WIRELESS WAKE-UP SENSOR NETWORK FOR STRUCTURAL HEALTH MONITORING OF LARGE-SCALE HIGHWAY BRIDGES

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ABSTRACT

To realize in-situ structural health monitoring of critical infrastructure such as bridges, we present a powerful, but also low power and flexible, wireless sensor node utilizing a wake-up transceiver. The sensor node is equipped with several kinds of sensors, such as temperature, pressure and acceleration for in-situ monitoring of critical infrastructure. In addition to these commonly used sensors in wireless sensor networks, some nodes are equipped with global navigation satellite system receivers (GNSS) and others with tilt and acceleration sensors of very high accuracy that were developed by Nothrop Grumman LITEF GmbH. We present a low power wake-up multi-hop routing protocol that is able to transmit data with little overhead by supporting the use of wake-up receivers in combination with long-range communication radios. The wireless sensor nodes and the routing protocol are tested at a large-scale highway bridge in south-west Germany, where a prototype network was installed in June 2015 following a first test installation earlier in June at the same bridge. A gateway node equipped with a Global System for Mobile Communications (GSM) modem transfers the network data to a remote server located at the University of Freiburg.

KEYWORDS

Monitoring of critical infrastructure, Wireless Sensor Network, Wake-up transceiver, wake-up multi-hop routing protocol, GNSS receiver

INTRODUCTION

Structural Health Monitoring (SHM) of critical infrastructure such as bridges can provide important information about structural performance and may help to detect anomalies or threats originating from damages or deteriorations at early stages. SHM can also be used to estimate remaining life time, to assist in bridge maintenance planning, to verify construction designs and to deliver important data in case of disasters or extreme events (Chang et al. 2003, Ko et al. 2005). According to Ahlborn et al. 2010, there exist three different techniques of SHM for bridges that can be classified into in-situ, on-site and remote monitoring techniques. In-situ monitoring techniques use sensors such as temperature, humidity, strain gauges, acceleration and others installed directly at a structure, whereas on-site monitoring techniques use more complex sensors such as laser scanner, different RADAR techniques and others that are brought to a structure during the event of monitoring. Remote monitoring is done from a greater distance, for example by analysing photographs of the structure taken from satellites or airplanes.

In respect to SHM, one important measurement is the three dimensional displacement of a structure or of parts of it. These measurements can be done by using on-site sensors such as laser scanners (Ahlborn et al. 2010, Yi et al. 2013, Cross et al. 2013) or by using in-situ measurement results provided by Global Communication System (GPS) receivers (Knecht and Manetti (2001), Yi et al. (2012), Meng et al. (2007), Nickitopoulou et al. (2006), Psimoulis et al. (2008)). In contrast to optical sensor systems, for example laser scanners or total stations, a GNSS based monitoring system provides several advantages, such as weather independency, absolute displacement measurements, autonomous operation and no need for line-of-sight connection between different measurement points (e.g. Yi et al. 2013). Applying Near Real Time static baseline processing, displacements of the range of 5 mm or greater can be detected as well as oscillation frequencies of up to and above 4 Hz (Günther et al. 2008. Psimoulis et al. 2007, Yi et al. 2013). Meng et al. (2005) recorded the dynamical response of the

Wilford Bridge in Nottingham, using Global Positioning System (GPS) receivers in combination with accelerometers to validate the data and improve the monitoring system performance.
Especially in-situ monitoring systems are often realized with the help of Wireless Sensor Networks (WSNs), as they are cheap and easy to install on existing structures (Chang et al. 2003, Ko et al. 2005, Ahlborn et al. 2010). WSNs consist of sensor nodes which are self- or battery-powered small units and communicate wirelessly to each other.

For long-term monitoring, sensor nodes are unattended over longer periods of time, since they are placed in remote areas where replacing of batteries is not feasible. Therefore, long node lifetimes are desired and the power consumption of WSNs has to be minimized. A possible way to save energy is an energy efficient communication protocol such as the on-demand communication approach (Al Ameen at al. 2010). Here, wireless sensor nodes have no synchronized listening and sleeping phases, but listen permanently in a low energy stand-by state and wake up to full functionality only after receiving a wake-up call or triggered by a sensor. An advantage of the on-demand communication approach is the low latency: since there exist no scheduled sleeping phases, messages can be sent immediately. For example, if a sensor detected a critical signal, this message may be transmitted to the gateway without further delay as would be the case when long and uninterruptable sleeping phases are implemented.

