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Low Power Wireless Sensor Network for Building Monitoring

[1] K.Uma Rani, [2] N.Sai Akhila, [3] T.Jayanthi
M.Tech(ECE), Assistant Professor, DVR College of Engineering and Technology, Medak,Telangana.
M.Tech(ECE), Assistant Professor, DVR College of Engineering and Technology, Medak,Telangana.
M.Tech(ECE), Assistant Professor, DVR College of Engineering and Technology, Medak,Telangana.

Abstract:
A wireless sensor network is proposed for moni-toring buildings to assess earthquake damage. The sensor nodes use custom-developed capacitive micro electro mechanical systems strain and 3-D acceleration sensors and a low power readout application-specified integrated circuit for a battery life of up to 12 years. The strain sensors are mounted at the base of the building to measure the settlement and plastic hinge activation of the building after an earthquake. They measure periodically or on-demand from the base station. The accelerometers are mounted at every floor of the building to measure the seismic response of the building during an earthquake. They record during an earthquake event using a combination of the local acceleration data and remote triggering from the base station based on the acceleration data from multiple sensors across the building. A low power network architecture was implemented over an 802.15.4 MAC in the 900-MHz band. A custom patch antenna was designed in this frequency band to obtain robust links in real-world conditions. The modules have been validated in a full-scale laboratory setup with simulated earthquakes.
Keywords: **Microelectromechanical systems (MEMS), remote monitoring, structural health monitoring, wireless sensor networks.**

I. INTRODUCTION

Buildings can progressively accumulate damage dur-ing their operational lifetime, due to seismic events, unforeseen foundation settlement, material aging, design error, etc. Periodic monitoring of the structure for such damage is therefore a key step in rationally planning the maintenance needed to guarantee an adequate level of safety and service-ability. However, in order for the installation of a permanently installed sensing system in buildings to be economically viable [1], the sensor modules must be wireless to reduce installation costs, must operate with a low power consumption to reduce servicing costs of replacing batteries, and use low cost sensors that can be mass produced such as MEMS sensors. The capability of MEMS and wireless networking for monitoring civil structures is well documented [2]–[4]. The presented work addresses all of the above requirements.

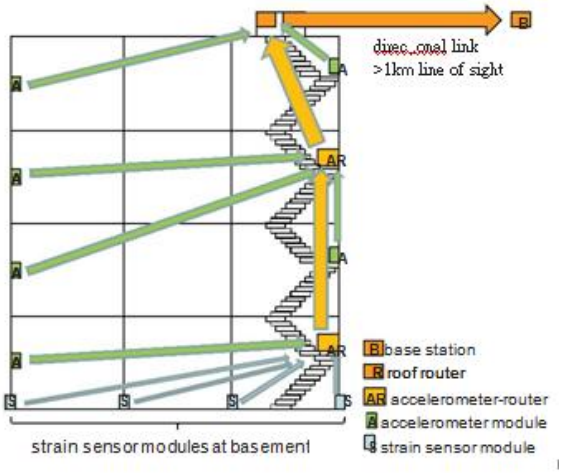

Fig. 1. Network architecture of the monitoring system in a building.

II.SYSTEM ARCHITECTURE

A. Network Architecture

The monitoring system consists of two types of sensor modules: strain sensing modules and acceleration sensing modules. They are placed in the building as shown in Fig. 1. The strain sensor modules are mounted at the lowest level of the building to estimate the vertical column loads and to measure the settlement and plastic hinge activation of the building after an earthquake. Horizontal acceleration is measured by two 3D acceleration sensing modules (where only the two horizontal axes are really required) at each level during an earthquake, allowing analysis of the seismic response of the whole structure. A typical 7-story, 24-column building requires approx. 72 strain sensors (3 per column) and 14 accelerometer modules (2 per floor).

The data obtained by the sensor system is wirelessly transmitted to a nearby base station using a line of sight link with a range of > 1 km. The line of sight link uses directional antennas to improve the link budget, but not so directional that alignment is required, which could pose a problem during seismic events. The receiver base station can store and process the data or forward them, immediately or later, using classical wide area network connection technology. In this way, provided all modules as well as the receiver base station have battery back-up power, the data acquired during seismic events can be properly recorded even in case of outages of the electric power and/or communication networks.

