# Conference Paper

## Joint Scheduling, Routing and Gateway Designation in Real-Time TSCH Networks

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## Abstract

This research proposes a co-design framework for scheduling, routing and gateway designation to improve the real-time performance of low-power wireless mesh networks. We target time-synchronized channel hopping (TSCH) networks with centralized network management and a single gateway. The end goal is to exploit existing trade-offs between the three dimensions to enhance traffic schedulability at systems' design time. The framework we propose considers a global Earliest-Deadline-First (EDF) scheduler that operates in conjunction with the minimal-overlap (MO) shortest-path routing, after a centrality-driven gateway designation is concluded.  Simulation results over varying settings suggest our approach can lead to optimal or near-optimal real-time network performance, with 3~times more schedulable flows than a naive real-time configuration.

# Joint Scheduling, Routing and Gateway Designation in Real-Time TSCH Networks

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## ABSTRACT

This research proposes a co-design framework for *scheduling*, *routing* and *gateway designation* to improve the real-time performance of low-power wireless mesh networks. We target time-synchronized channel hopping (TSCH) networks with centralized network management and a single gateway. The end goal is to exploit existing trade-offs between the three dimensions to enhance traffic schedulability at systems' design time. The framework we propose considers a global Earliest-Deadline-First (EDF) scheduler that operates in conjunction with the minimal-overlap (MO) shortest-path routing, after a *centrality-driven* gateway designation is concluded. Simulation results over varying settings suggest our approach can lead to optimal or near-optimal real-time network performance, with 3 times more schedulable flows than a naive real-time configuration.

## Keywords

Centrality, Network design, Low-power wireless mesh networks, TSCH.

## 1. INTRODUCTION

Wireless networks are at the heart of Industry 4.0 and the Industrial Internet of Things (IIoT) [11], offering more flexibility and scalability than their wired counterparts. Time-synchronized channel-hopping (TSCH) is widely regarded as the de-facto low-power wireless networking approach for demanding industrial applications, achieving ultra low-power and wire-like reliability [2]. Its core features are time-division multiple-access (TDMA) and frequency diversity, making it ideal for real-time communication, and therefore often applied to real-time monitoring and process control [9].

Theoretical and empirical studies have analyzed the predictable and, thus, analyzable aspects of TSCH [6, 9]. These works typically focus on prioritized packet scheduling [10] and routing methods [4] for improved real-time network performance. Our previous work looks at gateway designation [3], the convenient positioning/selection of the gateway within a given topology, for enhanced traffic schedulability.

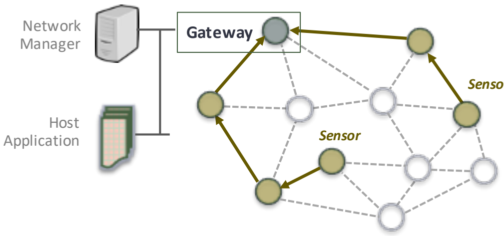

Figure 1: A low-power wireless mesh network.

In this work, we simultaneously deal with network design, routing and resource allocation to provide a joint configuration framework for improved real-time network performance in TSCH networks. We first look at joint minimal-overlap (MO) real-time routing and Earliest-Deadline-First (EDF) scheduling [4] then combine it with centrality-driven gateway designation [3]. The goal is to complement the benefits of the three approaches to further enhance the real-time properties of the network at the system design time. To the best of our knowledge, this paper proposes the first joint scheduling, routing and gateway designation framework for real-time TSCH-based networks.

## 2. PRELIMINARIES

We target low-power wireless sensor networks (WSNs) focused on industrial application in the broad sense (from smart farming to automotive). A typical network (see Fig. 1) is composed of several sensing nodes which have limited computation capabilities and energy. These nodes are interconnected wirelessly to more powerful networking equipment (e.g. access points) capable of hosting a gateway and/or a network manager. A gateway node is used to establish the connection between the sensor nodes and the host application. The specific application dictates the data collection process, i.e. the sampling rate at each sensor node.

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## 2.1 Network Model

We assume TSCH as the underlying medium access control (MAC) layer adopted to build up highly reliable and low-power networks. TSCH supports multi-hop and multi-channel communication over a globally synchronized TDMA scheme. Transmissions take place inside time slots of fixed duration allocated over up to $m = 16$ channels. A time slot allows transmitting a single packet and receiving its corresponding acknowledgement. A channel-hopping mechanism is used to improve reliability against multi-path fading and external interference. A global scheduler defines the channel and the time slot used by the different links. In this paper, we use a global EDF scheduling policy [8].

We model the long-term connectivity between the nodes by a unidirected graph $G = (V, E)$, where $V$ is the set of vertices (or nodes), $E$ the set of edges (or links) between those nodes. The number of vertices in $G$ is denoted by $|V_G|$; the number of edges, $|E_G|$.

