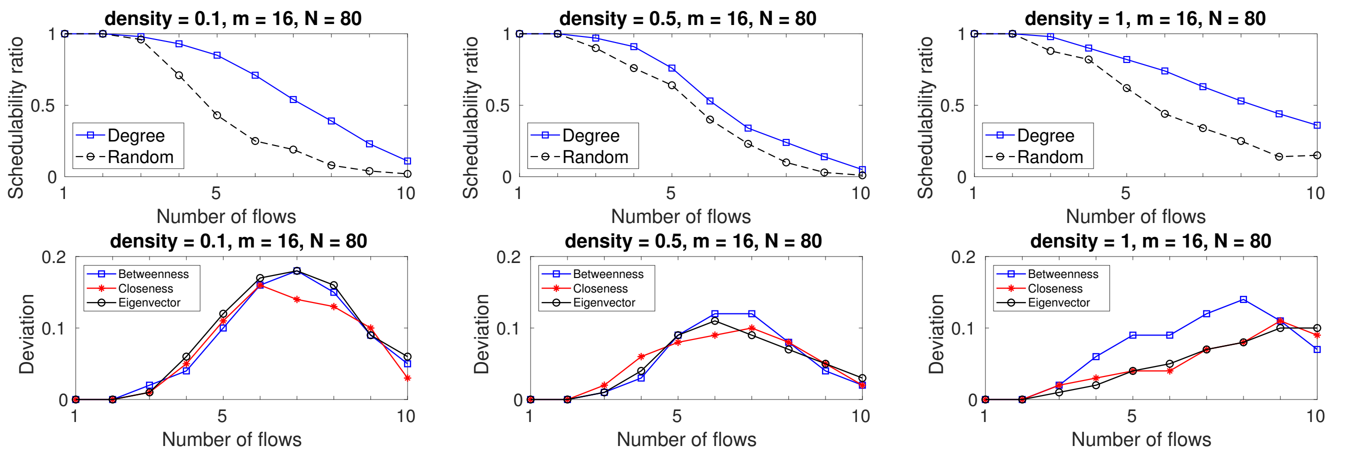

Fig. 2. The schedulability ratio under varying number of network flows $n \in [1, 10]$. On top, the comparison between the "degree" centrality and a random baseline when varying network density in $\{0.1, 0.5, 1.0\}$. Below, the absolute deviation of the other centrality measures w.r.t. the degree centrality.

(iv) **Eigenvector centrality (EC)**: quantifies how "influential" is a specific node w.r.t. others in a given network. A highly scoring node (or more "influential") will be connected to other nodes with a high *eigenvector centrality*. It can be determined based on the principal eigenvector of the adjacency matrix representing the network topology. For a given node $v_q \in V$, it can be expressed by Eq. 7, where x_k is the k^{th} value of the eingenvector x, $\lambda_{max}(A)$ is the largest eigenvalue of the $N \times N$ adjacency matrix A, and $a_{k,q}$ is the matrix element at the row k and column q.

$$EC(v_q) = \frac{1}{\lambda_{max}(A)} \cdot \sum_{k=1}^{N} a_{k,q} \cdot x_k \tag{7}$$

IV. Performance Evaluation

A. Setup

We consider a set of 100 mesh network topologies generated from random graphs. Each graph is created using a sparse uniformly distributed random matrix of $N \times N$ (with $N \in \mathbb{N}$) and target density Λ (with Λ in $[0, 1] \in \mathbb{R}$), where N is the total number of nodes or vertices including the gateway. We assume $N = 80$ for all the topologies. For each centrality metric, i.e. DC, CC, BC and EC, we choose the node with the highest score (i.e. centrality) as gateway. The remaining $N - 1$ nodes denote the field devices (e.g. sensors and/or actuators) and access points. A random subset of n field devices are assumed as sensors, which periodically communicate their measurements to (or through) the gateway. Each sensor node produces a single flow of real-time packets. We assume n varies within $[1, 10]$ for all the cases. The other $N - n - 1$ nodes act as relays forwarding packets towards the gateway. All packets are deadline-constrained and transmitted according to EDF scheduling. Allocation is centralized and transmissions are routed through hop-count-based shortest paths. The maximum number of per-slot/per-hop/per-channel transmissions w is set to 2, thus including 1 retransmission. The number of channels m is set to 16 for all the test cases. The result is a random set of n real-time flows for each network topology. For each flow, C_i is obtained directly from the multiplication of the route length of ϕ_i (in hops) and the length of the slot (configured to 10ms). We assume implicit deadlines, thus $D_i = T_i$, where T_i is the flow period. Moreover, as in [5], T_i is harmonically generated in the range $[2^4, 2^7]$ slots. This leads to a direct computation of the super-frame length, a.k.a. hyper-period (H), here considered its maximum value of 1280ms. Finally, for the assessment of schedulability we assume a worst-case factor $\Delta_{i,j}$ (as in [10]) and a time interval of evaluation $\ell = H$.

