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Ultra-Wide Band Sensor Networks in Oil and Gas Explorations

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Abstract

Seismic exploration and monitoring for oil and gas reservoirs is a peculiar application that requires a large number (1000–2000 nodes/sqkm) of geophone sensors deployed outdoors over large areas (≥ 40 sqkm) to measure backscattered wave fields from artificial sources. A storage/processing unit or sink node collects the measurements from all the geophones to obtain an image of the sub-surface. The existing cabling system to connect sensors is known to cause inefficiencies, large logistic and weight costs, as well as insufficient flexibility in survey design. Oil companies are therefore expecting that wireless connectivity will provide the enabling technology for future seismic explorations. This application represents a new challenging research area for the wireless community. Early results suggest that current off-the-shelf radio solutions do not guarantee the minimum requirements in terms of system usability and energy consumption, not even for current deployment size. This article presents a tutorial view to introduce the basic principles of seismic acquisition systems that are necessary to define the wireless geophone network specifications. Strict sampling synchronization constraint over large geographic areas, high precision sensor localization, and high data rate are all requirements calling for a scalable network system where Ultra-Wide Band radio transmissions play a key role as the only viable technology.

Introduction

A wireless sensor network is a well-known paradigm that collects a set of emerging technologies that will have profound effects across a range of industrial and scientific applications. Recent developments in wireless technologies and semiconductor fabrication of battery-powered miniature sensors are making the radio devices more cost-effective for a growing number of pervasive applications. New technologies such as millimetric wave and Ultra-Wide Band (UWB) [1] are expected to provide wireless connectivity for high data-rates within very short range distances.

Although a wide number of applications have been proposed for sensor networks, their market penetration is still very fragmented with volumes that are far from the full exploitation of the potentials of the latest cutting-edge technologies. The scientific community should provide innovative tools in all the new cable replacing applications to boost industry toward larger business volumes.

Wireless Geophone Networks for Seismic Exploration

The unavoidable need for oil and gas as leading energy sources for the next decades is pushing the oil companies to increase the investments in seismic exploration of new reservoirs and in new technologies to improve the quality of depth imaging for more efficient production [2].

Conventional cable-based land exploration operations (Fig. 1) rely on an acquisition phase that is based on telemetry cabling to handle remote control commands and to collect data samples from remote sensors (or geophones) in real-time. Seismic crews supervising each acquisition typically carry up to one third of a million sensors only for the operations over one survey. The use of cabling accounts for up to 50 percent of the total operating cost of a typical land survey and up to 75 percent of the total equipment weight [4]. Cable-based systems impose such stringent constraints on the survey design, efficiency, and cost that moving to wireless architectures is now regarded by oil companies as a natural evolution for high-resolution seismic explorations employing up to one million sensors within the next decade [3].

Wireless Geophone Network (WGN) is the acronym that will be used in this article to indicate the network architecture supporting future high-resolution cable-free seismic explorations. Technical limitations of off-the-shelf wireless technologies force current proposals for WGN architectures to choose wireless only for remote

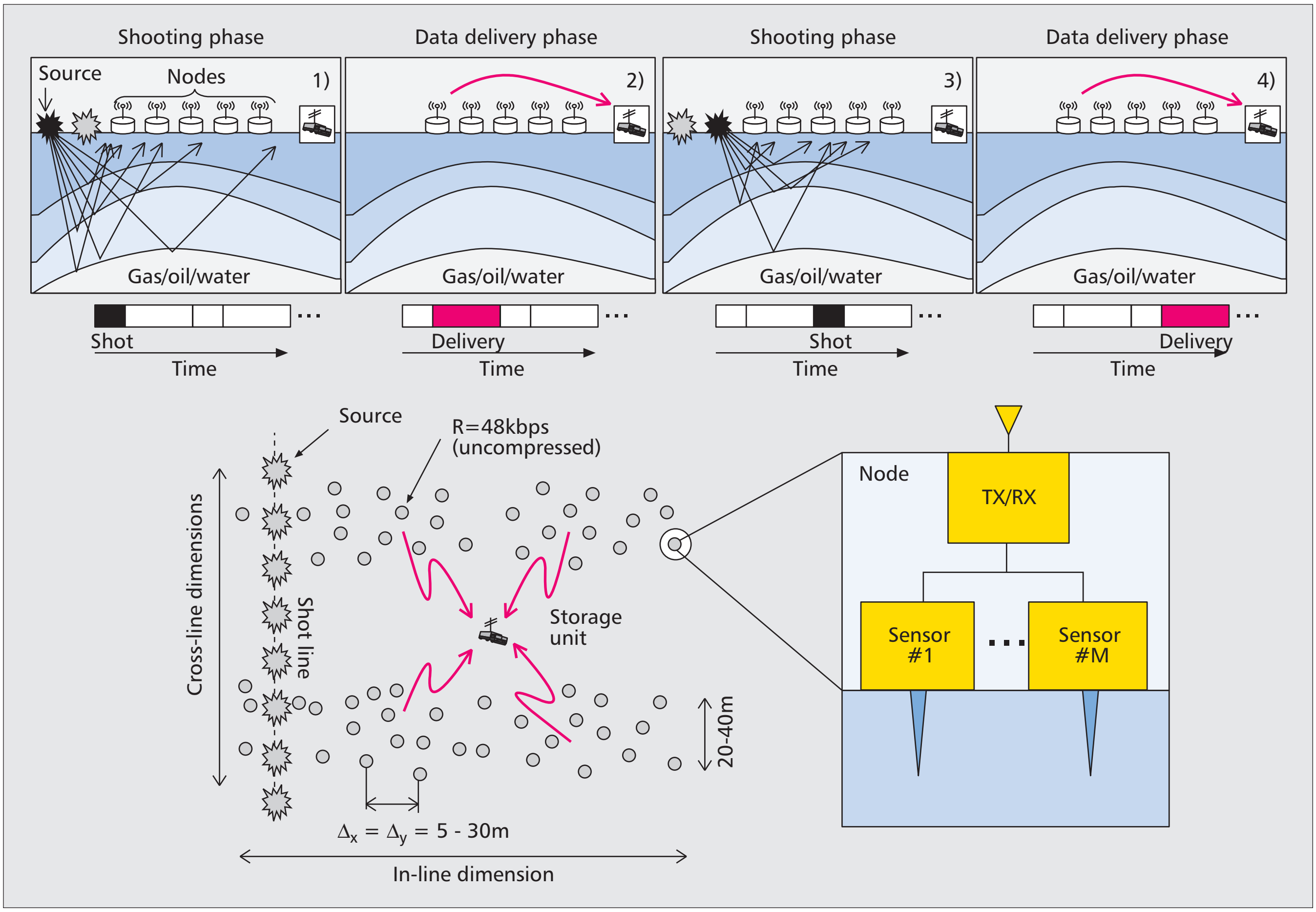


Figure 1. *Overview of land seismic acquisition system alternating shooting and delivery phases over a sequence of source locations (on top). Typical 2D WGN network topology and node structure (bottom figure).*

data quality control while cables are still mostly adopted for real-time data delivery [3]. Recent advances in wireless technology have led the scientific community to now be mature enough to meet the rigid constraints imposed by seismic acquisition systems [4].