Wardhana et al. 2003 analyses the reasons of bridge failures in the United States between the years 1989 and 2000. They analyse more than 500 failures of bridges, which had an average age of 52.5 years. Their analysis shows that the failures mostly took place during service life time and that 83% of the failures were triggered by an external event, like floods, earthquakes, fires, hurricanes, overloads and impacts of vehicles. This means, that continuous monitoring of bridges can be used to early detect such events or at least their impact which could be critical to the infrastructure. Taking this into account, on demand communication protocols can potentially save precious time by quickly broadcasting sensor data of triggering events. At the same time, on demand communication protocols can save energy by performing low duty cycling and asynchronous measurements.

Another advantage of wake-up transceivers, which support on demand communication, is their enhanced robustness because no clocks need to be synchronized. So, the embedded software may be reset at any time, e.g. if a fatal error state occurs. New nodes can easily be integrated into an existing network which is running in low duty cycle periods. Additionally, pulling data from the network or demanding extra measurements can be done easily – a great advantage during bridge maintenances. But the on-demand communication approach also poses new challenges, as sending of a wake-up signal can be more expensive than sending of a communication message (Bannoura at al. 2015). Another challenge arises from the lower sensitivity of the wake-up receiver compared to the sensitivity of the communication radio, which requires several wake-up messages to reach a sensor node in communication range (Bannoura et al. 2015). Therefore, protocols have to be used that are able to cope with these challenges.

Here, we present a powerful but flexible wireless sensor node utilizing the wake-up transceiver. The node is equipped with different kinds of common and cheap sensors, such as temperature, pressure and acceleration. Additionally, there exist sensor nodes that are equipped with a very accurate tilt sensor developed by Nothrop Grumman LITEF GmbH and sensor nodes that are equipped with high performance GNSS receivers from NOVATEL to improve the performance of the structural health monitoring system. We present a WSN installed on a large-scale highway bridge in south-west Germany and introduce a static wake-up multi-hop routing protocol. A Global System for Mobile Communications (GSM) gateway node is used to transfer the network data to a remote server.

RELATED WORK

Several WSNs have been introduced for SHM of bridges which usually consist of sensor nodes that acquire process and transmit data. Lynch and Loh (2006) give a comprehensive overview of wireless sensor node prototypes for SHM in academic and commercial context available during the years 1998 – 2005. In their work Lynch and Loh emphasize on the lower cost of installing a wireless monitoring system compared to tethered systems. They also reviewed available operational systems (OS), radio transceivers and data processing techniques to be used for SHM systems. Lynch et al. (2006) present a WSN consisting of 14 nodes to measure the acceleration response of the Geumdang Bridge.

Kim et al. (2007) present in a WSN deployed on the Golden Gate Bridge consisting of 64 nodes that measured ambient vibrations, and a base station that was a Laptop. Due to the large size of the Golden Gate Bridge the network included a 46 hops multi-hop route. Similar to this work, Whelan et al. (2009), Bocca et al. (2011) and

Sim et al. (2014) present a WSN consisting of several nodes that were connected by a single-hop star-type network to a base station (microcontroller notebook).
Kurata et al. (2011) presented a WSN on the New Carquinez Suspension Bridge in California based on the Narada wireless sensing units which feature a 2.4 GHz IEEE 802.15.4 radio standard. The Narada node, equipped with 5-AA batteries, had a lifetime of 40-45 hrs which could be extended by 60 % by using sleep modes. The sensor nodes send their data to a Narada server base station using single-hop links. The more powerful base station consisted of a low-power computer running a Linux OS and was equipped with a third generation (3G) modem to deliver the data to a remote database server.

