mental results show that synchronization precision has an error of less than 5μs (median) for a 30s resynchronization period.

Our acoustic sound technique focuses on consistently detecting the start of the arriving sound pulse. Attaching a timestamp at the beeper node is simple: right before applying voltage to the embedded buzzer we use the local (synchronized) clock to broadcast an RF message. At each listening node we identify a sound pulse produced by the beeper node by using the periodicity of the sound pulse and requiring the average peak-to-peak amplitude to surpass a certain predefined dynamic threshold, which is less susceptible to reflections. Then we attach a timestamp to the first peak-to-peak measurement that was of greater value than our dynamic threshold. The difference between the two timestamps at the beeper node and the listening node results in the time of flight for the sound pulse.

Overall, FLASH demonstrates that localization can be achieved with inexpensive off-the-shelf devices and yet be quite precise. Figure 1 shows part of our experimental setup, whereas Figure 2 shows our results for 1D and 2D localization. Using the Berkeley Mica2dot motes, the default microphone that already exists on the sensor platform and cheap simple buzzers, we were able to locate nodes at distances of up to 10m, depending on surrounding noise. The average error in localization precision is 11cm for distances up to 7m. However, our approach does not require either calibration or any special infrastructure. Furthermore, our method requires a single sounder and microphone per node, resulting in better energy efficiency compared to methods that use multiple sensor devices per node.

Future work in the area includes localization in outdoor and more demanding environments, such as in the presence of obstacles between nodes, intense noise in a room, temperature and humidity variations and outdoor environments. We believe that FLASH and similar techniques will play an important role in cyber-physical systems and in our efforts to better interact with and control our environment.

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High-Density Wireless Geophone Networks for Oil and Gas Monitoring and Exploration

by Stefano Savazzi, Vittorio Rampa and Umberto Spagnolini

Strong fluctuations in crude oil prices and the expected production peak of current reservoirs are pushing oil companies to increase their investment in seismic exploration. Replacing cabling with wireless technology should radically improve the quality of depth imaging and simplify acquisition logistics. Recent advances in Wireless Sensor Networks (WSN) now allow the wireless community to satisfy the rigid constraints imposed by seismic acquisition systems, which have a large number of sensors (> 10,000) over the monitoring area (> 5km²).

Strong fluctuations in crude oil prices are pushing oil companies invest more in seismic exploration of new oil reservoirs and in new technology to improve the quality of depth imaging. Seismic prospecting requires a large number of sensors (up to 30,000), such as geophones or MEMS-based (Micro Electro-Mechanical Systems) accelerometers. These are deployed over large areas (up to 30km²) to measure the back-scattered wavefield generated by an active excitation source. A storage/processing unit (sink node) collects measurements from all the geophones in real time to obtain an image of the sub-surface. Current telemetry is cable-based and usually requires hundreds of kilometers of cabling, which results in delays, high logistic costs and low imaging quality.

Wireless technology is thus expected to significantly improve the efficiency of oil exploration. Technical limitations in the data-rate efficiency, interference and battery use of current short-range wireless network architectures (eg WiFi, Bluetooth) forced previous proposals for wireless geophone system architectures to choose a combination of wireless and wired configuration. However, recent advances in WSN technology conveniently address the issues related to the strong constraints imposed by seismic acquisition systems. A Wireless Geophone Network (WGN) must support multiple acquisition settings and applications. Basic network requirements are: i) network throughput of 150kbps down to 50kbps for single component sensors; ii) real-time (or near real-time) acquisitions with strong delay constraints; iii) remote control by sink node and synchronous acquisition with a maximum timing skew of 10μs; and iv) accurate positioning of each sensor/geophone with an error of less than 1m to avoid degradation of the depth imaging quality.

Network Architecture

As shown in Figure 1, the proposed WGN architecture exploits different radio transmission technologies to efficiently handle both short-range transmissions (ie for short-distance low-power communication among geophones/sensors), and long-range transmissions (ie for seismic data delivery to storage units and geophone remote monitoring) that must cover distances of several kilometers. The hierarchical network design requires the deployment of a number of Wireless Geophone Gateways (WGGs) to collect data readings from a large number of wireless geophones (WGs) and forward the data to the storage unit (SU). These WG nodes are self-organized into independ-
ent sub-networks; ideally the number of devices per sub-network should be as high as 300 nodes to minimize the number of WGGs. This results in an aggregated (per sub-network) throughput of about 45Mbps (up to 60Mbps). Data delivery within one sub-network is obtained by multi-hop transmissions towards the WGGs; WG sensors are within 5-100m of inter-node distance to reduce both energy consumption and increase battery life.

