Pervasive UWB Sensor Networks for Oil exploration

S. Savazzi[1], L. Goratti[2], D. Fontanella[1,3], M. Nicoli[1], U. Spagnolini[1]
[1]D.E.I., Politecnico di Milano, Italy; [2]J.R.C., Ispra, Italy
[3] Institute of Geodesy and Navigation, FAF Munich Univ., Germany.
e-mail: (savazzi, nicoli, spagnoli)@elet.polimi.it, leonardo.goratti@jrc.ec.europa.eu, diana.fontanella@unibw.de

***Abstract*— Ultra-wideband (UWB) technology is now becoming mature enough to play a crucial role in a large variety of pervasive wireless sensor network applications. One of these applications is represented by land seismic exploration for oil and gas reservior. Seismic exploration requires a large number (2000 nodes/sqkm) of sensors to be deployed in outdoor over large areas (typ. 30 sqkm) to measure backscattered wave fields. A storage/processing unit (sink node) collects the measurements from all the sensors to obtain an image of the sub-surface in real-time. The UWB technology is proposed in this paper for replacing the cable connections between the sensors and the sink. UWB is the most suitable wireless technology for this application as it guarantees high data rate over short range links and self-localization with sub-meter accuracy. An UWB sensor network based on Multi-Band OFDM is designed for the specific problem. Amendmends to ECMA 368 specifications are also identified to allow for energy aware beaconing and self-localization.**

I. Introduction

Ultra-wide band (UWB) has attracted great attention from academia and industry in the past ten years. Nowadays it is a mature technology expected to play a crucial role in a large variety of pervasive wireless sensor network applications [1].

Land seismic exploration for oil reservoir requires a large number of sensors (geophones or accelerometers) to be deployed over wide areas forming large arrays that measure and digitalize back-scattered wave fields. A storage/processing unit (sink node) collects all the measurements from the geophones. Current cable-based surveys require hundreds of kilometers of cabling, moreover they impose stringent constraints on the survey design as the cables impact on the grid size and the particular acquisition geometry. Moving to wireless is now regarded by oil companies as a natural evolution for high-resolution seismic explorations [2]. The migration from cable systems to wireless will enable the deployment of an estimated one million sensors within the next decade [5].

Current proposals for wireless exploration architectures are based on a combination of WiFi links with cables [3]. Recent advances in UWB radio technology have led the wireless community to make a significant step forward to meet the rigid constraints imposed by seismic acquisition systems. The use of the Multi-Band OFDM [1] radio interface is proposed in this paper as the most suitable technology to *fully* replace the current cable system and guarantee real-time data delivery.

The goal of this paper is twofold: at first an introduction to the basic principles of seismic acquisition systems is presented, underlying the basic features and requirements. Next, a scalable network architecture is proposed based on the joint exploitation of MB-OFDM radio and wide-band 2.4GHz long range technology to attain the full cable replacing. The necessary amendments to ECMA 368 specifications are also identified to allow for energy aware beaconing and self-localization.

II. Oil exploration: a short tutorial

Conventional cable-based land exploration relies on telemetry cabling to handle remote control commands and to collect data samples from remote geophones in real-time. Seismic crews supervising the acquisition phase typically carry several hundred thousand sensors only for the operations over one survey [5].

In seismic exploration one (or more) energy *source(s)* are placed on the surface of the area of interest to generate short duration seismic pulses that create elastic waves propagating over the sub-surface [4]. Back-scattered wavefield is measured by 2D sensor arrays placed regularly (or quasi-regularly) on the surface (see Fig. 1), with typical spacings $5 \div 30m$.

Sensors (or geophones/accelerometers) are closely coupled to the ground to synchronously acquire and digitalize the displacement, velocity or acceleration of the ground. Each sensor measures the backscattered signal (seismic trace) over a fixed observation window. In geophysicist jargon, the *seismic channel* is used to refer to the stream of digitalized samples drawn from one sensor. Seismic channels are forwarded to a storage/processing unit to identify the geological structure of the sub-surface. As shown in Fig. 1, a land seismic 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]): *i)* the *shooting* phase where one (or more) source(s) of seismic energy are placed in a predefined position(s) and generate the elastic waves; *ii)* the *data delivery* phase where the backscattered seismic wavefield are synchronously sampled, quantized and either stored or forwarded by wireless nodes to the storage unit. The *node* (or *receiver*) might collect one sensor (or multiple sensors if using *multi-component receivers*). 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 [6] by combining the data received from all the nodes and for all the shootings.