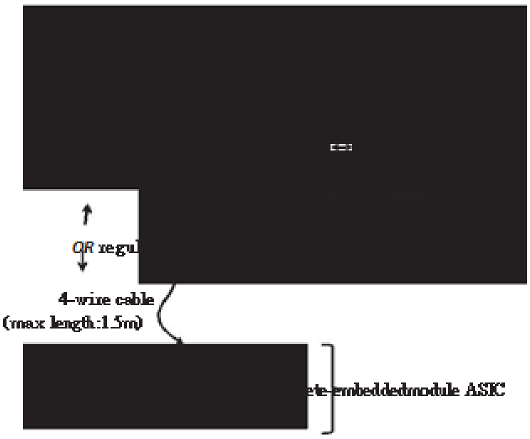

Fig. 2. Block diagram of a sensor module.

Fig. 3. Packaged accelerometer module with indication of axes.

In order to form a robust wireless link from all mod-ules, including the strain sensor modules at the basement of the building, towards the receiver base station, a multi-hop network architecture is used as shown in Fig. 1. On the roof of the building a dedicated router module (without sensor) is placed to forward the data between the sensor network and the receiver base station. Some accelerometer modules on intermediate floors can be configured as additional intermediate routers when required to obtain a robust link from all sensor modules in the building towards the roof router module. As shown on Fig. 1, it is recommended to place the router modules in or close to the stairwell for improved vertical floor-to-floor propagation through the building.

For lowest power consumption in the sensor modules, the network is implemented using indirect data transfer using polling on top of a standard 802.15.4 MAC. In this way, the end nodes' radio is powered down most of the time. Only the routers and base station have their receivers constantly on. To avoid rapid battery depletion, the modules with router functionality are mains-powered through an AC/DC adapter, with the battery serving only for back-up power in case mains power is interrupted. The end nodes (i.e. the large majority of installed sensor modules) are powered exclusively by their battery.

B. MEMS Sensors

The MEMS accelerometer consists of 2 transverse comb finger structures for the X and Y axis and a pendulating one for the Z axis and was fabricated with a surface micro-machined process from a 85 μm thick SOI wafer. It has 78 fingers with a total sensitivity of 2.02 pF/g. The Z sensor has an area of 2.17 mm^2 per plate. Innovative cap through connections were used. The main tradeoff in the design of the accelerom-eter is the sensitivity-bandwidth-linearity in all three axes, a challenge for the design given the different used structures. The XY and Z accelerometers are packaged together with the readout ASIC into a system-in-a-package and then mounted onto the printed circuit board as can be seen on Fig. 3.

The MEMS strain sensor is a longitudinal comb finger capacitor. The strain sensor fabrication procedure starts with a SOI wafer with a 500 μm thick handle, 50 μm thick fingers and 2 μm thick oxide layer with 400 fingers in the sensor and it has a sensitivity of 0.133 fF/$\mu\varepsilon$. Two anchors were etched-out of the surface to create the necessary clamps to attach the sensor to the rebar of a pillar. The fingers are protected with a borosilicate class cap.

The use of custom-developed MEMS sensors and read-out ASIC allows to meet the specific requirements of the building monitoring application and differentiates the presented system from the earlier prototype system presented in [6] and [7].

C. Sensor Module Architecture

The block diagram of the sensor modules is shown in Fig. 2. Both the accelerometer and strain sensing variants of the module use the same core components. For installation into the building these components are placed into a standard off-the-shelf plastic casing (see Fig. 3) that can be conveniently mounted on the floor, wall or ceiling using screws, and offering access for sporadic battery replacement if needed. The core components are:

A custom-developed low power capacitive sensor read-out ASIC [5]. This ASIC can be matched to either MEMS-based comb finger capacitive accelerometers or strain sensors in a half-bridge configuration. Its gain can be set by a number of integration pulses N, opti-mizing signal-to-noise ratio and bandwidth with power. In addition, the architecture suppresses residual motion artifacts. In combination with the MEMS strain sensor, it can measure a range of ±20 000 $\mu\varepsilon$ with a resolution of 10 $\mu\varepsilon$ and non-linearity <0.6%. In combination with the MEMS accelerometer it can measure an acceleration range of ±2.5 g with a resolution of 80 dB (13-bit) for vibrations between 10–100 Hz and a non-linearity <1%.