**Physical and MAC Layer Requirements**

The requirements of self-localization and frame synchronization make Ultra WideBand (UWB) technology the natural choice for short-range transmissions within each sub-network. To achieve positional accuracy with errors less than 1m, the travel-time estimation error for ToA-based (Time of Arrival) positioning must be in the order of 3ns with a minimum required signal bandwidth of 500MHz. UWB technology provides data acquisition, synchronization and localization without the use of fully GPS-based (Global Positioning System) WGN nodes. Moreover, recent advances in radio design (ie MB-OFDM or MultiBand Orthogonal Frequency Division Multiplexing) provide wireless devices with high data rates over short ranges of up to 480Mbps, and low power consumption (ie below 100mW in active transmission mode but down to 20μW in power-save mode). The MB-OFDM processing can also guarantee network scalability through time and frequency division by allowing the use of multiple sub-bands to separate the co-located sub-networks, and coexistence with other 2.4 GHz-based radio devices without significant cross-interference.

The high number of devices per sub-network and the large network size suggest the adoption of a number of distributed MAC (Medium Access Control) functionalities. Network topology should define a hierarchical structure where the WGG acts as an intermediate sink towards the storage unit. The WiMedia standard (ECMA-368 from ECMA International, the European Association for Standardizing Information and Communication Systems) has been chosen as the reference for the development of the WGN MAC. Transmission is organized in superframes with the beacon period (BP) carrying the essential information of each device. Logical device/sensor groups are dynamically formed according to the WiMedia protocol to facilitate the sharing of resources, while wireless medium reuse can be exploited over different spatial regions.

WGG supports specific extended functions compared to a standard WiMedia device. These functions allow: i) the Gateway to behave as an intermediate sink, forwarding data to the storage/processing node SU and controlling each sub-network; ii) contention-free resource negotiations to guarantee real-time constraints (eg quality of service and maximum delay); and iii) coexistence of long/short range transmissions.

Figure 2 illustrates the MAC layer framing structure adopted for each sub-network, while the probability of full network coverage versus the BP length is shown at the bottom of the same figure. Sensors/geophones are assumed to be deployed according to the requirements of a conventional seismic survey. Geophone deployment has a major impact

**Figure 1:** Wireless Geophone Network architecture.

**Figure 2:** MAC layer framing structure (top) used by each sub-network, and its impact on full network coverage (bottom).
A Software Platform for the Acquisition and Online Processing of Images in a Camera Network

by Thomas Sarmis, Xenophon Zabulis and Antonis A. Argyros

Applications related to vision-based monitoring of spaces and to the visual understanding of human behaviour, require the synchronous imaging of a scene from multiple views. We present the design and implementation of a software platform that enables synchronous acquisition of images from a camera network and supports their distribution across computers. Seamless and online delivery of acquired data to multiple distributed processes facilitates the development of parallel applications. As a case study, we describe the use of the platform in a vision system targeted at unobtrusive human-computer interaction.

Camera networks are increasingly employed in a wide range of Computer Vision applications, from modelling and interpretation of individual human behaviour to the surveillance of wide areas. In most cases, the evidence gathered by individual cameras is fused together, making the synchronization of acquired images a crucial task. Cameras are typically hosted on multiple computers in order to accommodate the large number of acquired images and provide the computational resources required for their processing. In the application layer, vision processing is thus supported by multiple processing nodes (CPUs, GPUs or DSPs). The proposed platform is able to handle the considerable technical complexity involved in the synchronous acquisition of images and the allocation of processes to nodes. Figure 1 illustrates an overview of the proposed and implemented architecture.

The platform integrates the hardware and device-dependent components employed in synchronous multi-camera image and video acquisition. Pertinent functionalities become available to the applications programmer through conventional library calls. These include online control of sensor-configuration parameters, online delivery of synchronized data to multiple distributed processing nodes, and support for the integration and scheduling of third-party vision algorithms.

System modules can communicate in two modes. Communication through message-passing addresses control messages to targeted or multicast recipients. The diversity of communicated information types is accommodated by data-structure serialization. Communication through shared-memory spaces provides visual data or intermediate computation results to the nodes of the host or of multiple computers. The large bandwidth requirements imposed by image transmission are accommodated by a Direct Memory Access channel to a local shared-memory space. For cross-computer availability of images, memory spaces are unified over a network link. The latency introduced by this link is compensated for by notification of nodes, regarding the partial or total availability of a synchronized image set. In this way, per-frame syn-