The main goal of this article is to disclose the specifics of this fairly unique industrial application to the wireless community and to propose the guidelines for a new architecture based on UWB technology. After a brief tutorial on land seismic acquisition systems, the WGN architecture is specifically designed according to the network requirements. Locating the geophones through self-localization techniques and adopting data compression algorithms to relax the requirements on network throughput are finally discussed as two areas that have the potential to largely improve the survey quality, while opening new research opportunities.

Review of Land Seismic Acquisition

In land seismic acquisition one (or more) energy *source(s)* such as dynamite or a controlled-source like vibrated plate or *vibroseis* are placed on the surface to generate elastic waves that propagate over the sub-surface. These elastic waves are reflected and refracted by media discontinuities with different elastic properties (Fig. 1). Backscattered wavefield is measured by sensors. In geophysicist jargon, the *seismic channel* is used to refer to the stream of digitalized samples drawn from one sensor. The number of seismic channels depends on the size of the survey. Large-size systems under design are targeting more than 300K channels simultaneously active, moving to one million within the next decade.

As shown in Fig. 1, the *node* (or *receiver* in geophysicist jargon) might collect one or multiple sensors (if using *multi-component receivers*). To simplify, the sensing operation is similar to a very large array of microphones. Sensors can be geophones or accelerometers: these are closely coupled to the ground to measure the back-scattered wavefield that conveys reflected elastic energy generated by seismic sources. After synchronous sampling, the seismic channels are forwarded by each node to a storage/processing unit to identify the geological structure of the substrate.

The acquisition system consists of two distinct phases that are repeated periodically (the reader might refer to the wide literature for more in-depth discussion, see e.g., [2]):

- The *shooting* phase where one (or more) source(s) placed in a predefined position(s) is generating the elastic wave.
- The *data delivery* phase where the seismic data is synchronously sampled, quantized, and forwarded by the nodes toward the

High node density and wide-azimuth are two key requirements in seismic acquisitions. High density of geophones provides a high-quality depth imaging while wide-azimuth enables highest resolution of depth images from back-scattered wavefield of side-view.

storage unit. Data collection is obtained by multiplexing data streams from multiple seismic channels.

As shown in Fig. 1, shooting and data delivery are repeated periodically by moving the seismic source(s) over predefined positions (see the map-view in Fig. 1). The storage/processing unit estimates the elastic discontinuities of the sub-surface by combining the data received from all the nodes. The Common Shot Gather (CSG) view collects the signals recorded by all the available nodes (seismic *traces*) during one shooting phase and can be used to visualize the digitalized seismic channels into a two-dimensional space-time grid.

Sensor Technology: Geophone and MEMS Accelerometers

Coil based geophones have been regarded as a proven technology and have been used for a long time by the seismic industry. Seismic data from geophones is obtained by measuring the voltage induced from the relative velocity of the magnet compared to the coil. Nodes are typically equipped with multiple analog geophones to perform electrical summation of the signals acquired. For each node one single trace is processed, digitalized, stored, and transmitted. Cabling is typically needed to serially connect the geophones to form arrays.

The adoption of micro-machined sensor (MEMS) accelerometers is expected to reduce the equipment weight to improve survey flexibility still by maintaining the same imaging quality of geophone arrays. The expected key advantage of MEMS accelerometers for seismic exploration is the broadband linear frequency response compared to geophones that typically extends from DC to 800Hz. MEMS can be printed on a tiny silicon chip with smaller size (1 cm) and weight (lower than 1 g) compared to coil based geophones (typical weight of 70-80 g) [2]. Compared to coil-based geophones, the introduction of MEMS as a future technology for cable-free surveys will pose more stringent constraints on battery lifetime of remote units.

To comply with the conventional notation, the term "geophone" will be used in the following sections to indicate the wireless node device, although it is understood that the whole sensor hardware will be subject to technological innovations.

High-Density and Wide-Azimuth Acquisitions

High node density and wide-azimuth are two key requirements in seismic acquisitions. High density of geophones provides a high-quality depth imaging while wide-azimuth enables the highest resolution of depth images from back-scattered wavefield of side-view.

Geophones are deployed on the surface to form pseudo-random 2D arrays with an application-specific deployment as outlined in Fig. 1. The 2D array can be virtually organized into strips (*receiver lines*) with nodes ideally placed over rectangular (or rhombic) lattice with horizontal (*in-line* Δ_x) and vertical (*cross-line* Δ_y) spacing (*offset*) of $\Delta_x = \Delta_y$ = 5–30m.

In practice, natural and man-made obstructions make the network deployment far from being regular. Strips can be 10km long (in-line dimension) and contain thousands of nodes. The number of lines should be large enough to guarantee wide-azimuth coverage, and this is typically obtained when the cross-line dimension is comparable with the in-line dimension for monitoring field extension of 20–100 sqkm. A similar layout is designed for source deployment to explore source/geophone reciprocity [2].

