Poster: Impact of Prioritized Network Coding on Sensor Data Collection in Smart Factories

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***Abstract*—Utilizing information from the production process is integral to smart factory concepts. In our example use-case, plastic industry, sensor information from the injection molding process helps to detect defective parts and provides automated guidance for process set-up. An enabler for such applications is a means to wirelessly collect machines' sensor information in harsh factory environments, and network coding has been proposed as a tool to implement suitable network protocols. Using pre-recorded sensor data from actual injection processes, we study the impact of network coding on the latency of sensor data collection. In particular, we show how network coding with prioritization helps to reduce delays until information becomes usable.**

I. INTRODUCTION

Many smart factory use cases strive to automate previously manual tasks via the utilization of highly detailed process information. In our example use-case, plastic injection molding, molten plastic is injected with high pressure and temperature into a form, termed the "mold." As the plastic cools down, the final product hardens out and is finally ejected from the mold. Here, relevant process information includes material pressure and temperature measured within the mold. Such information, in combination with machine learning techniques, allows the automated detection of a variety of product defects before they can reach the customer [1], [2].

In order to leverage process information, it has to be collected quickly from machines throughout the factory. A centralized server then acts upon results and, for example, issues alarms to operators should the process become unstable. Wireless transmission of sensor information is preferable, because it avoids expensive retrofitting of factories. Wireless transmission, however, can be difficult due to the harsh factory environment with metal obstruction and widespread factory areas that necessitate multi-hop capabilities.

Using network coding in our use case can improve the throughput, simplify routing decisions, and add robustness against packet loss. But using random linear network coding (RLNC) to transmit sensor information may result in intolerable delays due to the "all-or-nothing" property. This property states that it is highly unlikely that the server can decode parts of the sensor information before a sufficient number of linear combinations for, in our case, a complete injection cycle are received. A number of prioritized network coding schemes have been proposed to allow early decoding of a subset of a generation's information.

We study the impact of two prioritized network coding techniques – hierarchical network coding (HNC) [3] and iNsPECt [4] – on delays in sensor data collection. As a third mechanism, regular RLNC [5] serves as a baseline for our comparison.

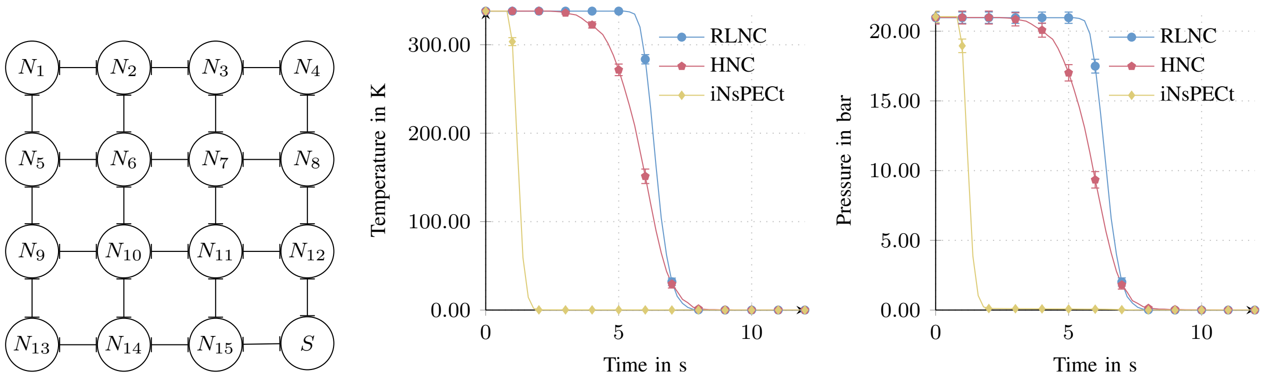
II. ENCODING AND TRANSMISSION SCHEMES

Using regular RLNC as an example, we explain how network coding in general can be applied to our sensor data collection use case. We then briefly introduce the two prioritized network coding mechanisms used in our comparison.

RLNC splits information into generations of data messages. In our case, a generation is one production cycle's worth of sensor information from a single sensor. Each message is a set of sensor samples and consists of several symbols over a finite field. We employ the common finite field $\mathbb{F}_{2^8}$, as it combines efficient byte alignment with sufficient protection from linear dependency. Each machine generates linear combinations of one generation's messages using *random* coefficients. Each machine then continually broadcasts these linear combinations until all neighbors can decode the current generation. Subsequently, the next generation is sent.

