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RELIABLE WIRELESS SOLUTION FOR TIME-CRITICAL COMMUNICATIONS IN SMART UTILITY ENVIRONMENTS

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ABSTRACT

The Generic Object Oriented Substation Event (GOOSE) protocol is a communication model that is defined by the International Electrotechnical Commission (IEC) 61850 standard which supports the sharing of time-critical information between Intelligent Electronic Devices (IEDs) within a substation. Due to strict requirements, GOOSE demands a fast, reliable, and deterministic network, which today is based on Ethernet networking technologies. Customers desire an alternative solution that is based on wireless radio technologies such as, for example, mesh-based networks. However, for a variety of reasons, it can be challenging to implement GOOSE over a wireless medium. Techniques are presented herein that support a reliable wireless solution for time-critical communication facilities such as GOOSE. Aspects of the presented techniques encompass using several radios coupled with an intelligent assignment of radio channels to avoid interference and employing duplication over such radios to carry critical information between IEDs. Use of the presented techniques yields an important level of determinism that allows critical information (such as GOOSE type 1A messages) to be carried over a wireless medium.

DETAILED DESCRIPTION

The Generic Object Oriented Substation Event (GOOSE) protocol, as defined in IEC 61850, supports the sharing of time-critical information between Intelligent Electronic Devices (IEDs) within a substation. The protocol allows a system to maintain protection-speed operations and issue time-critical control commands (such as, for example, tripping circuit breakers). Such operations require a fast, reliable, and deterministic network, which today is based on Ethernet networking technologies.

Customers desire an alternative solution that is based on wireless radio technologies such as, for example, mesh-based networks. However, for a number of reasons it is very challenging to implement GOOSE over a wireless medium. For example, GOOSE requires very low latency, up to approximately four milliseconds (ms), and wireless links may be unstable. Thus, GOOSE requires a communication infrastructure that offers very low latency, that provides reliability, and that is deterministic.

To meet such requirements, techniques are presented herein that support a reliable wireless solution for time-critical communications, such as GOOSE communications. The extreme nature of GOOSE (e.g., tripping within three ms) can probably never be achieved with low-rate wireless personal area networks (LR-WPANs) as defined under the Institute of Electrical and Electronics Engineers (IEEE) technical standard 802.15.4. However, achieving reliable and available communication by leveraging the Internet Engineering Task Force (IETF) work on Reliable and Available Wireless (RAW, see, for example, https://datatracker.ietf.org/doc/draft-ietf-raw-architecture) is possible.

Accordingly, aspects of the techniques presented herein improve current products by adding new methods to enable RAW and serve GOOSE and other real-time protocols that have similar requirements.

Among other things, the 61850 protocols may become very chatty in the case of a fault on the electrical lines. Relying just on regular quality of service (QOS) mechanisms will not work very well and new mechanisms must be developed in order to support 61850 messages over radio networks. The techniques presented herein offer a first step toward such an objective.

It is important to note that GOOSE is a publish-subscribe protocol that operates at the upper layer. Aspects of the techniques presented herein only provide the Layer 2 "underlay" for that protocol, such an underlay being composed of peer-to-peer (P2P) links that are made reliable and that have low latency. It is also important to note that such P2P links are well-known and preconfigured. For example, everything is set up in advance with multiple alternate channels for each IED. A typical number of neighbors is between two to four.

Aspects of the techniques presented herein leverage a number of established technologies. For example, the IETF RAW Architecture/Framework draft document (https://datatracker.ietf.org/doc/draft-ietf-raw-architecture) describes the general concept of multiple path and multiple radio communication for high reliability and availability. Additionally, the IETF RAW Technologies draft document (https://datatracker.ietf.org/doc/draft-ietf-raw-technologies) identifies the Time Slotted Channel Hopping (TSCH) mode of the IEEE technical standard 802.15.4 as one candidate medium for RAW. Further, in connection with Wi-Fi some products already leverage multiple radios for fast handoff and higher reliability through a +1 (or live-live) approach which can improve the capability that is offered in network access points that already support the Packet Redundancy Protocol (PRP).

Aspects of the presented techniques encompass several approaches that mitigate the shortcomings of a wireless medium so that such a medium can provide fast and deterministic data delivery.

In the United States, a transmitter may send up to one watt of power for up to 400 ms in the Sub-Gigahertz (or Sub-GHz) industrial, scientific, and medical (ISM) radio band (which is located at 9xx megahertz (MHz) in the United States). To provide fast and reliable transmissions, with the very short deadline of three ms that is required by GOOSE, one must ensure that multiple transmissions can happen immediately at all times. Such a capability requires keeping multiple channels free of traffic and having senders and receivers up and running at all times. In some instances, the hardware cost for such equipment can be two to three orders of magnitude higher than the cost of a radio chip to support such communications. Consequently, adding radios would only minimally impact the cost of goods.