978-1-4577-1764-2/11/$26.00

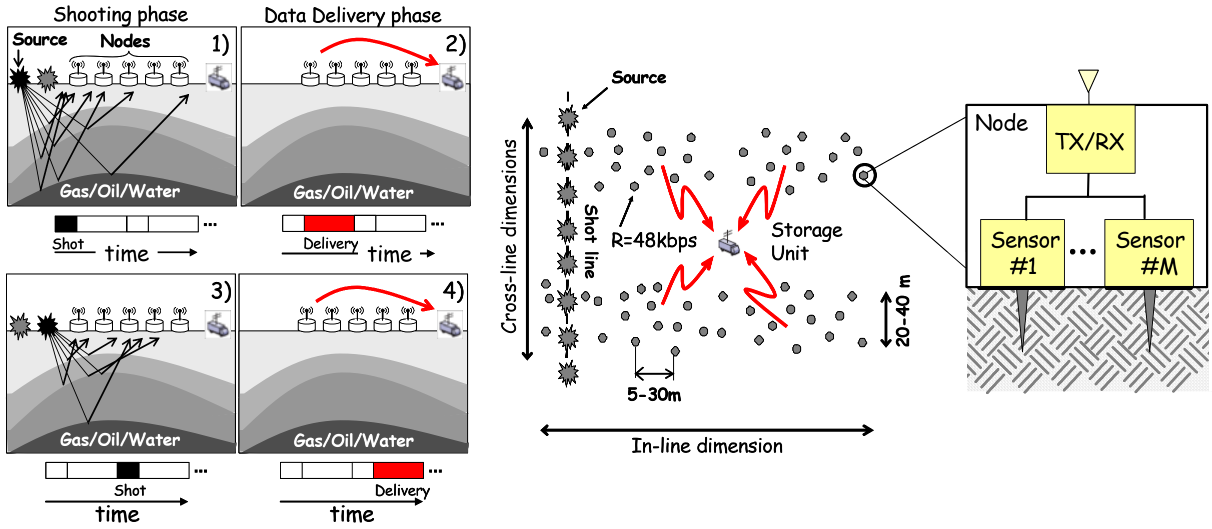

Fig. 1. (Left) Overview of land seismic acquisition system alternating shooting and delivery phases over a sequence of source locations. (Right) Typical 2D WGN network topology, node structure and system design configurations.

In what follows we focus on the *data delivery phase*. Wireless Geophone Networks (WGN) is the acronym that will be used to refer to the proposed network architecture for data delivery. The typical densities of active nodes in the WGN is 2000 nodes/sqkm [2], the field extension for one survey can be extremely large (up to 30 km^2, although larger field size is expected in the future). Sensors are deployed on the surface to form a number of receiver lines or arrays with an application-specific deployment as outlined in Fig. 1. Per-seismic channel data rate is $50kbps$: typically three component (3C) seismic accelerometers combine the data received from (up to) three different channels, so that the overall data rate is $150kbps$ [9]. Aggregated traffic over long multi-hop routes can easily reach $200 \div 300Mbps$. Lossy and loss-less compressions [10] are used to reduce the data rate per seismic channel. Battery life-time should be designed to cover $7 \div 30$ days. The reader might refer to [9] for further details about the basic network requirements. The effective position and elevation information for each receiver must be collected for accurate processing of traces. Natural and man-made obstructions can make the actual acquisition deployment to be largely different from nominal geometry. Accurate positioning with at least 1m accuracy is mandatory to avoid degradation of depth imaging quality.

III. WGN Architecture and Protocols

The real-time wireless telemetry system requires the entire seismic dataset to be transferred during acquisition. This is the solution that will be more deeply analyzed in the following as it *completely* replaces the cabling functionalities and does not require any data harvesting at the end receiver. Fig. 2 shows the hierarchical WGN architecture. Sub-networks are organized into clusters where nodes connect to the associated *cluster-head* device (referred to as Wireless Sensor Cluster-head - WSC). Leaf nodes (Wireless Sensors - WSs) are the low-power geophones: they periodically forward seismic data towards the associated cluster-head, receiving also control commands (e.g., acquisition start and stop commands). WSC nodes are connected in mesh mode and might be equipped with sensors as for the leaf nodes or be just relay nodes for coverage extension. Gateway nodes are coordinators of the sub-networks and are connected in mesh mode as well to transfer the seismic data from the sub-networks over long-range links.