Chae et al. (2012) successfully monitor the Yonjong Bridge with a WSN consisting of 45 nodes and a gateway station. The gateway includes a commercially available communication module to upload data to a remote server. The monitoring test provides three months of continuous data with 90 % transmission rate. Communication was based on commercial ZigBee modules but the authors did not provide figures on energy consumption of the modules. The installation includes dynamic (accelerometer and strain gauge) and static (wind and temperature) sensors which were connected as star- or mesh type network, respectively. The data are sent per single-hop to the gateway. To cover longer distances between node and gateway, directional antennas are used.

Hu et al. (2013) designs a WSN to monitor the Zhengdian Highway Bridge based on nodes, which uses a MSP430 microcontroller and a CC2420 radio. The nodes are running TinyOS, which uses MintRout to send data over multi-hops to a base station. Including an energy storage of 6750 mAh, a node is able to monitor continuously for around 168 hours, or when choosing a sampling period of 1 hour/day, lifetime can be extended to 168 days. The base station is connected via a USB connector to a powerful host computer.

In contrast to the studies above, we present a SHM system based on ultra-low-power wake-up sensor nodes, which supports the use of flexible and asynchronous measurement cycles ranging from seconds to hours and days. In sleep mode they consume only around 9 µW energy and due to their flexibility, their lifetime can be enhanced without losing precious time in case of important events, compared to fixed duty cycling measurements. The base station, equipped with a GSM modem, submits data to a remote server. A wake-up multi-hop network protocol is presented, which supports the use of the introduced sensor nodes

WIRELESS SENSOR NODES

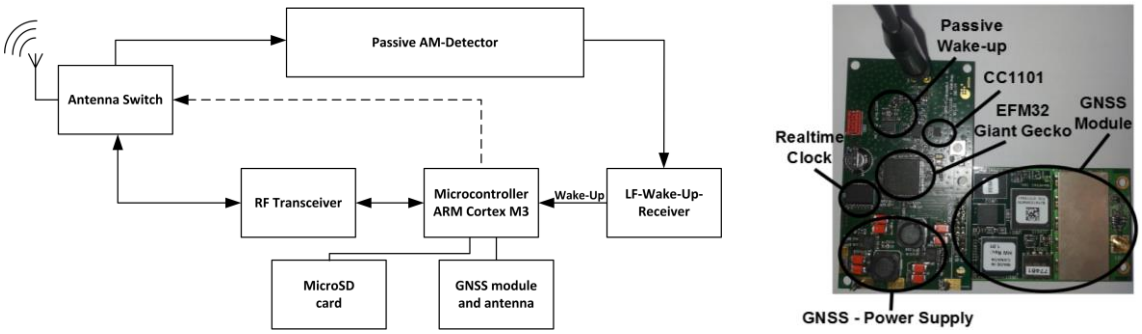
The wireless nodes used in this work are based on the sensor node introduced by Gamm et al. (2012). Featuring a wake-up transceiver, the nodes combine the advantages of fast communication, a small antenna and low current consumption. The microcontroller utilized on the boards is a powerful 32 bit EFM32 Gecko manufactured by SiliconLabs. It has many build-in features and interfaces like SPI, I^2C, multipurpose GPIOs and a 12 Bit ADC just to name some of them. It provides up to 128 kB RAM and several low power states to reduce energy consumption. To realize long-range communication a CC1101 radio is used that has a current consumption of 30 mA when transmitting at 10 dBm output power at 868 MHz. Its sensitivity is around -104 dBm. The 125 kHz wake-up receiver (AS3932) from austriamicrosystems has a current consumption of only around 3 µA in listening mode and, in combination with the passive modulation path, the board has a wake-up sensitivity around -50 dBm (Gamm et al. 2012).

The sensor nodes are equipped with a high precision realtime clock (PCF2129T) that has an accuracy of +/- 3 ppm. To store data from sensors and from the network each board has a MicroSD card that provides several GB of storage. To minimize power consumption, a circuit was developed that can be used to switch the SD-Card completely OFF by the microcontroller. The node is equipped with a temperature sensor (DS18B20), a three axis acceleration sensor (LIS3DSH) and a precision altimeter/pressure sensor (MPL3115A2). In wake-up listening mode the node has a current consumption of around 9 µW.