Aspects of the techniques presented herein support a new device that will be similar but will host five to ten radios. Aspects of the presented techniques dedicate some number of radios (e.g., three) to receive critical GOOSE type 1A messages at any time. Additionally, they also dedicate some number of radios (e.g., three) to transmit to such receivers also at any time and possibly in parallel. Such an arrangement consumes seven radios, including the main radio. It is important to note that the node may need to send to two other nodes at the same time. In order to save latency, three more radios may be added, quickly bringing the total count to 10 radio chains.

However, the additional bill of materials (BOM) cost (of, for example, one dollar for each radio) is negligible in comparison to the extra selling price (which may be several hundred dollars for such an ultra-reliable piece of hardware) for a network equipment vendor.

Aspects of the techniques presented herein allocate multiple dedicated radios and frequency channels for the most critical data delivery, such as GOOSE. When an urgent event occurs, multiple copies of the packet that transports the event information are generated and then delivered through different radios simultaneously over different well-separated channels. In accordance with the IETF's RAW, there will be a mix of fragmentation and network coding so that individual transmissions are shorter, and thus faster, and more reliable, since the chance of interference corresponds to the size of a packet.

Figure 1, below, depicts elements of an exemplary environment.

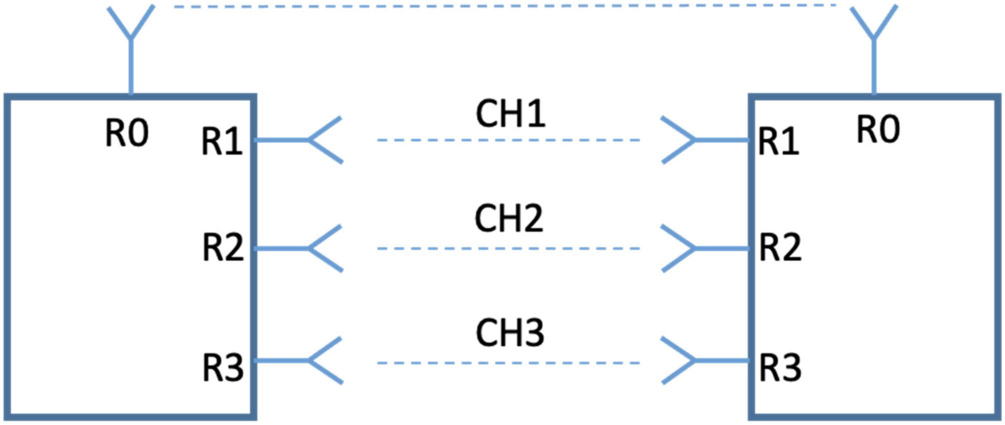


Figure 1: Exemplary Environment

As depicted in Figure 1, above, there are four radios in each of two devices. Radios R0 are responsible for low-priority data communications. Radios R1, R2, and R3 are responsible for the delivery of the most critical data. When an urgent event occurs, the same message is copied three times and then sent to the destination through the radios R1, R2, and R3 over channels CH1, CH2, and CH3, respectively. Accordingly, a node that may need to send and receive critical (e.g., type 1A) GOOSE messages needs at least six radios just for that purpose.

Note that a sender node with three radios that needs to send to more than one device will need to prioritize and then sequentially transmit to all of the receivers. Such a need highlights the desire to host more radios as described previously.

Further aspects of the techniques presented herein measure noise and rotate channels. Generally, a wireless medium (especially a free band) is unstable due to noise, interference, etc. In some instances, some channels may become deteriorating. To overcome such a condition, aspects of the techniques presented herein periodically rotate the channels. In particular, aspects of the presented techniques rotate at most one channel at a time to ensure that at least two channels remain fully functional at any given time.

Channel rotation, as described above, may encompass a series of steps, which will be briefly described below.

A first step includes measuring the noise levels of the dedicated channels. A second step includes, after identifying the worst channel, a device broadcasting a message to its neighbors informing them to change the worst dedicated channel. To guarantee stability, only that channel is changed at that time. For example, if channel CH1 is identified as the worst channel of three, it is changed to another channel (e.g., channel CH4). Channels CH1 and CH4 are taken from a list that is pre-allocated to the receiving device and the receiving device is the one that makes the decision to switch.

A third step includes the neighbors that are related to the GOOSE mesh all testing the new channel in a row. If the new channel is determined to be good enough for all, then it is kept. Otherwise, another channel is tried. When a channel is determined to be good for all of the direct neighbors in the GOOSE mesh (usually three to six neighbors) then the channel is selected and becomes active.

Still further aspects of the techniques presented herein encompass avoiding self-collisions. In a GOOSE application, when an event (such as, for example, an electrical fault) takes place, multiple devices in the same area might send messages simultaneously. Figure 2, below, illustrates elements of such a scenario.

