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Efficient Compressed Sensing-Driven Wireless Multi-Hop Seismic Data Transmission Network

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Abstract: In recent years, the advancement of cableless seismic data acquisition devices, particularly nodal seismographs, has revolutionized seismic exploration. However, traditional "blind acquisition" methods face significant limitations, including the inability to enable real-time monitoring, challenges in ensuring data transmission stability, and the inefficiency of device retrieval in large-scale exploration projects. To address these issues, this paper proposes an Efficient Com-pressed Sensing-Driven Wireless Multi-Hop Seismic Data Transmission Network (WMDTN), which inte-grates a hierarchical wireless multi-hop network (HWMN) and compressed sensing (CS) technology to optimize data transmission and reduce the volume of seismic data. The network architecture comprises a core network based on LTE for long-range communication and a multi-hop network utilizing Wi-Fi for short-range, high-density data transmission. The system employs advanced hardware components, including high-resolution ADCs, FPGA-based controllers, and dual-frequency GPS modules, to ensure precise data acquisition and synchronization. Furthermore, the pro-posed CS-based transmission method significantly enhances channel capacity by compressing seismic data while maintaining signal integrity, as evidenced by a 14 dB SNR at a 32% compression ratio. Experimental results demonstrate the network's robustness, with an average transmission rate of 1.161 MB/s in the core network and 0.459 MB/s in multi-hop networks, mak-ing it highly suitable for large-scale, real-time seismic exploration applications.

Keywords: Wireless Multi-Hop Seismic Data Transmission Network, Compressed Sensing, Hierarchical Wireless Multi-Hop Network, Orthogonal Matching Pursuit.

1. Introduction

In recent years, with the continuous advancement of technology, researchers have developed various types of cableless seismic data acquisition devices, also known as nodal seismographs. The traditional "blind acquisition" mode, when applied to nodal seismographs, presents several limitations. It fails to enable real-time monitoring, making it difficult to ensure the quality and efficiency of field exploration operations. The stability of data transmission based on wireless communication technology is challenging to guarantee, and the communication distance is limited, thus making it suitable only for small-scale seismic exploration projects. Moreover, upon completion of data acquisition, the devices need to be retrieved to obtain the data, which is time-consuming and labor-intensive for large-scale and extensive exploration projects. To better adapt to the use of nodal seismographs, researchers have developed a "semi-blind acquisition" mode, which allows for wireless control of nodal seismographs. However, real-time data transmission is required in applications such as microseismic monitoring, hydraulic fracturing monitoring, and geological hazard detection [1]. Wireless communication technologies are mutually constrained in terms of communication distance and link bandwidth, making it difficult for a single communication network to address the real-time transmission of massive data on a large scale. In terms of signal coverage, commonly used Wireless Local Area Network (WLAN) technologies have shortcomings such as short transmission distances, susceptibility to interference, and the presence of signal blind spots. Wide Area Network (WAN) can achieve long-distance data communication, yet satellite networks have limited communication rates, and WANs have obstacle blind spots in complex terrain environments. Additionally, large-scale, high-density acquisition arrays will generate vast amounts of data, which will significantly increase the load on wireless networks [2-3].

To address the issues, this paper proposes an efficient compressed sensing-driven wireless multi-hop seismic data transmission network (WMDTN). Firstly, this paper designs a cableless self-positioning seismic acquisition system and a hierarchical wireless multi-hop network (HWMN) to achieve fully wireless communication. Secondly, this paper utilizes the CS transmission method to reduce the large amount of seismic data acquired by the seismic acquisition system. Finally, actual data will be used to validate the effectiveness of the proposed wireless multi-hop seismic data transmission network.

