# Poster Abstract: A Harmony of Sensors

## Achieving Determinism in Multi-Application Sensor Networks

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***Abstract*—Several concurrent applications running on a sensor network may cause a node to transmit packets at distinct periods, which increases the radio-switching rate and has significant impact in terms of the overall energy consumption. We propose to batch the transmissions together by defining a *harmonizing period* to align the transmissions from multiple applications at periodic boundaries. This harmonizing period is then leveraged to design a distributed protocol called *Network-Harmonized Scheduling (NHS)* that coordinates transmissions across nodes and provides real-time guarantees in a multi-hop network.**

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## I. Introduction

Several deployments of sensor networks need to support multiple applications and services [1], and there is much scope for optimizing the behavior of network protocols in terms of radio duty-cycle and end-to-end guarantees. It is often the case that applications release packets independently in the network, which leads to excess energy consumption due to factors like increase in the number of packets, more frequent radio-switching and extra contention at the Medium Access Control (MAC) layer.

Energy consumed in transmitting a packet from a source node to a destination node depends on many aspects, and with common MAC approaches, a packet may undergo contention at several points in a multi-hop network, thus jeopardizing the deterministic behavior of the network and making any type of pre-runtime timing guarantees very difficult, if not impossible. In this work, we present the *Network-Harmonized Scheduling (NHS)* approach, in which radio transmissions from multiple applications are coordinated across a multi-hop network by *harmonizing* them around periodic boundaries while obviating the need for explicit MAC and routing layers. NHS is a simple and effective approach that is inspired from Rate-Harmonized Scheduling (RHS) [2] and applied to the context of multi-hop networking. By using NHS, it is possible to provide real-time performance guarantees in a multi-hop wireless network without any central coordination.

Even if the applications release one or more packets in a periodic manner, the overall packet transmission by a sensor node may no longer be periodic because of the mismatching periods in different applications. In such a case, the total number of packets released by a sensor node grows proportionally with respect to the number of deployed applications. All the packets may suffer contention at different hops in the network, if the underlying MAC layer is based on a carrier-sense mechanism. To overcome these issues, NHS aligns the packet releases from different applications around periodic boundaries at each node, and leverages this periodic behavior to harmonize the transmissions at the network level.

NHS includes a light-weight protocol that groups periodic batched transmissions from different devices, such that the nodes can turn on their radios when other devices transmit. We first describe the protocol assuming that all the nodes lie in a single broadcast domain. We further develop the protocol to support multi-hop scenarios, where we harmonize the packet transmissions in a periodic manner without any global state maintenance. One of the major advantages of this protocol is that it includes an implicit link-layer mechanism, and from its multi-hop operation, it can be inferred that dedicated route maintenance is also not required. Moreover, the protocol provides deterministic bounds on the end-to-end latency for packet delivery, and design parameters can be chosen such that the packet deadlines can be met for real-time applications.

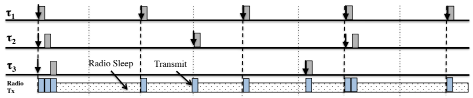
The implementation of NHS is simple, and does not require modification of application semantics. Applications only need to declare their period of operation and the maximum number of packets they may transmit in every round. Each node only maintains information about its neighbors, but can still achieve a performance similar to that of Time-Division Multiple Access (TDMA). NHS requires only a few cycles to converge to a stable schedule, and does not need additional information exchange if the network remains static. NHS can optionally provide a contention slot for supporting mobile and intermittently connected devices.

## II. Protocol Description

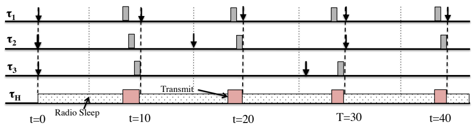
### A. Rate Harmonized Scheduling for Packets

Rate-harmonized scheduling (RHS) [2] is a policy that optimizes the execution of tasks on a uni-processor system such that the job executions of all the tasks are aligned near the period boundaries of the task with shortest period (most-frequent task). RHS makes sure that the task executions are harmonized and aligned in time, and the processor can optimally go to deep-sleep states more often and for longer time spans. We take inspiration from RHS to align packet transmissions by different periodic applications on a sensor node, such that that overhead of radio switching can be avoided, and the packets are released into the network in a periodic manner as shown in Figure 1.

With multiple tasks releasing packets at every $T_i$ time units, the transmission pattern can be irregular as shown with an example in Figure 1a. The packets in the example are transmitted using the well-known Rate-Monotonic Scheduling (RMS) approach. On the other hand, the packets from the various tasks are batched together with harmonizing period $T_H = T_1$ as shown in Figure 1b. RHS is implemented using




(a) Packet transmission from different tasks




(b) The schedule after harmonizing the transmissions.