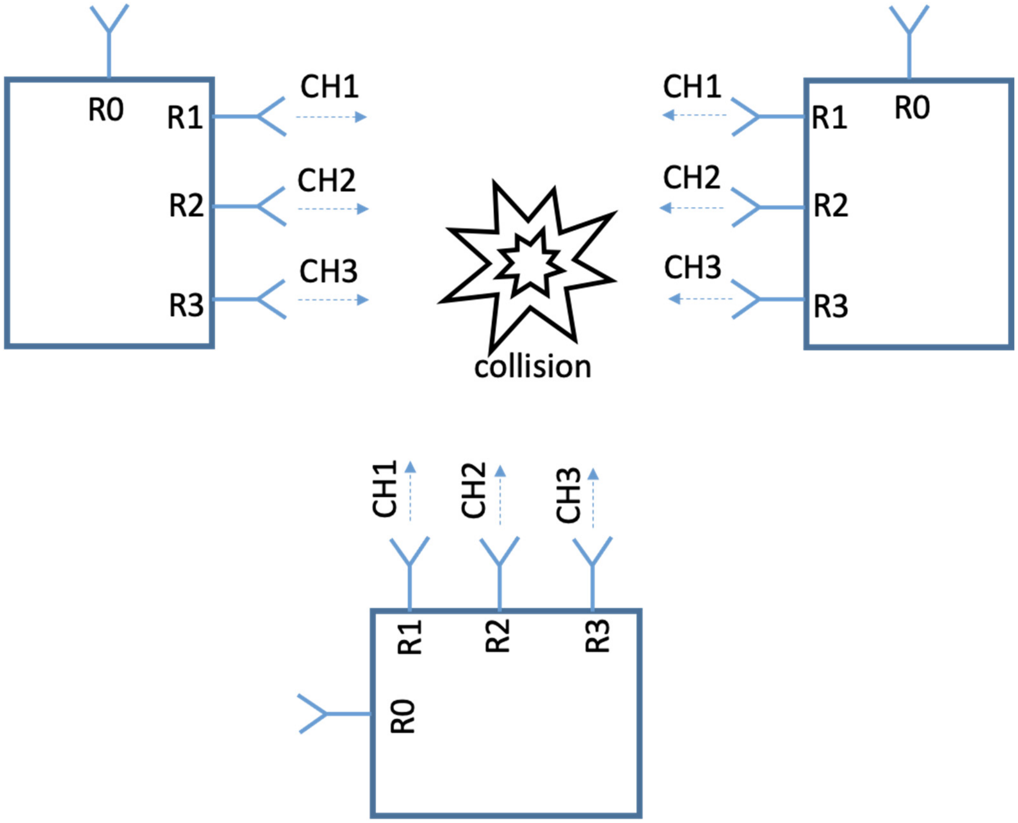
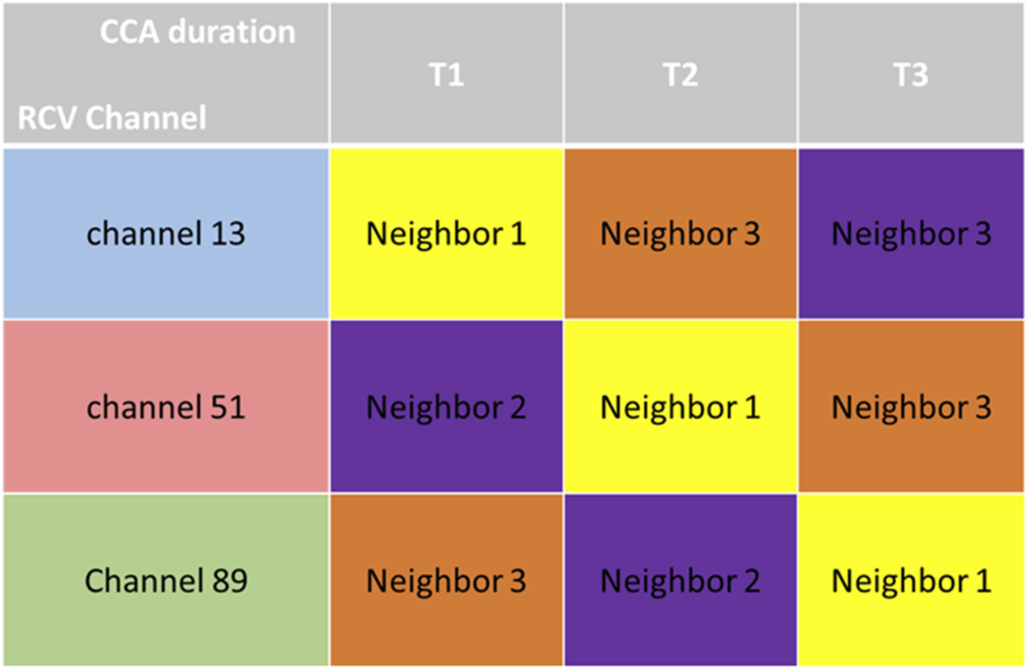


Figure 2: Exemplary Collision

GOOSE neighbors are configured with different lists of usable receive channels (out of the hundreds of channels that are available in the IEEE technical standard 802.15.4). As a result, there will not be two nodes receiving on the same channel resulting in an A->B collision with C->D. In some instances, two neighbors, say A and B, might discover the same alert and send it to node C at the same time.