Figure 1 (a) shows a schematic of a GNSS (Global Navigation Satellite System) receiver node including the passive wake-up path. The antenna is connected by a switch either to the main radio or to the wake-up receiver. The wake-up signal is obtained from the 868 MHz signal via the passive AM-Detector that consists of the matching network, a rectifier and a low pass filter. In case the wake-up receiver detects a valid input signal it triggers an interrupt in the microcontroller that toggles the antenna switch to the main radio. In this state, the sensor node is ready to receive and transmit communication messages. Relay nodes are similar to sensor nodes except they have no sensors on board. The base station is additionally equipped with a Global System for Mobile Communications (GSM) modem to transfer data to a remote server. To save energy, the GSM modem can be switched OFF by the microcontroller when the modem is not needed.

GNSS Sensor Node

Figure 1 (b) shows a photo of the GNSS (Global Navigation Satellite System) receiver node. It is based on the same hardware as the sensor nodes introduced above. A NOVATEL OEM615 GNSS receiver module can be connected to the board by using a simple 20 pin connector. A UART interface is used to configure the GNSS module and to read out the GNSS messages periodically. Figure 1 (a) schematically shows the GNSS receiver node including its hardware blocks. The NOVATEL OEM615 module supports GPS, GLONASS, Galileo and Compass frequencies, measurements up to 20 Hz and real-time kinematic positioning. Since the GNSS board draws around 6 A during start-up, a power supply circuit on the sensor node delivers this high peak currents for a short time. In active mode, the GNSS receiver draws constantly around 500 mA. To reduce the power consumption of the GNSS receiver node, the GNSS module is activated only periodically and can be switched OFF completely during times when it is inactive. Depending on the amount of satellites in view of the antenna, the amount of received data varies between several Bytes to several Kbytes per message. To send this amount of data wirelessly to the base station a wake-up multi-hop routing protocol was developed that is capable of sending data with little overhead. The protocol is introduced in the next section.



(a) (b)

Figure 1: Photo of a GNSS receiver node (a) and its schematic including the passive wake-up path (b)

Tiltmeter and Acceleration Sensor Node

Figure 2 schematically shows the tilt and acceleration sensor node. The sensor node is equipped with a very accurate tilt and acceleration sensor developed by Nothrop Grumman LITEF GmbH. The sensor has a reproducibility of more than 50 µg (one sigma) over the tested temperature range. The sensor is connected to the sensor board via the SPI interface and indicates a completed measurement by a busy signal. Internally the sensor uses a microcontroller, a digital to analog converter, an analog to digital converter and the sensor itself (MEMS-Chip). The board has a current consumption of around 80 mA when active and can be switched OFF completely to safe energy.

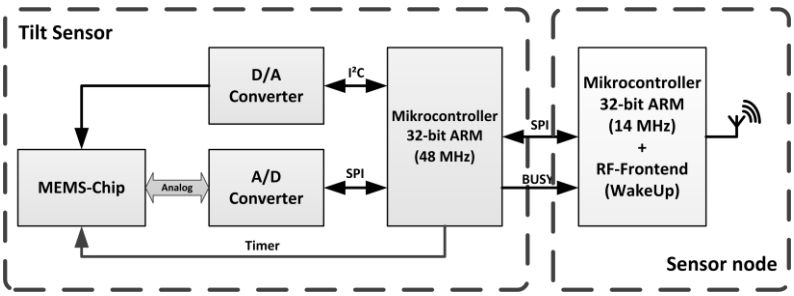


Figure 2: Schematic of the newly developed tilt and acceleration sensor connected to the wireless sensor board via SPI

WAKE-UP MULTI-HOP ROUTING PROTOCOL

Since to our knowledge no communications protocols for WSNs have been published, which support the use of wake-up transceivers, a new communication protocol needs to be developed. It should support both: wake-up receivers and long-range communication radios. Since the range of the wake-up receivers is small compared to that of the main radio, data and wake-up transmission is realized by a multi-hop routing protocol that supports sending of wake-up messages and data. The protocol stack consists of several layers. The lowest layer is responsible for the waking up of neighbouring nodes. The second layer handles single-hop message

transmissions and the top layer routs messages and forwards wake-up signals along multiple hops, if the destination is not a direct neighbour.

