Zero-Wire: Low-Latency Wireless Networking with Symbol-Synchronous LEDs

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Latency-sensitive applications for the Internet of Things (IoT) often require performance guarantees that contemporary wireless networks fail to offer. Application scenarios involving real-time control of industrial machinery, robotics, or delay-sensitive actuation therefore typically still rely on cables: today's wireless networks cannot deliver messages in a sufficiently small and predictable amount of time. Drop-in wireless replacements for these cabled systems would nevertheless provide great benefit by eliminating the high cost and complexity associated with running cables in harsh industrial environments [1]. The symbol-synchronous bus, introduced in this article and embodied in a platform called Zero-Wire, is a novel wireless networking paradigm that addresses this gap. Using concurrent optical transmissions, it strives to bring low-latency deterministic networking to the wireless IoT.

Expressed quantitatively, the performance dichotomy between wired and wireless is dramatic: in commercial wireless sensor systems, messages take hundreds to thousands of milliseconds to arrive at their destination, with jitter (i.e. variance in latency) in the tens of milliseconds [2]. Their wired counterparts, by contrast, offer fixed transmission delays well below one millisecond, enabling mission-critical real-time feedback loops that control manufacturing processes or provide tactile interaction to an operator [3]. The reason for this dichotomy lies in the difficulties encountered when interconnecting many wireless nodes.

- Radios on different nodes should not transmit concurrently to prevent mutual interference from corrupting the data that is being sent. Since a sending node in general cannot tell whether its intended recipient is being interfered with, **Medium Access Control (MAC) protocols** address this issue by allocating transmission slots to nodes

(impeding ad-hoc traffic) or by having them contend for the channel (leading to non-deterministic performance). In wired *bus networks* such as CAN [4], this problem is far less significant: they connect all nodes through a shared set of wires, so that they all encounter the same traffic at essentially the same time, as illustrated in Figure 1. In some bus networks, explicit channel allocation and harmful contention can then be avoided altogether: nodes abort low-priority transmissions in case of collisions, and do so before they corrupt higher-priority messages, by exploiting the interplay between actively and passively generated voltage levels [5].

- If the transmission range of a sending node is insufficient to immediately reach the destination, data frames may have to traverse a sequence of intermediate nodes, as shown in Figure 1. **Store-and-forward routing schemes** then make sure intermediate nodes receive and store all *symbols* that make up that data frame before forwarding it along a routing path to its destination. As such, these schemes involve path set-up and maintenance in possibly dynamic environments. The combined cost of routing and MAC is considerable: link-layer and network-layer throughput tends to differ by one order of magnitude [6]. Moreover, end-to-end latency scales as an integer multiple of the time it takes to transmit a single frame, since the latter is received and subsequently repeated at every hop.
- Nodes wirelessly transmit data using **radio transmissions** that take place in crowded parts of the electromagnetic spectrum, making them prone to transmission errors. In recent years, Optical Wireless Communication (OWC) has therefore attracted particular research interest due to the abundance of virtually unregulated bandwidth in the optical part of the spectrum. While the low-level design of OWC networks has been studied extensively, considerable drawbacks remain: wireless transmissions using LEDs and photodetectors have very limited transmission range and tend to require line-of-sight connections. Connecting many OWC nodes in a routed network

might help overcome these issues, but research towards multi-hop OWC is at an early stage. Furthermore, the directionality of optical transmission hardware complicates traditional MAC considerations [7].

Figure 1. Symbol-synchronous buses parallelise transmissions down to the symbol level to achieve wire-like behaviour.

If wireless networks are to one day support the variety of latency-sensitive embedded applications that still depend on wires, innovative solutions will be needed. Symbol-synchronous buses are one such solution, the essence of which is to eliminate the conventional radio-, MAC- and routing-based approach and to replace it with an optical network in which nodes rebroadcast any signal they observe, immediately after receiving it, without waiting for the completion of a data frame or even the first symbol in it.