## 2.2 Flow Model

The global traffic flow pattern is assumed as convergecast, directed toward a single gateway. Packets are generated by a subset of $n$ sensor nodes $\in V$; the remaining $|V_G| - n - 1$ nodes act solely as relays. Sensor nodes also relay packets. Each sensor node transmits a periodic (and deadline-constrained) data flow over a single route. We call $F = \{f_1, f_2, ..., f_n\}$ the resulting set of $n$ real-time network flows. Each flow is characterized by a 4-parameter tuple $f_i = (C_i, D_i, T_i, \phi_i)$. $C_i$ is the effective transmission time between the source node $s_i$ and the gateway, $D_i$ is the deadline, $T_i$ is the period, $\phi_i$ is the multi-hop routing path. Note $C_i$ does not consider interference from other flows. We assume a flow never stops, i.e. new packets are always generated. The $\gamma^{th}$ packet in flow $i$ is denoted $f_{i,\gamma}$; it is generated at time $r_{i,\gamma}$ such that $r_{i,\gamma+1} - r_{i,\gamma} = T_i$. In accordance with EDF, $f_{i,\gamma}$ needs to reach the gateway before its absolute deadline $[d_{i,\gamma} = r_{i,\gamma} + D_i]$.

## 2.3 Performance Model

We consider the supply/demand-bound based schedulability test proposed in [7] to quantify the real-time performance of TSCH-based networks under EDF [5]. This method evaluates if the *supply-bound function* (sbf) – the minimal transmission capacity offered by a network with $m$ channels – is equal or larger than the *forced-forward demand-bound function* [1] (FF-DBF-WSN) – the upper bound on the total network time demanded by a set of $n$ time-sensitive flows in any interval of length $\ell$.

Formally, the schedulability test can be presented by (1).

$$\textsc{ff-dbf-wsn}(\ell) \leq \text{sbf}(\ell),\ \forall \ell \geq 0. \tag{1}$$

Where sbf($\ell$) is a piecewise-linear function in all intervals $[h, h + l]$ that satisfies (2).

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

FF-DBF-WSN [7] is composed of two main terms: *(i)* **channel contention** due to mutually exclusive scheduling on multiple channels, equivalent to FF-DBF for multiprocessors [1], and *(ii)* **transmission conflicts** due to multiple flows encountering on a common half-duplex link.

$$\begin{aligned}\textsc{ff-dbf-wsn}(\ell) = \ & \overbrace{\frac{1}{m}\sum_{i=1}^{n}\textsc{ff-dbf}(f_i, \ell)}^{\text{CHANNEL CONTENTION}} \ + \\ & \underbrace{\sum_{i,j=1}^{n}\left(\Delta_{i,j}\cdot \max\left\{\left\lceil\frac{\ell}{T_i}\right\rceil, \left\lceil\frac{\ell}{T_j}\right\rceil\right\}\right)}_{\text{TRANSMISSION CONFLICTS}}\end{aligned} \tag{3}$$

This results in (3), where $\Delta_{i,j}$ is a factor representing the path overlapping degree between any pair of flows $f_i$ and $f_j$ $\in F$ (with $i \neq j$) in a given network $G$, defined by (4).

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

$\delta(ij)$ is 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 $q^{th}$ and $q'^{th}$ path overlap between $f_i$ and $f_j$ are called $Len_q(ij)$ and $Len_{q'}(ij)$, respectively, with $q \in [1, \delta(ij)]$ and $q' \in [1, \delta'(ij)]$. In convergecast, the factor expression is simpler since all paths are directed to the same root: only one path of arbitrary length is shared between any pair of flows. This implies $\Delta(ij) = 3$ for overlap paths larger than 3 hops.

# 3. A REAL-TIME TSCH FRAMEWORK

We consider the problem of co-designing the communication schedule, the routing topology and identifying the gateway to improve traffic schedulability. We build upon our prior research: the insights on joint EDF-MO scheduling and routing [4] and the centrality-driven network designation strategy [3]. While these works have already demonstrated – separately – their benefits, we show in this paper that combining the featured EDF-MO real-time scheduling and routing method with a judicious centrality-based gateway designation increases schedulability by up to 80% with respect to a naive real-time configuration.

## 3.1 Joint EDF-MO Scheduling and Routing

Minimal-overlap (MO) shortest-path routing is a greedy meta-heuristic search to find a suitable set of flow's paths that reduces the *overall path overlapping degree* in the network [4]. The *overlaps* – the set of nodes shared between two different flow paths – have a direct influence on the analysis of worst-case end-to-end delays for TSCH-based networks [10]. This, in turn, can be translated into an impact on network schedulability under a global EDF policy [12, 4]. The joint EDF-MO configuration takes advantage of this inbred network relationship to provide a set of disjoint paths which minimizes the number of overlaps among flow paths, regardless of the node designated as a gateway.