UWB technology is here proposed to fulfill the tight constraints of the real-time telemetry system. UWB has bandwidth larger than 500 MHz so that it can provide good location estimation quality [13] and it can also support large data rates. 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 2.4 GHz based (wide-band) radio technologies, without paying meaningful cross-interference.

In 2007 the WiMedia Alliance and the European Computer Manufacturing Association (ECMA) proposed a number of protocol specifications (ECMA-368 standard [8]) that enabled Multi Band Orthogonal Frequency Division Multiplexing (MB-OFDM) for transmission of extremely high-speed data (up to $480Mbps$) within short-ranges of up to $5 \div 10$ meters and (expected) 30 meters in outdoor line-of-sight (LOS) environments (with data rates scaling down to $53.3Mbps$) [1]. MB-OFDM radio is multi-channel: available frequency spectrum is divided into 14 bands of $528MHz$ each, time and frequency-domain spreading codes (over groups of continuous bands) are also defined for interference management. Concatenated forward error correction (FEC) coding is used to provide link reliability: the encoder combines the convolutional coding over the OFDM sub-carriers and the Reed Solomon outer encoding.

ECMA-368 prescribes a beacon-enabled network architecture with transmissions organized in superframes (see Fig. 3 on top). A Beacon Period (BP) is placed at the beginning and contains up to 96 Beacon Slots (BS). BSs are transmitted at every superframe by all devices and carry essential information on devices status: supported data rate, received signal-

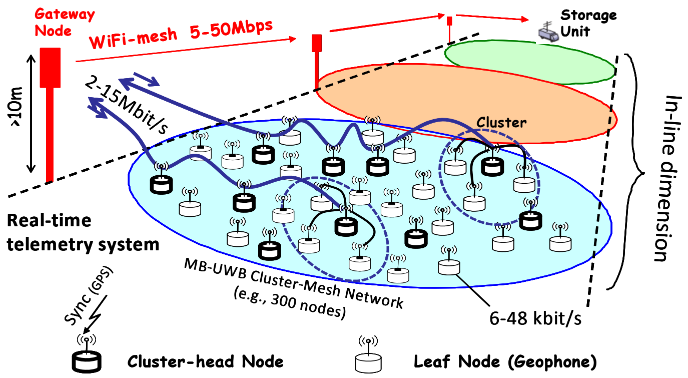

Fig. 2. Wireless Geophone Network system architecture.

strength, beacon period occupancy information, available and reserved transmission resources. The remaining part of the superframe is sub-divided into slots (medium access slots - MAS) of $256\mu s$ each. Devices can send their information after reserving collision-free slots through dynamic TDMA or by using prioritized random slotted access.

The use of broadband technologies is mandatory to manage the long-range mesh network of Gateways. Evolutions of industrial WiFi networks (IEEE 802.11n/s) with long-range support are currently under testing and could be attractive for their use in unlicensed frequency bands.

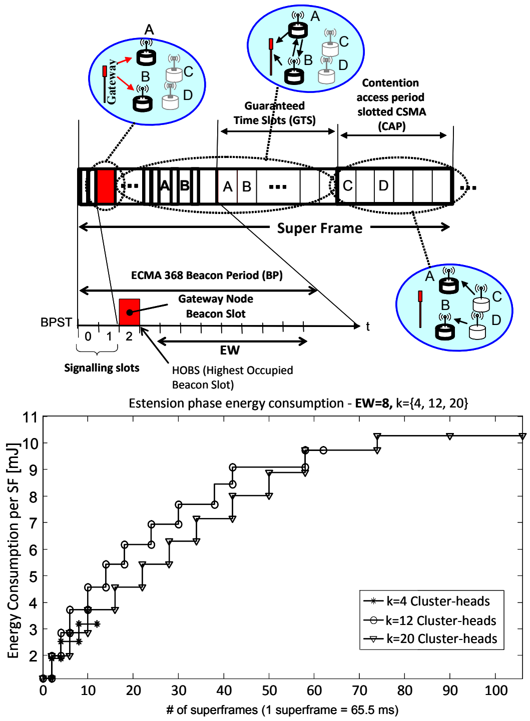

Fig. 3. Energy consumption (per superframe) assuming $k = 4, 12, 20$ cluster-heads joining the WGN and for EW=8 slots. Transmit and receiving consumption values are 200 mA and 350 mA, respectively [12] (voltage of 3.6 V).