Symbol-synchronous transmission

As shown in Figure 1, symbol-synchronous buses reduce latency and jitter by parallelising retransmissions between source and destination nodes as much as possible. More precisely, *relay nodes* forward a symbol immediately after observing it, which means that transmitted symbols quickly move away from the node that initiated their transmission in a wave-like fashion [8]. Latency is hence determined only by the transmission time of a single frame and a relatively small propagation delay. The result is virtually deterministic timing behaviour similar to that of wired bus networks. Peripherals, such as IoT sensors and actuators, are not required to relay themselves, and may instead connect to a mesh of full-duplex relays.

The key innovation of the proposed type of network lies in the timing of transmissions and relays. Nodes synchronise their transmissions such that the symbols that they still have to relay can be distinguished from symbols they have already forwarded and should not be relayed again. This scheme prevents feedback loops from tying up the network indefinitely. More precisely, nodes relay incoming symbols at a time offset such that the offset between a signal's first arrival and any relayed version perceptible to the same node is smaller than the symbol duration. This constraint guarantees at least one moment during the transmission of every symbol where nodes in a one-hop neighbourhood are *symbol-synchronous*: they all transmit and receive the same symbol.

The timing of transmissions and relays distinguishes symbol-synchronous transmission from other low-latency mesh networking techniques, such as *synchronous transmission* [9] (popularised by Glossy [10]) and *cut-through forwarding* [11]. These techniques relay frames at a larger offset, respectively the duration of an entire frame or multiple symbols, which further increases latency, forces them to deal with feedback through e.g. message identifiers, channel modelling or channel hopping, and necessitates MAC and routing considerations. In a symbol-synchronous bus, by contrast, all relay nodes transmit essentially concurrently, so the bus simultaneously connects source and destination(s) through any and all paths that exist.

Addressing interference

To successfully propagate and decode information in the bus, nodes must discern a single initial signal amidst interference from a collectively much stronger set of slightly time-offset signals that are emitted by neighbouring relay nodes. Optical transmission, i.e. modulating the intensity of an LED, offers a solution: intensity modulation encodes information in the power envelope of a signal, rather than in the low-level properties of the underlying

electromagnetic wave, such as its phase or frequency. Moreover, LED light is incoherent, meaning that its phase remains consistent for a very short period of time, thus mitigating location-dependent phase offsets that might result in destructive interference between concurrent signals. Interference between optical transmissions can hence be understood, mitigated and designed for at the (de)modulation level [12]: the resulting signal is the sum of the power envelopes of the interfering signals, and it is not meaningfully affected by out-of-reach low-level phenomena. Nodes in a symbol-synchronous bus therefore rely on (de)modulation logic that is specifically designed to pick up on an initiating signal among many copies of the same signal that slightly lag behind it, rather than treating interference as a given or trying to cancel it out. Symbol-synchronous relaying aids this process by constraining what symbols can be transmitted concurrently, and how far apart they can be in time.

Prototype

The Zero-Wire platform [13] instantiates a symbol-synchronous bus based on on-off keying: nodes transmit data by toggling an LED on and off. This results in an extremely low barrier to entry for resource-constrained peripherals. All that is required to transmit data is to blink an LED at an arbitrary but fixed modulation speed. The network's intelligence lies in the relay nodes: they host a transceiver that implements symbol-synchronous (de)modulation logic. Conceptually analogous to a radio chip, the transceiver interfaces with an LED and photodetector to transmit and receive data, processes the received signals, and attaches to an external processor or microcontroller that handles application logic. For the purposes of this article, the transceiver was implemented in software and consists of roughly 500 lines of C code, which can be run on an ordinary microcontroller. Transmission and reception circuitry were taken from the DenseVLC hardware platform [14].

Results

As shown in Figure 2, Zero-Wire was evaluated on a 25-node testbed. The nodes were all positioned in the same plane on a 5-by-5 grid and oriented such that their LEDs point towards a grey painted surface, connecting them through their signals' diffuse reflection. The dimensions of the testbed and the relative positions of nodes within it, also shown in the figure, were chosen to enable an examination of how the network's performance scales with parameters of the network topology. Key results are illustrated in Figure 3.

