Synchronous Ultra-Wide Band Wireless Sensors Networks for oil and gas exploration

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Abstract—**The fluctuations of the price of crude oil is pushing the oil companies to increase the investments in seismic exploration of new oil and gas reservoir. Seismic exploration requires a large number ($500 \div 2000$ nodes/sqkm) of sensors (geophones or accelerometers) to be deployed in outdoor over large areas (≥ 20 sqkm) to measure backscattered wave fields. A storage/processing unit (sink node) collects the measurements from all the geophones to obtain an image of the sub-surface in real-time. Current connectivity is cable based and requires hundreds of kilometers of cabling causing delays, high logistic costs and low imaging quality.**

This paper serves as a tutorial to introduce the basic principles of seismic acquisition systems from a wireless communication perspective and provides a number of requirements/specifications for the physical, MAC and network layer to develop wireless sensors networks tailored for oil (and gas) exploration. The Wireless Geophone Network (WGN) system will replace the actual cabled systems used in on-shore seismic acquisition. Oil companies are currently pushing for wireless solutions. Early results suggested that a fully WiFi network does not satisfy all the requirements. This motivates the use of a mixture of technologies. In the proposed system wireless UWB devices/sensors are simultaneously sensing, self-localizing and synchronizing while delivering data to Gateway devices in mesh mode. Gateways forward the aggregated traffic to storage unit over long range.

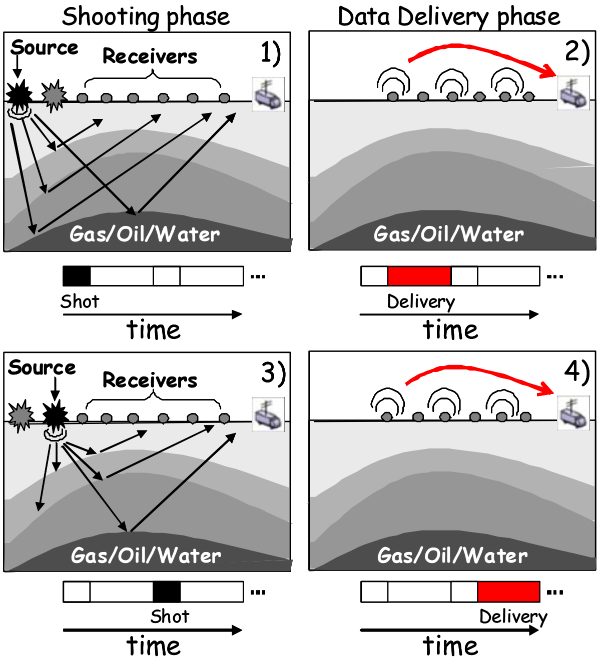

Fig. 1. Land seismic acquisition. Seismic waves are generated at surface by sources that are activated on different times and locations, elastic waves are back-scattered from sub-surface and are received by geophones. For every shot geophones recordings are delivered to the storage unit.

I. INTRODUCTION

Wireless Sensor Networks (WSNs) represent well-known paradigm that collects a set of emerging technologies that will have profound effects across a range of industrial, scientific and governmental applications [1]. A WSN is made up of a group of battery-powered wireless sensor nodes: each node possesses the ability to monitor some aspect of the environment and is able to share its measurements by communicating wireless through other nodes towards some destination (a Storage Unit - SU, or fusion center) where data from the network is gathered and processed.

Recent developments in wireless technologies and semiconductor fabrication of miniature sensors are making WSNs smaller and more cost-effective for a growing number of pervasive applications. New radio technologies such as UWB and Multi-Band OFDM (MB-OFDM) [2] are expected to provide tiny and ultra-low power sensors with the capability of supporting raw data rates of up to $500 Mbps$ within very short range distances. The most promising opportunities to apply these technologies primarily arise in networks that are composed by a large number of radio terminals with stringent delay requirements and high throughput. Although a wide number of applications have been proposed for WSN [3], their market penetration and volumes do not currently seem to offer the expected opportunity to *fully* explore the potential of these technologies. Wireless community could therefore look at the new cable replacing applications that can guarantee WSN systems to move towards larger business volumes.

