Minimal-Overlap Centrality-Driven Gateway Designation for Real-Time TSCH Networks

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***Abstract*—This research proposes a novel *minimal-overlap* centrality-driven gateway designation method for real-time wireless sensor networks (WSNs). The goal is to enhance network schedulability by design, particularly, by exploiting the relationship between path node-overlaps and gateway designation. To this aim, we define a new metric termed *minimal-overlap network centrality* which characterizes the *overall overlapping* degree between all the active flows in the network when a given node is selected as gateway. The metric is then used to designate as gateway the node which produces the least overall number of path overlaps. For the purposes of evaluation, we assume a time-synchronized channel-hopping (TSCH) WSN under centralized earliest-deadline-first (EDF) scheduling and shortest-path routing. The assessment of the WSN traffic schedulability suggests our approach is dominant over classical network centrality metrics, namely, eigenvector, closeness, betweenness, and degree. Notably, it achieves up to 50% better schedulability than a degree centrality benchmark.**

***Index Terms*—Centrality, Network design, TSCH, WSN.**

I. INTRODUCTION

The Industrial Internet of Things (IIoT) is dramatically increasing the adoption of wireless technologies in several industries [1]. Wireless sensor networks (WSNs), as one of the key enabling technologies for IIoT, allows gathering (wirelessly) critical sensor data in a variety of industrial fields [2], ranging from manufacturing to automotive. Time-synchronized channel-hopping (TSCH) is one of the major multi-channel medium access control (MAC) protocols for industrial WSNs offering improved reliability and support for real-time communication [2]–[4].

Industrial WSNs are usually formed by tens to hundreds of devices that deliver *deadline-constrained* sensor data toward a common gateway [3]. The gateway - an essential node enabling seamless communication with external entities - also plays a role in real-time network operation. In particular, our recent study on TSCH WSNs [5] has shown that a simple but rather effective criterion for gateway designation can remarkably enhance real-time WSN performance by design. Resorting to the notion of *network centrality* (i.e., a relative measure of the importance of the node according to its position in the network), the authors explored common metrics from social network analysis for improved schedulability. Despite the promising results, none of the assessed metrics dominated over the others and optimal performance was far from being achieved. A challenge we attempt to address herein.

We propose a novel *centrality-driven gateway designation* method for real-time WSNs based on the reduction of path node-overlaps in shortest path routing. We deal with alike foundational questions of work [5], but we solve the *gateway designation* problem by proposing a novel flow-informed metric termed *minimal-overlap* centrality. This metric requires knowing the routing approach beforehand to compute the overall *overlapping degree* resulting from the encountering of all active flows in the network elements. This measure is inspired by the *minimal-overlap* routing protocol [4], which reduces the overall overlapping degree of the network using a greedy heuristic that weights the network links based on the node-overlaps between flows.

By contrast, this work reduces the network global overlapping degree by judiciously choosing as gateway the node that *minimizes* the overall number of overlaps. While a schedulability-optimal choice could be made using enough computational power, we explore here a less demanding method that does not require fully assessing network schedulability to achieve near optimal real-time performance. The method resorts to shortest path routing for simplicity, but the concept can be easily extended to different routing schemes without loss of generality. To our knowledge, this is the first centrality-driven gateway designation method specifically designed to reduce end-to-end deadline misses in WSNs.

II. SYSTEM MODEL

A. Wireless Network

The communication network is abstracted as an undirected graph $G = (V, E)$ where V is the set of vertices or nodes and E is the set of edges or links between those vertices. The order

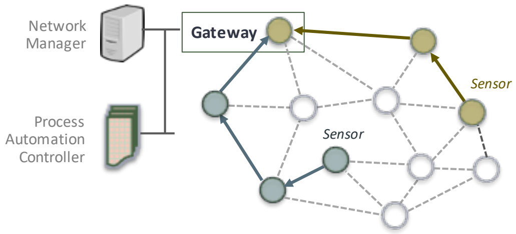


Fig. 1: An illustration of a multi-hop WSN.

of graph G is denoted as $N = |V|$, of which a set of $N-1$ nodes act as sensor nodes while one node acts as a gateway. The gateway node is used for enabling communication with external entities (e.g., network manager) forming a wireless mesh network with the remaining nodes (Fig. 1).

