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Wireless Sensor Network with Temperature Compensated Measuring Technology for Long-Term Structural Health Monitoring of Buildings and Infrastructures

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Abstract

Damage to buildings occurs if a construction component fails. The result is a partial or total collapse which can be dangerous for people for example if it's a bridge or a large hall. The collapse of the terminal building at the Airport Charles de Gaulle in Paris and the damage at the historic City Archives of Cologne are typical examples of such accidents. Another problem is the contradiction of the increasing volume of traffic (particularly heavy traffic) and the great age of bridges. The probability increases that the load-bearing capacity of a bridge decreases. For example the collapses of the Mississippi Bridge and of the Inntal Motorway Bridge can be seen as results. Therefore it is necessary to control endangered structures during their life span.

In order to prevent these kinds of accidents, the Federal Institute for Materials Research and Testing developed a radio-based, self-configuring measuring system in cooperation with the ScatterWeb Company, Berlin (Germany). This measuring system consists of identically designed sensor modules which are self-sustaining, wireless, act as transmitters and receivers and are equipped with a special sensor technology for long-term monitoring of buildings or engineering facilities. The sensor unit uses strain gauges for stress analysis and contains interfaces for additional sensors. The system in particular applies to buildings and structures for transport and traffic and large-scale industrial facilities, where a subsequent wiring installation is difficult or impossible.

"Keywords: Multi-Hop WSN; SHM; Temperature and Frequency Compensation;"

1. Introduction and Motivation

Environmental conditions influence the behavior of measurement systems. In particular the electronic components are affected by the temperature and the relative humidity. Particularly in the field of structural health monitoring the influence of temperature and relative humidity to the applied external strain gauge sensor can be significant. In addition to the influence on the measuring system, the multihop

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radio network can be affected in its radio frequency. The radio frequency can be changed by a change in temperature, resulting in instabilities of the wireless network and particularly effecting the multihop characteristics.

2. System Concept

The BAM-ScatterWeb System consists of network nodes, which provide data transmission and receiver at the same time. Each node combines the radio and the measuring unit [1, 2]. Via wireless communication the nodes build up a self-configuration network using the license-free ISM Band at 868 MHz. An adequate radio range has to be realized to monitor large objects those which are difficult to access. The multihop architecture (Figure 1) enables the data transmission from the measuring point to data acquisition unit in multiple steps from node to node, no direct (single hop or point to point) transmission is necessary. Through that the range is maximized and network stability is provided, which allows integration and replacement of single nodes without disturbing the operation of the system.

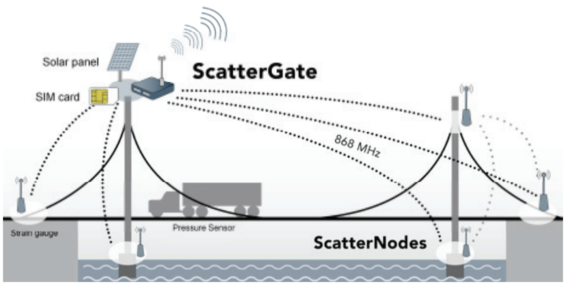


Fig. 1. Application example illustrating the multihop radio based network.

A wireless system for long-term monitoring using strain gauges requires an energy-efficient circuit design. The presented system is based on an innovative concept of combining radio communication and strain gauge sensors. An alternative measuring method is used based on a Time-to-Digital Converter (Figure 2, 2) instead of the standard Wheatsone Bridge (Figure 2, 1). According to this alternative measuring method, highly accurate strain measurements are possible by reducing the energy demand to a minimum.