Shooting-Blind vs. Real Time Telemetry Systems

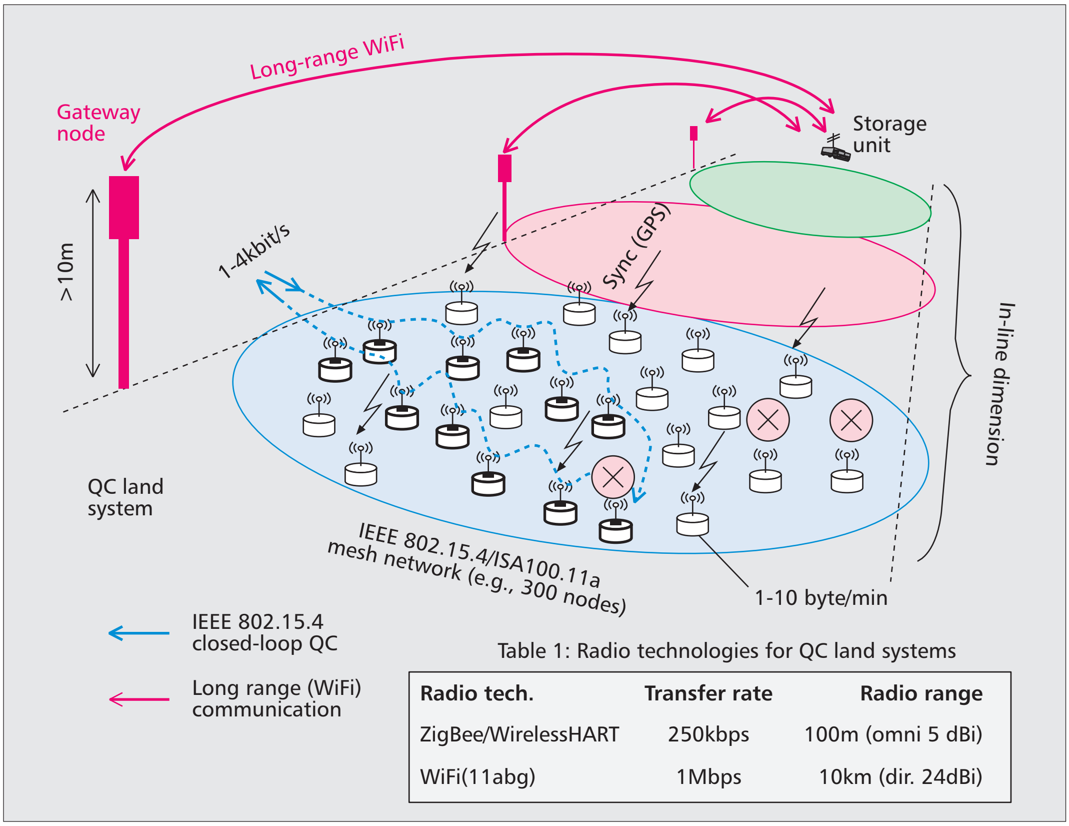
Local data storage with cable-free nodes sending only few bits for data quality control (QC) is clearly the most simple alternative (although not fully competitive) to conventional wired telemetry. The control unit is referred to as "blind" since it does not receive seismic data while shooting. After synchronous sampling, seismic data are stored for the whole survey duration with time-stamps that label each shooting phase and downloaded into the global data storage only at the end of the survey when geophones are collected back.

Faulty recordings severely impair the whole acquisition with unacceptable loss of depth resolution (and re-shooting after all), so remote QC of seismic data during acquisition is therefore mandatory. QC parameters are transmitted by each wireless device either periodically or on demand (Fig. 2). The data-rate for QC information typically ranges between 1-10 bytes/min and it is one order of magnitude lower compared to the full seismic data transfer thus relaxing the requirements on network throughput.

Wireless QC shooting-blind systems have stricter requirements and higher security concerns compared to conventional wireless sensor network applications. First, they should provide a low delay service to guarantee a timely access to measurements and control information over large-size survey areas. Second, end-to-end data reliability has to be high enough to guarantee an efficient response to any possible alarm condition. Third, the choice of the low-power wireless technology should guarantee the highest reliability in harsh environments (forests, urban/suburban scenarios, etc.) where propagation of radio signals might suffer from a significant level of interference and non-line-of-sight. These requirements are common to a broader class of closed-loop automatic industrial process control systems.

The IEEE 802.15 Task Group 4e is currently pushing to enhance the 802.15.4-2011 MAC to better support these specific industrial markets. The problem of defining the necessary policies to support mesh networking to extend network coverage is instead the main focus of the IEEE 802.15 Task Group 5 [5]. Industrial organizations such as HART, ZigBee, and the International Society of Automation (ISA) are also pushing toward the definition of common specifications for wireless industrial process control. It is therefore envisaged that these standards will play a crucial role for the next generation wireless seismic equipment in the future.

A real-time wireless telemetry system requires the entire seismic data to be transferred during acquisition (while shooting). This is the solution that will be more deeply analyzed in the following sections as it *completely* replaces the cabling func-



Radio tech.	Transfer rate	Radio range
ZigBee/WirelessHART	250kbps	100m (omni 5 dBi)
WiFi(11abg)	1Mbps	10km (dir. 24dBi)

Figure 2. *Shooting blind Quality Control system (QC land system) architecture.*

tionalities. Data delivery enables real-time monitoring of the overall process at the control unit to identify faulty traces with a great speed up of the overall acquisition. In addition, by eliminating the need for local data harvesting, it reduces the risks of data loss caused by equipment malfunctions.

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Network Requirements for Wireless Seismic Exploration

Even if the last decade has witnessed many new products and standards in the area of wireless communications, real-time seismic acquisition has many peculiarities that are not common to other wireless sensing networks. A typical survey of 300K co-located live-channels is still fairly complex to be fully wireless with the available technology. To simplify, the amount of traffic/connections is comparable to those that one cellular phone operator handles in a medium size city [4]. In addition, remote units are left unattended for such a long time that self-organization of the network and low power consumption become mandatory requirements. In what follows we focus on the *data delivery phase* of the real-time WGN telemetry system where battery-powered nodes are equipped with radio transceivers.

Network Throughput

Some basic data-rate budget analysis is mandatory to better capture the throughput requirements of the network. Given that the minimum seismic wavefield sampling time is $T_s = 0.5$ ms, the data-rate of one seismic channel generated by one sensor with $N = 24$ bits/sample A/D is $R_c = N/T_s = 48$kb/s with typical value of $R_c = 12$kb/s for sampling time $T_s = 2$ms. The aggregated bit-stream generated by one wireless node scales with the number of seismic channels that are locally processed and multiplexed. The type of sensor and the method by which seismic data is routed to the storage unit (e.g., by multi-hop transmission) have major influences on the amount of aggregated data rate.

As an example, aggregated bit-stream from one node that is multiplexing 2000 seismic channels easily reaches $2000 \times R_c = 100$Mb/s. A survey deploying 300K seismic channels might require the deployment of 100K tri-component wireless receivers: this system would need to support a sum-throughput of 4.8Gb/s that scales down to 1.2Gb/s if using $T_s = 2$ms. Supporting such a high aggregated throughput is quite unusual for conventional sensor networks, and it requires the adoption of specific wide-band (or multi-carrier) radio technologies [1] to improve the spectral efficiency. In addition, the adoption of *data compression* techniques is also mandatory to relax the data rate requirements.

Deployment and Network-Layer Management

Nodes are deployed in pre-defined spots according to the acquisition geometry outlined earlier. Node placing is done prior to the shooting/delivery phase and in most cases it is a one-time activity [4]. Some geophones can be added to the network while acquisition is in progress, e.g., to add new lines for enhancing the azimuth coverage or replacing faulty sensors.

Encryption methods should guarantee secure communication between all the wireless equipment to keep the seismic trace information from being decoded by other parties. The advanced encryption standard AES-128 complies with the requirements of seismic acquisition.

The network is mostly static as nodes are not required to change their location after their initial deployment. This suggests that the time during which any two wireless devices can stay within the communication range is long-enough to justify protocols supporting hierarchical networks with self-configuring entities. Channel fading impairing the wireless links might still exhibit large-scale fluctuations over time due to environmental influences or land surveyors operations.

The expected number of devices required for seismic applications calls for an enormous address space. This suggests that the use of IPv6 over the low-power wireless network (e.g., 6LoWPAN) might become a candidate option in the near future. A number of reasons make IPv6 also attractive for network-layer management: these include the support of interoperability for heterogeneous networks and the availability of a huge library of tools and utilities to guarantee flexibility in many different network conditions.

