A TDMA-MAC Protocol For A Seismic Telemetry-Network With Energy Constraints

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Abstract

The requirements for a seismic telemetry-network are even more stringent than the well known problems of sensor networks. Existing medium access control (MAC) protocols suggest reducing energy consuming network activity by reducing costly transmissions and idle listening. Furthermore, it is required to set up communication patterns in different priority levels as well as ensuring fast handling of critical events. A protocol is proposed that operates with two parallel sets of time schedules in a time-division-multiple-access (TDMA) sense of periodic activity for listening and for transmitting. Synchronization packets sent from a central base station ensure optimal response times.

Keywords: TDMA, energy constraints, seismic sensor network, priority level scheduling

1 Introduction

At least since the 2004 Indian Ocean earthquake, which triggered a series of devastating tsunamis that killed nearly 230.000 people, setting up efficient tsunami warning systems is considered to be urgent. Detecting tsunamis is a rather difficult issue and a network of sensors is needed for that purpose. A research project in collaboration between the University of Salzburg, Austria, the Indonesian Universitas Gadja Mada of Yogyakarta and the Indonesian Aerospace Agency LAPAN in Jakarta, focuses on the development of a sensor network for telemetric gathering and processing of seismic data.

The design has to satisfy many of the typical requirements for sensor networks, as well as some specific ones. The following requirements are usually well understood and handled in sensor network design:

- Energy is limited and thus, the energy consumption of the sensor itself as well as network energy consumption must be reduced. The nodes of sensor networks usually have to operate highly power-efficient since it is inconvenient or impossible to replenish the energy source frequently [8]. In other words, the protocol itself should be energy efficient [1].
- Storage size is limited so the amount of buffered packages must be controlled [8].
- Only the information absolutely needed should be transmitted. Control packet overhead is one of the main reasons for waste of energy [1].
- Conflicting channel access must be avoided [6]. Apart from messages not arriving in time, collisions lead to increased energy consumption due to costly retransmissions [1].

- Packets must only be received by the addressed destination node. Overhearing, that is receiving of packets addressed to other nodes, as well as overemitting, describing the situation in which a destination is not ready to receive while the sender transmits packets, again lead to waste of energy [1].
- Further characteristics that are described to be important [1] are scalability and adaptability to changes. The ideal protocol is easily adapted to changes in topology, additional nodes and is robust with respect to nodes being shut down due to exhausted energy resources. However, the presented project aims to set up a network with a fixed number of nodes, such that it is not important to provide the possibility of adding nodes or changes in topology.
- The integrity of transmissions must be assured. Usually this is done via checksums. If a checksum is not valid at the receiver, a retransmission-request is being sent.
- Integrity can be assured by acknowledged communication; The sender sends it's data and waits for a certain amount of time for the acknowledgment-message from the receiver. After a so-called time-out, the sender stops waiting for the receiver's acknowledgment and starts a retransmission. Also, if the receiver sends a retransmission-request because it detected damages by getting an invalid checksum, the sender starts a retransmission. Only if the receiver acknowledges the transmission's success, the sender concludes that the data has reached it's destination.

These are not the only requirements to consider when choosing a protocol for a network of seismographs. The following aspects and requirements may render well-established solutions unsuitable:

- Seismology depends on international accumulation of large sets of compatible high quality data in standardized formats from networks around the globe [2]. Therefore the design has to handle a specific data format, implying the necessity to handle data packets of pre-defined size.
- The spectrum to host the carrier must be freely accessible. The project's technicians have thus chosen a spectrum between 400 and 470MHz.
- The architecture is planned to comprise a central sink- or base-station, where data from sensor nodes is collected.
- The maximal distance between nodes is 30km, the minimal distance is 1km.
- There might be nodes in locations, that are reachable only by the base station. In general, the network's topology should not rely on relay nodes. Nodes are likely to not communicate with each other.
- It is planned to use directed antennas to satisfy a) energy constraints, b) reachability of nodes at distances up to 30 km and c) to avoid collisions.