2. Design of Wireless Multi-Hop Transmission System

The network architecture of WMDTN is illustrated in Figure 1. This network primarily consists of a data center, gateway nodes, sensor nodes, compressed sensing (CS) technology, Long-Term Evolution (LTE) technology, and Wi-Fi. Figure 1 demonstrates the connections and data transmission relationships among these components. Initially, data acquisition is performed, with numerous sensor nodes distributed across the monitoring area to collect seismic-related data. These nodes may interact and perform preliminary processing through Compressed Sensing (CS) technology. Subsequently, data transmission is achieved, where the sensor nodes transmit the collected data to the gateway nodes via CS. Upon receiving the data, the gateway nodes then transmit it to the data center, which is located on a truck, using LTE or Wi-Fi communication technologies. Finally, data storage and analysis are conducted, with the data center receiving data from the gateway nodes for further processing and storage, facilitating subsequent research and analysis.

The HWMN is constructed based on seismic topologies (linear, parallel, star, and other regular topologies). It comprises a core network utilizing LTE links and a multi-hop network employing Wi-Fi links. To prevent the seismic data volume from becoming excessively large, the seismic data is compressed using CS before each wireless transmission.

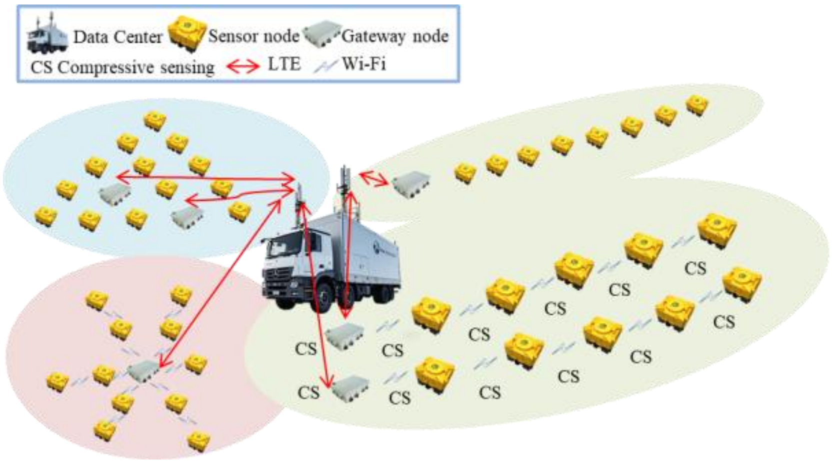


Figure 1. Overall structure of hierarchical wireless multi-hop seismic data transmission system

2.1. Hardware Design

The hardware circuit design of one of the nodes in the WMDTN is illustrated in Figure 2. It primarily consists of three 2Hz coil geophones (CDJ-S1), a three-component cableless self-positioning seismograph (GEIWSR-II), a wireless communication module, and a power supply. The geophones are utilized to detect ground vibrations, converting mechanical vibration signals into electrical signals. The cableless self-positioning seismograph performs preprocessing tasks such as amplification and filtering on the weak electrical signals output by the geophones, thereby enhancing signal quality. It then converts the analog signals into digital signals at a specified sampling rate, facilitating subsequent processing and transmission. The wireless communication module incorporates communication technologies such as Wi-Fi and LTE, which are employed to transmit the processed data to external devices or data centers. Wi-Fi is suitable for short-range, high-speed data transmission, while LTE enables long-range wireless communication, ensuring reliable data transmission across various environments. The power supply provides stable electricity to the entire system, ensuring the equipment operates seamlessly.

The CDJ-S1 geophone incorporates a spring spider mechanism, which is meticulously engineered through the utilization of OBe beryllium bronze spring strips subjected to laser cutting and subsequent preheating treatment post-forming. This advanced manufacturing process ensures the precise and accurate measurement of seismic signals, thereby enhancing the fidelity of data acquisition in seismic exploration applications. The CDJ-S1 exhibits a sensitivity of 1800 mV/cm/s ± 10%, with an operational frequency range extending from 2 Hz to 100 Hz, making it exceptionally suitable for capturing a broad spectrum of seismic activities with high precision and reliability.

