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Design and Layout of an Energy Autarkic Wireless Sensor Network in Underground Metro Tunnels

Scott Kempf[1], Niklas Schnelle[1], Jonah Vincke[1], Prof. Dr. Frank Schäfer[1]
[1] Fraunhofer Institute for High-Speed Dynamics, Ernst-Mach-Institut, EMI, Freiburg, Germany,
scott.kempf@emi.fraunhofer.de

Abstract

The transition to a society increasingly reliant on underground mass transportation in the 21st century has led to heightened demands on safety and security of its passengers concerning terror attacks and natural disasters. The Fraunhofer Ernst-Mach-Institut, in coordination with several partners in India and Germany, is developing an integrated security management and emergency response system. The system is based on energy self-sufficient wireless sensor networks for the communication of security relevant sensing information reliably to the central management system.

In this paper, the system requirements, layout and operating modes are described. Based on these, an energy consumption assessment was compiled and the requirements for the energy harvesting sub-system were defined.

Key words: wireless sensor networks, critical event monitoring, energy harvesting, underground public transportation, civil security

Introduction

The intensification in global urbanization and the resultant migration to underground mass transportation infrastructure have given rise to new and significant security-related social challenges. Recent terror attacks [Madrid, 2004; London, 2005; Moscow, 2010; Minsk, 2011; Brussels, 2016], natural disasters [Prague, 2002; New York, 2012] and other fatal accidents demonstrate the vulnerabilities of such underground mass transportation infrastructure.

The bi-national and multi-disciplinary security research project SenSE4Metro [1] attempts to address these vulnerabilities through, among other approaches, the development of a robust and comprehensive wireless sensor network (WSN)-based tunnel monitoring system. Initial threat analyses and scenario definitions have provided the necessary inputs for defining the requirements concerning sensor data, network layout and operation, and interface definitions.

In order to provide an independent, reliable and retro-fittable system, the WSN must be energy independent. The proposed system employs vibration- and wind-powered energy harvesting solutions. This paper describes the initial layout and related energy requirements of the two node types based on proposed WSN operation modes and the subsequent requirements for the energy harvesting sub-systems.

State-of-the-Art

This work focuses on the overall energy balance for a specific WSN application, which spans several distinct WSN components (energy harvesting, RF communication, critical event monitoring, tunnel application, low-power sensors, etc.). Because the specific configuration constitutes a novel application, the literature research focuses on a variety of these individual aspects.

For instance, there is a significant collection of works regarding WSN application in tunnels. Most applications are aimed at structural health monitoring (SHM) in railway/metro tunnels, either during construction [2] or over the tunnel lifetime [3]. Some approaches apply to continued operation (non-railway applications), such as closed-loop applications [4] or personnel monitoring [5]. These and similar works are interesting when considering RF limitations and routing protocols in tunnels, however, they primarily consider a periodic communications scheme and battery driven energy supply and therefore do not consider the same constraints posed by the application herein.

More applicable for the consideration of the communication scheme are critical event monitoring applications. Most schemes found are based on flexible routing possibilities. The method presented, for instance, in [6] provides increased efficiency through improved sleep scheduling, whereas [7] presents an assessment, including energy consumption, of various routing protocols.

Regarding energy harvesting, several papers address tunnel-based wind harvesting and track-based vibration harvesting.

There are several surveys which address vibration energy harvesting for generic applications using the piezoelectric effect [8], [9], or more recently, the electromagnetic effect [10]. In these cases, in some part due to the limitations in sizing, the frequency regimes described are often limited to below a few hundred hertz.

[11] specifically addresses piezoelectric harvesting of track vibrations in underground rail applications. While the results demonstrate a feasibility with regard to the magnitude of harvesting, it is unclear whether the solution presented would be sufficient for the energy demands of a practical application in a real-world environment. [11] and [12] respectively provide analyses of rail vibration profiles in underground and above ground railway settings.

Wind harvesting in tunnels has also been assessed as a means of energy harvesting. [13] describes both the air flow profile and the application of wind energy harvesting for the supply of an SHM application in a metro environment. Reviews, such as [14], are also available for a more general look at wind energy harvesting by various principles.

The sensor system layout was described in an earlier published work by Vincke et al. [15], and therefore, related work on this aspect will be omitted for brevity.

System Requirements

The requirements for the system under discussion were defined based on the performance of a terroristic threat analysis of past attacks and events in metro, tunnel and rail-based infrastructure using the EMI-developed Terroristic Event Database (TED) [1], as well as feedback from first responders.