As mentioned above, the sensitivity of the wake-up receiver is lower than that of the communication radio and data can be sent over longer distances than wake-up messages. The routing protocol as depicted in Figure 3 makes use of this behaviour: by building a chain of woken nodes and transferring data to the most suitable receiver, nodes in between can be skipped during data communication. In Figure 3 node 13 sends for example a wake-up signal to node 12, which forwards the wake-up to node 11 and so on, until a defined maximum number of forwards, or the destination is reached. Data can then be sent directly from node 13 to one of the woken nodes 10, 11 or 12.

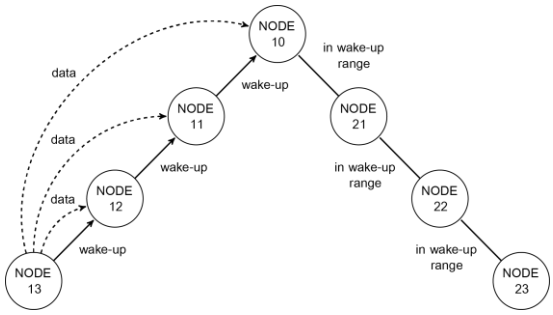


Figure 3: Schematic of the wake-up multi-hop routing protocol developed in this work

Figure 4 shows the sequence diagrams of the routing protocol for the different cases of (a) sending data to a direct neighbour, (b) sending data to a two-hop distant neighbour and (c) sending data to a three-hop neighbour. Decision, to which node data will be sent, is done at the node that started communication by sending a routing request (REQ). The node evaluates the request acknowledges (REQ_ACK) received from the participating nodes (nodes B, C and D). Further nodes are called by forwarding the routing request (FWD_REQ). Implemented parameters to support the decision are: available data slots at the receiving node and hop distance from the starting node. It is possible to include further parameters like link quality, receiver signal strength or remaining energy to increase the stability of the network.

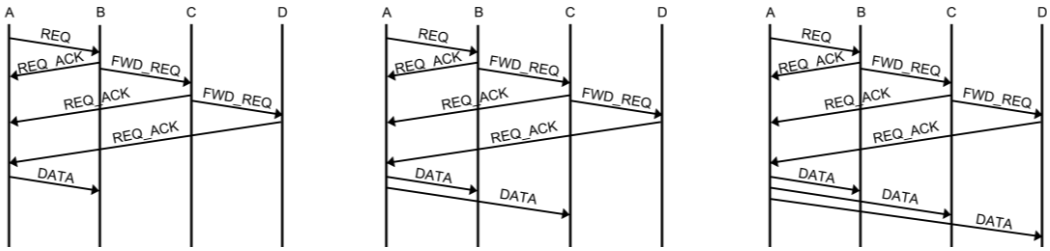


Figure 4: Sequence diagram of the routing protocol for the three different cases of communication to next neighbour (a), two hops neighbour (b) and three hops neighbour (c)

Once the communication link to a node is established, up to 64 data packets consisting of up to 256 bytes size each (max. 16 kB) can be transmitted. After transmission, the link gets closed and the participating nodes fall back to sleep, again. The same routing scheme is repeated until all data reached their destination.

The embedded software is implemented as a state machine as depicted in Figure 5. At the beginning, a sensor node is in SLEEP state in which it consumes only minimal energy. A low-energy timer transfers the node from sleep either to start a sensor measurement (state MEAS), or to check if there is data available in the memory that is not yet sent (state STORE).

In case there are already prepared data slots available, for example from a previously aborted sending, the sleep state will be left and data transfer is initiated by sending a wake-up signal (state SEND WAKE-UP). After a measurement, sensor data is stored in a ringbuffer on the microSD card and data packets are prepared and moved into one of up to 64 available data slots. If there are no free slots available the data is kept in memory to be processed later.