A critical aspect of the sensor network is that the data being processed is a matter of survival. If a sensor, specifically a seismometer, detects a seismic wave, it is crucial to precisely locate the source of an earthquake in three dimensions, to determine if a tsunami is likely to be emitted. Warnings to populations at the coast must be given within a maximum of 15 minutes. Furthermore, using a network of seismometers spaced in an array provides information about the time it takes for a seismic wave to propagate away from the hypocenter. Thus, the fact that we are working on seismic data leads to additional requirements:

- Information about seismic waves exceeding a certain threshold of magnitude (e.g. >6 Richter-scale) must be delivered with highest priority.

- If one node records such a critical event, some kind of cross-validation must be done to avoid false alarms (i.e. caused by a heavy truck passing next to one sensor).
- Transmissions must be encrypted to prevent intruders from causing false alarms.
- Transmitted data sets must contain the time of registration of the data, which is necessary to locate the hypocenter. This requires some clock synchronization between all nodes and in particular with the sink node where all information converges.
- The sensor network should provide four priority levels to support the different earthquake warning stages.

The levels are distinguished in the period between routinely collected data:

- While in level four, the least critical level, seismic data from the sensors are reported routinely every 6 hours...
- ...the third level is being entered if the measured seismic waves exceed a certain magnitude (e.g. level 3 Richter-scale) once. Then, sensors report the measured waves every 15 minutes. Obviously they return to level four if no further seismic events are being registered during two cycles, that is, after 30 minutes.
- Instead, if low seismic activity continues, level two is activated, in which sensors report the measured data to the base station every minute so that the resulting detailed information may be reported to some emergency institution. Again, nodes return to level three if no further seismic events are being registered after 15 minutes.
- The highest level of priority should be reserved for the case of emergency, when actually earthquake-like seismic waves are detected (>6 Richter-scale). In this level a sensor reports its data to the base station every 15 seconds.

1.1 Energy ressources

The technical design specifies the use of solar cells as a renewable energy source. Considering the weather in Indonesia (total annual precipitation about 2500 mm and about 145 rainy days per year) it is mandatory to save energy. We assume a maximum power consumption of approximately 18 W for transmitting and 1.2 W in normal operational state with receiving enabled. Switching off the receiving module might save another 0.5 W. The high cost for sending results from the assumption that a transmitting power of up to 6 W may be needed to reach the most distant stations.

Concluding, we have an energy consumption factor of 26 between passive and transmitting modes. The transmitting mode is by far the most expensive mode of operation with respect to energy consumption. Obviously, idle listening should be avoided as well, since it is another source of waste of energy [1]. These observations have led many researchers in the field [8] to the conclusion, that medium access control (MAC) layer design is of critical significance for power saving. The wireless radio may be switched on and off by fine-grained control. Thus, a protocol is needed that allows putting the nodes into a very low power consuming sleep or still a very energy-efficient passive mode as often and as long as possible. However, this leads to the fundamental question [8]: When should a radio module switch to a low power mode and for how long?

1.2 Data-format

Almost all seismic data worldwide is publicly available and up to now there is no modern and internationally accepted archiving and exchange format standard for digital waveforms like SEED [2]. The Standard for the Exchange of Earthquake Data (SEED) [4] is designed to handle the requirements of international data exchange. However, SEED is a complex standard defining a large set of contextual information records in each data packet. It is designed to globally distribute all the contextual information required to process seismic data, using a harmonized format and standardized protocol. MiniSEED, in contrast, includes only one or two of these records, containing only a subset of protocol information. With its light weight design it meets all the requirements of near real time data exchange [7]. Therefore, miniSEED was selected for our project, together with a code compression as in Steim1 or Steim2. MiniSEED data packets can contain integration constants that can be used to check data integrity when decompressing. Data packaging and compressing is done in a higher layer of the protocol stack in this project. Thus, this requirements are not a topic of the presented protocol specification. It is possible to pack miniSEED information from all nodes in a SEED data file. This might be done by the central base station before forwarding data or warnings.