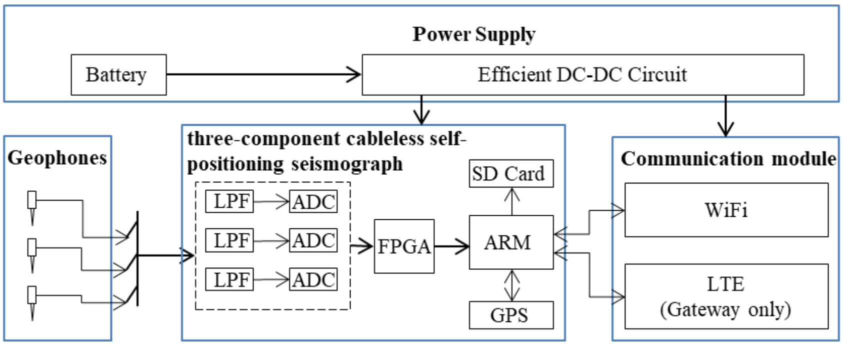


Figure 2. Hardware scheme of sensor nodes and gateway nodes

The system incorporates a sophisticated data acquisition unit centered around a 32-bit high-resolution Analog-to-Digital Converter (ADC), i.e. ADS1282, which serves as the core component for signal acquisition. The acquisition and test control functions are managed by a Field-Programmable Gate Array (FPGA) of the Cyclone IV series, which facilitates three-channel data conversion, acquisition, and channel testing for weak seismic signals. Prior to analog-to-digital conversion, the seismic signals undergo processing through low-pass filters (LPF) to effectively eliminate random noise, thereby enhancing the signal-to-noise ratio and ensuring the integrity of the acquired data.

At the heart of the system lies the AT91RM9200, a high-performance Central Processing Unit (CPU) that integrates an SD card storage unit, a GPS positioning module, and a time synchronization unit. The wireless communication infrastructure is composed of Wi-Fi and LTE modules, with the latter exclusively utilized in gateway nodes, enabling robust and remote wireless data transmission capabilities.

The GEIWSR-II system employs a comprehensive noise level control strategy, which encompasses three critical aspects: source impedance matching circuits, suppression of external interference, and power supply and ground line decoupling. As a result of these meticulous design considerations, the GEIWSR-II achieves an exceptionally low noise level of 0.57 µV within the frequency range of 3 to 200 Hz, as validated by rigorous testing.

Furthermore, the system adopts an integrated approach combining GPS time service with a Real-Time Clock (RTC), enabling synchronous sampling across 4000 channels with a synchronization precision of 10 microseconds. The GEIWSR-II is equipped with a dual-frequency GPS OEM board, which endows the data acquisition system with static relative positioning functionality, achieving centimeter-level positioning accuracy. This integration ensures precise spatial and temporal synchronization, which is paramount for high-resolution seismic data acquisition and analysis.

2.2. Hierarchical Multi-Hop Network

As illustrated in Figure 1, the network communication is primarily composed of LTE and Wi-Fi. The core network, based on LTE links, is designed to support large-scale, real-time, and high-volume data acquisition. The multi-hop network, based on Wi-Fi links, consists of numerous subnets, each primarily comprising gateway nodes that connect the data center and sensor nodes.

2.2.1. Core Network Design

The core network primarily connects the data center and sensor nodes. Gateway nodes communicate with the data center via LTE links and utilize a dedicated network protocol to communicate with sensor nodes through Wi-Fi links, thereby enabling communication between the data center and sensor nodes. Additionally, the network employs Orthogonal Frequency Division Multiple Access (OFDMA) and Multi-User Virtual Multiple Input Multiple Output (MU-V-MIMO) technologies to achieve real-time data transmission. OFDMA is used for both uplink and downlink, with the bandwidth allocated to the uplink being greater than that of the downlink. The multi-antenna technology in the LTE standard aims to achieve higher spectral efficiency, which can exponentially increase the channel capacity of the communication system without increasing transmission power or spectrum resources. Simultaneously, it enhances the peak data rate of gateway nodes and the overall capacity of the network.