Low-Power Operation and Energy Harvesting

The system needs to be designed to work *continuously* for days (7–30 days). This poses stringent constraints on the radio transceiver and the medium access control (MAC) policy to preserve battery life [6]. In addition, while coil based geophones require no electrical power to operate, power consumption for MEMS is in the order of tens of milli-watts. Today commercial batteries used for industrial applications have an energy density below 800 Joule/g with typical capacity of 19Ah. However, their performance can be worse at low-temperatures. Although research has shown that it is possible to increase energy density by tenfold within a few years with a corresponding reduction of battery weight, the battery capacity typically doubles only every 8-10 years. The introduction of energy harvesting technologies [12] is therefore expected to be the most relevant breakthrough for next generation wireless land acquisition systems for battery recharging or even battery-less devices.

Synchronous Acquisition and Localization

Back-scattered elastic wavefield is synchronously sampled and A/D converted all over the survey area. Synchronization in cable-free systems needs to distribute the time-reference over the survey area with 10–20μs of tolerable sampling skew/jitter. For large surveys (≥ 40 sqkm), timing can be provided by several master clock references (e.g., GPS/GALILEO) where each clock distributor covers an area of 1–3Km radius. This solution reduces the jitter accumulation of time references as for chain-connected equipment in multihop/mesh communication.

Accurate node positioning is mandatory to avoid severe degradation of depth imaging. Satellite navigation systems fail to provide localization if satellites are not visible such as in jungle or forest areas. However, mesh topology can reduce the number of GPS equipped devices by exploiting the concept of cooperative localization that can reach an accuracy below 1m.

Data Protection and Security

Security algorithms are mandatory to assure the full protection of the infrastructure functionality and the wireless seismic equipment. Encryption methods should guarantee secure communication between all the wireless equipment to keep the seismic trace information from being decoded by other parties. The advanced encryption standard AES-128 complies with the requirements of seismic acquisition.

Wireless Geophone Networks: Cluster-Mesh Architecture

Given the large field extension of the survey, an heterogeneous network that exploits the advantages of long and short-range radio technologies seems to be the natural solution. Figure 3 shows the hierarchical WGN architecture: the wide scene is broken into sub-networks managed by a *Gateway* node serving as coordinator (and local sink) connected to the storage unit. The Gateway node is expected to manage two radio technologies: the long-range technology is used to connect to the storage unit while the short-range radio is used to cover the sub-network. The hierarchical architecture proposed to comply with the requirements of oil exploration has the merit of introducing network scalability. Sub-networks are organized into clusters where nodes connect to the associated cluster-head device. Leaf nodes are the geophones that periodically forward seismic data toward the associated *cluster-head*, also receiving control commands (e.g., acquisition start and stop commands). A cluster-head node might be equipped with sensors as with the leaf nodes or be just a relay node.

Ultra-Wide Band Technology for Seismic Data Delivery

The WGN requires tight time synchronization and mandatory self-localization. Given all the constraints, UWB technology might become the most reasonable choice at the physical layer. UWB signals have bandwidth larger than 500 MHz (or fractional bandwidth larger than 0.2) so that they can provide a high quality delay/ranging estimation [8] and large data rates to support bursty traffic. UWB signals are confined in (unlicensed) frequency bands and with stringent emission power spectral density limitations so that they can be used for short-range transmissions in conjunction with other 2.4 GHz based wide-band radio technologies without paying meaningful cross-interference. UWB technology was first proposed for imaging applications in the 1990s, when time domain impulse radio (IR) was the leading PHY layer communication technology. To support advanced high data-rate applications, two UWB technologies have emerged: the direct-sequence (DS-UWB) and the multi-band (MB-UWB). DS-UWB adopts variable length spreading codes for binary phase shift keying modulation; RAKE receiver is implemented to mitigate multipath fading. In 2007 the European Computer Manufacturing Association (ECMA) proposed a number of protocol specifications (ECMA-368 "High Rate Ultra Wideband PHY and MAC standard") that support the transmission

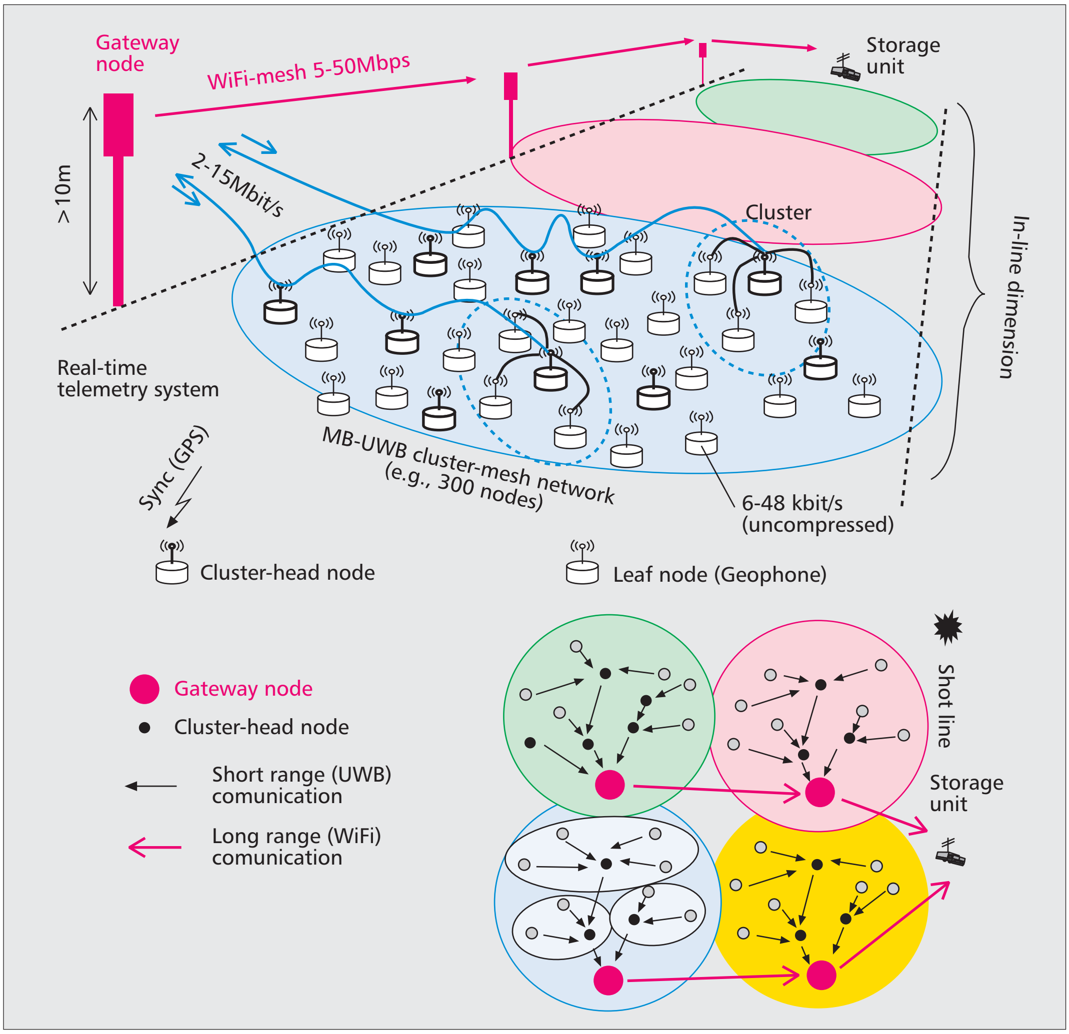


Figure 3. *Real-time telemetry system: wireless geophone network (WGN) cluster-mesh network architecture.*