2 Related Work

Many researchers have worked out solutions for different specifications of sensor networks. Among those protocols, here WLAN, that is almost considered as classic work, and two protocols that can serve as models for some useful techniques to the present project, will be discussed.

2.1 IEEE 802.11: WLAN

The IEEE 802.11 [11] standards specify communication in wireless local area networks (WLAN) in 2.4, 3.6 and 5 GHz frequency bands. This MAC protocol works for ad-hoc networks (Distributed Coordination Function, DCF) and centralized systems (Point Coordination Function, PCF). There are some reasons why WLAN is not suited well for the purpose of the SEISDAC project:

- 802.11 divides the bands into channels. Specifically, 802.11b uses the direct sequence spread spectrum signaling and 802.11g orthogonal frequency division multiplexing. Both modulation techniques are very useful to identify senders when they continue sending permanently and concurrently. In fact, this is what should be avoided for the presented application. In this context, the senders should actually be passive for most of the time, to save energy.
- WLAN comes along with complex functions of coordinating and modulating channels. In contrast, in the presented scenario, there is no need for a highly elaborated but energy consuming medium access management.
- WLAN is based on the CSMA/CA technique for medium access control. CSMA/CA, in turn, relies on communication between all nodes. However, if nodes are too far from each other so that no communication is possible, a base station would send a jam-signal if nodes are accessing the medium at the same instant of time in order to make them aware of the collision. As a consequence, all senders must send the data again. As stated before, retransmissions are costly and should be avoided to save energy. If WLAN would be implemented with polling (PCF-mode), stations would be idle-listening all the time in order to be able to answer the poll from the base station immediately. Obviously, there is no way to implement WLAN without wasting energy.
- Furthermore, the data packets are expected to be very small. The miniSEED format packet length is specified with 512 bytes [4]. The WLAN standard is designed to

transmit frames with a payload of 0 to 2304 bytes, while there is a MAC header of 30 bytes (including 4 EUI-48 adresses) bytes and a frame check sequence of further 4 bytes. MiniSEED packets in WLAN frames would add further 34 bytes of framing for WLAN protocol information additionally to the header of the miniSEED-format [7]. It is strongly assumed that a simple protocol gets along with less header information.

2.2 Sensor-MAC (S-MAC)

As its name suggests, S-MAC [12] is specifically designed for sensor networks and adapts the idea of handling the sleep-or-not-to-sleep problem at the MAC layer. In a more detailed view, S-MAC is based on locally managed synchronizations and periodic sleep-listen schedules, based on these synchronizations. The synchronizations are taken by a broadcast SYNC-signal to immediate neighbors. Based on this synchronization, nodes form clusters to set up a common sleep-wake schedule. Indeed, we are in search for a protocol with a possibility of synchronization, in order to get seismic data along with time-information. Furthermore, the sleeping periods can be broken up by events, i.e., unpredictable seismic waves. Thus, it is not possible to get along with a common sleep-wake schedule.

2.3 Two-Radio architecture

A two-radio architecture allows a node to alert a neighbor with a special wakeup-signal before sending packets for that destination [8]. The protocol brings a clear advantage in reducing power consumption under the condition that the second radio uses much less power via either a low duty cycle or hardware design. Event driven protocols can be combined with wakeup channels as in [10], where this is done for mobile communication devices such as PDAs, mobile phones etc. However, waking up a neighbouring node is useful only for networks where sensors communicate directly (known as *local gossip* [1]) since centralized information exchange by hands of *convergecast* and *broadcast* [1] always has the centralized node involved as a receiver or sender. Our requirements thus make such an approach infeasible. Instead, the low-cost channel could be useful for some other purpose such as sending synchronization signals or acknowledgements. However, channel usage is subject to lower protocol layers and will thus not be discussed in the following sections.

