A High-Rate Data Acquisition Protocol with Relative Topology Reconstruction

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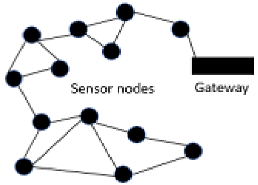
Sensor networks motivation

- Dense sensor systems need many measurements with predictable timing
- Wireless links are convenient, but can introduce interference, packet loss, and variable delay
- Wired networks remain attractive for structural monitoring, smart buildings, industrial monitoring, and embedded sensing surfaces

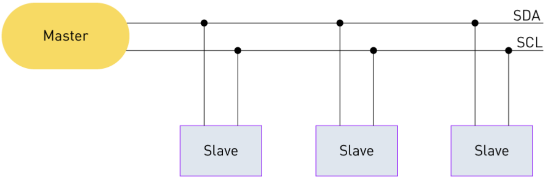


Design target

A low-cost wired protocol that collects data quickly and also tells the logger how the network is connected.

Problem

- Request-response bus protocols query devices one by one
- Total acquisition time grows with the number of nodes
- Complex wiring and branches can hurt signal integrity



Deployment issue

A device ID usually does not reveal physical or connection position, so manual mapping becomes fragile when nodes are moved or replaced.

Proposed solution

A UART-based data acquisition protocol for sensor networks, requiring two UART interfaces per node and reconstructing relative parent-child topology from the data stream.

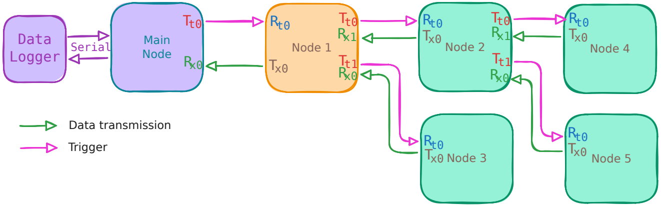
- High-rate cascading data collection
- Simple node hardware
- Relative topology reconstruction without a manually prepared map

Related work

Approach	Basis	Topology	Interface	Topology reconstruction
Modbus RTU over RS-485	RS-485	Bus	One RS-485	No
SPI daisy chain	SPI	Linear	One SPI	Yes, line position
Bidirectional UART daisy chain	UART	Linear/ring	Two UART	Yes, line position
XDense	UART	Grid	Four full-duplex UART	No
Presented approach	**UART**	**Flexible two-child layout**	**Two UART**	**Parent-child reconstruction**

Key difference: the proposed method combines simple UART hardware with flexible branching layouts and automatic relative topology recovery.

System architecture



- Data logger connects to the main node
- Main node starts acquisition and sends the sampling frequency
- Each sensor node can have a right and left child
- Data moves upward toward the logger

Proposed protocol

1. A node is triggered by its parent
2. It immediately sends the message prepared in the previous cycle
3. It triggers child nodes and reads their messages
4. It measures its own sensors and prepares the next-cycle message

Data from nodes farther away in the connection structure arrives later. The logger can realign samples with a sliding window whose size depends on maximum network depth.

Message format

$$M = [ID,\ D,\ R,\ L,\ CRC]$$

- ID: node identifier
- D: sensor payload
- R, L: relative offsets to right and left children; zero means no child
- CRC: error detection

Example: three-node chain

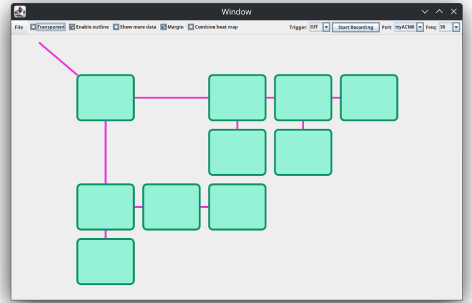
$$[ID_i, D_i, 1, 0, CRC_i,\ ID_{i+1}, D_{i+1}, 1, 0, CRC_{i+1},\ ID_{i+2}, D_{i+2}, 0, 0, CRC_{i+2}]$$

