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ZigBee Sensor Network Platform for Health Monitoring of Rails Using Ambient Noise Correlation

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Abstract: WSNs (wireless sensor networks) can be used for railway infrastructure inspection and vehicle health monitoring. SHM (structural health monitoring) systems have a great potential to improve regular operation, security and maintenance routine of structures with estimating the state of its health and detecting the changes that affect its performance. This is vital for the development, upgrading, and expansion of railway networks. The work presented in this paper aims at the possible use of acoustic sensors coupled with ZigBee modules for health monitoring of rails. The detection principle is based on acoustic noise correlation techniques. Experiments have been performed in a rail sample to confirm the validity of acoustic noise correlation techniques in the rail. A wireless communication platform prototype based on the ZigBee/IEEE 802.15.4 technology has been implemented and deployed on a rail sample. Once the signals from the structure are collected, sensor data are transmitted through a ZigBee solution to the processing unit.

Key words: Wireless sensor networks, ZigBee, IEEE 802.15.4, acoustic noise correlation, signal processing, passive Green's function reconstruction, NDT (non-destructive testing), rail monitoring.

1. Introduction

Transportation is an activity that involves significant risks due to the displacement speed of the moving parts (vehicles, cabins, etc.) and materials used in this context are exposed to severe operating conditions leading to premature wear, deformations, and failures. This obviously requires serious and costly maintenance strategies.

Until recently, in the railway industry, technicians walk along the rail tracks to detect any defects or missing component [1, 2]. Automated vision systems have been developed to eliminate or minimize the visual inspections by humans, but still detection is limited to visible anomalies. Other technologies for finer local inspection and detection of early damage were developed including: eddy current [3] and fiber optic sensors [4, 5]. Emission-reception of ultrasound waves is also well-known method in the railway industry [6-10]. Though efficient, these methods ordinarily require planning interventions depending on traffic. This can lead to disruption of rail services and even periodic shutdown, meaning significant costs for railway companies. Other important aspects are implicated: reliability and security. Indeed, it is possible that unforeseen technical problems appear between two planed inspections with, at the least, enormously costly and possibly dramatic consequences.

For these reasons, the concept of intelligent infrastructure [11, 12], with, in particular, continuous monitoring capabilities is currently receiving growing interest. One of the key issues for the intelligent infrastructure concept is the use of WSNs (wireless sensor networks). WSNs [13] are wireless networks of spatially distributed and autonomous devices. They use sensors to cooperatively monitor infrastructure, structures, and machinery. WSNs and data analytics allow the railways to turn data into intelligence. They provide decision support through continuous real-time data capture and analysis to identify defects [14]. WSN monitoring provides continuous, near real time and

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autonomous data acquisition, increased frequency of monitoring compared with manual inspection; improved data accessibility, data management, and data use compared with non-networked systems as all data can be collected and processed centrally. They also permit combination of data from a wide variety of sensors and turning them into information about the status of important structures, vehicles and infrastructure.

The objective of this work is to study the feasibility of wireless network based on IEEE 802.15.4/ZigBee technology for the transmission of sensor data. Experiments are performed on a rail sample to validate the possibility of using the noise correlation technique for rail health monitoring is presented. The ability of extracting information from noise correlation is an undeniable advantage for the WSN conception. The advantage of such technique is using only passive sensors. Thus, necessary hardware is limited and consumption of the wireless monitoring system could be lower.

First, the proposed WSN architecture and network topology for rail health monitoring is described. Then, the experiment demonstrating the ZigBee transmission of sensor data to the base station is presented. The study of the propagation characteristics to predict the propagation law that rules attenuation of the signal in the train environment along with the multipath characteristics is performed and the communication range of the ZigBee technology in these conditions is determined. In Section III, a study about the passive detection method is described.

2. ZigBee WSN for Rail Monitoring

Several communication techniques are used in WSNs in railways [15, 16]. Inter-sensor communications and sensor to base station transmission are usually short range. The base station transmits gathered data back to the control center, and this requires long-range communication. WSNs can use technologies based on standard mobile telephony (Bluetooth, GSM, GPRS, and UMTS) or broadband techniques such as Wi-Fi, WPANs (Wireless Personal Area Networks) (IEEE 802.15.4 and ZigBee [17]) or WiMax [18]. The system proposed in this study investigates the ability of using ZigBee/IEEE802.15.4 technology for the communication between the sensors and the base station.