A. Framing structure and energy-aware beaconing design

The Gateway and the WSC nodes are GPS synchronized and issue a single beacon in a reserved BS. The beaconing concept of ECMA is suitable for the specific application as it guarantees easy-to-spread synchronization, acquisition timing and connectivity for large size networks [8]. The Gateways have the role of intermediate sinks and periodically issue a unique reference time valid for all the device within the sub-network and referred to as the beacon period start time (BPST). After detecting the BPST, each WSC transmits beacon frames within the BP to maintain and propagate the reference time.

Low-energy consumption is a key requirement that must be carefully addressed for seismic exploration applications. Since ECMA specifications are not optimized for low energy [8], amendments to the standard are proposed here by borrowing some principles from the IEEE 802.15.4a specifications. To preserve energy, scaling down the number of devices that access the BP is mandatory to reduce the beacon collision probability and the time all the devices should stay active to decode the beacon information. One possible solution is to grant only to the WSCs and the Gateway nodes the right to access to the BP, while the other (reduced function) leaf nodes can be designed only to receive beacons, with no right to occupy any slot in the BP. Fig. 3 shows the energy consumed during the distributed beaconing phase for a typical case of k WSC cluster-head nodes simultaneously joining the BP (k is ranging from $k = 4$ to $k = 20$). To model the access of the BP by the WSC nodes, we consider a set of k devices forming a closed network (no other devices appear in the scenario). The Gateway is powered up earlier than the others to provide the BPST for the newcomers. The newcomer WSC devices join the network by attempting to acquire a unique collision-free beacon slot by using a slotted Aloha (S-Aloha) type of access in a predefined set of slots called extension window (EW). In order to model the multiple access of the WSCs to acquire a collision-free beacon slots we used an absorbing Markov chain that includes the effects of multipath fading impairments (for further details the reader might refer to [12]).

Leaf nodes WSs inside clusters communicate to the WSC node using random access within the final part of the superframe. Cluster-head nodes have to transfer all the (aggregated) seismic data to the Gateway. Since only a fraction of the cluster-heads are covered by the Gateway, routing of seismic data is mandatory. The cluster-head nodes use the so called distributed reservation protocol (DRP) defined in 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).

IV. Cooperative Localization

In this section a more in-depth analysis on the achievable accuracy of distributed localization is given. The main objective of the proposed cooperative localization protocol is to exploit the high precision ranging capability of UWB signals to provide accurate node location estimation. It is assumed that Gateways and WSCs use measurements from Global Navigation Satellite Systems (GNSS). Instead, reduced-function WSs