A. Wireless Geophone Networks for oil and gas exploration

The envisioned production peak of current oil and gas reservoirs is pushing the oil companies to increase the investments in seismic exploration of new oil reservoirs and in new technologies to improve the quality of depth imaging. In particular, investments on land surveys are increasing as it becomes now economically feasible to extract oil from formerly inconvenient reservoir (e.g., dense oil on low-porous fields, sub-urban environments, etc..). Middle and long-term projects aim to define the real capacity of existing oil fields (e.g., South Fuwaris Field) or to get a better resolution over areas as large as the whole Kuwait (17.820 sqkm) [4]. Seismic

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exploration requires a large number of sensors (geophones or accelerometers) to be deployed over wide areas to form large arrays that measure (and digitalize) back-scattered wave fields. A storage/processing unit (sink node) collects all the measurements from all the geophones. Typical cable-based surveys require hundreds of kilometers of cabling, linked by thousands of connector contacts. Moreover, cable-based architectures impose stringent constraints on the survey design as the cables impact on the grid size and the particular acquisition geometry. The logistic and weight costs caused by cables for high density receivers can be heavily reduced up to 50% by deploying geophones equipped with wireless trans-receivers to form a Wireless Geophone Network (WGN) [6]. Moving from wired to wireless has several advantages: first of all, WGN can reduce the high cabling, installation and maintenance cost of traditional wired data-acquisition systems. Furthermore, tiny wireless devices are easily deployable to make the acquisition structure more flexible and dense (say $1000-2000$ devices/sqkm) with improved monitoring quality (sub-surface imaging).

Although proposals for cable-free system date back to the seventies, the introduction of WiFi and Bluetooth technologies offered new prospects and technological solutions to system designer. However, technical limitations of WiFi/Bluetooth (in terms of data-rate efficiency, interference, battery-use, propagation-loss, etc...) force the current proposals for WGN architectures to choose a mix of wireless and cables [5]. Recent advances in WSN technology have led the wireless community to become *now* mature to meet the rigid constraints imposed by seismic acquisition systems.

The goal of this paper is twofold: at first it is provided a tutorial to introduce the basic principles of seismic acquisition systems by underlying the basic features from a wireless communication perspective. Second, a number of requirements/specifications for the physical, MAC and network layer are analyzed in order to develop wireless sensors networks for oil exploration. The proposed Wireless Geophone Network (WGN) system is based on a mixture of technologies: wireless devices/sensors are simultaneously sensing, self-localizing and synchronizing while delivering data to Gateway devices in mesh mode. Gateways forward the aggregated traffic to a central storage unit over long range.

The paper is organized as follows: after a brief tutorial on land seismic acquisition system (Sect.II), in Sect.III it is proposed a mixed architecture that can fit with the constraints of WGN. Once defined the architecture, the main PHY and MAC layer requirements are outlined in Sect. IV and Sect. V, respectively.

II. LAND SEISMIC ACQUISITION SYSTEMS

In this section we provide an outline of the basic principles of seismic prospecting (the reader might refer to the wide literature for more in-depth discussion, see e.g., [4]-[5]). On the surface, one (or more) energy source(s) (e.g., dynamite or a controlled-source as a vibrated plate) referred to as *source point* generates elastic waves that propagate over the sub-surface. These elastic waves are reflected and refracted by any media discontinuity with different elastic properties. Sensors (geophones or MEMS based accelerometers) measure the back-scattered wavefield that convey reflected elastic energy. Digital signals are sent to a storage/processing unit (sink node). Acquisition system consists of two distinct phases that are repeated periodically:

1) the *shooting phase* where one (or more) source(s) placed in a predefined position(s) is generating the elastic wave;
2) the *data delivery phase* where the digital seismic data is measured and forwarded by the geophones to the storage unit.

As shown in figure 1, shooting and data delivery are repeated periodically by moving the impulse source(s) over a grid of (typically) $20 \div 30m$ of spacing (shot interval, see 2D network geometry in figure 2). The storage/processing unit estimates the elastic discontinuities of the sub-surface by combining the data received from all the geophones. The goal is to create a picture of the sub-surface that might be indicative of new oil/gas reservoir. The quality of depth imaging scales with the number of geophones (e.g., the receiver density) and on the field extension.

In what follows the *data delivery phase* is considered by focusing on the basic network requirements (in terms of sensor density and throughput), details on network topology are also summarized in figure 2. The reader might refer to [5] for further details on the analog and digital processing to be carried out locally at each sensor/geophone.