To apply prioritized network coding techniques to our industrial use case, we pre-process sensor information such that it can be divided into different priority layers, as described in [6], We apply discrete cosine transform (DCT) to each production cycle's sensor information and divide its output into blocks of coefficients. Blocks with low-frequency coefficients provide an early preview of a complete sensor cycle, whereas blocks with high-frequency coefficients incrementally increase precision to enable more demanding detection techniques. We again use one injection cycle as a generation, but we use blocks of coefficients as the prioritized network coding mechanisms' prioritization layers. To generate a linear combination associated with a given priority layer, the prioritized network coding (PNC) codes combine only messages of equal-or-lower layers. In our case, this concept translates to only lower-or-equal frequencies of the DCT-provided spectrum of sensor information. As the prioritized layers form a linear subspace in the decoding matrix, they can generally be decoded earlier and, therefore, reduce delays in data processing.

In our evaluation, we study the impact of HNC [3], a PNC protocol, on the delay after which information is usable by the central server. We also study the impact of layer selection, a central aspect of PNC protocols, on decoding delay. To that extent, we compare HNC, which selects priority layers at random, with iNsPECt [4], which employs limited knowledge



(a) Grid topology with one sink. (b) Temperature error. (c) Pressure error.

Fig. 1. Topology and average sensor error over time.

on neighboring network nodes' decoding states to determine ideal layers.

III. Factory Network Model and Evaluation

We use a wireless network model in which nodes broadcast their messages. Our topology, given in Figure 1a, represents a typical factory layout with rows of machines in a regular grid and node distances of 30 m. The fifteen nodes, N_1 to N_{15}, represent the machines where the sensor data is measured. One sink node, S, is the factory's central server system. We consider a single sensor for each machine. More sensors in machines bring a constant factor for the amount of required transmissions, analogous to a higher sample rate.

We evaluate using the discrete event network simulator ns-3 (version 3.25) with YANS Wifi model, 802.11g MAC, and 2.4 GHz PHY using log-distance propagation loss model ($\gamma = 3.0$, which is in line with a range modern factory environments [7]) combined with Rayleigh fast fading. We use real, pre-recorded sensor information from the injection molding process. Our sensor information stems from a 25 s long production cycle that was sampled at 500 Hz rate. Each measured sample is a 4 B floating-point number. We split frequency components into five priority layers with a generation size of 53 frequency components to limit each data message's size to 1008 B. For the PNC-iNsPECt variant, we set the data-feedback ratio to $1 : 2$. Each sample shown in the following is the average over five simulation runs of 200 s simulated duration each, using different sub-streams of ns-3's PRNG. Error bars depict 95% confidence intervals (assuming normal distribution), but might not be visible if the error is negligible. During each run, several production cycles are transmitted to the sink.

Figures 1b and 1c show the simulation results for temperature error over time and pressure error over time. The time measurement starts with the first message being transmitted, which explains the initially very high average error that results from production cycles without any frequency components decodable at the server. Generally, it can be seen that the preview provided by the PNC scheme iNsPECt quickly gains precision and is virtually indistinguishable from the original sensor information much earlier than RLNC can provide any information. HNC also gains precision more quickly on average than RLNC. The overhead of the HNC scheme, however, results in RLNC providing the full picture before HNC can lower the remaining error below 1 K or 1 bar. In contrast, PNC achieves such a low average error approximately four times as fast as RLNC for both temperature and pressure readings. The maximum time until each production cycle was available with full precision was 8.40 s with our baseline RLNC. As a result of the principal message overhead imposed by PNC schemes, iNsPECt and HNC required up to 9.20 s and 17.80 s, respectively, until the preview reached full precision. Especially with iNsPECt, however, the error is extremely low during the time after which RLNC finished transmission.

IV. Conclusion

We studied the impact of prioritized network coding for smart factory use-cases using real sensor information from plastic industry. Our results suggest that iNsPECt provides significant benefits over non-prioritized RLNC, whereas HNC can only provide a coarse preview before RLNC provides the full picture.

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