Algorithm 1 presents a pseudo-code of the MO routing based on its theoretical definitions in [4]. The algorithm consists of three major procedures: EDGEUPDATE (lines 1-4), CALCOVERLAPS (lines 5-7) and the main method MOGH (lines 8-21). The latter determines a new set of flow paths $\Phi_k$ and its corresponding overall number of overlaps $\Omega_k$ at each $k^{th}$ iteration to find the set of paths that provides minimal overlapping. This procedure stops when $\Omega_k = 0$, or after a $k_{max}$ number of iterations. EDGEUPDATE updates the weights of the link for the input topology $G_{in}$, returning

**Algorithm 1** Minimal-Overlap (MO) Routing

```
Input: $G$, $F$, $k_{max}, \psi$
Output: $\Phi_{opt}$, $\Omega_{opt}$
procedure EdgeUpdate($G_{in}, \Phi_{in}$)
    $W^k_{i,j}(u,v) = 1 + \sum_{e=1}^{\delta^{(k-1)}_{i,j}} \psi$
    $G^{out} \leftarrow G_{in}(V, E^{weighted})$
    return $G^{out}$
procedure CalcOverlaps($\Phi_{in}$)
    $\Omega_k = \sum_{i,j}^{n} \Delta_{ij}$
    return $\Omega^{out}$
procedure MoGH($G, F, k_{max}$)
    $k = 0$                                          ▷ Initial Solution Start
    $\Phi_0 \leftarrow$ ShortestPath($G, F$)          ▷ Hop-count-based
    $G^0 \leftarrow G$
    while $k \leq k_{max}$ and $\Omega^{min}_k > 0$ do       ▷ Greedy Search
        $G^k \leftarrow$ EdgeUpdate($G^{k-1}$, $\Phi_{k-1}$)
        $\Phi_k \leftarrow$ ShortestPath($G^k, F$)      ▷ Weight-based
        $\Omega_k =$ CalcOverlaps($\Phi_k$)
        if $\Omega_k < \Omega_{min}$ then
            $\Omega^{min}_k = \Omega_k$
            $\Phi^{min}_k = \Phi_k$
        else
            $\Omega^{min}_k = \Omega^{min}_k$
        $k = k + 1$
    $\Phi_{opt} = \Phi^{min}_k$, $\Omega_{opt} = \Omega^{min}_k$.          ▷ Best Solution
```

a new weighted graph $G_{out}$ over which new paths and overlaps are calculated. Cost function $W_{i,j}(u,v)$ determines the weight of an edge $(u,v)$ in $G_{out}$ as function of $\delta_{i,j}$ and $\psi$. The former is the number of overlaps between the paths of flows $f_i$ and $f_j \in F$ at graph $G_{in}$; the latter a user-defined parameter used to control the speed of convergence of the algorithm. The ShortestPath procedure provides the shortest sequence of edges between two nodes in the graph, resorting to classical weighted or hop-count-based shortest-path mechanisms (e.g. Dijkstra). The CalcOverlaps procedure returns the total number of overlaps in the network by summing every $\Delta_{i,j}$ factor (as defined in Section 2), and which represents the overlapping degree experienced by the paths of any pair of flows $f_i$ and $f_j \in F$.

### 3.2 Centrality-Driven Gateway Designation

To further enhance network schedulability, we consider the centrality-driven network designation strategy proposed in [3]. We use *network centrality* from graph theory to provide convenient graph-based positions to designate the gateway in order to improve real-time network performance, by design. Specifically, it uses the four most common centrality metrics in social network analysis: degree, betweenness, closeness and eigenvector centrality, considered as near optimally correlated for the purposes of benchmarking.

Table 1 [1] formally summarizes these four metrics.

Table 1: Network Centrality Metrics.

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

## 4. PERFORMANCE EVALUATION

### 4.1 Simulation Setup

**Wireless network**. We consider a set of 100 mesh topologies generated from synthetic graphs. Each topology is created using a sparse uniformly distributed random matrix of $N \times N$ of zeros and ones, with target density $d$. $N$ represents the total number of nodes, including the gateway; $d$ is the portion of other nodes each vertex is linked to. We assume $N = 75$ and $d = 0.10$ for all topologies. We assume the network is TSCH-based with $m = 16$ channels available, and 10 ms time slots.

**Network flows**. A subset of $n \in [1, 25]$ nodes is chosen randomly as sensor nodes which transmit periodically deadline-constrained data toward a single gateway. The rest of nodes act as relay. Each period is randomly generated as $2^\eta$, with $\eta \in \mathbb{N} \in [2, 7]$ slots. This implies a super-frame length of $H = 1280$ ms. $C_i$ is computed directly from the number of hops in $\phi_i$ and $D_i = T_i$.