3 Proposed solution

3.1 Topology

As mentioned earlier, apart from converging communication to a central base station, nodes must not communicate with each other. This results from the requirements of using directed antennas, gathering data from all sensor nodes to integrate information as well as from the necessity to avoid data collisions. The best solution to such a specification is the star-topology.

Obviously, directed antennas have a direction that must be pre-defined at network-setup as long as they are not re-directable. As in the presented project, this is not the case and antennas at sensor nodes will be directed to communicate with the base station. The base station will be provided with an adequate solution in order to reach and to be reachable by all sensor nodes.

By sake of simplicity we claim that an event is either a seismic wave, that must be detected by multiple nodes or it is a false alarm (i.e. a heavy truck passing next to the sensor). Actually, there is no reason to prefer the direct alert from a node to all other nodes over centralized handling, since information must be collected centrally in each case to evaluate the relevance of and to calculate seismic informations from multiple measures before submitting the information.

Avoiding collisions is easier handled in a star-topology than in direct involvement between sensor nodes. Direct communication comes along with lots of collision problems, especially in the scenario when multiple sensors detect an event simultaneously [5]. In the worst case, this may lead to a situation where collisions are so frequent that the communication is, in fact, slowed down to a level below a type of centralized communication. Since critical events in a seismic network can be of vital importance, it is necessary to provide time-deterministic transmissions, that is, transmissions are never exceeding an acceptable range of time. Note that centralized communication, in addition, eases power saving: If only one node, that is, the central node, is idle-listening, all other nodes may sleep until their sensor detects a critical wave or until a routine-report is scheduled.

Beside obvious advantages, networks with a star-topology suffer several disadvantages. First, it is necessary that the central base station is provided with a reliable, ideally uninterruptible power-supply. The requirement of being uninterruptible is even stronger than having the power-supply being self-contained. Thus, it is advised to use a battery-backup.
Second, cross-validation of false alarms takes more time if it is done over a central node and would be faster if it was directly handled by neighboring nodes. Furthermore, a network with star topology should have at least one alternative node that can immediately take over the function of the central base station in the case of its failure. This is crucial because the network is not working at all without a central base station. However, handling these problems is beyond the topic of the presented paper and is thus being omitted in the following.

3.2 Event Driven Strategy

Event driven protocols are not unusual in wireless sensor networks [5, 10]. In event driven protocols, communication is executed only on demand, virtually without active idling (i.e., listening). In doing so, energy is being saved because a sleep mode is entered as long as no event occurs. This ideally results in a behavior in which as long as a node will not send or is not receiving, it is in sleep mode.

3.2.1 Events

Basically, there are two types of events:

- The first type of an event occurs when a nodes sensor gets a relevant signal. That is, a seismic wave of certain magnitude. The sensor triggers a wake-up to its radio module and sends the data as soon as possible to the base station.

- The other type of event is time-triggered, that is, an activity of periodical occurrence. In the presented project, time-triggered reports submit the routinely collected data with a periodicity according to the four priority levels to the base station.

For the latter type it is obvious that the receiving node knows the time when it should listen, since packets arrive periodically. The further type of events occurs at unexpected time.

3.2.2 Communication pattern on events

In the following it is being analyzed why this communication pattern is suited well to critical event handling. Additionally, a parallel structure of priority-listening-levels to priority-sending-levels is being introduced by considering the following possible scenarios:

- The first node detecting a seismic wave of certain magnitude reports it to the central base station. The base station has no other events and acknowledges the sender. The sending node is aware of the critical content of the message and enhances its periodicity of listening to the highest level.
- The first reporting station now listens every 15 seconds if it gets a critical warning, indicating that also other stations got the seismic signal or a all-clear message if - after a certain time-out period - no other station reported an event.
- If more sensors detect a seismic wave they report the event to the central node and receive immediately a critical warning signal that alters the sending-priority as well as the listening-priority levels.