The primary requirements were derived from the resultant scenario definitions and include:

- the definition of measured environmental effects/variables:
    - water ingress via water depth (mm),
    - fire outbreak via smoke (presence over threshold ppm/ppb) and temperature (°C), and
    - explosions via peak pressure (MPa) and impulse (Pa·s);
- the recognition of train passage events/the localization of trains in tunnels;
- the definition of a spatial sensing resolution (e.g. 100 m);
- the definition of the power source (energy harvesting);
- the definition of the method of communication (wireless); and
- the implementation and layout of user interfaces for the different stakeholders (first responders, operators and passengers).

System Layout and Proposed Operational Modes

Based on these requirements, SMERS was designed using two types of sensor nodes working in tandem: ground-level sensing nodes (water ingress detection), and a wall-/ceiling-level sensing nodes (fire and explosion detection). The two node sets should be powered by rail vibration and airflow, respectively. Figure 1 demonstrates the sensor layout and radio transmission segments.

It was recognized early on that the potential to provide sufficient energy via rail vibration harvesting could present a significant bottleneck for the system in design. Therefore, two modes of operation are proposed: one in which both node chains forward messages to the sink nodes, and one in which the lower

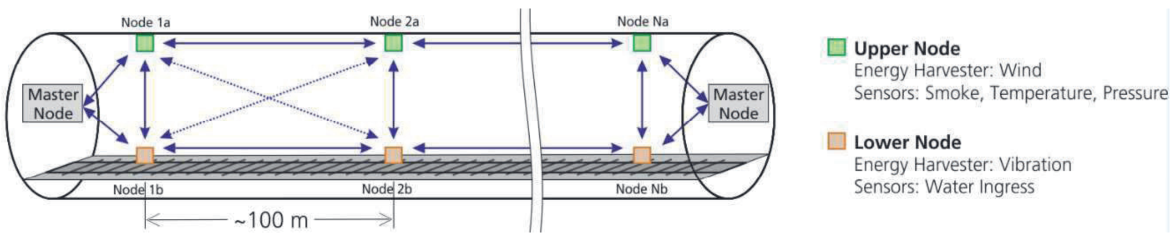

Fig. 1. SMERS sensor node placement concept with potential radio communication segments [15].

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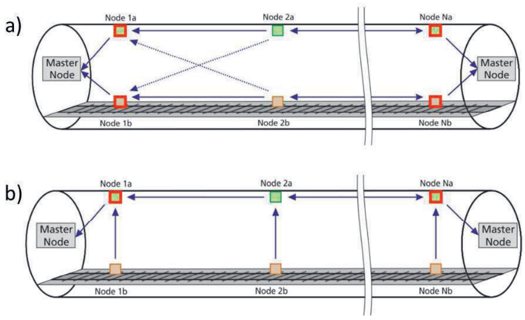

Fig. 2. Message forwarding modes parallel forwarding (a) and with lower nodes in tx-only (b). The respective energy critical nodes are highlighted. Modified from [15].

nodes, during normal (non-event) operation, function as transmission only nodes, thereby reducing or eliminating reception energy costs. Figure 2 demonstrates the two possible message forwarding schemes. By altering the channel check rate of the upper nodes, the amount of energy shifted from the lower to the upper nodes, as well as the communication latency, can be customized based on application environment. The relevance of the energy critical nodes will be discussed later in this paper.

The design of the system for energy sustainability is only necessary during normal operation. While the system should be able to run indefinitely (neglecting component deterioration), the energy storage system will include enough stored energy to power the system in an unsustainable way (continued sensor activation and increased resolution, switching on passenger feedback systems, such as LED lighting, etc.) for an extended period of time during disaster events. For this case, transmission only nodes are also fitted with reception circuits, but the channel check rate is kept extremely low.

WSN-Node Design

Technically, the wireless sensor nodes are designed as three distinct subsystems: communications, sensing and energy harvesting. These subsystems are implemented as separate electronics boards with a standardized interface in order to be individually exchangeable based on application requirements. The microcontroller is located on the communication board but also controls the other subsystems. Figure 3 shows the radio (with adapter board) – which is currently comprised of the Texas Instruments' SimpleLink CC2650 Evaluation Module Kit (CC2650EMK) [16] with adapter – and sensing subsystems.

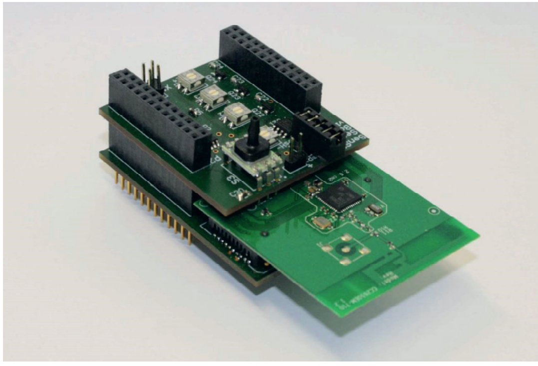

Fig. 3. Demonstration board including sensor board (upper) and communications board (lower: CC2640EMK + adapter).