2.1 Sensor Nodes Design

An overview of the sensor types used in railway health monitoring systems and the measurements produced is provided in Ref. [19]. Sensor devices are mounted on boards. The board forms a platform combining mobile computing, wireless communication, and routing with sensor devices. Typical sensor node architecture is outlined in Fig. 1.

The sensor board generally comprises one or more sensors, a microcontroller, RF transceiver, data storage (memory), and a power source. The board can also comprise a localization device and/or energy harvesting system. Multiple sensor boards for WSNs are available [20].

In this study, XBee S2B RF modules [21] are used for the radio communication. These modules work at 2.4 GHz free ISM (Industrial, Scientific and Medical) band with a maximum radiated power of 18 dBm. Our sensor nodes are based on Arduino due microcontroller board. This board contains an Atmel SAM3X8E ARM Cortex-M3 CPU. To connect the RF module to the

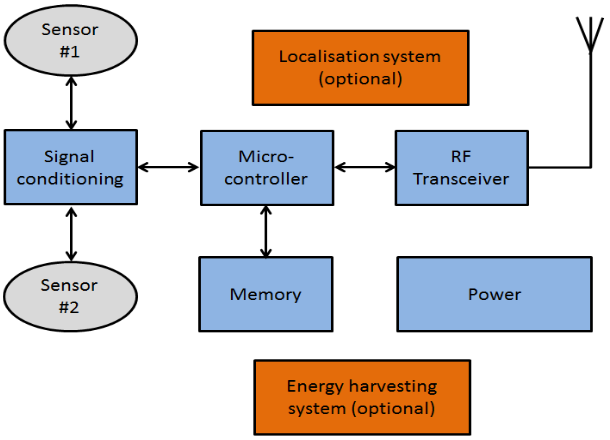

Fig. 1 Sensor node architecture example.

Arduino due board, an RF shield was designed (see Fig. 2). The transmitter is configured with Coordinator XBP24BZ7 firmware in API mode.

2.2 Communication Medium: IEEE 802.15.4/ZigBee

The standard, IEEE 802.15.4, defines the PHY (PHYsical layer) and MAC (Medium Access Control) sublayer specifications for low data rate wireless connectivity with fixed, portable and moving devices with no battery or very limited battery consumption requirements typically for WPANs in the operating space of 300 m. IEEE 802.15.4 specifies two PHYs: an 868/915 MHz DSSS (direct sequence spread spectrum) PHY and 2450 MHZ DSSS PHY.

The 868/915 MHz PHY supports over-the-air data rates of 20 kb/s and 40 kb/s, and 2,450 MHz PHY supports an over-the-air data rate of 250 kb/s. The characteristic of DSSS allows the use of low-cost digital IC realizations. The PHY chosen depends on local regulations and user preference. A total of 27 channels, numbered 0 to 26, are available across the three frequency bands. Sixteen channels are available in the 2,450 MHz band, 10 in the 915 MHz band, and 1 in the 868 MHz band. Two different device types are designed in IEEE 802.15.4; FFD (full-function device) and RFD (reduced function device). The FFD can operate in three modes serving as a PAN (Personal Area Network) coordinator, a coordinator or a device. An FFD can communicate with RFDs or other FFDs, while an RFD can only communicate with an FFD. In the ZigBee standard three topologies are defined: Star, Mesh, and Tree topology. These are shown in Fig. 3.

2.3 ZigBee WSN System for Rail Monitoring: Feasibility Study on a Rail Sample

The measurement system used in the laboratory for this study consists of a 2 m-length rail sample, which represents the structure to be monitored. Five circle PZ27-piezoelectric transducers of 27 mm-radius and 0.43 mm-thickness, one used as a transmitter placed at a position A and the others as receivers placed at positions B, C, D, and E respectively. The transducers have been glued on the rail foot using glue allowing mechanical impedance adaptation. The signal acquisition is performed by a ZigBee wireless network. Signals received by the transducers are conditioned and then transferred to the wireless nodes. The base station is connected to a computer. The wireless nodes communicate the sampled signals to the base station. The data received by the base station are sent to the computer via USB link for saving. The post processing of the recorded data is achieved with Matlab® software (see Fig. 4).