2.2.2. Multi-Hop Network Design

Seismic data in the multi-hop network adopts a relay transmission method, which can extend the signal transmission distance, expand the coverage area, and achieve long-distance, stable signal transmission. Sensor nodes complete networking through a dedicated protocol based on Wi-Fi links, and data exchange between nodes is achieved through multi-hop relays. This method can satisfy non-blind coverage of signals in the measurement area and remote access of WLAN technology.

The HWMN structure proposed in this paper differs from traditional Wireless Sensor Networks (WSN) and the Internet. HWMN is a network with a regular topology that can collect data in real-time and achieve "many-to-one" communication. Due to issues such as link conflicts and packet loss, existing network protocols (such as IP and AODVjr) cannot be directly applied to multi-hop networks. Therefore, combining the characteristics of wireless networks and seismic topology, this paper defines a private routing protocol and data transmission protocol, enabling networking and data transmission. The GS1011 wireless communication module serves as the hardware carrier for data transmission. By porting the embedded Linux operating system and constructing network protocols in user space, networking and data transmission of all nodes are achieved.

To obtain reliable and real-time data, the data transmission protocol must provide guarantees for all data, ensuring that lost data can be quickly recovered. Combining the characteristics of static topology and Ad hoc multi-hop communication, we use a hop-guaranteed data transmission mode, actively acknowledging (ACK) individual data packets and the last data packet, and using negative acknowledgment (NACK) to detect and recover lost data packets.

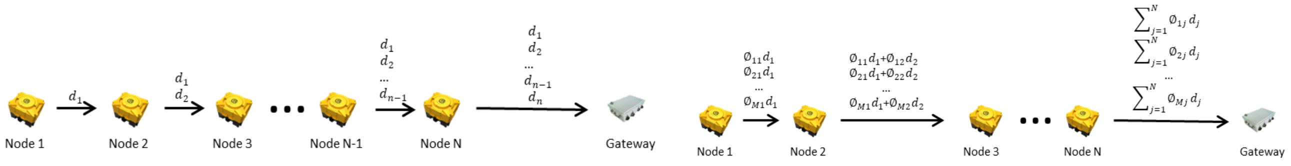
3. Transmission Method Based on Compressive Sensing

The communication traffic increases linearly with the number of nodes in the structure of multi-hop network, as illustrated in figure 3(a). There is obvious transmission bottleneck in multi-hop networks with limited communicating resources [4-5].

To address this issue, this paper proposes a transmission method based on Compressed Sensing (CS), as illustrated in Figure 3(b). During the transmission process, the recorded seismic data is encoded into a fixed-length code using a measurement matrix derived from Compressed Sensing theory. The seismic data acquisition process in the multi-hop network can be represented by Equation 1:

$$y_i = \Phi x_i \tag{1}$$

Where y_i denotes the encoded seismic data during the i-th acquisition, x_i represents the original seismic data during the i-th acquisition, and Φ is the measurement matrix. According to Compressed Sensing theory, Φ is an independent and identically distributed matrix following a normal distribution.