Multiple access is governed using TSCH protocol, one of the operating modes of IEEE 802.15.4 standard. TSCH uses fixed size TDMA slots combined with multi-channel hopping, allowing concurrent transmission over up to $m = 16$ different channels with global synchronization. A time slot allows transmitting a single packet and receiving the corresponding acknowledgement. All packet transmissions are managed centrally using an earliest-deadline-first (EDF) scheduling policy and a (hop-count) shortest path routing algorithm.

B. Real-Time Flows

In terms of traffic flow, a subset of sensor nodes transmit (potentially an infinite number of) *deadline-constrained* data with a fixed period T_i; the remaining nodes act as relays to transmit it towards the gateway. The resulting set of n real-time data flows is denoted as $F = \{f_1, f_2, \ldots, f_n\}$. Each data flow is characterized by a 4-parameter tuple $f_i = (C_i, D_i, T_i, \phi_i)$, where C_i is the transmission time between the source node s_i and the gateway, D_i is the (relative) deadline, and ϕ_i is the multi-hop routing path. The term $f_{i,\gamma}$ represents the γ^{th} transmission of flow f_i released at time $r_{i,\gamma}$ such that $T_i = r_{i,\gamma+1} - r_{i,\gamma}$. $f_{i,\gamma}$ is constrained to reach the gateway before its absolute deadline $[d_{i,\gamma} = r_{i,\gamma} + D_i]$.

C. Real-Time Performance

The real-time performance of the centralized TSCH network under EDF [6] is evaluated resorting to the supply/demand-bound based schedulability analysis presented in [7]. The method evaluates if the *supply-bound function* (sbf) [i.e., minimal transmission capacity offered by a WSN with m channels] is equal or larger than the *forced-forward demand-bound function* [8] for WSN (FF-DBF-WSN) [i.e., upper bound on the maximum demand imposed by a set of n time-sensitive flows assessed in any interval of length ℓ]. Formally, this WSN traffic schedulability test is posed as:

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

The $\text{sbf}(\ell)$ is such that satisfies the following conditions:

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

The upper bound on network demand FF-DBF-WSN [7] is composed by two terms, namely i) **channel contention** (i.e., accounts for mutually exclusive scheduling on multiple channels, being equivalent to FF-DBF for multiprocessors [8]) and ii) **transmission conflicts** (i.e., delay contribution due to multiple flows encountering on a common half-duplex node):

$$\text{FF-DBF-WSN}(\ell) = \overbrace{\frac{1}{m}\sum_{i=1}^{n}\text{FF-DBF}(f_i,\ell)}^{\text{CHANNEL CONTENTION}} + \underbrace{\sum_{i,j=1}^{n}\left(\Delta_{i,j}\cdot\max\left\{\left\lceil\frac{\ell}{T_i}\right\rceil,\left\lceil\frac{\ell}{T_j}\right\rceil\right\}\right)}_{\text{TRANSMISSION CONFLICTS}} \tag{3}$$

where $\Delta_{i,j}$ is a path overlapping factor between any pair of flows f_i and $f_j \in F$ (with $i \neq j$) as defined in [9]. Formally, this factor is defined as:

$$\Delta_{i,j} = \sum_{k=1}^{\delta(ij)} Len_k(ij) - \sum_{k'=1}^{\delta'(ij)} (Len_{k'}(ij) - 3) \tag{4}$$

where $\delta(ij)$ indicates the total number of overlaps between f_i and f_j of which $\delta'(ij)$ are the ones larger than 3. The length of the k^{th} and k'^{th} path overlap between f_i and f_j are named $Len_k(ij)$ and $Len_{k'}(ij)$, respectively, with $k \in [1, \delta(ij)]$ and $k' \in [1, \delta'(ij)]$. In the convergecast case all paths are directed to the root and thus only one path of arbitrary length is shared between any pair of flows.