In this experiment, the response to an active short duration excitation is measured and transmitted to the base station using ZigBee technology. To conduct this experiment, the measurement methodology is as follows: at first, the transmitter at A is excited by an electric signal. The excitation signal consists of one cycle sine pulse train at a central frequency 50 KHz, amplitude 10 V. The signals received at the points B, C, D, E and F are conditioned (filtered, amplified), sampled

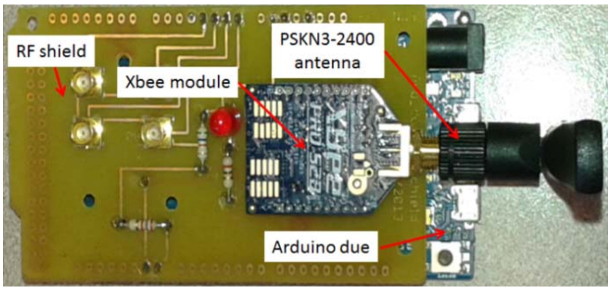

Fig. 2 Picture of the sensor node used in this study.

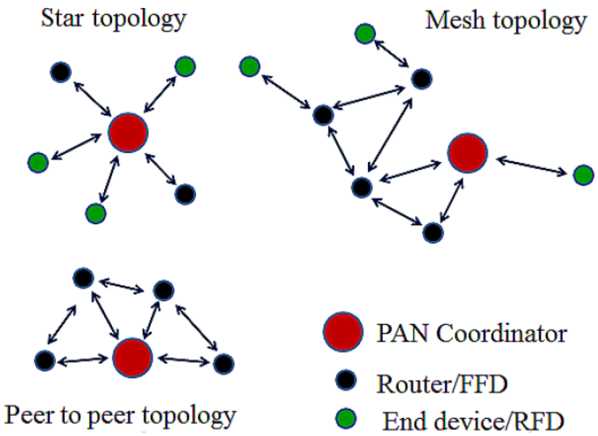

Fig. 3 ZigBee network topologies.

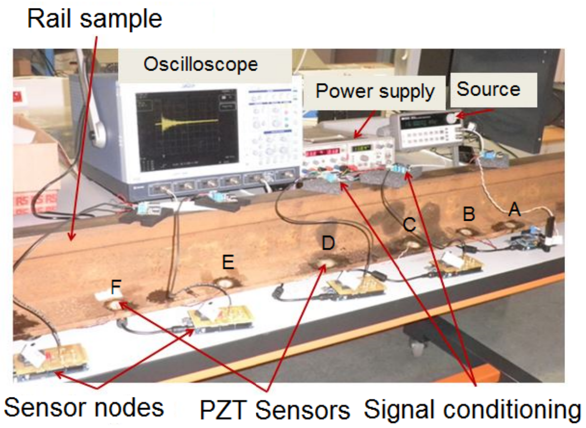

Fig. 4 ZigBee-based sensor network for rail monitoring.

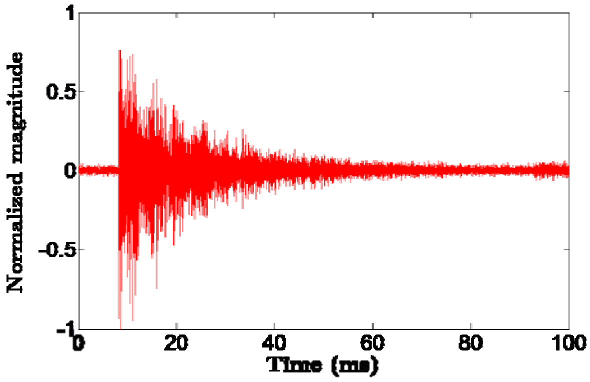

Fig. 5 Typical signal received at the point B.