According to aspects of the techniques presented herein, the neighbors may be distributed across time by either spreading them over different time slots or simply configuring them with different Clear Channel Assessment (CCA) wait times depending upon the channel. Figure 3, below, depicts elements of an illustrative example.



CCA duration RCV Channel	T1	T2	T3
channel 13	Neighbor 1	Neighbor 3	Neighbor 3
channel 51	Neighbor 2	Neighbor 1	Neighbor 3
Channel 89	Neighbor 3	Neighbor 2	Neighbor 1

Figure 3: Illustrative Neighbor Distribution

As depicted in Figure 3, above, a receiving device receives GOOSE type 1A messages on channels 13, 51, and 89. The device's neighbors (i.e., 1, 2, and 3) are currently set to talk to the device on those channels. Also depicted is an additional setting (i.e., the CCA wait time) that they will each incur.

Based on the example that was presented in Figure 3, above, if neighbors 1 and 3 need to talk to this node, neighbor 1 will wait less than neighbor 3 on channels 13 and 51 but neighbor 3 will wait less than neighbor 1 on channel 89. As a result, neighbor 1 gets to send two copies while neighbor 3 sends one copy. At the next time slot, the matrix is rotated and the reverse takes place. Typically, the operations may be run three times to enable every sender to send at least three times, one in each channel, if it so wishes.

It is important to note that RAW and different existing products that employ alternate radios to avoid a gap during handoff have a unicast orientation, whereas GOOSE is a publish-subscribe protocol. Consequently, when an alert arises multiple nodes in the vicinity will alert multiple other nodes, which may result in collisions that could degrade the system. Aspects of the techniques presented herein deal with that particular issue by employing transmit and receive radios that are separated in the frequency domain, with multiple receivers that are distributed to allow either one sender on multiple channels or more senders and less redundancy at a given time, but spread over time.

Under aspects of the techniques presented herein, transmissions may be acknowledged and a sender that receives an acknowledgement before the three rotations are completed may withhold the re-transmissions and free the associated slots. Such a sender may use the resource for a second message, otherwise the next in line with CCA in the timeslots where the sender would now be first will have an opportunity send an additional copy.

Under existing approaches (such as TSCH and the 6TiSCH IETF working group) the matrix that was presented in Figure 3, above, would not allow for a slot reuse. In other words, instead of indicating CCA delays for the same time a 6TiSCH matrix would show the time slot allocation at three different times.

Further, CCA is a listening time and the medium access control (MAC) will be programmed not to use a time slot if CCA detects a signal. GOOSE has a built-in backoff repetition mechanism (mostly to deal with central processing unit (CPU) -limited IEDs that may skip a message) that is counter-productive to a lower layer but which is accounted for by aspects of the techniques presented herein. While PRP, which works at an upper layer, could if needed be used in addition to the techniques presented herein, PRP was initially designed to work on wired networks to deal with an Ethernet link failure and not really to deal with radio transmission packet losses or interference.

It is important to note that while the narrative that was presented above focused on a GOOSE orientation, aspects of the techniques presented herein may be applied to many other real-time protocols (e.g., fieldbus) such as, for example, the Process Field Net (Profinet) technical standard, Modbus, and the Distributed Network Protocol 3 (DNP3) which are also defined by the IEC. Each of those protocols are used in an industrial environment. Under GOOSE the most critical messages are the GOOSE type 1A messages and they may be easily differentiated or isolated by the EtherType.

Additionally, while elements of the narrative that was presented above focused on the IEEE technical standard 802.15.4, aspects of the techniques presented herein may be applied to other paradigms such as, for example, Resource Units (RUs) within an orthogonal frequency-division multiple access (OFDMA) environment. In brief, all real-time protocols may benefit from aspects of the techniques presented herein.

In summary, techniques have been presented herein that support a reliable wireless solution for time-critical communication facilities, such as GOOSE. Aspects of the presented techniques encompass using several radios coupled with an intelligent assignment of radio channels through runtime noise analysis of the communications to avoid interference and employ duplication over such radios to carry critical information between IEDs, which can dramatically increase the reliability of transmissions. Use of the presented techniques yields an important level of determinism that allows critical information (such as GOOSE type 1A messages) to be carried over a wireless medium.