The resulting types of listening are the following:

- **normal:** Listening occurs after each sending period, when the central station sends an acknowledgement indicating the successful receiving as well as the current priority level.
- **synchronization:** Nodes listen until the SYNC-packet is being received to determine the slot to send a packet containing information of a seismic event.
- **warned:** Listening is done every 15 seconds, independent of the sending priority level, after a node has reported a critical event before any other node did. This is crucial to distinguish false alarms from real emergency cases.

3.3 Time Division Multiple Access (TDMA)

TDMA is denoted as another method of conserving energy in sensor networks [1]. TDMA is used to schedule traffic. Each node has a specified time slot in which it is scheduled to send or receive. Consider for example figure 1. 7 nodes are scheduled, each consuming an equal part of a cycle. Node with ID=1 sends in slot 1, node with ID=2 sends in slot 2 etc. In slot 3, node with ID=3 sends a packed and receives immediately an acknowledgement. Such an approach allows nodes to sleep when they are not scheduled. Obviously, it is not feasible for ad hoc networks, since it is based on a relatively static topology and traffic patterns should be more regular. However, this is exactly what we are going to do: The number of sensor nodes might be unchanged and each priority level determines the length of sleep phases between periodically sending of data to the base station. This leads to a regular traffic pattern except the case in which a node senses a critical event that must be reported immediately to the central node. Thus, the remaining question is how to handle medium access in this unpredictable case.

Our requirements on immediateness accept a latency of 15 seconds even in the case of the critical, highest priority level. With TDMA, a critical event triggers the sensor node to enter the schedule of highest priority level. Then, it might determine the time-slot when it is scheduled (regardless other sensors use their scheduled periods or not) and starts transmission in the next available period. The latency of such a strategy is of maximal 15 seconds since each node is allowed to send once in each cycle.

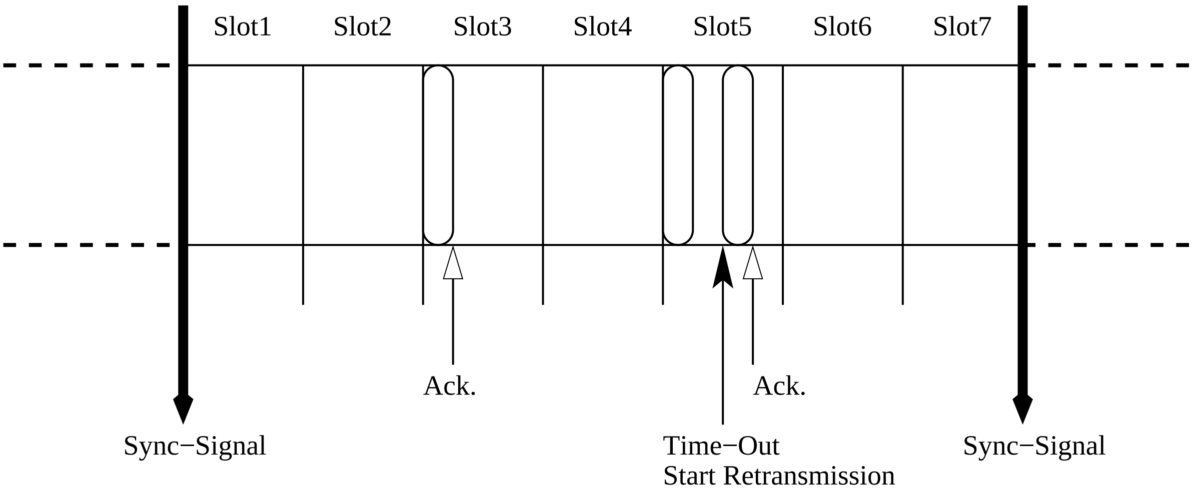

Figure 1: Scheme of a TDMA-cycle. Node with slot-id=3 receives an acknowledgement after having sent it's packet. Node with slot-id=5 starts a retransmission after time-out.