The evolutionary road for high-throughput UWB should include sensor networks as the secondary (or even primary) target application. In particular, wireless telemetry for high-density seismic exploration is one of the candidate applications where the high data-rate UWB technology can be seen as the only suitable option.

of UWB signals through Multi Band Orthogonal Frequency Division Multiplexing (MB-OFDM). High-speed communication supports up to 480Mbps that are guaranteed within short-ranges of 5-10m indoor. Extended range to 30m is expected in outdoor line-of-sight environments with data rates scaling down to 53.3Mb/s.

So far, market penetration of UWB technology for personal area networking is limited while WiFi standard evolutions have the benefit of cheaper chips that demonstrated a considerably higher appeal to the consumer applications market. In order to fully exploit the potential of the latest technologies, we believe the evolutionary road for high-throughput UWB should include sensor networks as the secondary (or even primary) target application. In particular, wireless telemetry for high-density seismic exploration is one of the candidate applications where the high data-rate UWB technology can be seen as the most suitable option for PHY.

High Data-Rate UWB Technology and Framing Structure for WGN

Given the requirements of the application in terms of data-rate and network scalability, time-domain based IR-UWB technology could not be considered as an option. The complexity of RAKE receivers and the critical synchronization requirements currently prevent full-function implementations of DS-UWB technology. MB-OFDM radios combine the benefits of OFDM transmission with the network scalability offered by multi-band transmission. The MB-OFDM medium access control is also expected to enable considerable spatial reuse and network scalability through the use of time-frequency (TFI) and fixed- frequency (FFI) codes to interleave information data over adjacent frequency bands or consecutive OFDM blocks. Although sensitivity to timing errors, phase noise, and frequency offsets still represent challenging problems for advanced circuit design, the implementation of MB-OFDM technology is less critical compared to DS-UWB. In addition, it received wider support from a large number of manufacturers and consortiums [7]. MB-OFDM is therefore envisaged as the physical layer technology for cable-replacing within each sub-network.

Framing structure is taken from the ECMA-368 standard with some modifications that are mandatory for the oil exploration application: these are outlined in Fig. 4. The Beacon Period (BP) is placed at the beginning and contains up to 96 Beacon Slots (BS). BSs are transmitted at every superframe and carry essential information on device

The Gateway and the cluster-head nodes are GPS synchronized and issue a unique beacon in a reserved BS. The beaconing concept of ECMA guarantees easy-to-spread synchronization, acquisition timing and connectivity for large size networks.

status (neighbour information, data rate, signal-strength), beacon period occupancy information, available and reserved transmission resources. The remaining part of the super-frame is sub-divided into slots (medium access slots — MAS) of 256ms each. Devices can send their information after reserving collision-free transmission resources in terms of one or more MASs, or by using random access within the final part of the super-frame to avoid interference with collision-free transmissions.

The Gateway and the cluster-head nodes are GPS synchronized and issue a unique beacon in a reserved BS. The beaconing concept of ECMA guarantees easy-to-spread synchronization, acquisition timing and connectivity for large size networks [7]. In addition, the distributed beaconing concept constitutes a unique opportunity to support highly dense and large size networks resulting as the interconnection of many clusters of sensors (piconets). The Gateway node behaves as intermediate sink and periodically issues a unique reference time valid for all the devices within the sub-network and referred to as the beacon period start time (BPST). After detecting the BPST, each cluster-head transmits beacon frames within the BP to maintain and propagate the reference time.

Energy-Aware Beaconing Design

Low-energy consumption is a key requirement that must be specifically addressed for WGN. Since the ECMA specification is not optimized for low energy [7], amendments to the standard are therefore recommended by adapting some principles from the IEEE 802.15.4 specifications. ECMA defines the distributed access to the BP throughout the mechanisms of extension and contraction when k devices ($k \geq 2$) make random access on n ($n \leq 8$ as ECMA specified value) free slots left purposely after the highest occupied beacon slot (HOBS). Since cluster-head nodes have to keep the receiver active for *all* the announced length of the BP, unnecessary long and fragmented BPs cause energy waste from idle listening. Scaling down the number of devices that access the BP is mandatory to reduce the time all the devices should listen for beacons and minimize the power expenditure for receiving. To that end, it is proposed to modify the ECMA standard to give only the cluster-heads and the Gateway nodes the right to access the BP, while the other (reduced function) leaf nodes can only receive beacons, with no right to occupy any slot in the BP. Energy consumption per super-frame during BP listening is quantified in Fig. 4 for different BP configurations and access schemes. According to ECMA, BP expands when newcomer cluster-head nodes are requesting for beacons: the energy expenditure per super-frame varies correspondingly as shown in Fig. 4 (red curves). The proposed scheme for WGN is referred in Fig. 4 as coordinated access (black curve). This scheme allows the cluster-head nodes to compete making first access on the two signalling slots instead of expanding the BP by randomly choosing a BS after the HOBS. The device that wins the contention is granted the right to transmit a beacon frame using the first unoccupied beacon slot.

The numerical example illustrated in Fig. 4 provides a basic concept of the overall system by assessing the device battery lifetime and the delay experienced during network set-up. In this case study it is assumed that each cluster-head is coordinating a maximum of 15 leaf nodes. Leaf nodes are randomly deployed over the linear/strip network deployment illustrated in Fig. 1 now with spacing that ranges between 5-10m as typical for a high-density survey. In each sub-network, the number of active cluster- heads aggregating seismic data from leaf nodes is 20. Energy consumption measurements are taken from a non commercial MB-OFDM transceiver used as a testbed [9]. Simulations of distributed beaconing are verified through an OPNET simulator. The ECMA-368 compliant distributed access causes a saturation of the beacon period when a relatively large number of devices contend for beacon slots (this is also the case of Fig. 4). On the other hand, the proposed coordinated access is likely to prevent this to happen, at least for all the population values that are of interest for oil exploration application. Compared to distributed access, coordinated access increases the network set-up delay in exchange for larger node lifetime: this is reasonable for static environments where beacon slot association remains fixed for a large fraction of time. Network set-up for beaconing and resource allocation has a duration of 42 sec for coordinated access while 11 sec are required for ECMA compliant access. The energy consumption per superframe is assumed to remain constant until battery depletion: this makes it possible to compute the expected battery life of the cluster-heads that are closest to the Gateway as these represent the bottleneck of the system and typically experience the smaller lifetime. For a commercial battery with capacity 19Ah, the worst-case cluster-head lifetime for coordinated access is 29 days of continuous recording mode, while it scales down to 14 days for ECMA compliant access. Notice that today land acquisitions require continuous recording for 7–10 days, while next generation telemetry systems will require battery lifetime of several weeks (and up to 1–2 months) [15]. To support larger lifetime, additional investigations are required to tune PHY layer parameters to enable further energy savings.