Node operation

$M \leftarrow [ID,\ readSensors(),\ 0,\ 0,\ CRC]$
while true **do**
  if nodeTriggered **then**
    send(M)
    $rightM \leftarrow$ triggerAndReadRight()
    $leftM \leftarrow$ triggerAndReadLeft()
    $rightIndex \leftarrow (rightM \neq null)?1 : 0$
    $leftIndex \leftarrow (leftM \neq null)?1 + nodeCount(rightM) : 0$
    $M \leftarrow [ID,\ readSensors(),\ rightIndex,\ leftIndex,\ CRC,\ rightM,\ leftM]$
  end if
end while

Relative topology reconstruction

- The logger receives one serialized stream
- The root ID acts as a synchronization point
- When the root appears again, one full network frame has been received
- Relative indexes reconstruct parent-child edges

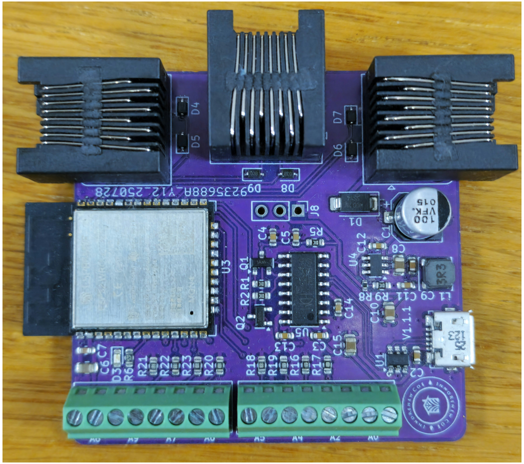


Reconstruction algorithm

Read root packet
Append packets until root ID repeats
if any packet has invalid CRC **then**
    discard frame and resynchronize
end if
for $i = 0$ to $|nodes| - 1$ **do**
    if $nodes[i].rightIndex > 0$ **then**
        add edge $nodes[i] \rightarrow nodes[i + rightIndex]$
    end if
    if $nodes[i].leftIndex > 0$ **then**
        add edge $nodes[i] \rightarrow nodes[i + leftIndex]$
    end if
end for

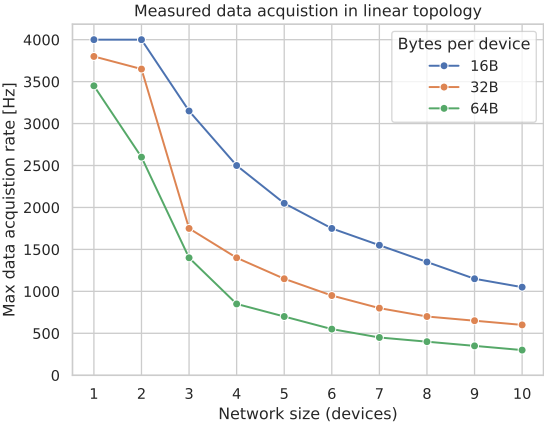
CRC failures are handled conservatively: the frame is discarded before it can corrupt the reconstructed topology.

Experimental setup

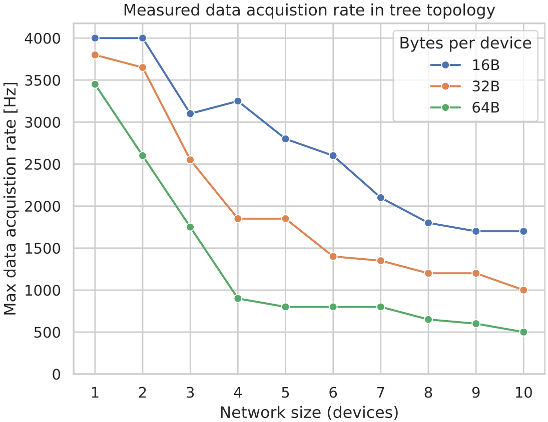


- ESP32 based nodes
- UART communication at 2 Mbps
- Connectors for one parent and up to two child nodes
- Tested with linear and tree-like cases as representative layouts