III. MINIMAL-OVERLAP CENTRALITY-DRIVEN GATEWAY DESIGNATION FOR REAL-TIME WSNS

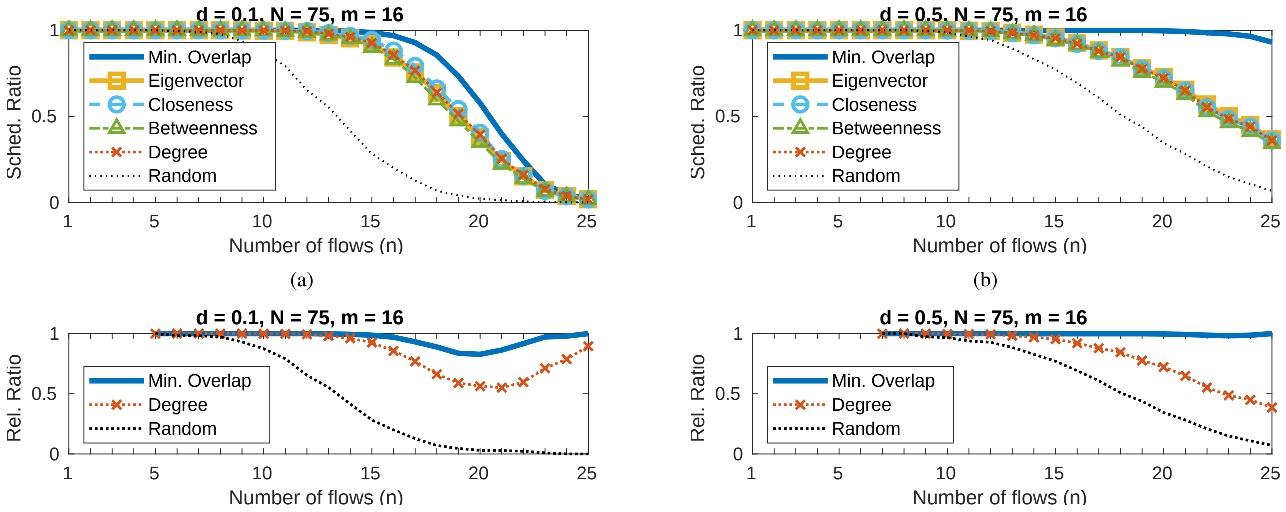
Given the system model presented in Section II, we consider the problem of how to designate a node as gateway for improved WSN traffic schedulability. To this purpose, resorting to the notion of *network centrality*, we propose a new centrality metric that characterizes the relationship between the *overall* path node-overlaps and gateway designation. Similarly to [5], the proposed metric is then used to designate as gateway the node with the highest centrality score. Classical network centrality metrics are also considered for benchmarking purposes.

A. Minimal-Overlap Network Centrality

Specifically, we propose a new network centrality metric termed *minimal-overlap* (MO) centrality. This metric is built upon the computation of the overall *path overlapping* resulting from the superposition of all flow routes in the network when directed to a given node $v_q \in V$. The importance (centrality) of the node v_q is reflected by the following expression:

$$MO(v_q) = \frac{1}{\sum_{i,j=1 \land i \neq j}^{n} \Delta_{i,j}^{q} + 1} \tag{5}$$

where the factor $\Delta_{i,j}^{q}$ is the overlap contribution from flows f_i and f_j (Eq. 4) when their routes ϕ_i and ϕ_j are directed toward node v_q, and n is the number of flows in the set F. Note that we consider only a subset of $N-n$ nodes as gateway candidates v_q, since the remaining are defined as sources. Without loss of generality, we also assume the routes are computed using a hop-count-based *shortest-path* algorithm.