As a radio protocol, the IEEE 802.15.4 standard in 2.4 GHz ISM-Band was chosen as the physical layer. On top of it, a protocol from the Rime protocol family of the Contiki project is applied. In contrast to, for instance, 6LoWPAN, this dispenses with implementing the entire internet protocol (IP) stack and instead provides alternative custom lightweight networking protocols design specifically for low-power WSNs. Specifically the Collect protocol has been extended to provide increased forwarding-chain lengths and lower energy demands.

It is necessary for the WSN-nodes to remain in sleep mode as long as possible in order to reduce the overall energy consumption. For this reason, transmission messages are only created during train passage events during normal operation. As there is no wake-up reception circuit available on the commercial board, reception wake up is accomplished by performing periodic channel checks. The successful transmission of a message to a sleeping reception node requires the continued

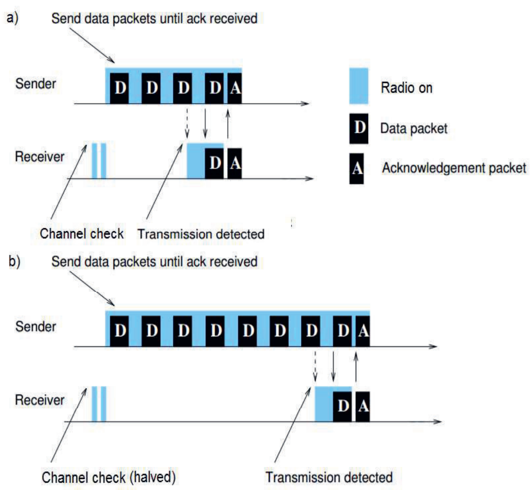

Fig. 4. Contiki broadcast and channel checking protocol with reference and halved channel checking rates, modified from [17].

transmission of the message until a receiving node checks the transmission channel. By decreasing the channel check rate, the average energy for a listening device can be reduced (overall time in sleep mode is increased). The trade-off of this is higher transmission costs (worst-case transmission costs are based on duration between channel checks) and higher transmission latency. Figure 4 demonstrates transmission loads based on two different channel check rates.

Energy Balance Calculation

The energy chain is comprised of generation, storage and consumption. The communication and sensing subsystems belong to the consumption component, whereby the energy harvesting subsystem provides both generation and storage.

Consumption

As described above, the energy consumption is divided between the sensor subsystem and the communications subsystem.

The sensing subsystem was developed using ultra-low-power (ULP) components. The smoke, temperature and water ingress sensors achieve ULP by remaining predominantly in sleep, or inactive, mode. Based on the individual requirements, they are switched on every several seconds to perform measurements. The ultra-sound (explosion) detector operates passively until a peak pressure threshold is exceeded, whereby the circuit is switched on for higher resolution (pressure and time) measurements. The system is described in more detail in [15]. The average consumptions based on the defined measurement duty cycles during normal operation are approximately 13 µW for upper nodes and 36 µW for lower nodes.

The analysis of the communications subsystem consumption is based on the analytical synthesis of experimentally measured values. Because metro systems differ in terms of train periods, lengths, etc., certain assumptions regarding the application case were made:

- Network length: 20 nodes (2 km);
- Train passage period: 5 min; and
- Message transmission duration: 10 ms.

As described before, during normal operation, transmissions are only created during train passage events.

Using a 4 Hz channel check rate for reception, measurements were made to characterize the communications consumption.

Tab. 1: Measured consumption variables for the communications subsystem (assumptions: 4 Hz channel check rate, 10 ms reception duration, worst-case transmission duration).

Mode	Consumption		
	Power (P)	Duration	Energy per Transmission (E)
Sleep	6.5 µW	-	-
Listening	149.5 µW	-	-
Rx	22.340 mW	10 ms	220 µJ
Tx	19.077 mW	250 ms	4.77 mJ

The listening consumption power and the worst-case transmission duration can be modified by increasing the channel check rate.

For forwarding messages, it is assumed that the load is evenly distributed in both directions to the end sinks. This means that the end nodes (immediately next to the sink nodes) are presented with the greatest loads (energy critical node). For this reason, the consumption calculation is performed based on these nodes.