Cooperative Transmission with Guaranteed Time Slots

Leaf nodes inside clusters are reduced function devices as these communicate to the cluster-head node using random access within the final part of the superframe. Each individual geophone device collects a relatively small amount of data compared to the capacity of an MB-OFDM radio link (up to R_c = 48kb/s without compression) so that the use of random access becomes a reasonable choice. In the process of sending information to the Gateway node, the cluster-heads must instead process and route large volumes of seismic data with typical range of 2–15 Mb/s (e.g., to aggregate 300 seismic channels). Therefore, for cluster-heads the use of a distributed resource reservation policy for routing data toward the Gateway is mandatory. The cluster-head nodes use the so called distributed reservation protocol (DRP) defined by ECMA-368 to route data between themselves. Transmission resources for cluster-heads are assigned in the form of one (or more) guaranteed time slot(s). Resource allocation can be

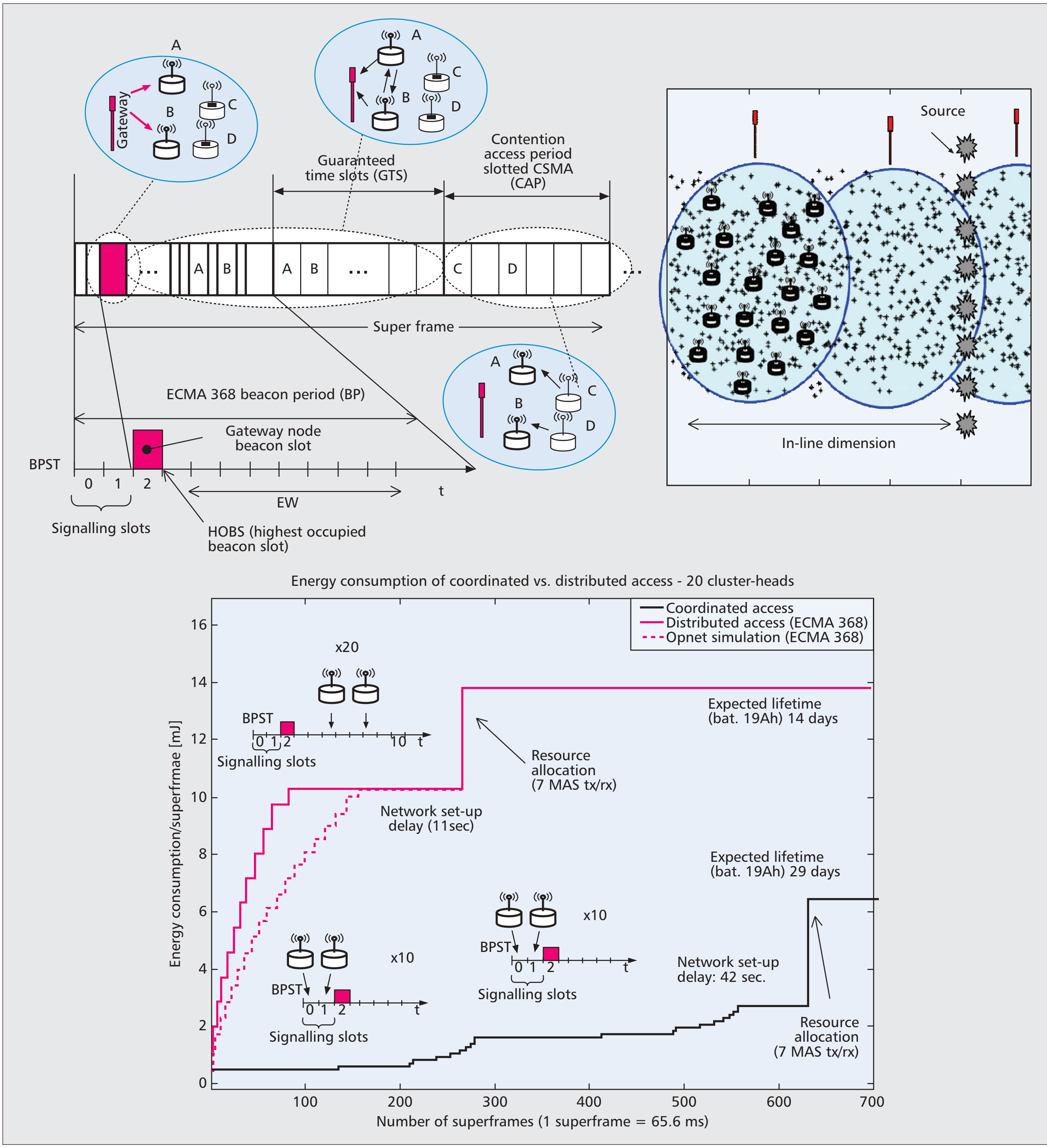


Figure 4. *Energy consumption (per superframe) assuming 20 cluster-heads joining the WGN. Transmit and receiving current consumption values are 200 mA and 350 mA, respectively [9] (voltage of 3.6 V). Cluster-heads are coordinating a maximum of 15 leaf nodes randomly deployed over the linear/strip network deployment (see top righ-corner sub-figure) with spacing that ranges between 5 and 10m. Battery lifetime for cluster-heads closest to the Gateway is computed by assuming: i) 300 active seismic channels per sub-network; ii) compression factor* N = 5 *bit/sample; iii) battery capacity 19Ah; iv) receivers are equipped with geophones. Set up delays are 11sec (red curves) and 42sec (black curve) for distributed and coordinated access respectively. Estimated lifetime is 29 days for coordinated access while it reduces to 14 days for distributed access. Simulations of distributed beaconing are verified through OPNET simulator (dashed curve). Top left-corner sub-figure: framing structure for WGN.*

granted through the exchange of request/reply messages embedded within the beacon frames. Enabling cooperative transmissions among the cluster-head nodes [10] is also highly recommended to guarantee efficient data delivery toward the Gateway. Cooperative network architectures [11] allow cluster-heads serving as relays to perform DRP requests for other devices in case transmission resources are not sufficient to transfer all the aggregated data to the Gateway .