(a)

(b)

(c)

(d)

Fig. 2: **Top**: Schedulability ratio of 1000 random topologies for different number of flows with target density 0.1 (a) and 0.5 (b) resorting to the gateway designation methods based on i) classical network centrality metrics (e.g. degree centrality) and ii) the proposed minimal-overlap network centrality. **Bottom:** the deviation in terms of schedulability from the best and worst possible gateway assignments.

B. Classical Network Centrality Metrics

For comparison, we consider the 4 most common network centrality metrics in the literature, namely, eigenvector, closeness, betweenness and degree. For completeness, the definitions of those metrics are given in Table I [1]. More details on these metrics within the context of gateway designation in real-time WSNs can be found in [5].

TABLE I: Classical Centrality Metrics.

Metric	**Definition**
Eigenvector	$EC(v_q) = \frac{1}{\lambda_{max}(A)} \cdot \sum_{j=1}^{N} a_{j,q} \cdot x_j$
Closeness	$CC(v_q) = \frac{1}{\sum_{p \neq q} distance(v_p, v_q)}$
Betweenness	$BC(v_q) = \sum_{q \neq r} \frac{spr_{r,s}(v_q)}{spr_{r,s}}$
Degree	$DC(v_q) = \frac{degree(v_q)}{N-1}$

IV. PERFORMANCE EVALUATION

A. Simulation Setup

Wireless network. We consider 1000 random topologies built using a synthetic generator of network graphs. Each topology is generated with a target node density d using a sparse uniformly distributed random matrix with dimension $N \times N$. We use $N = 75$ for all experiments. We consider that the TSCH network operates with $m = 16$ channels.

Network flows. A subset of $n \in [1, 25]$ vertices of G is chosen randomly as source nodes transmitting periodically deadline-constrained data to the gateway. The parameters of each data flow $f_i = (C_i, D_i, T_i, \phi_i)$ are defined as follows. C_i is computed by multiplying the time slot duration (10 ms) with the number of hops in the path ϕ_i. D_i is set in implicit-deadline model, i.e. $D_i = Ti$. T_i is harmonic and randomly generated in the range of $[2^4, 2^7]$ as in [5]. This implies a super-frame length of $H = 1280$ ms.

Real-time assessment. We assess schedulability over a time interval equal to the super-frame, i.e., $\ell = H$, and when all the $m = 16$ channels are available. EDF and shortest path routing are assumed for all transmissions. Concerning $\Delta_{i,j}$, we use precise computation derived from the network topologies.

B. Results & Discussion

Schedulability Analysis. Fig. 2 presents the schedulability ratio as a function of the number of flows considering two network densities, namely 0.1 (left) and 0.5 (right), and different methods for gateway designation, namely minimal-overlaps and classic network centrality-based. We also compute the best and worst schedulability-driven gateway selections obtained with extensive search as well as a random selection. As expected, the schedulability ratio decreases for larger number of flows in all configurations due to the larger channel contention and transmission conflicts. Conversely, higher network density increases the number of potential paths between any given pair of nodes, favoring schedulability.

The results show that the minimal-overlap gateway designation method achieves higher schedulability for all numbers of flows and densities when comparing with a method based on classical centrality metrics (e.g. degree or betweenness centrality). We argue this is caused by the MO method decreasing, by design, the number of overlapping paths allowing to reduce transmission conflicts (Fig. 3), thus improving the timely delivery of data. As expected, the proposed method is also

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[1] **Notation.** EC: $\lambda_{max}(A)$ is the largest eigenvalue of the adjacency matrix $A = [a_{j,q}]_N$, where $a_{j,q}$ is the matrix element at row j and column q, and x_j is the jth value of the eigenvector x of graph G. CC: $distance(v_p, v_q)$ is the shortest-path (hop-count) distance between vertices v_p and v_q, with $p \neq q$, $\forall\ v_p \in V$. BC: $spr_{r,s}$ is the number of shortest paths between any pair of vertices v_r and v_s, and $spr_{r,s}(v_q)$ is the number of those paths passing through node v_q; DC: $degree(v_q)$ denotes the number of edges of node v_q which are directly connected to any of the rest $N-1$ nodes in the graph G.