Network geometry and size. High density land seismic acquisition systems will provide up to $N = 20.000 - 30.000$ sensors simultaneously active [4] with typical densities of 2000 sensors/sqkm. 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 figure 2. A receiver line might consist of up 2000 geophones: each line is made of multiple micro-lines with sensors ideally placed over rectangular (or rhombic) lattice with horizontal (in-line) and vertical (cross-line) spacing of $\Delta_x = 10 \div 30m$ and $\Delta_y = 5 \div 10m$, respectively. Natural and man-made obstructions make the network deployment far from being regular in practice. Distance among two receiver lines can be as large as 300 meters. A similar topology is designed for the sources deployment.

Network throughput. Sensor activity consists in sampling back-scattered wave-field with minimum sampling time $T_s = 0.5ms$, samples are digitalized using $b = 24$ bits resulting in an overall per-node data rate of $R = b/T_s \simeq 50kbps$. Typical three component (3C) seismic accelerometers combines the data received from (up to) three different channels so that the overall data rate can be three times larger as $R \simeq 150kbps$. Since one survey might require up to 30.000 sensors, the aggregated throughput for one survey, where all sensors are transferring real-time all data to storage unit, can be as high

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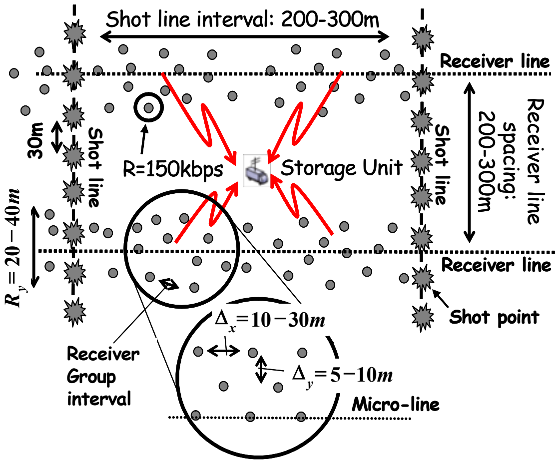

Fig. 2. Seismic acquisition: 2D network topology.

as $N \times R \simeq 4.5Gbps$[1].

Delay constraints and real time telemetry. Land surveyors that are monitoring the status of the recording process must be capable of controlling the quality of the received data in real time (soon after each shooting phase). Real-time transmission needs to be therefore guaranteed so that data readings from sensors can be delivered before the next shooting phase is started. The system needs to be designed for working *continuously* for days ($3 \div 7$ days) so that seismic instrumentation might be left unattended for a long period.

Synchronous acquisition and remote control. The storage unit provides with the necessary functions of *i)* starting and ending acquisition; *ii)* uplink/downlink monitoring of each sensor; *iii)* synchronizing the acquisition with maximum timing skew that is a fraction of the sampling time T_s, say below $10\mu s$.

Localization. Seismic acquisitions require land surveyors to collect the effective position and elevation information for each receiver. A complication in measuring the true receiver position is that natural and man-made obstructions can make the actual acquisition deployment to be largely different from nominal geometry. Accurate positioning after geophone deployment (with error below $1m$) is mandatory to avoid degradation of depth imaging quality.

III. WIRELESS GEOPHONE NETWORK: ARCHITECTURE

A Wireless Geophone Network (WGN) must support multiple acquisition settings and applications [7]. Compared to cable-less systems, it is expected to provide better spatial sampling and reduced logistic costs. The network must be independent on the type of sensor (as for geophones or accelerometers). Short-range wireless technologies offer some very attractive features for WGN deployment such as high data rate, low power consumption and efficient multiple access control strategies. However, these technologies are limited by the restricted coverage capabilities that constrain the extension of the seismic field. Although long-range radio technologies (e.g., WiFi or WiMax) could in principle provide the necessary coverage even for the largest field extensions (by mesh mode), they are not designed for energy efficiency (and suffer from significant weight costs and low battery-life), nor for arbitrary deployment and low-complexity self-configuration. These constraints enforce practical limits on the maximum number of (WiMax or WiFi compliant) devices that can be deployed.