Measured acquisition rate



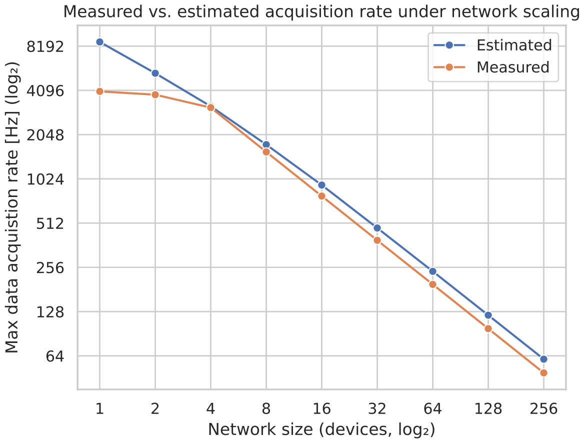
Linear layout



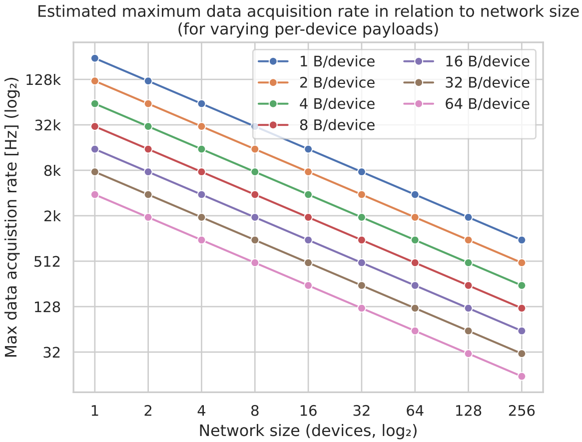
Branched / tree-like benchmark

- Frequency decreases as node count and payload size increase
- Linear layout is worst case because every message travels through one chain
- Branched layouts perform better because different paths can be collected in parallel

Predictability and scaling



Measured vs. theoretical (16 bytes)



Estimated scaling by payload size

The protocol behavior can be estimated from network size, per-node payload, connection depth, branching structure, and UART speed before building the full deployment.

Conclusion and future work

Conclusion

The protocol combines simple UART hardware, predictable high-rate acquisition, and automatic relative topology reconstruction for flexible wired sensor layouts built from two child connections per node.

- Test the protocol in smart-building and floor-sensor deployments.
- Add differential signaling to improve communication robustness over longer cable distances.

References I

- G. Thomas, "Introduction to the Modbus protocol," *The Extension*, vol. 9, no. 4, pp. 1–4, 2008.
- N. C. Gaitan, I. Zagan, and V. G. Gaitan, "Evaluation of the performance of the Modbus RTU communication protocol for consecutive address transactions and improvements related to ModbusE," *The Journal of Supercomputing*, vol. 82, no. 2, p. 71, 2026.
- A. Hermanis, R. Cacurs, K. Nesenbergs, and M. Greitans, "Efficient real-time data acquisition of wired sensor network with line topology," in *2013 IEEE Conference on Open Systems*, pp. 133–138, 2013.
- X. Sun, "Bidirectional multi-device daisy chain communication architecture and verification based on UART serial communication protocol," *Highlights in Science, Engineering and Technology*, vol. 81, pp. 583–591, 2024.
- J. Loureiro, R. Rangarajan, and E. Tovar, "Distributed sensing of fluid dynamic phenomena with the XDense sensor grid network," in *2015 IEEE 3rd International Conference on Cyber-Physical Systems, Networks, and Applications*, pp. 54–59, 2015.