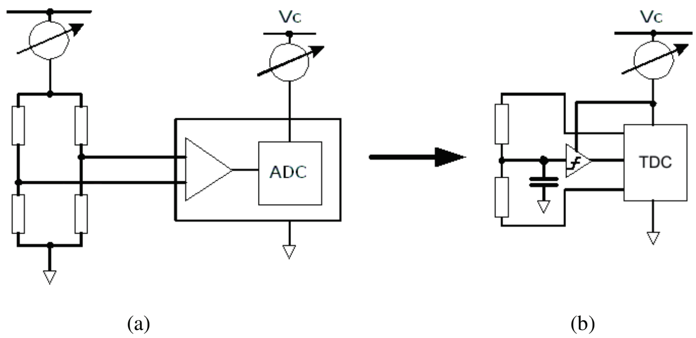
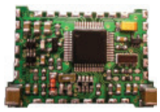


Fig. 2. (a) Scheme of the conventional measurement circuit, Wheatstone bridge, and
(b) the developed alternative low energy measurement circuit, Time to Digital - Converter.

The implementation of the measurement method has been accomplished on the module shown in Figure 3. The measurement module is manufactured in SMT design and can be electronically cascaded.

Besides very low energy consumption, the developed module has a high temperature stability and a good measuring accuracy over the measurement range of ±32000 µm/m.

Four measurement modules are integrated in the outdoor device (Figure 3). The model layout is designed for outdoor use under weathering and consists of protection class IP66. It is validated for operating conditions in the range between -30 and +80°C. Two configurations are possible: 8 strain gauges half bridges and 4 temperature sensors or 6 strain gauge half bridges (equals 2 rosettes) and 2 thermo-hydro sensors (for data compensation at each rosette). The connection for the strain gauges or other sensors is implemented via four IP66 plug-and-screw couplings. Standard D-cell batteries allow a service-free operation of more than 200 days, with measurements every minute and a permanent bi-directional communication to the network.



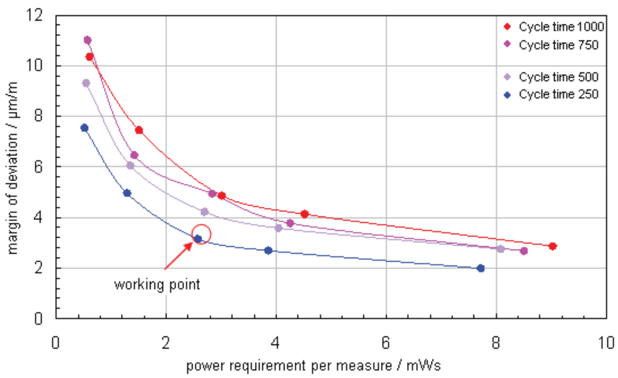
(a)

(b)

Fig. 3. (a) implemented measurement module (SMT) with a dimension of 30 mm (W) - 20 mm (D) - 4.2 mm (H), and (b) the outdoor device with four SMT modules

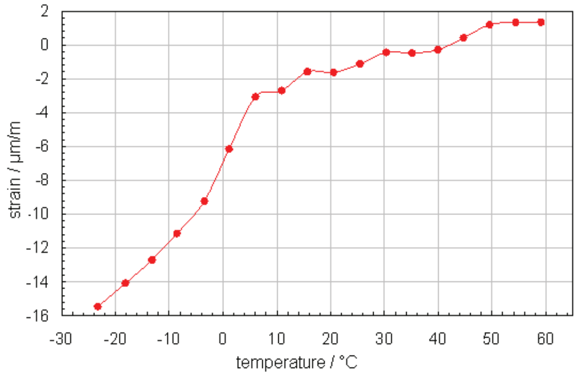
3. Implementation and Compensation

High measurement accuracy and reliability should be ensured by parameterization of the developed electronics e.g. via the configuration of the measurement frequency. The system supports measuring frequencies up to 50 kHz, but also low frequency measurements every 24 hours with high accuracy (deviation < 3µm/m) are possible. To optimize the battery runtime the energy consumption was minimized. The variation of the measurement accuracy against the energy requirement results in an optimum working point. Diagram 1 displays the maximum measurement error for the required energy depending on the setting of the measuring chip (cycle time). Due to these investigations the working point for the measurement system was established.