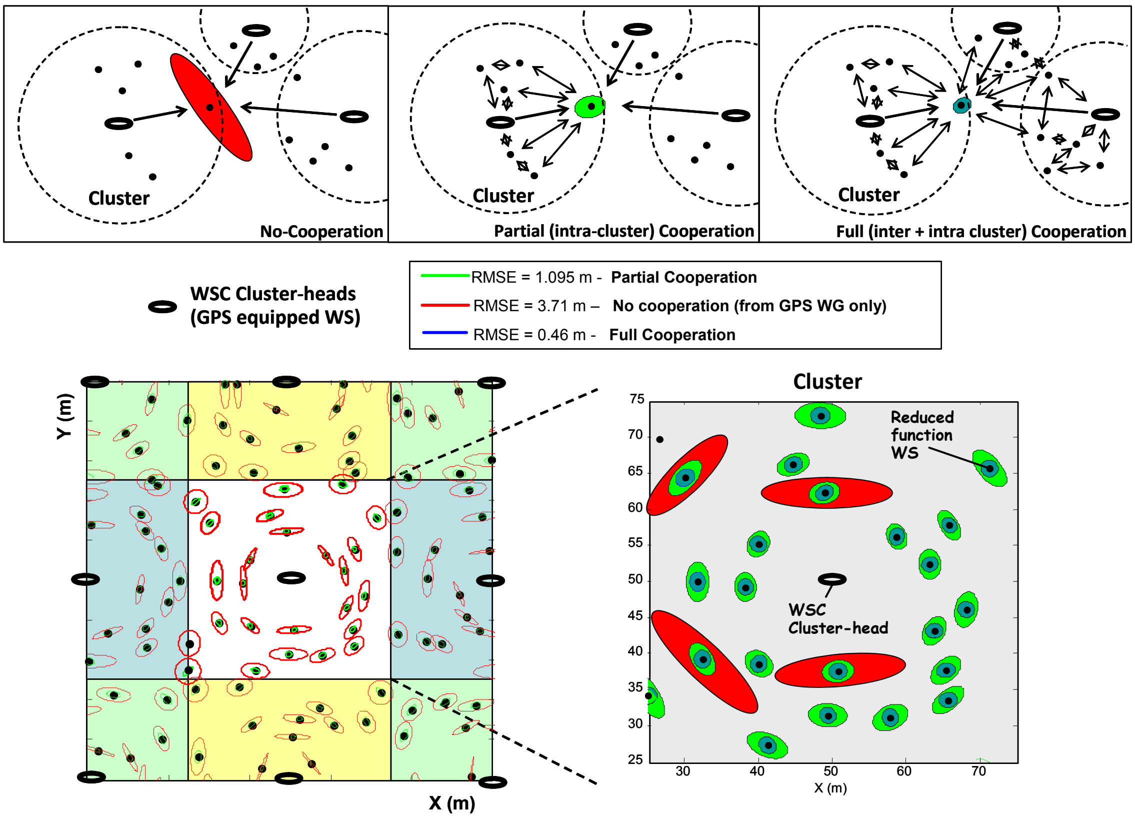

Fig. 4. Cooperative localization for WGN. CRB uncertainty ellipses for location estimation using 9 anchors. Three settings are analyzed: i) 'no-cooperation': tri-lateration from anchors; ii) 'partial cooperation': cooperative localization within the clusters (intra-cluster) and iii) 'full cooperation': fully cooperative localization (inter + intra cluster).

are not equipped with a GNSS receiver while they can estimate their positions by combining information from neighboring WSCs and WSs. In the following analysis the positions of Gateways and WSCs are supposed to be known, although in practical applications these are affected by uncertainties. GNSS positioning errors can be strongly reduced through augmentation systems or long time averages. The focus of this section is to highlight the advantages of cooperative localization with respect to conventional techniques. Numerical values are provided for comparison purposes.

Consider N UWB devices belonging to the same beacon group with locations $\theta_1, \ldots, \theta_N$, each defined by a pair of spatial coordinates $\theta_k = [x_k \; y_k] \in \mathbb{R}^2$, $k = 1, \ldots, N$. We assume that the first N_u nodes are leaf nodes (WSs) with unknown positions $\boldsymbol{\theta} = [\theta_1 \cdots \theta_{N_u}]^T = [\mathbf{x}^T \; \mathbf{y}^T]^T$, with $\mathbf{x} = [x_1 \cdots x_{N_u}]^T$ and $\mathbf{y} = [y_1 \cdots y_{N_u}]^T$, while the remaining $N_r = N - N_u$ are cluster-heads (WSC) located in known positions $\boldsymbol{\theta}_r = [\theta_{N_u+1} \cdots \theta_N]^T$ (e.g., through GPS). In cooperative localization [7], the estimation of the $2N_u$ parameters $\boldsymbol{\theta}$ is obtained from pairwise measurements $\{z_{k,\ell}\}$ made between any pair of (either known or unknown) nodes k and ℓ. Focusing on Time of Arrival (ToA) estimation, $z_{k,\ell}$ represents the estimate of the propagation delay $\tau_{k,\ell}$ between nodes k and ℓ. Each unknown WS node has a limited coverage and makes measurements only to reference devices (WSCs) located within a radius r from itself.

The proposed protocol reflects the cluster-mesh architecture illustrated in Sect. III-A where the leaf nodes (WS) without GPS are coordinated by the cluster-head that serves as anchor node. The specific cluster-mesh topology at MAC layer prevents the WSs to communicate with other devices outside the cluster. Localization protocol is initiated by a newcomer WS requesting the location information to a target WSC. Once the target WSC declares its availability to serve as cluster-head for the requesting WS[1], it assigns to all the WSs in the cluster a reserved time slot (localization beacon slot) used to propagate the training symbols for ranging estimation. In the next phase, ranging measurements are made by listening over all the localization beacons including those transmitted by all the WSC-anchors in the beacon-group. The noisy ToA measurement made by node k over the ℓ-node localization beacon can be modeled as follows:

$$z_{k,\ell} = \tau_{k,\ell} + e_{k,\ell}, \qquad (1)$$

where $\tau_{k,\ell} = h(\theta_k, \theta_\ell) = |\theta_k - \theta_\ell| / c$ (with c the speed of light) and $e_{k,\ell} \sim \mathcal{N}\left(0, \sigma^2_{k,\ell}\right)$ is the measurement uncertainty, here assumed Gaussian and uncorrelated to the other measurement errors $\{e_{m,n}\}_{m \neq k, n \neq \ell}$. Possible bias due to non-line of sight propagation can be included in the analysis as described in [7]. To remove the unknown clock off-set that affects the local ToA estimates, all the measurements (from WSC-anchors and WSs within the cluster) need to be fed-