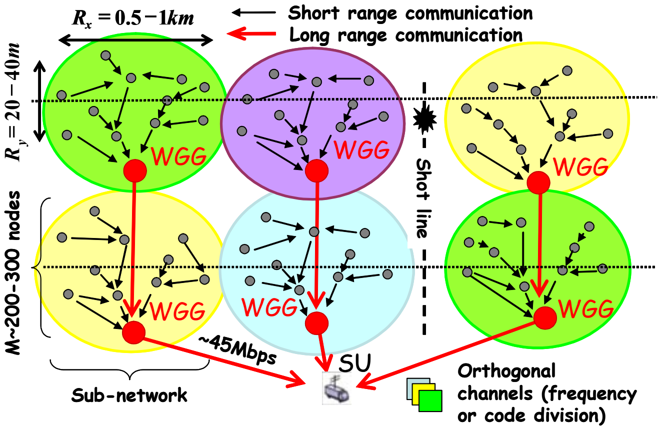

Fig. 3. Wireless Geophone Network system architecture

The large field extension (of several sqkm) and the high receiver density require the WGN to exploit appropriate radio transmission technologies to efficiently handle either *short-range transmissions* (e.g., for short-distance low-power communication among geophones) and *long-range transmissions* (for seismic data delivery to storage unit and geophone remote monitoring) that must cover distances of several kilometers. Creating a network that is able to support multiple radio technologies requires the deployment of specific wireless infrastructure to handle the coexistence of short-range and long-range radios. Figure 3 describes a hierarchical Wireless Geophone Network architecture supporting short and long range transmissions. The design requires a number of Wireless Geophone Gateways (WGGs) that are strategically deployed to collect data readings from a (large) number of wireless devices. The network is made of the following three network entities.

Wireless Geophones (WG) are devices/sensors that are receiving and digitalizing back-scattered waves. These are forming independent mesh sub-networks that are operating independently. Different channels/frequencies are used to separate transmission of co-located sub-networks. WG device functions include:

1) Simultaneous sensing an external measurement (synchronized acquisition with timing skew in the order of $1 \div 10\mu s$);
2) Acquiring self-localization of actual positions;
3) Exchanging the following information with the Gateway: *i)* received seismic measurements; *ii)* device position-elevation information; *iii)* time-stamp and shot number information.

Wireless Geophone Gateway (WGG*)* serves as Coordi-

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[1] Typical aggregated throughput can vary depending on the type sensor (number of components) and field extension. Aggregated throughput of one receiver line can be in the order of $300Mbps$

TABLE I

PHY LAYER REQUIREMENTS FOR SEISMIC ACQUISITION SYSTEM.

Short-range communication (within one sub-network)	
Per-link throughput	$45Mbps$ (short range)
Sub-network size	$\sim$ 300 nodes
Range (outdoor)	$10-30m$ (max $50m$)
Power consumption (Active) (Power Save)	$100mW$ $20\mu W$
Target Bit Error Rate	10^{-5}
Device Synchronization	Frame alignment max error: $1\mu s$.
Number orthogonal channels	> 3
Localization	(error $< 1m$)
Long-range communication (WGG)	
Per-link througphput	$100Mbps$
Range	$2km$

nator for one sub-network of WGs. WG Gateway is a GPS-equipped device with a reserved identification known by all WG devices in the sub-network. Gateway should guarantee the following mandatory functions:

1) Propagate the framing structure and clock information (to guarantee synchronized acquisition) to all connected WGs (all the WGs belonging to the same sub-network);
2) Propagate downlink control messages to connected devices: START/STOP and SLEEP;
3) Enable transmission resource reservations for new WGs;
4) Receive and store uplink data from WG devices (Gateway is acting as an *intermediate* sink node);
5) Guarantee full interoperability among short and long-range radio technologies.

Storage Unit is the WGN Coordinator and collects the data received from all the WGGs. Storage unit is capable of controlling each WGG (and thus each WGs) through the following essential broadcast (downlink) control messages:

1) START/STOP: Acquisition start/stop at pre-defined time-stamp;
2) ACK: Acknowledge data frames from WGGs (or WG sub-networks);
3) REGISTER: Register new connected WGGs (or WGs sub-networks) and trace the position of connected WGs
4) SLEEP: Force devices (e.g., belonging to one sub-network) to enter in power save mode (sleep mode) for a predefined time interval.