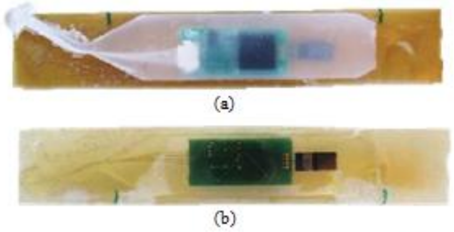

Fig. 4. Strain sensor front-end module on polyimide carrier. (a) Top view. (b) Bottom view.

2) A low power 16-bit successive-approximation analog-to-digital converter (Analog Devices AD7683).

3) A low power microcontroller (TI MSP430) to control the sensor data acquisition and temporarily store the data in a 64 K × 16 bit SRAM memory (Cypress CY62126).

4) A low power wireless IEEE 802.15.4-compatible mod-ule (Atmel ATZB-900) operating in the 900 MHz band. This frequency band was chosen in preference to the more common 2.4 GHz band because it offers a larger propagation range for the wireless commu-nication. The wireless module includes a radio chip (Atmel AT86RF212) and a baseband microcontroller (Atmel AVR) which needs to be active only during wire-less communication events. The radio communication capability throughout the building has been successfully shown using these radio modules using the prototypes from [6] and [7].

5) A custom patch antenna was designed for the modules. The patch antenna is tuned for 868 MHz operation with

an efficiency of 51% using standard FR4 material as the substrate. Its size is 5 × 5 × 1.3 cm^3. Its shape and radiation pattern is optimized for wall-, floor- and ceiling-mounting in the building.

6) The modules are powered by a an 8.5Ah C-cell long operating life primary Lithium Thionyl Chloride battery (Tadiran SL-2770), suitable for 10 to 25 years of oper-ation.

D.Strain Sensing Front-End Module

The MEMS strain sensor is packaged together with the readout ASIC into a special front-end strain sensing module (Fig. 4) which is embedded inside the reinforced concrete onto the reinforcing bar, preferably prior to the pouring of the concrete. As shown in Fig. 5, the sensor is mounted on a polyimide carrier which in turn is glued onto the reinforcing bar. A variant of this package exists in which the carrier is thin steel, which offers the additional possibility for welding the carrier to the reinforcing bar. The module is molded in PDMS silicone to protect the components from the environment during installation and pouring of concrete, while remaining a mechanically compliant package to avoid distorting the strain sensor measurement. This front-end strain sensing module is connected to the rest of the module through a small 4-wire cable with a maximum length of 1.5 m.

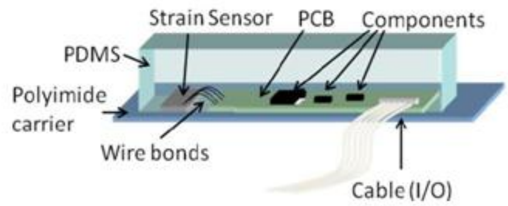

Fig. 5. Drawing of strain sensor front-end module indicating the components.

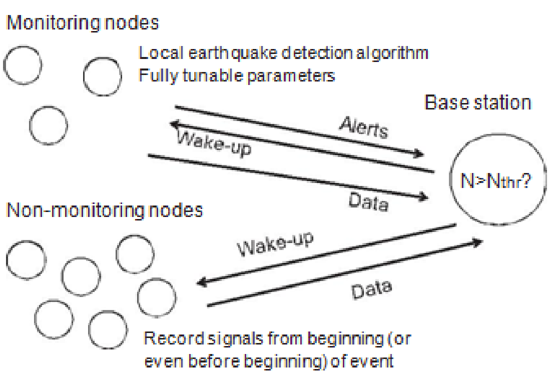

Fig. 6. Diagram of distributed earthquake wake-up procedure.