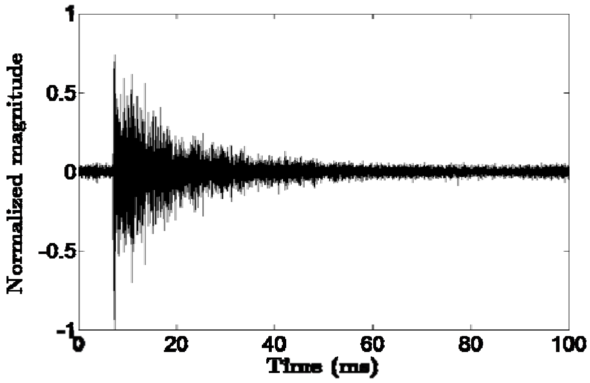

Fig. 6 Signal received by the base station from the sensor B.

and quantified at the node boards, and then sent to the base station via the ZigBee network. Fig. 5 shows a typical signal received at point B.

Sensor data are transmitted to the base station successfully. Example of sensor data is shown in Fig. 5. An example of wirelessly transmitted data is presented in Fig. 6. It is clear that these waveforms are similar. This experience demonstrates the ability of collecting data sensors using low cost, low consumption and flexible WSN.

2.4 ZigBee/IEEE 802.15.4 Communication Range

In our previous work a study and characterization of the IEEE 802.15.4 channel running at 2.4 GHz inside buildings is achieved [22].

In this work, in order to evaluate the communication technology in real conditions (train environment), analysis of the signal propagation in these conditions is required. This study is necessary to predict the propagation law that rules attenuation of the signal in the railway environment along with the multipath characteristics and to know the communication range of the system. Experiments to estimate the received power function of the distance between the transmitter and the receiver are performed in a rail track environment. Along the rail line the receiver (Sensor node) has been separated from the transmitter. The measures are realized every 1 m up to distance of 30 m from the transmitter. Then, 5 m up to distance of 40 m from the transmitter. Finally, 10 m up to distance of 76 m from the transmitter. This experiment is shown in Fig. 7.

In ideal propagation conditions and considering a clear LOS (line-of-sight) path between the transmitter

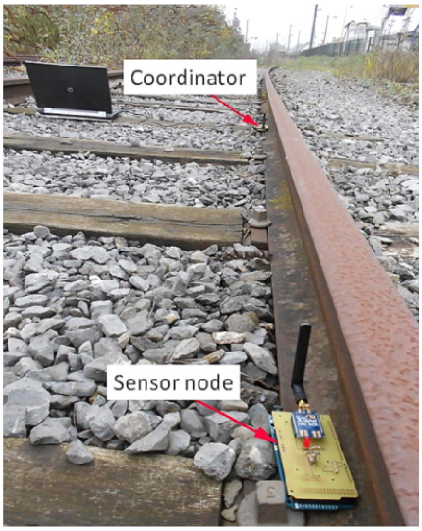

Fig. 7 Picture of the received power measurement in a railway environment.

and the receiver, the received power is predicted by the Friis Equation [23] as

$$P_r(d) = P_t G_t G_r \frac{\lambda^2}{(4\pi)^2 d^2} \tag{1}$$

where P_r is the received signal power, P_t the transmittedpower, G_t and G_r are the transmitting and receiving antenna gains respectively. λ is the wave length.

In reality, the received power at certain distance is a random variable due to multipath propagation effects. The Log-normal and shadowing model [24] is a generic model and an extension to the Friis free space model. It is used to estimate the average path loss over a wide panel of environments. The average received power in (dBm) is given by Eq. (2):

$$\overline{P}_r(\mathrm{dBm}) = P_t(\mathrm{dBm}) - \overline{P}_L(d_0) - 10n\log\left(\frac{d}{d_0}\right) - X_\sigma \tag{2}$$

where, $\overline{P}_r$ is the average predicted power, $\overline{P}_L(d_0)$ is the measured path loss at reference distance d_0, n is called the path loss exponent, and is usually empirically determined by field measurement, X is a Gaussian random variable with zero mean and standard deviation σ. σ is called the shadowing deviation, and also obtained by measurement.

Fig. 8 shows the received power as function of distance between the receiver and the transmitter. Measured values obtained from the rail track scenario are compared to the log-normal and shadowing model (Log-dist) that predicts the received power by Eq. (2). The received power predicted by the log-normal and shadowing equation is closer to the measured values. In fact, the log-normal and shadowing model appears accurate to predict the signal propagation characteristics in the considered conditions. It takes into account fluctuations of signal due to reflections and multipath effects. Fluctuations are noted in the measured values. This is because the rail track includes rails which induce reflections and multi path propagations. The communication range between two sensor nodes is approximately equal to 76 m.