Continuous recording (for real-time data transfer) is guaranteed as long as long-range transmission of WGG towards the storage unit can be engaged during the upcoming shooting phase without delaying the next data delivery phase. Long/short range transmissions need therefore to coexist over the same medium by using different frequency bands to avoid mutual interference. In what follows, we outline the main technological requirements for the two-tier architecture illustrated. To ease the reading, requirements are divided into PHY (Sect. IV) and MAC (by limiting the analysis to the sub-network management in Sect. V) layers.

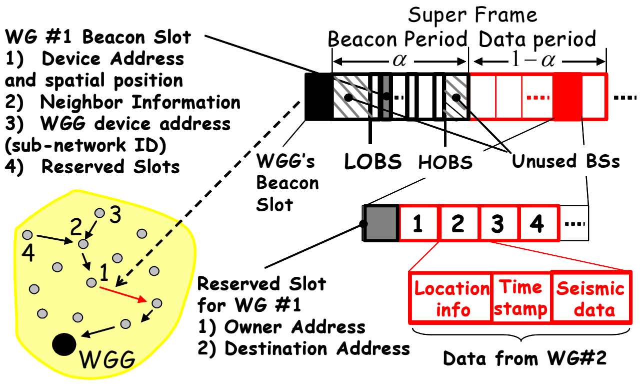

Fig. 4. Framing structure and essential MAC layer requirements: WG Gateway provides the BP and acts as intermediate sink with a reserved Beacon Slot and address. Each WG locally selects its BS and is carrying data of other sensors within its reserved slot.

IV. PHYSICAL LAYER REQUIREMENTS

Mandatory PHY layer requirements are confined in Table I. The number of devices per sub-network should be as high as $M \sim 300$ nodes to minimize the number of Gateways. This results in an aggregated (per sub-network) throughput of $R \times M \sim 45Mbps$. Data delivery within one sub-network is obtained by multi-hop transmissions towards the Gateway namely to reduce energy consumption (and battery life). Therefore, WG devices that are neighbors to the Gateway will handle all the aggregated traffic from all the other WGs in the sub-network.

Requirements on self-localization and frame synchronization (see Table I) can make UWB technology the most natural choice for short-range WG-to-WG (multi-hop) transmissions within one sub-network [8]. For low-power transmissions where Signal to Noise ratio is limited, a position accuracy with error below $1m$ needs travel time estimation error for (ToA based positioning [10]) in the order of $3ns$ with a minimum required signal bandwidth of $500MHz$. The use of UWB can allow for the acquisition of the synchronization without the need of deploying fully GPS-equipped WGN (with savings in term of costs and battery-use). Moreover, recent advances in radio design allow for devices supporting high data rates (larger than $45Mbps$) within short ranges and low power consumption (below $100mW$ in active transmission mode and down to $20\mu W$ in power save mode) [2]. Multi Band OFDM radio can generate UWB signals conforming with the data rate and power consumption requirements: similarly as for 2.4 GHz-based radios, the MB-OFDM processing can also guarantee network scalability through time and frequency division (enabling the use of multiple sub-bands) to separate the co-located sub-networks of WGN in figure 3. Another key property of UWB technology for WG transmission is that it can be used for short-range in conjunction with other 2.4 GHz-based long-range radio technologies like WiFi (IEEE 802.11n/s) and WiMAX (IEEE 802.16d), without paying meaningful cross-interference.

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V. MEDIUM ACCESS CONTROL REQUIREMENTS

The large number of devices per sub-network ($M \sim 300$) suggest the adoption of a number of *distributed* MAC functionallities. At the same time, the network should support the hierarchical topology with the Gateway acting as an intermediate sink towards the Storage Unit. Logical WG groups are formed around each WG to facilitate resource sharing while wireless medium reuse can be exploited over different spatial regions (spatial reuse). The following specifications for MAC and Network layer are mandatory for WGN:

Beacon enabled network. Sub-network should be beacon enabled and organized in piconets that are self-coordinated [9]. Beacon Slots (BS) are located in a predefined part of a super-frame structure (see figure 4) referred to as Beacon Period (BP). Only BSs can be sent during BP. Each device is able to select its own BS within the BP through a *distributed* assignment procedure.