B. Results & Discussion

Figure 2 (top) shows the schedulability ratio achieved with a gateway designation based on DC and on a random baseline. These results suggest that, under varying topologies and workload conditions, DC is always better than (or equal to) the baseline. Notably, DC achieves up to $\sim 30\%$ better schedulability under particular settings. These plots also suggest that higher gains are obtained under moderate workload, particularly at the low and high network connectivity levels. Note that connectivity is varied here through node density, where a value of 1 represents a fully linked network, i.e. with each node linked to every other node in the network.

Figure 2 (bottom) shows the absolute deviation of the schedulability ratio achieved with the other types of centrality with respect to DC, which we consider as reference for these plots. In all cases, our outcomes show that these other centrality measures are always better than or equal to DC, achieving up to $\sim 18\%$ of additional improvement. However, none of these centrality metrics dominated the others in all the cases evaluated, thus exploring their synergy holds a promise. In particular, BC was able to achieve the largest gains for all densities, while EC and CC were better only under particular configurations. EC was almost always equal or slightly better than BC for the lowest density case, but generally worse for the high and medium densities. CC shown, in general, smallest gains and a more unsteady performance, but still remarkably if compared to the random baseline. DC, though not dominant, remains the simplest, thus preferable from a complexity viewpoint.

V. Related Works

The notion of network centrality applied to wireless networks can be easily found in prior literature, see e.g. [4], [11]. Centrality, among other structural properties of network graphs has a natural and almost direct application in communication networks. It was found to be beneficial e.g. for information dissemination in delay-tolerant networks [11] where the inherent dynamism of their node pair relationships (i.e. wireless links) shows a good match with the idea of *social contacts*. Also, its role in reducing traffic congestion in information-centric networks is noteworthy [12], particularly, as a means to improve caching and content delivery performance. Centrality is, in fact, a subject of large applicability in wireless networks, often exploited from the perspective of network modeling or protocol design. A few concrete examples of its application in other network-related domains include routing [13], topology control [14], security [15], gateway designation [16], etc.

In spite of this wide dissemination, the concept of centrality has not been considered, yet, as a valuable insight into the structural properties of real-time networks. While a similar direction to improve timeliness has been presented in [16], this work did not focus on the cornerstone aspect of real-time performance, i.e. schedulability. To the best of our knowledge, our work is the first at using a centrality-driven gateway designation as a mean to improve schedulability in WSAN.

VI. Conclusions

This research proposed network centrality as a criterion to designate a node as gateway in real-time TSCH WSANs. Simulation results under varying configurations show that this approach can achieve up to $\sim 45\%$ schedulability improvement over a random baseline. Particularly, we assessed 4 of the most common centrality definitions borrowed from social network analysis (i.e. degree, closeness, betweenness and eigenvector), and we observed that none dominates the other ones in all the cases considered in this work. These preliminary findings offer not only an opportunity to improve real-time WSAN design, but also a promising research direction to understand the underlying nature of centrality in these networks. We identify two immediate directions. First, to research novel methods for gateway designation (and node role assignment) in real-time WSANs, particularly justified by the observation that an arbitrary (random) decision is far from optimal. Second, to explore other concepts in social network analysis that may become beneficial from a real-time systems perspective. We believe these two directions are promising not only for real-time WSANs but also for related fields, e.g. networks based on time-sensitive networking (TSN) and software-defined networking (SDN), where both (i) the problem of gateway (or controller) designation and (ii) the exploitation of social network properties, have not been fully explored for real-time performance.

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