Figure 2. The Zero-Wire testbed.

Latency. As in a wired bus, latency is proportional to the amount of data to be transmitted and the data rate of the bus. Zero-Wire thus enables wireless sub-millisecond latency across multiple hops. Latency is virtually deterministic: for any given data rate and frame length, it varies by no more than tens of microseconds across traffic endpoints or experimental replicates. Variance in latency due to hop-by-hop relaying across paths of different lengths is negligible, since the main source of such variance is propagation delay between neighbouring nodes (roughly $2.5 \mu\text{s}$ per hop).

Figure 3. Key performance characteristics of Zero-Wire. From left to right: latency, reliability, and goodput.

Reliability. For messages no longer than a few bytes, the fraction of frames that is correctly delivered across the network is practically constant at 99% up to a data rate of 20 kbps, after which reliability collapses as the symbol-synchronicity time constraint can no longer be met consistently. Reliability primarily depends on frame length and favours considerably shorter frames than in typical IoT networks: delivery ratios decrease by roughly one percentage point when using 128-bit instead of 32-bit frames. As in wired buses like CAN, contention has no significant effect: when configuring two nodes to transmit concurrently, the high-priority transmission is received as reliably as transmissions that are not contended with.

Goodput. Goodput increases with the data rate up to 20 kbps, i.e. up to the point at which the network stops operating reliably. When considering frame length, goodput is subject to a trade-off: longer frames allow to amortise per-frame overhead over a larger amount of payload data but are also considerably more likely to be corrupted. Goodput-optimal frame lengths are situated between 128 and 256 bits and result in a goodput of 19 kbps. Further analysis reveals that goodput decreases as the network diameter increases: as in wired bus networks, propagation delays impose a limit on the maximum data rate at which the bus can operate. Increasing network density, i.e. increasing the number of redundant links in a network, tends to improve goodput, however: it allows for longer frames at a given reliability level.

Range. Zero-Wire, like other OWC platforms, is a short-range technology: initial measurements indicate that the prototype's reliability breaks down

rapidly beyond 2 metres of range for a single pair of nodes, and that low data rates are more robust over longer distances. Quantifying range as a single number is somewhat problematic because of its relationship with transmission power, topology density and directionality of the optical front-end. Moreover, the impact of a network's diameter – and thus that of a node's range – on end-to-end performance (e.g. latency) may be considerably smaller than for conventional architectures. A complete investigation of Zero-Wire's transmission range therefore requires the design of low-power peripheral hardware and deployment scenarios fine-tuned to the type of network it introduces.

Performance limitations. Many of the phenomena that drive Zero-Wire's performance are contingent on the number of intensity samples per symbol and the time it takes to process such a sample. As all signal processing is currently done in software, the sampling interval is artificially constrained. In our vision, future versions of the transceiver should therefore be implemented as a dedicated hardware module.

Conclusion and outlook

Symbol-synchronous buses are a paradigm for free-space optical communication that breaks conventional abstractions concerning medium access control, store-and-forward packet switching, and routing. The Zero-Wire platform implements this paradigm; empirical results in a laboratory setting demonstrate how Zero-Wire attains performance characteristics and interaction patterns that, until now, have been considered impossible to deliver over wireless mesh networks and are reminiscent of those found in wired bus networks.

As wireless embedded systems become increasingly large, dense and ubiquitous, other limitations towards low latency remain. Current networks extract data from essentially one node at a time, incurring high latency if applications monitor complex phenomena using many nodes. Bus networks

again offer a unique solution: if nodes in a bus concurrently transmit different data, symbols interact in ways that allow aggregate information to be extracted at very low latency [15]. Our future research efforts will hence investigate protocols that exploit this property to immediately retrieve relevant information from the network as a whole, rather than waiting for raw data held by individual nodes.

Acknowledgements

This research is partially funded by the Research Fund KU Leuven, Jonathan Oostvogels' PhD fellowship (11H7921N) of the Research Foundation – Flanders (FWO), and the FWO D3-CPS project. The authors thank Jona Beysens and Qing Wang for their support concerning DenseVLC.

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