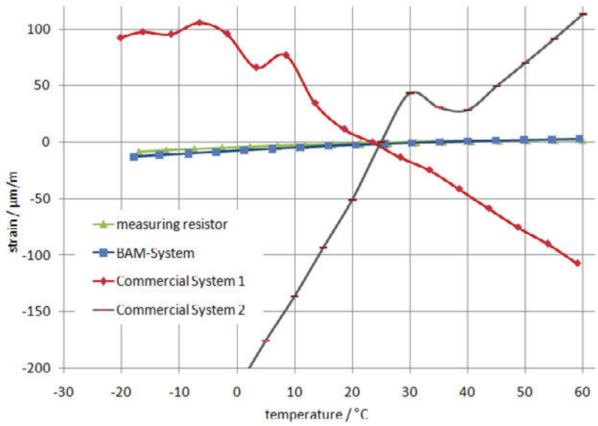
Diag. 1. The chart illustrates the variability of the measured values to the required energy per measurement and the establishment of the working point for the measuring system.

Adverse environmental conditions make the use of a robust measurement technique necessary. The developed measurement techniques allow the compensation of the temperature at the measuring point and in the measurement module. The result is a temperature-dependent error of less than 0.2 (µm/m)/K, as shown in Diagram 2.



Diag. 2. The diagram shows the temperature-dependent drift of the developed measurement technique

Temperature tests were compared with other wireless sensor modules and all modules were provided with the same temperature-stable resistors (Vishay, VSMP0805, 350 Ω, 0.01 %, ±0.2 ppm/°C). The tests were conducted in climate chambers in a temperature range from -20 to 60 °C, while the temperature experiments were repeated four times. The results of the various modules are shown in Diagram 3.



Diag. 3. The chart illustrates the absolute temperature-dependent drift of the tested measurement systems

To test the practicability of the developed system, long-term experiments were conducted. Some modules were placed on the rooftop with direct sunlight and others inside the building. In these experiments the local differences of temperature were more than 40 K. As a result some differences in temperature-dependent drift could be observed between the involved modules. But of higher relevance are the errors in data transmission. These transmission errors are caused by temperature differences and additional errors were induced by the interference from humidity, rain or snow on the modules, see Figure 4.

Fig. 4. Long term test of the developed instrument, under harsh conditions with over 10 cm of snow.

Origin of the transmission errors was a deliberate shift of the transmission and receiving frequency of the radio chip (CC1020). A solution of this problem is implemented by an automated shift of the radio frequency for each receiving package. This is done by reading the automatic frequency control AFC register automatically and converting the result into a frequency shift [3], see Prog. 1. The frequency shift occurs only to the children nodes in the network, while the gateway is the fixed frequency point.

```
afc = ReadFromCC1020Register(CC1020_AFC);                  // read the automatic frequency control value from CC1020

freqAfcRxbuf.bytes.b1 = 0;                                  // read the receiving frequency from CC1020
freqAfcRxbuf.bytes.b2 = ReadFromCC1020Register(0x04);
...
freqAfcTxbuf.bytes.b4 = ReadFromCC1020Register(0x0A);       // read the transmission frequency from CC1020

if(afc & 0x80) {                                            // test of negative AFC
        drift -= (-(afc) * 2);                              // calculate the new frequency drift
        freqAfcRxbuf.l1 += drift;                           // modify the actual frequency value
        freqAfcTxbuf.l1 += drift;
  }
  else {
        drift+= (afc * 2);
        freqAfcRxbuf.l1 += drift;
        freqAfcTxbuf.l1 += drift;
  }

  WriteToCC1020Register(0x04, freqAfcRxbuf.bytes.b2);       // write the receiving frequency in the CC1020
  ...
  WriteToCC1020Register(0x0A, freqAfcTxbuf.bytes.b4);       // write the transmission frequency in the CC1020
```

Prog. 1. Calculation of the frequency drift using the automatic frequency control value

4. Conclusion

The system characteristics including temperature compensation and radio frequency drift adjustment enable the system perfectly for SHM applications. The result is a stable-working multi-hop SHM system, which is energy efficient and long-term stable. For these aspects the developed system shows better results than the compared systems available on the market.

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