WG Gateway and relaying capability. The large size of the WG sub-network (see figure 3) prevents the Gateway to monitor each WG through direct connection. WG devices should be capable of relaying data to/from other devices.

Contention free access. The stringent requirements in term of delay should prevent the adoption of contention based access methods (at least without any prioritized service). Contention-free methods should be considered for WGN at the price of a longer connection set-up phase (but still reasonable as WGN is expected to work continuously for several days). A device is successfully connected if transmission resources (i.e., BSs and time slots for data delivery) are (collision-free) reserved for uplink and downlink communication towards the Storage Unit. A device can be connected to a Storage Unit through intermediate devices serving as relays as for multi-hop/mesh communication.

WG functions. Connected WG must declare: i) information about its neighbor nodes; ii) the number and the position of collision-free time slots; iii) the Gateway address that is acting as intermediate sink for the WG device; iv) its spatial position (after self-localization is achieved).

VI. WIMEDIA MAC MODIFICATIONS SUPPORTING WGNS

WiMedia MAC (standard ECMA 368 [11]) has been chosen as a reference standard to be used in order to develop the MAC for WGN. According to the requirements outlined in Sect. V, WiMedia MAC supports fully distributed functionalities that can met the requirements on network scalability. However, a number of modifications are required namely related to the Gateway that is acting as sink node as for conventional wireless sensor networks. In WiMedia MAC transmission is organized in superframes with the Beacon Period (BP) placed at the beginning. Superframe is subdivided into 256 slots (medium access slots - MAS) of $256\mu s$ each. Up to 96 Beacon Slots (BS) of $85\mu s$ form the BP. BSs carry essential information on devices status (active or hibernation mode, supported data rate, RSSI), beacon period occupancy (BPOIE), available and reserved transmission resources (MAS reservations). Each device is constrained to transmit its own beacon and BSs are locally assigned without any central coordination.

The inherent hierarchical structure of WGN constrain the WG Gateway node to support specific extended functions (see Sect. III) compared to a standard WG device. These functions should allow the Gateway to behave as intermediate sink collecting data for the Storage Unit. WiMedia MAC allows the exploitation of i) spatial reuse, ii) distributed beacon assignment (as for self-organizing networks), iii) distributed resource reservations and iv) advanced beaconing management. However, these specifications do not support devices with extended functionalities and acting as sink nodes (as for typical sensor networks). In addition, the large number of devices have a dramatic impact on network performance. Assume that WGs are one-by-one randomly activated on by land surveyors (according to the topology described in Sect.II) and *after* the Gateway is activated. The groups of WGs that are out of the range of the Gateway (out of the Gateway's beacon group) would create their own BP after scanning for existing beacons. Asynchronous beacon groups (with unaligned BP Start Time - BPST) might come into two-hop range when new WGs are deployed, resulting in superframe overlap and strong interference. If the number of WGs is large multiple BP merging (as prescribed by WiMedia [11]) might be rather unpractical. Essential modifications to WiMedia MAC are the follows (other requirements for the framing structure are confined in figure 4).

BS transmission. To avoid multiple BP merging, we propose the Gateway node to be the *only* device that is allowed to create the BP. Gateway is uniquely identified by a reserved BS (e.g., the first slot after the signalling slots, see figure 4) and a device address known by all the WGs (to identify the sub-network). When activated, WGs should periodically listen for a new BP that can be received from the Gateway itself or relayed by intermediate WGs.

Beacon period optimization. The large number of devices and geophone density deployed poses limiting constraints on how many devices can successfully obtain a BS (without creating collisions) and be ready for resource negotiation. A long BP might allow a large number of nodes to obtain a BS without collision, at the price of a reduced time for data delivery [12]. The BP duration α (see figure 4) needs to be optimized based on the acquisition parameters.

BS assignment. Random beacon slot selection and beacon contraction [13] may cause severe connection delays, namely for a large network size. Being the network fixed, more sophisticated BS assignment techniques (to avoid long back-off periods) should be developed.

Fixed Frequency Interleaved channels. Different Fixed Frequency Interleaved (FFI) channels are associated to interfering (co-located) sub-networks. WGs belonging to the same sub-network are prevented to use other channels.