E. Measurement Initiation

1) Accelerometer Modules: The main trigger for the record-ing of an acceleration measurement is the detection of the start of an earthquake. The detection is done using a distributed earthquake detection mechanism as shown in Fig. 6. When the output of the built-in accelerometer in a selected number of monitoring nodes exceeds a certain minimum threshold, during a certain minimum time, these monitoring nodes provide alerts to the base station. The base station software will decide based on the number of monitoring nodes providing alerts whether to wake up the entire network of acceleration sensing nodes over the radio The monitoring nodes are selected based on their location and amount of environmental noise. Ground-level nodes may be suitable candidates, provided they are sufficiently far removed from disturbance sources such as heavy traffic. The selection of monitoring nodes can be done dynamically from the base station. This allows for example to disable the monitoring function on nodes that report unusually high numbers of false alarms. To that purpose, the hardware and software of the monitoring nodes are identical to that of the non-monitoring nodes. The monitoring function is an optional function which can be enabled or disabled during operation by the base station. After the nodes have been woken up the recorded data is read out by the base station which sequentially requests the data of each sensor module.

The parameters for this wake-up mechanism can be fully configured from the base station and wirelessly updated at

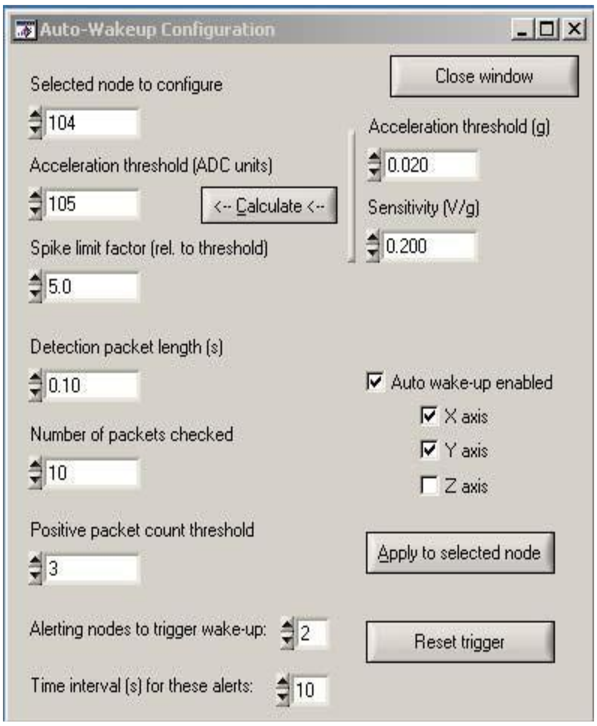

Fig. 7. User interface showing per-node tunable parameters of the earthquake wake-up procedure

any time. Fig. 7 shows the user interface with the parameters that can be configured individually for each node as well as the global wake-up threshold settings.

To support this scenario, the wake-up of (most of) the acceleration sensing nodes to initiate measurement has to be done over the radio link. This also implies that it is possible to wake up the nodes via the base station over the radio link at any chosen time independent of the presence of an earthquake, which is a desired functionality for testability and monitoring of the system. It also means that all modules in the network will be woken up during a detected event, even if the accelerations locally at some modules have not (yet) reached a value exceeding the trigger threshold.

It is required to be able to record the early onset of an earthquake event, even before and certainly no later than 1 ms after it reaches a pre-set trigger threshold. In order to do this, the accelerometer is constantly running at 3 × 200 Hz sample rate with the measurements recorded in a 54-second loop buffer. This requires an ultra low power sensor and readout. The power consumption of the 3D accelerometer and 3-channel readout operating continuously is 125 μA at 3 V.

The node must be woken up within 54 seconds after the start of the recording of interest to avoid the loop buffer overflowing which would lead to data loss. To respond timely to an event triggered from the base station, the radio polling interval of the accelerometer modules is set to 15 seconds. This allows the event trigger to propagate sufficiently fast to the entire network to ensure the loop buffer contents containing the data for the event are preserved for all nodes. Once a node's loop buffer is full, recording will continue in a secondary 54-second buffer until the next event trigger. After an event, the data

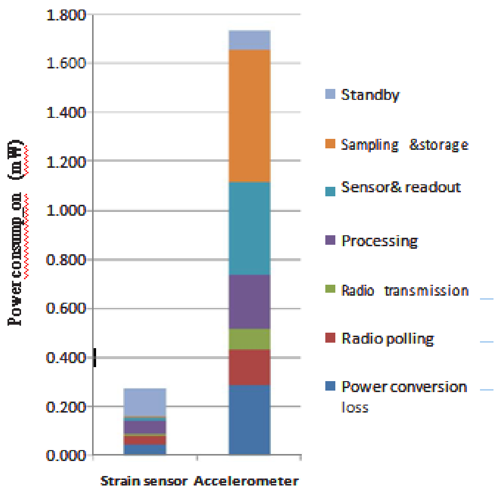

Fig. 8. Sensor module power consumption results.