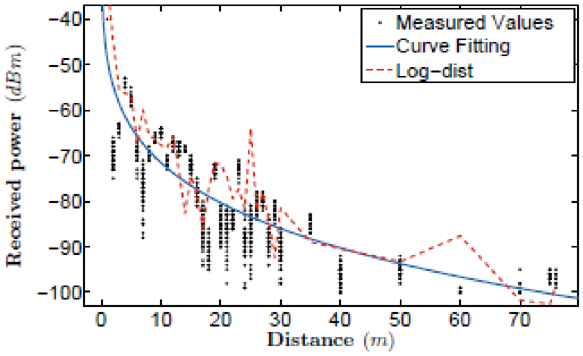

Fig. 8 Comparison between the measured RSSI and the theoretical predicted power function of distance between the transmitter and the receiver.

3. Passive Detection Method

In this section, we focus on the noise correlation techniques applied to the received signals for passive detection of a defect in the rail sample. The principle of these techniques is the reconstruction of active responses by correlation of random noise propagated in the medium. In railway applications, wheel-rail interaction could constitute a source of such noise. The possibility of extracting the active responses from noise correlation is an undeniable advantage for the WSN conception. This method does not need to employ any electronics for the acoustic emission, thus, necessary hardware is limited. Indeed, non-intrusiveness and low consumption are key issues for effective conception of the wireless SHM (structural health monitoring) system.

Theoretical and experimental studies in several areas [25-28], have shown that the active acoustic signal between two measurement points can be passively estimated from the time derivative of the correlation function of the signal recorded at those points.

An experimental result about the effective reconstruction of the active response from the cross-correlation function of noise fields is shown here. The experiments are performed on a 2 m-long rail sample.

Two PZ27-piezoelectric transducers of 27 mm radius and 0.43 mm thickness have been glued on the rail foot at positions A and B. A function generator is used to generate the excitation signal at transducer A and the signal received at transducer B is acquired using an oscilloscope synchronized with the function generator and linked to a computer through a GPIB interface (Fig. 9a).

The transmitter (A) is excited with an electric signal $s_0(t)$ corresponding to a one-cycle sine pulse train at 50 kHz and with an amplitude of 10 V. The measured signals are averaged over 128 acquisitions in order to improve the SNR (signal to noise ratio). Fig. 10 shows a signal measured in this manner. It is a typical reverberated signal consisting of the direct propagation from A to B and a large number of multiple reflexions, scattering, mode conversions on the domain boundaries (edges of the rail) and possible inho-mogeneities. After 80 ms, this signal is completely attenuated.

For the noise-correlation experiment, the function generator is removed and both transducers A and B are used as receivers. In order to generate acoustic noise in the rail, ten piezo electric transducers of the same type and similarly glued on the rail foot at positions S_i are successively fed by an electrical noise generator (Fig. 9b).

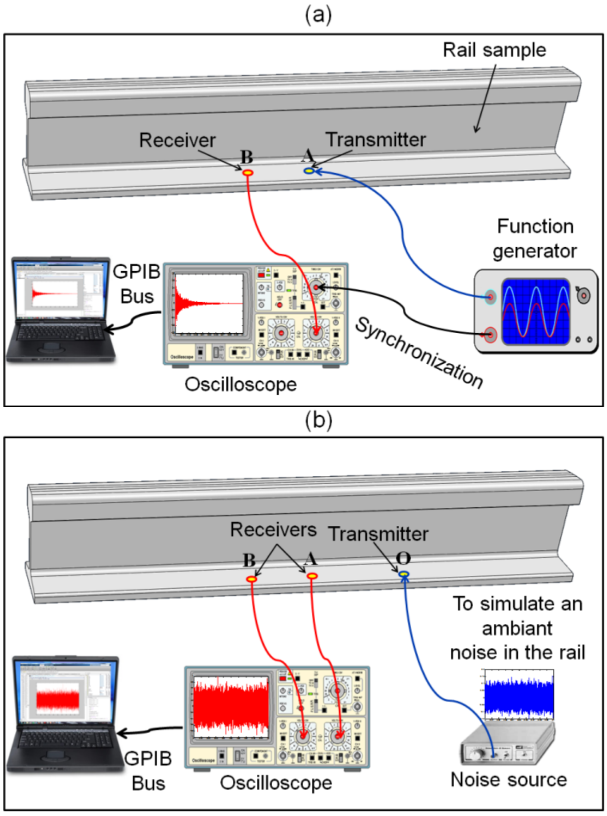

Fig. 9 Experimental setup: (a) active experiment, and (b) noise-correlation experiment.