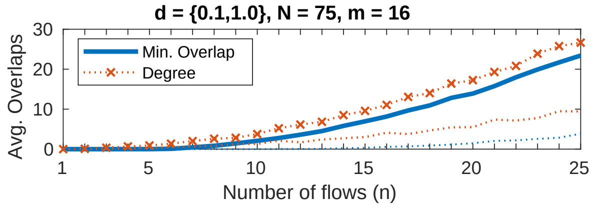

Fig. 3: Average number of overlaps of 100 random topologies when varying network flows for two gateway designation methods and two extreme densities, namely 0.1 (solid line) and 1.0 (dotted line).

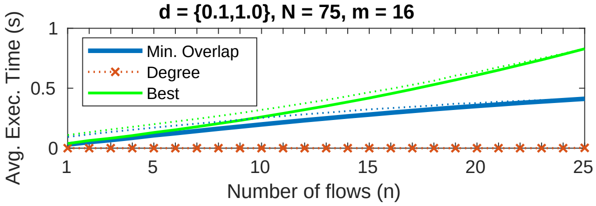

Fig. 4: Execution time for different gateway designation methods considering up to 25 network flows and two extreme target densities, namely 0.1 (solid line) and 1.0 (dotted line).

clearly superior to the random baseline, further demonstrating the significance of judicious gateway designation.

We also analyze how the proposed method deviates from the system optimal gateway election (Figs. 2c and 2d). The metric *relative ratio* is defined as the ratio between the schedulability ratio of a given method to the schedulability ratio of the best and worst performing nodes in the network, with a value of 1 denoting best and 0 the worst performance. The results show the performance of the proposed method is only slightly below the best method, having the maximum degradation of $\sim$20% for a density of 0.1 and 20 simultaneous flows. We highlight this degradation is negligible for larger densities (e.g. $d = 0.5$) since the overall overlapping degree decreases for increasing density (Fig. 3), which was also confirmed by previous studies [4]. Finally, the results in Fig. 2 also reveal the performance improvements of the proposed method, in general, increase for higher density and higher number of flows when comparing with other centrality-based metrics or random gateway assignment.

Computational Cost. Fig. 4 depicts the average execution time for the different gateway designation methods and the optimal gateway designation. Regarding the classical centrality-based designation method, we solely present the result for degree centrality for visual clarity and because this has the lowest execution time among all metrics. We also present result for two extreme density values of 0.1 (solid line) and 1 (dashed lines). The setup for this experiment used MATLAB R2020b on Ubuntu 18.04 LTS on a laptop with an Intel Core i7-6500U CPU at 2.5GHz and 4GB of DD3 RAM.

The results confirm the low execution time of the degree-centrality gateway designation. On the other hand, minimal overlaps designation considerably decreases the execution time when compared against optimal gateway designation, particularly for higher number of flows. Note that the optimal method uses extensive search with full schedulability analysis for each case, while the MO metric just requires computing the number of overlaps in the network given a set of flows. The results also show that the density has a minimal impact on the average execution time. Overall, the proposed method provides a good trade-off between achievable schedulability ratio (near optimal) and computational cost (about half the value of the optimal method).

V. CONCLUSIONS

This paper presented a novel gateway designation method for real-time WSNs based on minimizing the number of path overlaps in the network. Simulation results show improved schedulability ratio when comparing with other classic centrality-based gateway selection methods, achieving nearly optimal performance under specific conditions (e.g. larger network densities) while showing lower execution times than the optimal case. As future work, we intend to extend the method to multiple gateways, as well as to evaluate its applicability in the context of wireless edge-node placement.

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