must be wirelessly read out from each node to the base station one by one, a process which may take several minutes for multiple nodes. If a new event is detected before all the data of the first event is read out, the new event cannot be recorded since it would cause the loss of the data of the first event-a choice which could hypothetically be made from the base station if the relative importance of the second event were to outweigh that of the first event. In practice, the time interval between actual events is expected to be sufficiently large that this limitation is not a problem for the application.

2) Strain Sensor Modules: The main measurement scenario for the strain sensor is a periodic readout. Samples are taken at a configurable sample rate between 10 seconds and 18 hours. The strain sensor modules use a radio polling interval of 60 seconds. This also allows manual wake-up functionality from the base station, again useful for monitoring and testa-bility reasons. Unlike for the accelerometers, in the case of the strain sensors the sensor and read-out ASIC can be entirely shut down between measurements. This results in a lower power consumption and longer battery life. Since a typical building requires many more strain sensors than accelerometer modules, it is useful for the strain sensors to have the longest battery service life.

III. RESULTS

A. Power Consumption

Fig. 8 shows the measured power consumption in the sensor modules for strain sensor and accelerometer modules and how it is broken down according to the different components of the system. The total average power consumption is 0.274 mW for the strain sensor modules and 1.73 mW for the accelerometer modules. With the abovementioned C-cell size battery this implies a battery life of 12 years for the strain sensor modules and 2years for the accelerometer modules.

B. Laboratory validation

Because it is not feasible to create controllable earth quake like conditions in an action building, the validation of the modules is done in the laboratory on a full scale reinforced concrete frame, reproducing a subcomponent of the building.

During the laboratory tests, actuators apply to the frame the loads transmitted by the rest of buildings as well as simulated earthquake conditions based on previously recorded signals from real earthquakes[8].

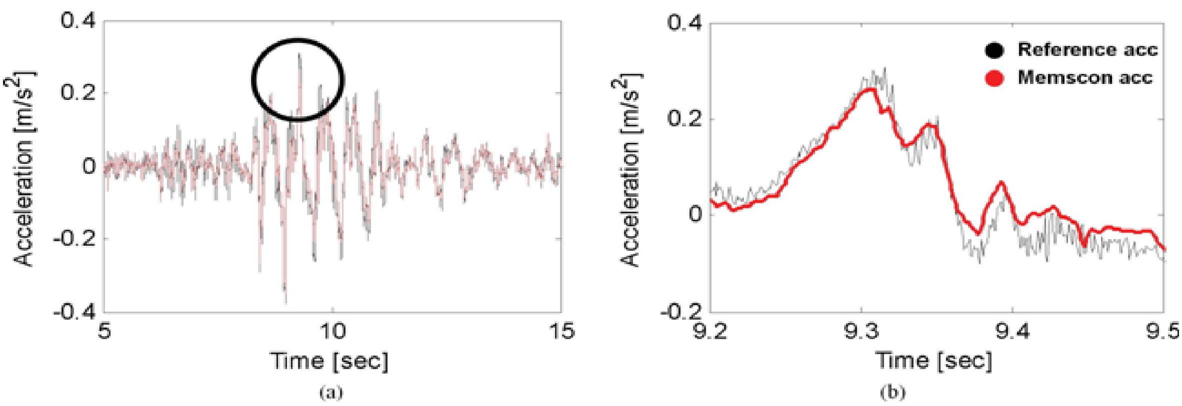

Fig. 9. (a) Wireless sensor module acceleration signal output (lowpass-filtered for noise reduction) on full-scale model with simulated earthquake and comparison to reference accelerometer (traditional piezoelectric uniaxial-wired accelerometer). (b) Enlargement of the peak of the signal.