Fig. 1: Example timeline showing batching of packets in (b) compared to intermittent behavior in (a).

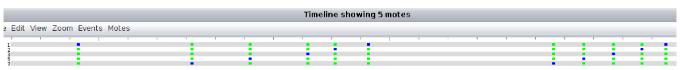



Fig. 2: Aligning packet transmissions before the scheduled transmission by the root node.

a simple queueing mechanism, where every job of all the tasks submits packets to a harmonizing task, $\tau_H$, instead of directly copying them into the radio-buffer. $\tau_H$ then transmits all the packets in its queue with a period of operation equal to a *harmonizing period*, $T_H$. As the packets from a node are transmitted in a contiguous manner (back-to-back) as a bunch, which we call a *batch*, the number of radio switchings is reduced significantly.

### B. Single Broadcast Domain

Once the packet transmissions from multiple tasks are batched around the harmonizing period, $T_H$, we can design a distributed and online protocol to align packets transmitted by multiple nodes in a single broadcast domain. The working of this protocol can be seen from the screenshot of COOJA simulation of NHS, shown in Figure 2.

- Once the nodes listen from the root, the nodes locally create a schedule by using slots as a monotonic function of node id, such that the nodes with a higher id transmit earlier, and those with lower id transmit later.
- Just before the start of the next cycle, the nodes transmit in their chosen slot, and take note of any empty slots.
- Then the nodes autonomously compress the schedule, so that the peers and the root only need to listen to the medium periodically for short durations.

### C. Harmonization in a multi-hop network

We then extend the above approach to a multi-hop scenario where all the nodes have to send their data to a sink in the network. The main goal of this protocol is to enable scheduled transmissions in a distributed manner, without requiring global knowledge of the network-topology and without explicit time-synchronization. In our approach, we achieve the required 2-hop distance by dividing each period into three equal time-slices and nodes at consecutive hop-levels transmit only in non-overlapping slices. The number of slices can be greater or equal to 3, and we call it repetition- or *cadence-factor,* $\omega$.

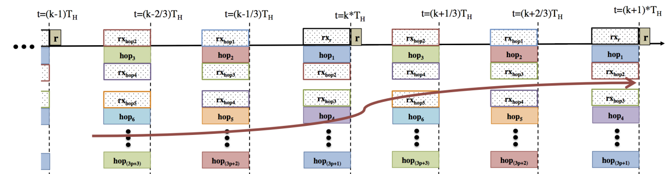


Fig. 3: Multi-hop NHS operation at steady state, also showing the listening intervals at each hop. The bold arrow shows the data-collection process from 6 hops spread over 2 periods.

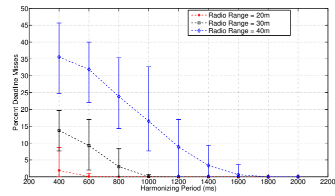



Fig. 4: Deadline misses (packet drops) with $T_H$ with different radio ranges.

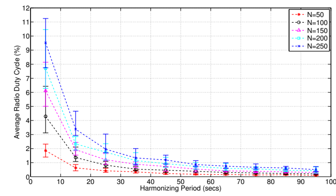



Fig. 5: Average radio-duty cycle with the increase in the harmonizing period.

By dividing the period into $\omega$ number of slices, NHS ensures that nodes at the $h^{th}$ hop-level, transmit at the boundary of $(\omega - 1)$ slices after the transmissions from the nodes at $(h-1)^{th}$ hop level. This ensures that simultaneous transmissions in NHS are guaranteed to have a hop-distance of three, making sure that no collision occurs at any receiving node. The overview of this operation is shown in Figure 3.

## III. Evaluation

We also simulated the operation of the Network-Harmonized Scheduling protocol to evaluate its deterministic behavior and energy-efficiency. Firstly, we measured the effect of the choice of harmonizing period on the number of packets that miss the minimum deadline. Longer deadlines are bound to provide better performance in terms of deadline misses by allowing the choice of larger $T_H$. Smaller harmonizing periods will require more packets to be transmitted within a smaller window, thus more deadlines will be missed. In Figure 4, we show the decrease in deadline misses as the harmonizing period increases, for different values of the radio-range. The results for average radio duty-cycle for a network of with varying network size are shown in Figure 5. With a network size of 100 nodes, NHS can achieve about $0.50\%$ duty-cycle at a period of $60$ secs. The duty-cycles remains below $2\%$ for periods greater than 20 secs with a network size of 200 nodes.

Our work shows that it is possible, and beneficial at the same time, to coordinate network access by multiple application across multiple hops in a simple manner, without global state maintenance. This approach results in deterministic network operation, and allows pre-runtime delay guarantees to be derived for the protocol.

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