[1] Details on the WS-to-WSC association procedure are not discussed here.

back to the target WSC using the available uplink slots (for the WSs) and the reserved BSs (for the WSC-anchors). Uplink slots are temporarily reserved (for positioning) to the WSs for broadcasting the ToA measurements. Allocation of uplink slots to WSs is handled by the target cluster-head serving as coordinator for the cluster. The target WSC can now assign a location to the WSs as for any pair (k,ℓ) of devices both $z_{k,\ell}$ and $z_{\ell,k}$ are available and clock-offset can be canceled (by exploiting both uplink and downlink for two-way message exchange).

A. Cramer-Rao bound performance analysis

Let the ToA measurements received by the WSC be arranged into the vector $\mathbf{z}$ where, based on the Gaussian assumption, it is $\mathbf{z} \sim \mathcal{N}(\mathbf{h}(\boldsymbol{\theta}), \mathbf{Q}(\boldsymbol{\theta}))$: $\mathbf{h}(\boldsymbol{\theta})$ is the vector of length M collecting *all* the terms $\{h(\theta_k, \theta_\ell)\}$, while $\mathbf{Q} = \mathbf{Q}(\boldsymbol{\theta})$ is the diagonal covariance matrix having as diagonal entries the variances $\{\sigma^2_{k,\ell}\}$. The range accuracy $\sigma_{k,\ell}$ is chosen according to the ToA estimation [13]: $\sigma_{k,\ell} = c/(2\sqrt{2\text{SNR}} \times B)$, where c is the speed of light, the SNR of the radio link scales with the inter-node distance $d_{k,\ell}$ as $d_{k,\ell}^{-\alpha}$ with path-loss exponent $\alpha = 3$ and $B = 528$ MHz is the effective signal bandwidth. Notice that to minimize co-channel interference and guarantee network scalability, transmissions within one sub-network of WSCs use one single sub-band as for Frequency Fixed Interleaved - FFI- channels. It is understood that significant performance improvements could be expected in case multiple sub-bands would be used.

For ToA-based cooperative localization, the Cramer-Rao bound (CRB) to positioning mean squared error (MSE) is a powerful indicator of the maximum achievable positioning accuracy assuming that the target WSC (in charge of locating the requesting WSs) has perfect knowledge of the ToA measurements statistics. CRB can be calculated according to [13] as briefly recalled in the following. For any unbiased estimate $\hat{\boldsymbol{\theta}} = [\hat{\theta}_k, \hat{\theta}_\ell] = [\hat{\mathbf{x}}^{\text{T}}\ \hat{\mathbf{y}}^{\text{T}}]^{\text{T}}$ it is: $\text{Cov}(\hat{\boldsymbol{\theta}}) \geq \mathbf{F}^{-1}$, where $\mathbf{F}$ is the $2N_u \times 2N_u$ Fisher information matrix (FIM). For the Gaussian measurement model herein adopted the FIM is $[\mathbf{F}]_{k,\ell} = [\mathbf{H}^{\text{T}}\mathbf{Q}^{-1}\mathbf{H}]_{k,\ell} + 1/2\,\text{tr}(\mathbf{Q}^{-1}\partial\mathbf{Q}/\partial\theta_k \times \mathbf{Q}^{-1}\partial\mathbf{Q}/\partial\theta_\ell^T)$ with $\mathbf{H} = \partial\mathbf{h}(\boldsymbol{\theta})/\partial\boldsymbol{\theta}^T = [\mathbf{H}_x\ \mathbf{H}_y]$ denoting the $M \times 2N_u$ gradient matrix.

In Fig. 4 we consider the localization problem for a sub-network composed by 112 WSs (now indicated with '•'), with unknown positions and 9 WSCs located in known positions (now indicated with circular markers). The nodes are regularly distributed on a grid with spacing of 10m along both directions, and then independently moved according to a random uniform noise in the square of 10m×10m centred on their initial positions. Each cluster includes the WSs inside the 50m×50m area surrounding the respective WSC.