(a) Conventional transmission mode (b) CS-based transmission mode

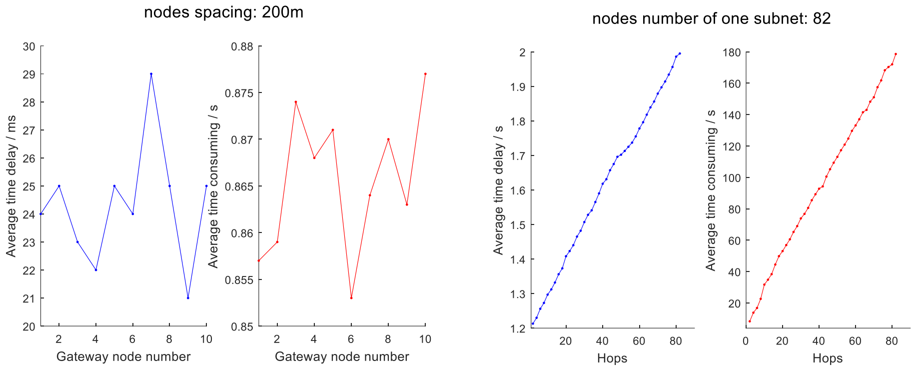
Figure 3. The schematic diagram of seismic data transmission

To retrieve the original seismic data, a decoding algorithm must be designed to transform the fixed-length code back into the original seismic data [6]. First, it is essential to explore the sparsity of the seismic data to ensure a high probability of recovering the original signal. Subsequently, a recovery algorithm within the framework of Compressed Sensing is employed to reconstruct the original data from the encoded data under the constraint of sparsity. The entire decoding process can be expressed by the following formula:

$$\tilde{\theta}_i = \underset{\theta}{\arg\min} \|\theta_i\|_0, \text{ subject to } y_i = \Phi\Psi\theta_i \tag{2}$$

$$\tilde{x}_i = \Psi\tilde{\theta}_i \tag{3}$$

Where Ψ represents the sparse transformation matrix, and θ_i denotes the corresponding sparse coefficients. To obtain the sparse transformation matrix for the original data, this paper introduces an enhanced K-SVD algorithm, termed Sequential Parallel Atom-updating Dictionary Learning (SPADL). Given the computational burden of the K-SVD algorithm in high-dimensional scenarios, the improved algorithm aims to meet two key requirements: accelerating the convergence speed of dictionary training and achieving the desired level of sparsity. Specifically, this paper proposes the introduction of a priority sequence during the sparse approximation phase, utilizing a parallel atom-updating approach to implement the dictionary update stage, rather than computing Singular Value Decomposition (SVD) for each atom in the dictionary update stage. This method is designed to expedite convergence and control the cardinality of the representations. Ultimately, the recovery algorithm employed in this work is Orthogonal Matching Pursuit (OMP).

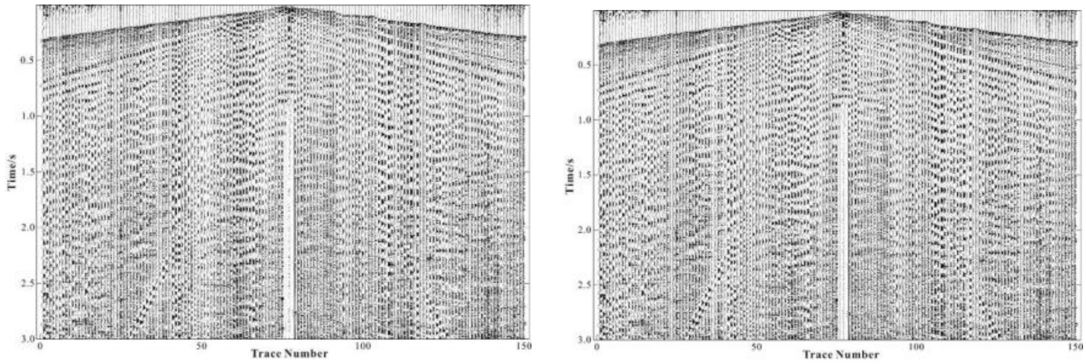


(a) Core networks (b) Multi-hop networks

Figure 4. Test results of average time delay and time consuming of HWMN

In order to evaluate the remote communication capabilities of the system, a core network was constructed by randomly selecting 10 gateway nodes, with a fixed spacing of 200 meters between any two adjacent nodes. As illustrated in Figure 4(a), statistical analysis revealed that the average time delay across the 10 nodes ranged from 21 to 29 milliseconds, while the average time required for data transmission was measured to be between 0.854 and 0.877 seconds. Consequently, the average transmission rate of the core network was determined to be 1.161 MB/s.