After successful filling the message queue, sending of data is initiated with a wake-up signal (state SEND WAKE-UP). Successfully waking of the neighbour node, is indicated by a wake-up acknowledge and a routing

request is sent (state SEND R_REQ) containing destination ID, number of data packets and max number of wake-up hops. Then, the node listens for route request acknowledgments sent by the woken nodes (state WAIT R_ACK). If at least one node that answers has a free slot available, the node starts to send all possible data packets (state SEND DATA). After successful sending, or if any error occurs, the node exits its current state and goes back to sleep. The state machine of the receiver is similar to that of the transmitter.

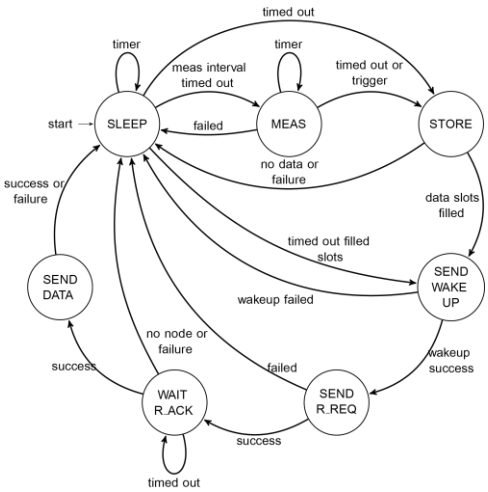


Figure 5: State machine of a sensor node for data transmission

DEPLOYMENT AT THE NECKAR VALLEY BRIDGE WEITINGEN

Figure 6 shows a photo of the Neckar Valley Bridge Weitingen on Highway 81 from Stuttgart to Singen. The bridge is 900 m long and around 127 m above ground at its highest point. The bridge is constructed of five spans and its two end spans consist of inverted cable stay towers that support massive beam spans of 263 m on the southern side and 234 m on the northern side. The locked coil cables are 120 mm and 105 mm thick respectively.

Figure 6: Photo of the Neckar Valley Bridge Weitingen

The upper part of Figure 8 shows schematically the Neckar Valley Bridge in Weitingen. The lower part is a schematic of the first span of the bridge with the deployed WSN during June 2015 including the different kind of sensor nodes. The deployed WSN consisted of several sensor nodes and a base station. The base station (node-10) was placed approximately in the middle of the first span (depicted as blue star in Figure 8). A relay node (node-21/41, green square) was placed near the base station and used to forward data to the base station from sensors farer away. Four sensor nodes (node-22, node-42, node-43 and node-51) were placed inside the box girder at different places (red triangles in lower part of Figure 8). The GNSS receiver was installed at the beginning of the first span (dark-red cross). The antenna was attached to the bridge using a 10 m long cable as can be seen in left side of Figure 7 and as dark-red circle in the schematic. Two tilt sensor nodes (node-23 and node-31, purple circles) were attached to a steel girder, the first approximately in the middle of the first span and the other near the beginning of the bridge. The right side of Figure 7 shows exemplary a photo of deployed node-42 inside the hollow box girder.

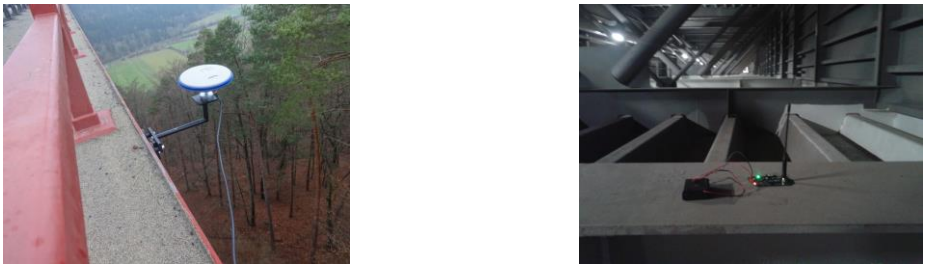


Figure 7: Photo of the GNSS antenna attached to the bridge (left) and a photo of the deployed node-42

This installation was an extension of a previous installation done some days before. The second installation introduced the GNSS receiver node and node-43 which was used to examine the achievable wake-up range inside the hollow box girder. The distance between node-42 and node-43 (two red triangles on the right side) was approximately 125 m, as can be seen in Figure 8. Further focus of this installation was to examine the hard- and software in a realistic environment.