Geophone Cooperative Localization

Geophones stay active in the field for several days but can be moved during the acquisition and they need to be accurately localized for processing purposes, even if a satellite could lack from visibility. Cooperative localization [13] provides a method to exploit the high accuracy ranging of UWB signals in conjunction with measurements from satellite-based positioning systems. The geophone localization protocol based on the cooperative framework reflects the architecture illustrated in Sect. IV-B where the leaf nodes (without GPS) are controlled by the anchor nodes (cluster-head nodes with GPS) and are prevented from communicating with other nodes outside the cluster. Cooperative localization is adopted for MB-OFDM PHY layer supporting a single OFDM band of 528 MHz and by implementing data communication over standard-compliant FFI channels.

Localization is based on times of arrival (ToA) estimation. Each node computes the distance toward at least three neighboring nodes from the estimation of the propagation delay. According to the Cramer Rao Bound (CRB) for ToA estimation [13] the range accuracy for delay estimation scales as $c/2\pi\sqrt{2\mathrm{SNR}} \times \beta$ for the signal-to-noise ratio SNR, effective bandwidth β = 500 MHz, and $c = 3 \times 10^8$ m/s.

The use of cooperative localization techniques can balance the degradation in localization accuracy experienced by MB-UWB radios as compared to IR-UWB. The example in Fig. 5 illustrates this concept: it shows the mean squared error (MSE) on the location accuracy [14] for different strategies and in terms of the error region around each node with 91 percent of confidence. Errors have been computed using the CRB for the ideal case of line-of-sight connections and path-loss exponent 3. Clock bias is not considered as round-trip measurements are assumed. Three different localization methods are compared: in the first one (case 1) nodes can estimate their positions based on the propagation delays measured from the GPS-equipped anchors within the visibility range (30m in this case). The observed average location accuracy is 3.7m (case 1, red ellipses) and it is far from being acceptable for seismic exploration. According to the WGN architecture introduced in Sect. IV-B, the nodes can exploit the opportunity to make additional ranging measurements with all other leaf nodes belonging to the same cluster: this cooperative localization approach (case 2, green ellipses) yields an accuracy of approximately 1m and it is suitable for seismic exploration application. The last case (case 3, blue ellipses) is shown as performance benchmark. In this case leaf nodes can ideally exchange ranging measurements with all the devices, irrespective of which cluster they belong to [14]. Average accuracy for this fully cooperative localization scheme is now below 0.5m.

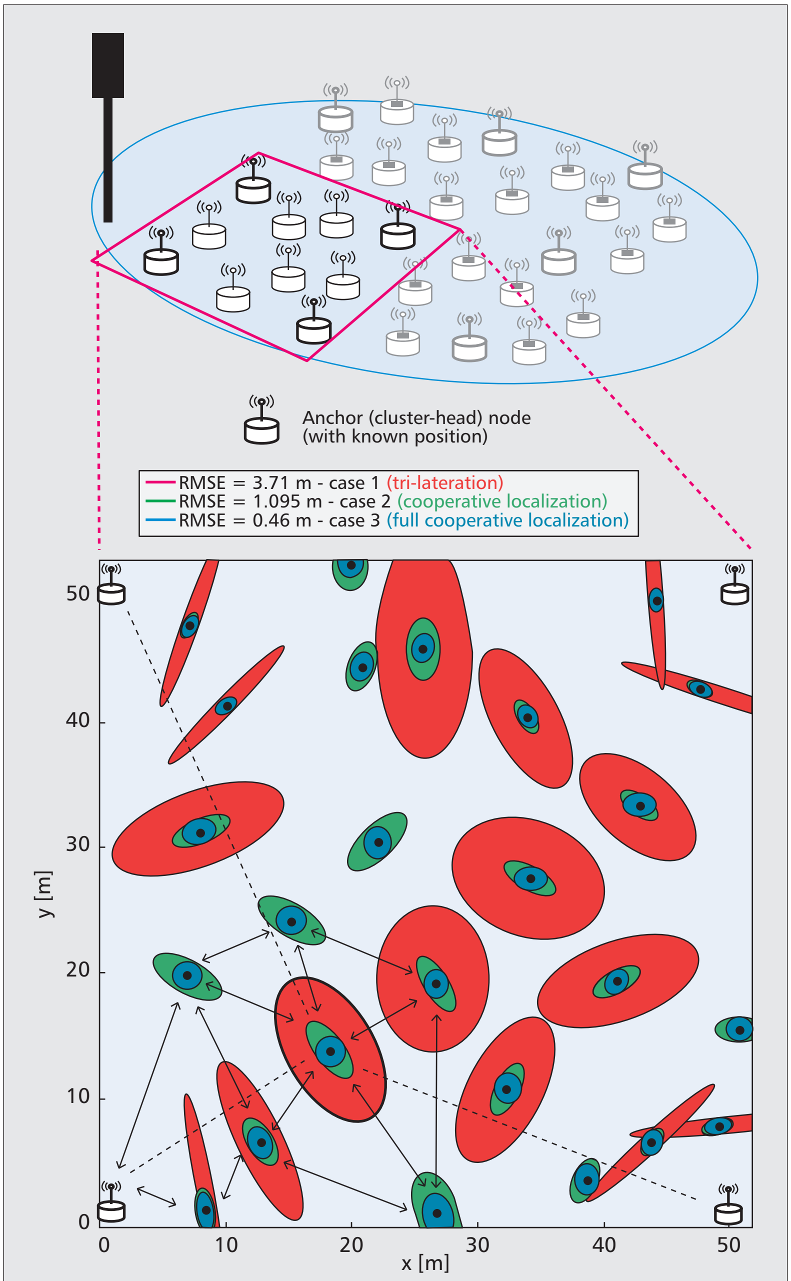
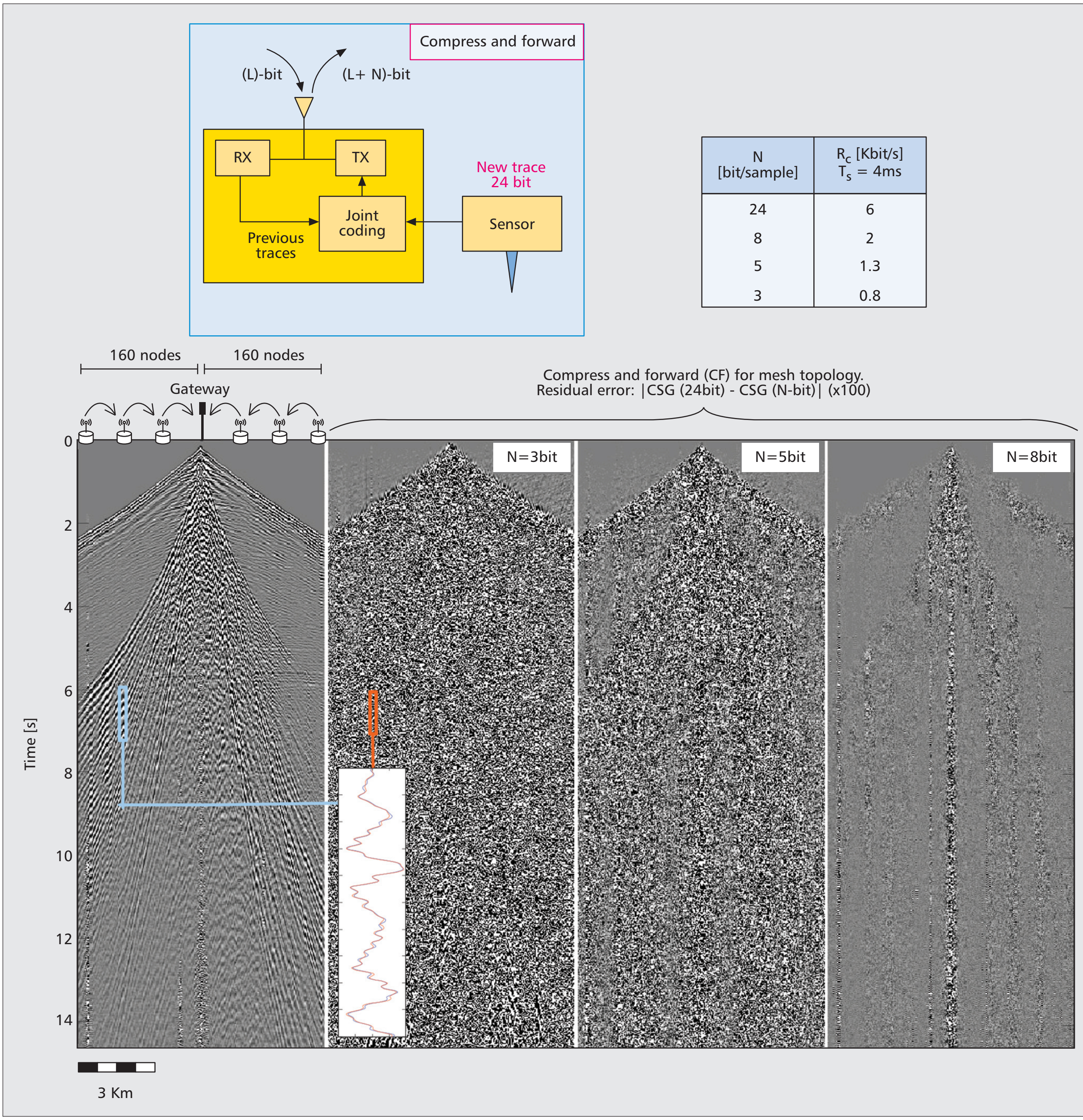