To further assess the performance of the multi-hop networks and verify the correctness and stability of the proprietary protocols, a subnet with a linear topology structure was established, where the spacing between nodes was set at 40 meters. This subnet successfully achieved the interconnection of 82 nodes, including gateway nodes, with a total networking time of 102 seconds. In the time delay test, the results, as depicted in Figure 4(b), indicated that the average time delay for the minimum hop (the second hop) was 1.213 seconds, while the average time delay for the maximum hop reached 1.965 seconds.



(a) Profile formed by conventional collection method (b) Profile formed by CS

Figure 5. Comparison of single shot records

Additionally, in the transmission rate test, it was concluded that the average single-hop transmission time was 2.179 seconds, with an average single-hop transmission rate of 0.459 MB/s. These findings demonstrate the robustness and efficiency of the proposed network architecture and protocols in facilitating reliable data transmission across multiple hops.

After conducting a comprehensive evaluation of the performance of the Hierarchical Wireless Multi-hop Network (HWMN), two subnets were meticulously constructed, and the seismic vibrator was subsequently activated to initiate data acquisition. Upon completion of the data recording process, seismic data was downloaded on two separate occasions via two distinct gateway nodes. Figure 5(a) presents the single-shot record in its uncompressed form, while Figure 5(b) illustrates the recovered result of the same single-shot record utilizing Compressed Sensing (CS) techniques.

When the profile depicted in Figure 5(a) is considered as the reference signal, the recovered result, achieved with a 32% compression ratio, exhibits a Signal-to-Noise Ratio (SNR) of 14 dB. This outcome demonstrates that the CS-based transmission method can triple the channel capacity while maintaining artificial noise at a level below 18% of the signal strength. Consequently, this CS-based transmission method is deemed highly suitable for a broad spectrum of engineering geological exploration applications, offering a significant enhancement in data transmission efficiency without compromising signal integrity.

4. Conclusion

This paper presents a comprehensive solution to the challenges associated with traditional seismic data acquisition and transmission methods by introducing an Efficient Compressed Sensing-Driven Wireless Multi-Hop Seismic Data Transmission Network (WMDTN). The proposed system leverages a hierarchical wireless multi-hop network (HWMN), which combines LTE-based core networks for long-distance communication and Wi-Fi-based multi-hop networks for localized, high-density data transmission. The integration of compressed sensing (CS) technology enables the efficient reduction of seismic data volume, addressing the limitations of conventional transmission methods that struggle with the massive data generated by large-scale seismic arrays. The hardware design incorporates high-precision geophones, 32-bit ADCs, and FPGA controllers, ensuring accurate signal acquisition, preprocessing, and synchronization across 4000 channels with a precision of 10 microseconds.

The CS-based transmission method is particularly noteworthy, as it encodes seismic data into fixed-length codes using a measurement matrix derived from CS theory, thereby tripling channel capacity while maintaining artificial noise below 18% of the signal strength. This method, combined with the Orthogonal Matching Pursuit (OMP) recovery algorithm, ensures high-fidelity data reconstruction, achieving a 14 dB SNR at a 32% compression ratio. Experimental validation confirms the network's efficiency, with the core network demonstrating an average transmission rate of 1.161 MB/s and the multi-hop network achieving 0.459 MB/s, alongside robust time delay performance.

In conclusion, the proposed WMDTN represents a significant advancement in seismic exploration technology, offering a scalable, efficient, and reliable solution for real-time data acquisition and transmission in large-scale and complex geological environments. The integration of advanced wireless communication technologies, compressed sensing, and high-performance hardware components ensures that the system is well-suited for a wide range of engineering and geological applications, paving the way for future innovations in seismic data processing and analysis.

Acknowledgements

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