**Real-time performance assessment**. We consider the performance model described in Section 2. We evaluate the schedulability over an interval equal to the super-frame length, $\ell = H$, when all the channels are available. We further assume network management is centralized, scheduling uses a global EDF policy, and routing can be either a hop-count-based shortest-path routing (Dijkstra) or the featured MO routing described in Algorithm 1. For MO, we further consider the following: $\Psi = 0.1$ and $k_{max} = 100$.

### 4.2 Preliminary Results & Discussion

Fig. 2a (top) presents the schedulability ratio when a gateway is designated based on the degree centrality and a shortest path routing is assumed. Fig. 2b (top) shows equivalent results for a gateway designation based on the DC when the MO routing is considered. Both configurations also include the case when the gateway is designated randomly. The results show that a joint EDF-MO-DC framework can schedule up to 3 times more flows than a basic routing configuration, and up to twice more than the EDF-MO tuple. Notably, achieving up to 80% better schedulability than a naive real-time setting.

Figs. 2a (bottom) and 2b (bottom) presents the absolute deviation in terms of schedulability ratio of the other centrality metrics w.r.t. the DC. These results suggest none of the metrics dominates over the others, regardless of the routing used. We also observe the deviation among the metrics remains larger (up to $\sim 20\%$) for the shortest path routing, and almost marginal ($< 3\%$) when MO is used.

Overall, the reported results highlight the relevance of applying a judicious gateway designation in real-time TSCH

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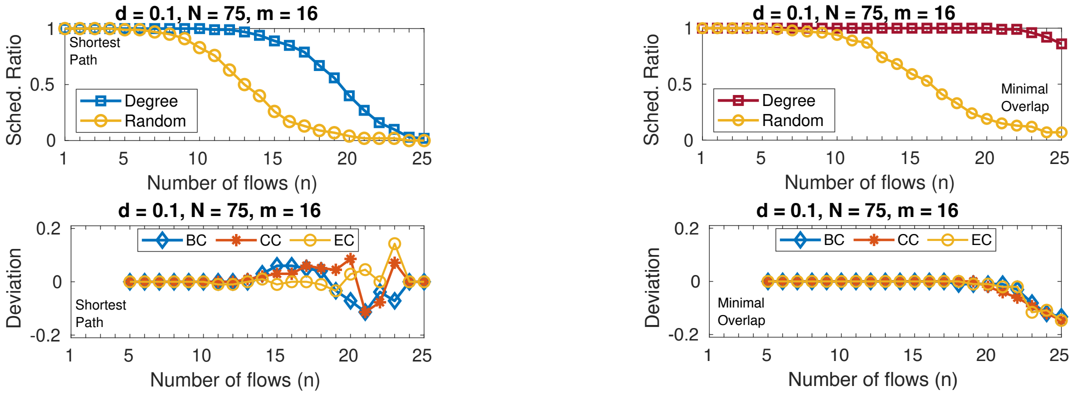
[1] **Notation. DC**: $degree(v_q)$ is the number of edges of node $v_q$ directly connected to any of the rest $N-1$ nodes in the graph $G$. **BC**: $sp_{r,s}$ is the number of shortest paths between any pair of vertices $v_r$ and $v_s$, and $sp_{r,s}(v_q)$ is the number of those paths passing through node $v_q$; **CC**: $distance(v_p, v_q)$ is the shortest-path (hop-count) distance between vertices $v_p$ and $v_q$, with $p \neq q$, $\forall\ v_p \in V$. **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 $j$th value of the eigenvector $x$ of graph $G$.



(a) Shortest Path Routing

(b) Minimal Overlap Routing.

Figure 2: **Top**: The schedulability ratio under varying number of network flows $n \in [1, 25]$ for both shortest path routing and minimal-overlap routing when using the *degree centrality* metric for gateway designation compared to a random benchmark. **Bottom**: The absolute deviation in terms of schedulability ratio of the other centrality metrics w.r.t. the degree centrality.

networks, even if a real-time routing scheme is considered.

# 5. CONCLUSIONS

This paper presents a novel framework towards joint scheduling, routing and gateway designation in real-time TSCH networks. By resorting to prior methods for joint routing and scheduling, and centrality-driven gateway designation, we show by simulation that a combined approach which takes into account all three dimensions can improve schedulability by $\sim$ 80%, scheduling up to three time more real-time flows than a basic configuration. We are working on further investigating the performance of the framework with a broader range of varying parameters (network density, number of channels, number of gateways) as well as to study its applicability in related real-time network domains (wireless TSN, 5G).

# 6. ACKNOWLEDGMENTS

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