The noise correlation function R_{AB} is experimentally estimated from finite-time correlations averaged over a number M of acquisitions for each noise source. The results obtained for every source are then summed, which yields the following correlation estimator:

$$\tilde{R}_{AB}(t) = \frac{1}{M}\sum_{n=1}^{N}\sum_{m=1}^{M}\int_0^T s_A^{(m,n)}(\tau)s_B^{(m,n)}(t+\tau)d\tau \qquad (3)$$

where T is the recorded signal duration and $s_X^{(m,n)}(t)$ is the signal recorded at X in the m^{th} acquisition of the

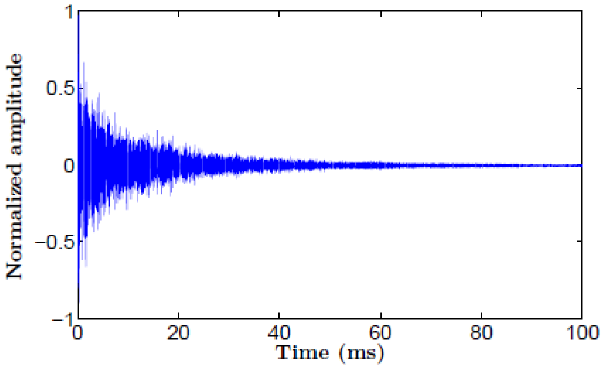

Fig. 10 Typical response measured by the receiver at *B* when transducer *A* is excited by a one-cycle pulse train at 50 kHz.

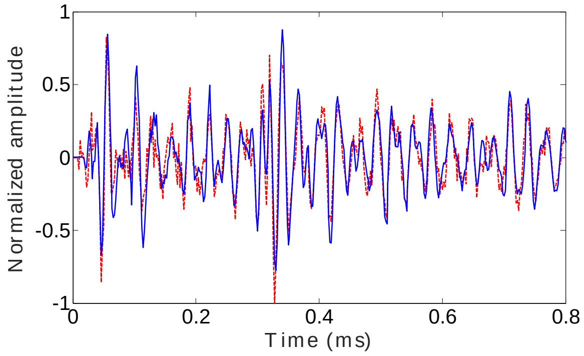

Fig. 11 Comparison between the measured active response $s_{AB}(t)$ (____) and $\frac{d\tilde{R}_{AB}(t)}{dt}$ (----) obtained from the estimated noise-correlation following Eq. (3) for N = 10 noise sources, and M = 10 acquisitions for each source.

measurements performed when the $\mathrm{n^{th}}$ noise source $\mathrm{S_n}$ is active.

In Fig. 11, the time-derivative of $\widetilde{\mathrm{R}}_{\mathrm{AB}}(\mathrm{t})$ obtained with the 10 noise sources is compared to the active response $\mathrm{s_{AB}(t)}$. The presented waveforms have been normalized with respect to their maximum values. Wave packets appear correctly reconstructed. Very good estimation (or "reconstruction") of the active response is noted.

4. Conclusions

The main challenge of wireless SHM systems in railway applications is determining the best measurement technologies to use. The SHM system must be reliable, accurate to enable effective and continuous monitoring in harsh and inaccessible environments and must be cost effective.

In this context, this paper has presented a feasibility study of application of wireless sensor network based on IEEE 802.15.4/ZigBee communication technology for the data collection from sensors to the base station. This technology is proposed to avoid the cumbersome and high cost of conventional wired systems. ZigBee network of 5 nodes is developed and sensor data transmission is demonstrated. The working of such network in real conditions, in this case, railway environment is tested and the transmission range between two neighboring nodes is estimated to 76 m.

Then, for the defect detection, preliminary study about an original technique based on passive reconstruction of the impulse response between two points of the medium is described. It is shown that a good quality of active response reconstruction from noise field correlation is achieved with sufficient number of acquisitions and the number of distributed noise sources.

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