Distributed (route) Reservation Protocol (DRP). Hard reservations should be used for resource negotiations over the routes towards the Gateway. Reservation Requests (for explicit negotiation) should be made for both uplink and downlink communication (this is necessary as the Gateway node must be capable of controlling each WG device by downlink messages). DRP concept should be extended to allow for multi-hop route reservation. A route reservation is

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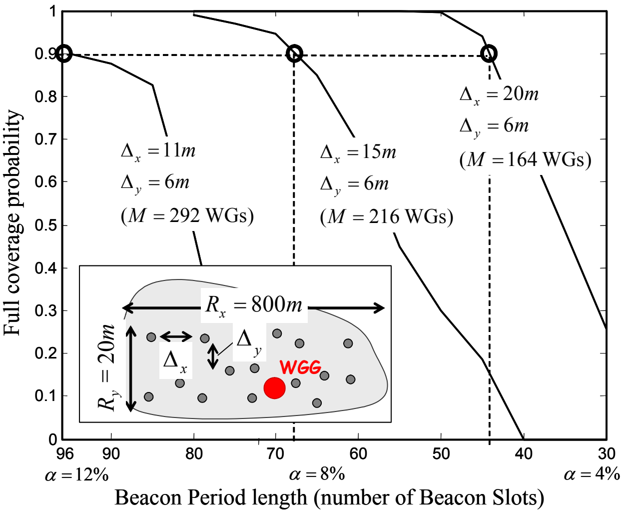

Fig. 5. Probability of full network coverage versus the length of the Beacon Period. Different acquisition geometries are considered ($\Delta_x = 11m, 15m, 20m$) with $\Delta_y = 6m$, $R_x = 800m$ and $R_y = 20m$.

a collection of DRP reservations that guarantee sensor data to be forwarded to the Gateway node through a number of reserved MAS. A route reservation negotiation can be obtained by forwarding DRP reservation requests towards the Gateway.

A. Numerical analysis

In this section, BP duration α is optimized numerically to guarantee full coverage, so that *each* WG in the sub-network is uniquely associated to one unused Beacon Slot (without collision). For a given BP duration (expressed in terms of number of BSs) the full coverage can be achieved with a given probability that is calculated by averaging over random network topologies. Figure 5 shows the full coverage probability for different WGN deployments ($\Delta_x = 11m, 15m, 20m$) and corresponding sub-network size (of $M = 164, 216, 292$). Beacon Protocol is conforming to the framing structure of WiMedia[2]: to keep BP slot occupancy as compact as possible (still without increasing complexity), local BS assignment phase is modified so that unused BSs can be selected by each WG either after the Highest Occupied BS (HOBS) (as prescribed by the standard) and, similarly, *before* the Lowest Occupied BS (LOBS), see also figure 4. This allows WGs out of Gateway's extended beacon group to reuse the first BSs of the BP that are chosen by the devices that are contiguous to Gateway. Both HOBS and LOBS indicators need to be received within the BPOIE. MB-OFDM radio supports a throughput of $45 Mbps$ at a (TX) range (outdoor channel with a path loss exponent of 3) of $30m$. Carrier Sensing (CS) range is $50m$. Irregularity of the surface constrains the geophone nominal positions (described by in-line Δ_x and cross-line Δ_y spacing) to be affected by a random (here uniformly distributed) error with maximum value $6m$. Figure 5 shows the probability of full network coverage versus the length of the Beacon Period. Geophone deployment (e.g., in-line spacing Δ_x) has a major impact on framing structure design (a similar reasoning holds for UWB CS and TX ranges). High node density increase the number of devices that are not allowed to reuse the same BSs, thus requiring larger BP. On the other hand, a smaller density $\Delta_x = 20m$ (still reasonable for seismic acquisition) can ease the requirements on the BP. Markers refer to optimized BP lengths for 90% probability of full network coverage for varying receiver spacings. Higher geophone densities ($\Delta_x < 11m$) might require the maximum BP length to increase compared to what prescribed by WiMedia.

VII. CONCLUDING REMARKS

In this paper we introduced the basic principles of seismic acquisition systems from a wireless communication perspective. A number of requirements/specifications for the physical and MAC layer are provided in order to develop dense wireless sensors networks for oil exploration. The proposed Wireless Geophone Network (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. In the proposed system wireless UWB devices/sensors 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 wireless community is *now* becoming mature enough to develop a fully compliant system that can be ready for very dense land surveys expected within the next few years [7].

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