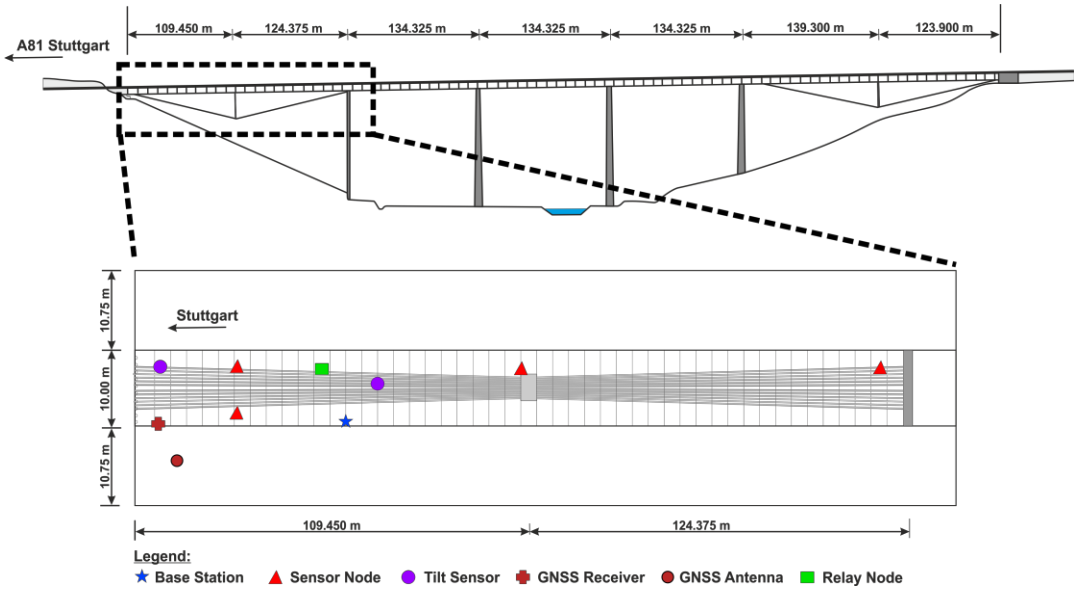
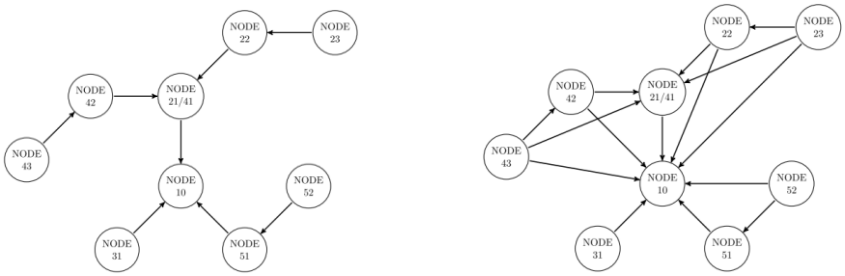


Figure 8: Schematic of the Neckar Valley Bridge Weitingen on the upper half and sensor sodes deployment inside the hollow box girder of the northern span in the lower part

Figure 9 (a) shows the topology of the wake-up network, where each node is able to wake its direct neighbour. Node-43 for example, is in a three hop wake-up distance to the base station, whereas node-52 is in a two hop wake-up distance to the base station. Figure 9 (b) depicts the network topology when all nodes are active. Due to the longer communication range (compared to the wake-up range), additional paths between nodes can be established and the communication hop distances from nodes to the base station can shrink to one hop.