Figure 5. *Cooperative localization for WGN. MSE region for location accuracy with 91% of confidence for: i) conventional tri-lateration from anchors; ii) cooperative localization within the clusters and iii) fully cooperative localization. The SNR of the radio link scales with the inter-node distance* d *as* $d^{-\alpha}$*, with* $\alpha = 3$*. Average node spacing is 10m.*

Compress and Forward of Seismic Data

Even if high precision 24 bit A/D acquisition is routinely adopted to comply with large a dynamic of signals, source-coding tailored for the application largely reduces the overall data-rate to fit into the throughput limitations of low-power wireless solutions. The source coding scheme proposed here reduces the data-rate by exploiting the correlation of signals since larger correlation results in a lower number of bits per sample. To comply with the WGN architecture outlined earlier, every cluster-head node serving as a relay accumulates the data received from previous cluster-head nodes and compresses the observation by exploiting the trace-by-trace correlation. This compress and forward scheme is illustrated in Fig. 6. According to the multi-hop



N [bit/sample]	R_c [Kbit/s] T_s = 4ms
24	6
8	2
5	1.3
3	0.8

Figure 6. *Compress and forward for multi-hop with incremental seismic data encoding (data courtesy of eni exploration & production). Residual error (× 100) compared to original data (left image) for* N = *3, 5, 8 coded bit/sample (with detailed view of original and compressed* N = *3 bit/sample). Corresponding bit rate per seismic channel for varying coded bit/sample* N *is shown in the top-right corner table (for* T_s = *4ms).*

transmission, the new trace measured by the single-component node is jointly coded with previous ones and compressed. Before applying the incremental encoding, discrete time-warping is implemented by the cluster-head to align previous traces as described in [15]. The purpose is to explore the practical benefits arising from the joint exploitation of the temporal and the spatial coherence of seismic data that is made available by the multi-hop radio architecture. Compression is obtained at the price of some additional computational burden for each device.

Being a lossy data compression scheme, a practical example illustrates the limits. At the bottom of Fig. 6 it is shown the so called CSG with N = 24 bit/sample A/D: vertical axes depict arrival travel times measured by one sensor, while horizontal axis gathers the traces recorded sequentially from all the linearly deployed nodes in a one-shot operation. In this example, each relay node collects the data from the local sensor(s) and performs an incremental coding based on the data decoded from the previous devices. Data is forwarded to the Gateway placed halfway

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over a line of 320 nodes (single-component receivers). As sketched in Fig. 6, every node receives L bits/sample accumulated from previous hops and adds N bit/sample for each sample to represent the additional information drawn from the local new trace. The accumulated $L+N$ bits/sample are forwarded to the next node according to the multi-hop transmission scheme. Figure 6 shows the residual error when the source coder uses $N = 3,5,8$ bits/sample (instead of uncoded 24 bits/sample), with a meaningful reduction of the required bit rate for every seismic channel R_c (see the table on the top-right corner of Fig. 6). A reduction of R_c up to 3/24 compared to the case without compression can increase the number of channels each device is able to multiplex.

Compress and forward for high data rate seismic surveys is a new application-specific area of research driven by the need of real-time fully wireless instrumentation.

Concluding Remarks

In this article we introduced the basic principles of seismic acquisition systems from the wireless communication perspective. A number of requirements/specifications for the physical and MAC layer are provided in order to develop dense wireless geophone networks for oil exploration. The proposed WGN architecture is based on a mixture of network technologies that are working in cooperation to guarantee a large-scale, real-time, synchronous and spatially-dense monitoring system that reliably delivers the sensed data across the wireless network. In the proposed system wireless UWB nodes are simultaneously sensing, self-localizing and organizing into a cluster-mesh architecture for data delivery (compress and forward relaying). Gateways forward the aggregated traffic from UWB nodes to a central storage unit over long range radio links.

The recent technological advances clearly suggest that the wireless community is now becoming mature enough to develop a fully wireless system ready for the very dense land surveys expected by the oil exploration and monitoring industry within the next few years.

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