A final consideration on designing a TDMA-schedule is the length of a slot. The sensors all operate on the same type of data, that is, data packet size is equal for all sensor nodes. Furthermore, the packets are of equal priority. Thus, the communication cycle should be divided in equal sized time-segments among all participating nodes such as shown in figure 1. Proposing a data-rate is not the purpose of this work but it must be mentioned, that it is not enough to choose a data-rate so that sender get along with the slot size when transmitting a packet. The data-rate must be adapted to the number of nodes and the resulting slot-size as well as to the time-out epoch, so that at least two retransmissions can take place in one slot. Such a case is illustrated in figure 1, where node with ID=5 sends a packed in slot 5 and, after a certain time out, starts a retransmission.

3.4 Clock Synchronization

Clock synchronization is usually done by a SYNC-packet, broadcasted by the central-base station, according to a master-slave pattern. In the FlexRay protocol's static segment [9] this is done by a SYNC-packet at each begin of a schedule-cycle. Note that this results in very low listen-periods for sensor nodes but, however, many transmitted SYNC-packets from the central base station. The base station must send SYNC-packets every 15 seconds in order to provide fast responses to critical events. This synchronization via a central station satisfies also the requirement of precisely synchronized clocks in order to get accurate calculations on the location of a hypocenter and wave propagation regardless of the schedule.

SYNC-packets can also be used for other purposes. It was stated earlier that the base station must provide an all-clear message or a critical warning in response to a node's critical report, depending on either other sensor nodes got the seismic wave, too, or if one node was likely to cause a false alarm. These messages can be included in the SYNC packet opportunely by using only two bits representing the priority level and one further bit to indicate a warned status. Thus, the warned-listening type is reduced to a periodic listening to the SYNC-packets in order to know if the warning is still enabled or not as well as to get information about the current priority level.

3.5 Energy considerations

As mentioned earlier, the base station in a network with star topology will consume much more energy than the sensor nodes because it is idle listening and because it must send SYNC-packets every 15 seconds. Nevertheless, this tradeoff may be handled with a second, power saving radio-channel for control data. That is, the SYNC-packets for clock synchronizations as well as the acknowledgement packets, that are received in the listening schedules as alert, warning or all-clear message, can be sent via a highly power-efficient channel as in [8]. However, we additionally assume that the base station is either in a more reachable area so that service and maintenance of e.g., a backup-battery, can be done easily, or it is connected to power supply line or is provided with some other reliable current source or generator.

4 Conclusion

We summarize the following building blocks for a telemetric seismic sensor network protocol:

- Collision control in converging messages is best done by round-robin TDMA-schedules, with each sensor node being provided with a unique slot in each communication cycle.
- When a sensor registers a seismic wave of critical magnitude, it listens to get the next SYNC-packet to determine the next time-slot when it is scheduled.
- In order to save energy, there are four priority levels for sending information in a convergecast way from sensors to central base station and, analogously, four priority levels of listening on broadcast messages from central base station to sensor nodes. Additionally, sensor nodes listen in case they have to synchronize before starting a transmission as well as after sending a critical information in order to validate it's relevance.
- There are two types of messages from the base station to the sensor nodes; SYNC-packets and acknowledgement-packets. The second type can be a pure acknowledgement to indicate a correct transmission or otherwise a request for retransmission. SYNC-packets contain two bits indicating the current priority level as well as a bit indicating a warned state.
- Control data transmission as well as scheduling may be done with greatest energy efficiency when a second, low-cost radio is available additionally to the data channel.

We have proposed a flexible TDMA schedule along with simple and efficient event handling for a seismic sensor network, in order to avoid collisions and to save energy. The protocol is designed to satisfy the requirements when handling life-critical data.

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