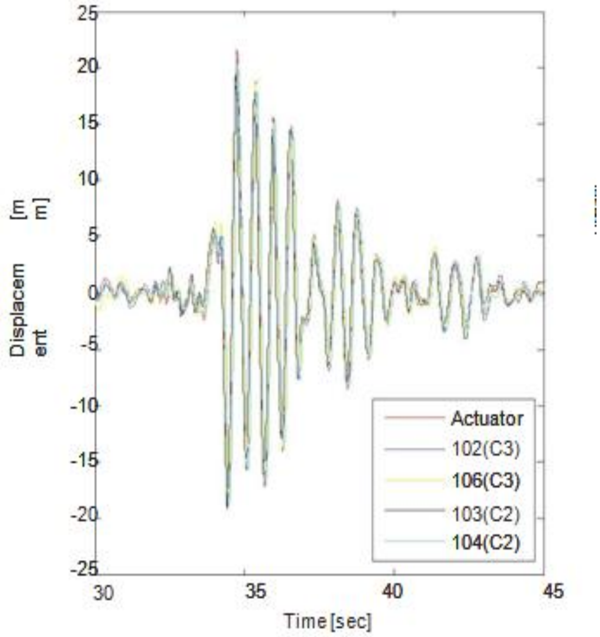

Fig. 10. Calculated displacements (by double integration) from wireless sensor module acceleration output on full-scale model and comparison to the actual applied displacement from the actuator providing the simulated earthquake.

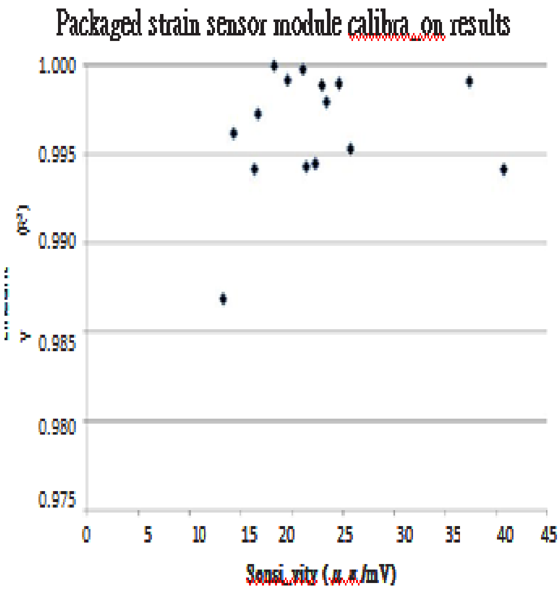

Fig. 11. Calibration results on strain sensor front-end modules.

Fig.9 shows an example result of the laboratory validation of the accelerometer on the full-scale building during a simulated earthquake compared to the output traditional wired piezoelectric uniaxial accerelometer(PCB 393C) used as reference.

Compared to the reference signal the signal from the wireless accelerometer modules is smoother due to the lowpass filtering post-processing 25Hz that has been performed in the data acquisition software in this case as required by the building monitoring application. Otherwise the signals correlate well. of the acceleration signals to the actual displacement applied from the actuator. As can be seen in fig.10, the calculated displacements from the measurements of the wireless acceleration sensor modules correspond very well to the actual displacement.

However, the most interesting result for the monitoring application is the comparison of the calculated displacement through double integration The strain sensor front-end modules have been validated in the laboratory in a specially constructed calibration setup in which a known strain is applied to the module and its output is recorded. The resulting sensitivity and linearity parameters are shown in fig 11. All sensors are highly linear, but there is a significant spread in the sensitivity, which means that individual calibration of each sensor is required.

IV. Conclusion

The presented wireless system for building monitoring takes advantage of the unique features of custom-developed MEMS sensors and read-out ASIC combined with an opti-mized network and module architecture, to realize a solution which offers long battery lifetime and potentially low cost in manufacturing, installation and maintenance, while providing high-quality sensor data at the right time.

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Miss. K Uma Rani is presently working as an Assistant Professor of Electronics and Communication Engineering in DVR Engineering College Hyderabad, India has done M.Tech from JNTU Hyderabad.

Mrs. T Jayanthi is presently working as an Assistant Professor of Electronics and Communication Engineering in DVR Engineering College Hyderabad, India has done M.Tech from JNTU Hyderabad

Miss. N. Sai Akhila is presently working as an Assistant Professor of Electronics and Communication Engineering in DVR Engineering College Hyderabad, India has done M.Tech from JNTU Hyderabad