We show the Cramér-Rao Bound on the location accuracy for three different cases: *i)* WSs estimate their positions using only the information coming from the WSCs (with GPS) that are included in the area of radius $r = 75$m. This approach referred to as 'no-cooperation' (red ellipses); *ii)* WS makes measurements with all other WSs in its own cluster (according to the proposed Cooperative Localization Protocol) and with WSCs in the radius r. This approach is referred to as 'partial-cooperation' (green ellipses); *iii)* WSs communicate with all their neighbors (both WSs and WSCs) included in the area of radius r. This approach is referred to as 'full-cooperation'[14] (blue ellipses). Average root mean square errors (RMSE) for partial and full cooperation approaches are in the order of 1m, thus making these solutions both suitable for land acquisition applications. The use of single-band as for FFI channels penalizes the performance of the 'no-cooperation' strategy as RMSE= 3.7m.

V. Concluding remarks

In this paper the requirements/specifications for the PHY and MAC layers are provided in order to develop dense wireless sensors networks for oil exploration. The proposed WGN system 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. MB-OFDM devices are simultaneous sensing, self-localizing and coordinating while delivering data to Gateway devices in mesh mode. Gateways forward the aggregated traffic to a central storage unit over long range. The recent technological advances clearly suggest that UWB technology is *now* becoming mature enough to be employed for a wireless telemetry system to support highly dense land surveys.

References

[1] Y. Rahayu, T. Rahman, R. Ngah, and P. Hall, "Ultra Wideband Technology and its Applications," Wireless and Optical Communications Networks, WOCN. 5th IFIP International Conference on, 2008.

[2] B. Peebler, "Looking ahead to 2020 in the world of geophysics," First Break, vol. 29, no. 1, pp. 31-32, Jan. 2011.

[3] S. Savazzi, U. Spagnolini, "Land cable-less systems for telemetry services: current limitations and emerging technologies," First Break, vol 29, no. 2, pp. 73-79, Feb. 2011.

[4] Oz Yilmaz,"Seismic Data Analysis. Processing, Inversion and Interpretation of Seismic Data" vol I and II, Stephen M. Doherty Editor, Society of Exploration Geophysicists (SEG), 2001.

[5] G. R. Rached, "Channel-count requirements for 3D land seismic acquisition in Kuwait," EAGE 69th Annual Conference and Exhibition, London, Expanded Abstract, 2007.

[6] M.Nicoli, V.Rampa, U.Spagnolini, "Hidden Markov Model for Multidimensional Wavefront Tracking," IEEE Trans. on Geoscience and Remote Sensing, vol.40, n.2, pp.651-662, March 2002.

[7] N. Patwari et al. "Locating the nodes," IEEE Signal Proc. Magazine, pp. 54-69, July 2005.

[8] Standard ECMA-368, "High Rate Ultra Wideband PHY and MAC standard," December 2007.

[9] S. Savazzi, U. Spagnolini, "Synchronous Ultra-Wide Band Wireless Sensor Networks for oil and gas exploration," Proc. IEEE Symposium on Computers and Communications, Sousse, Tunisia, July 2009.

[10] S. Savazzi, D. Molteni, U. Spagnolini "Energy-Aware Compress and Forward systems for Wireless Monitoring of Time-Varying Fields," Proc. of IEEE PIMRC, Istanbul, Turkey, 26-29 Sept. 2010.

[11] V.M. Vishnevsky, A.I. Lyakhov et al., "Study of Beaconing in Multihop Wireless PAN with Distributed Control," IEEE Trans. on Mobile Computing, vol. 7, no. 1, pp, 113-126, Jan. 2008.

[12] L. Goratti, A. Rabbachin, S. Savazzi, M. Latva-aho, "Analysis of Multi-Band UWB distributed beaconing over fading channels," Proc. IEEE International Conference on Ultra Wideband [Invited Paper], Bologna, Italy, 14-16 Sept. 2011 .

[13] S. Gezici et al., "Localization via ultra-wideband radios: a look at positioning aspects for future sensor networks," IEEE Signal Processing Mag., vol. 22, pp. 70–84, July 2005.

[14] M. Nicoli and D. Fontanella, "Fundamental performance limits of TOA-based cooperative localization," Proc. IEEE ICC, June 2009.