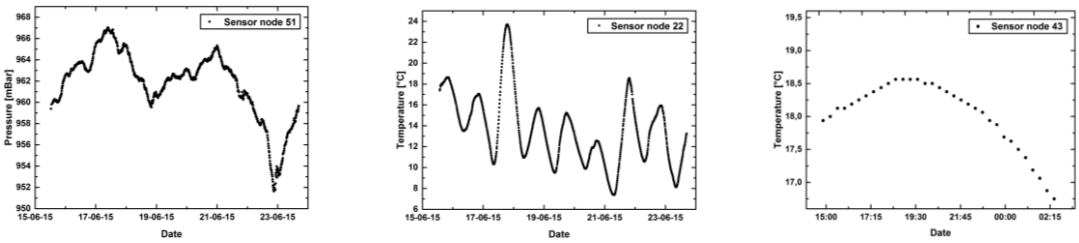
(a) (b)

Figure 9: Wake-up network topology (a) and communication network topology (b)

RESULTS

The WSN was installed in June 2015 at the Neckar Valley Bridge Weitingen as introduced in the previous Section. Node-31 and node-51 were sending via a single hop link to the base station, and the others nodes were

linked via a multi-hop connection to the base station. The distance between nodes-42 and -43 was around 125 meters, which is a remarkable distance since the wake-up range in free space is only around 50 m. In our first assumption, this large wake-up range is probably due to the hollow box girder of the bridge that acts in this case as a waveguide for radio signals. The base station successfully transmitted the sensor data to the server in Freiburg at least for a period of one week and still continues to send data during writing of this article, as can be seen in Figure 10 (a) and (b) which show air pressure measured at node-51 and temperature measured at node-22, respectively. Figure 10 (c) shows the temperature readings of node-43 for a period of around 12 hours. After that the sensor stopped sending of data probably due to problems that occurred during a write cycle on the SD-Card.



(a) (b) (c)

Figure 10: Pressure measured at node-51 (a), temperature at node-22 (b) and temperature at node-43 (c)

In this first test run, the GNSS receiver was configured to log at a frequency of 0.1 Hz for a period of 30 minutes every 6 hours. During the time the GNSS receiver node was logging it received 1847 observations, 40 navigation, 44 Glonas navigation and 32 Ionospheric correction messages in total. Figure 11 shows the skyplot of the receiver where it received data from 9 satellites. The GNSS data was visualized with RTKNAVI version 2.4.2

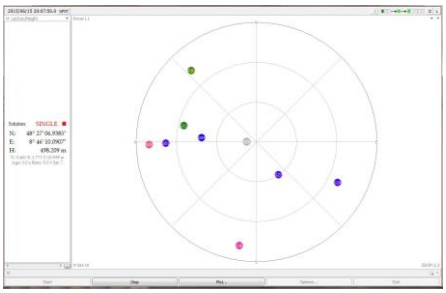


Figure 11: Skyplot from the GNSS data of node-52 visualized with RTKNAVI 2.4.2

CONCLUSIONS

In this article, we introduce low power wireless sensor nodes with integrated wake-up transceiver. Due to their powerful microprocessor the nodes are very flexible and can be equipped with different kinds of sensors for structural health monitoring. In combination with wake-up receivers, the nodes achieve very low power consumption and support different features, such as asynchronous measurements, distribution of important detections with low latency, or pulling of data from the network at any time. Further on, we introduce a routing protocol that supports wake-up receivers and combines them with the advantages of long-range communication radios. A prototype sensor network consisting of several sensor nodes, a base station and a remote server has been installed and tested at the Neckar Valley Bridge Weitingen south-west Germany in June 2015. A Global Navigation Satellite System (GNSS) receiver node was introduced and tested in combination with the wake-up WSN which utilizes the wake-up multi-hop routing protocol as introduced in this work. The setup was running for at least 10 days and is still sending data during time of writing of this article. A base station continuously transmits sensor data to a remote server at the University of Freiburg. To optimize the resolution and the dynamical behaviour of the GNSS data analysis, enhance the network will be further enhanced by additional GNSS receiver nodes in the near future. To improve the overall performance of the network, its long-term stability will be improved by using smart software routines that are able to cope with broken hardware components. In addition we will focus and the development of a dynamic routing protocol to enable easy integration of nodes into an existing network and on the development of a database on the server to analyse and visualize the data.

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