The average consumption during normal operation can be ascertained from the conditions and assumptions described above. Equations (1), (2) and (3) define the average consumptions based on task, whereby P = power, E = energy (E_{rx} = 220 µJ, E_{tx} = 4.77 mJ), T = period (T_{train} = 5 min or 300 s) and $N_{forward}$ = number of forwards/transmission (within a period).

$$P_{base} = \begin{cases} P_{listening}, & tx/rx\ nodes \\ P_{sleep}, & tx-only\ nodes \end{cases} \quad (1)$$

$$P_{rx} = \frac{N_{forward} \cdot E_{rx}}{T_{train}} \quad (2)$$

$$P_{tx} = \frac{(N_{forward} + 1) \cdot E_{tx}}{T_{train}} \quad (3)$$

Using the initial parallel message forwarding scheme presented in Figure 2, the energy critical nodes will have to receive in each case 9 messages (upper and lower) and transmit 10 (9 + 1 self-initiated) per train passage period (assumed: 5 minutes). Using the modified messaging forwarding scheme, energy critical upper nodes will now be burdened with forwarding 19 messages (9 upper nodes and 10 lower nodes) and transmitting one self-initiated. In this case, there is no energy critical lower node, as all lower nodes have the same constraints, namely transmitting one self-initiated message per period.

Table 2 demonstrates the calculated energy requirements based on the conditions described above.

Table 2: Average communications consumption based on the two message forwarding schemes and conditions described in text (assumption: 5 minute train passage interval).

Consumption Component	Scheme (a)	Scheme (b) upper	Scheme (b) lower
P_{base} / µW	149.5	149.5	6.5
P_{rx} / µW	6.7	14.1	-
P_{tx} / µW	159.0	318.0	15.9
P_{total} / µW	**315.2**	**481.6**	**22.4**

The initial measurements were performed using a very low channel check rate. Increasing the channel check rate increases the listening component of the total power consumption, but lowers the worst-case transmission costs (duration and energy per transmission). Doubling the channel check rate almost doubles ($P_{listening}$ = 6.5 µW + 35.75 µW/Hz) the listening power, while halving the transmission power required. Figure 5 demonstrates the average power consumption as a function of the channel check rate for the proposed network.

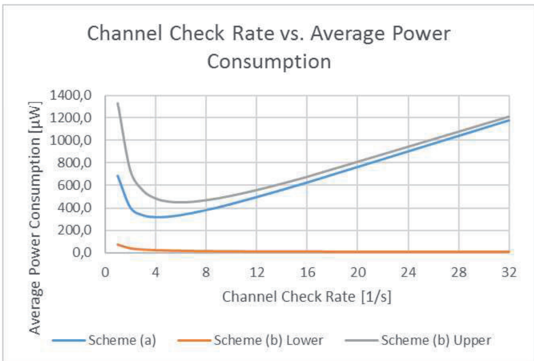

Fig. 5. Average power consumption as a function of channel check rate for both schemes.

Of course, latency is also improved by increasing the channel check rate.

Storage

The energy storage subsystem serves to supply both long-term energy storage for periodic consumption during non-generation periods, as well as short-term energy storage for peak consumption requirements (typically transmission/reception).

In the application described, periodic consumption (in this case between train passes) is covered by the system dimensioning for prolonged non-sustainable operation following event detection (higher sensor polling rate, activation of LED activation for passenger information).

Peak consumption requirements are covered by capacitors integrated into the radio circuit.

In this case, the energy storage itself can be neglected in the power balance. Charging efficiencies shall be considered based on harvester generation characteristics.

Generation

Based on the requirements listed above, the power is supplied by an energy harvesting subsystem. The system has been conceptualized using separate harvesting mechanisms for the upper and lower nodes and is currently in development.

The energy source selected for the upper nodes is the sustained airflow within underground metro tunnels. Between the constant low-pressure ambient draft and the high-pressure train passage events, there should be sufficient airflow for a properly laid out wind generator.

The supply for the lower nodes is more critical, which instigated the design of the second message-forwarding scheme mentioned earlier. The energy-harvesting scheme has been conceptualized as vibration energy harvester using a piezoelectric cantilever design.

The assessment of the other sub-systems has been used to define the requirement for such harvester designs. Assuming a 4 Hz channel check rate and 10 second train passages at 5 minute intervals, the 328 (upper) and 351 (lower) µW average requirements correspond conservatively (assuming no harvesting during inactive period) to 9.8 mW and 10.8 mW during train passage events. For the second scheme, this corresponds to 15 mW for upper nodes and 1.8 mW for lower nodes. Previous projects [11], [14], [18] with similar aims have demonstrated that such yields are feasible.

Conclusions

A critical event monitoring system has been designed and is being developed for the monitoring of underground metro tunnels based on the results of potential threat analyses. The system is based on three component WSN-nodes, which are powered through energy harvesting and rely on ULP sensor and communications technology.

An energy consumption assessment using experimental measurements and an analytical synthesis based on two different communication forwarding schemes has been described. The energy consumption assessment provides the inputs required for the design and layout of two energy harvesting subsystems for this environment, which based on literature research, appear to be feasible.

The next step is the development and documentation of these energy harvesting subsystems, which will be performed within the next months in the framework of the same project.

Acknowledgements

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