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## Mobile Map Services

► Location-Based Services (LBS)

## Mobile Sensor Network Data Management

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### Synonyms

MSN data management; Mobile wireless sensor network data management

### Definition

Mobile Sensor Network (MSN) Data Management refers to a collection of centralized and distributed algorithms, architectures and systems to handle (store, process and analyze) the immense amount of spatio-temporal data that is cooperatively generated by collections of sensing devices that move in space over time.

Formally, given a set of $n$ homogenous or heterogeneous mobile sensors $\{s_1, s_2,...,s_n\}$ that are capable of acquiring $m$ physical attributes $\{a_1, a_2,...,a_m\}$ from their environment at every discrete time instance $t$ (i.e., datahas a temporal dimension), an implicit or explicit mechanism that enables each $s_i$ $(i \leq n)$ to move in some multi-dimensional Euclidean space (i.e., data has one or more spatial dimensions), MSN Data Management provides the foundation to handle spatio-temporal data in the form $(s_i, t, x, [y, z,]a_1[,...,a_m])$, where $x$, $y$, $z$ defines three possible spatial dimensions and the bracket expression "[ ]" denotes the optional arguments in the tuple definition. In a more general perspective, MSN Data Management deals with algorithms, architectures and systems for in-network and out-of-network query processing, access methods, storage, data modeling, data warehousing, data movement and data mining.

### Historical Background

The improvements in hardware design along with the wide availability of economically viable embedded sensor systems have enabled scientists to acquire environmental conditions at extremely high resolutions. Early approaches to monitor the physical world were primarily composed of passive sensing devices, such as those utilized in wired weather monitoring infrastructures, that could transmit their readings to more powerful processing units for storage and analysis. The evolution of passive sensing devices has been succeeded by the development of *Stationary Wireless Sensor Networks (Stationary WSNs)*. These are composed of many tiny computers, often no bigger than a coin or a credit card, that feature a low frequency processor, some flash memory for storage, a radio for short-range wireless communication, on-chip sensors and an energy source such as AA batteries or solar panels. Applications of stationary WSNs have emerged in many domains ranging from environmental monitoring [15] to seismic and structural monitoring as well as industry manufacturing.

The transfer of information in such networks is conducted without electrical conductors (i.e., wires) using technologies such as radio frequency (RF), infrared light, acoustic energy and others, as the mobility aspect inherently hinders the deployment of any

technology that physically connects nodes with wires. Since communication is the most energy demanding factor in such networks, data management researchers have primarily focused on the development of energy-conscious algorithms and techniques.

In particular, declarative approaches such as TinyDB [9] and Cougar [16] perform a combination of in-network aggregation and filtering in order to reduce the energy consumption while conveying data to the *querying node (sink)*. Additionally, approaches such as TiNA [13] and MINT Views [17] take into account intelligent in-network data reduction techniques to further reduce the consumption of energy. *Data Centric Routing* approaches, such as directed diffusion [8], establish low-latency paths between the sink and the sensors in order to reduce the cost of communication. *Data Centric Storage* [14] schemes organize data with the same attribute (e.g., humidity readings) on the same node in the network in order to offer efficient location and retrieval of sensor data.

The evolution of stationary WSNs in conjunction with the advances made by the distributed robotics and low power embedded systems communities have led to a new class of *Mobile (and Wireless) Sensor Networks (MSNs)* that can be utilized for land [3,5,10], ocean exploration [11], air monitoring [1], automobile applications [7,6], Habitant Monitoring [12] and a wide range of other scenarios. MSNs have a similar architecture to their stationary counterparts, thus are governed by the same energy and processing limitations, but are supplemented with implicit or explicit mechanisms that enable these devices to move in space (e.g., motor or sea/air current) over time. Additionally, MSN devices might derive their coordinates through absolute (e.g., dedicated Geographic Positioning System hardware) or relative means (e.g., *localization techniques*, which enable sensing devices to derive their coordinates using the signal strength, time difference of arrival or angle of arrival). There are several classes of MSNs which can coarsely be structured into the following classes: (i) highly mobile, which contains scenarios in which devices move at high velocities such as cars, human with cell phones, airplanes, and others; (ii) mostly static, which contains scenarios in which devices move at low velocities such as monitoring sensors in a shop floor with moving robots; and (iii) hybrid, which contains both classes such as an airplane that has sensors installed on inside and outside.

## Foundations

The unique characteristics of MSNs create novel data management opportunities and challenges that have not been addressed in other contexts including those of mobile databases and stationary WSNs. In order to realize the advantages of such networks, researchers have to re-examine existing data management and data processing approaches in order to consider sensor and user mobility; develop new approaches that consider the impact of mobility and capture its trade-offs. Finally, MSN data management researchers are challenged with structuring these networks as huge distributed databases whose edges consist of numerous "receptors" (e.g., RFID readers or sensor networks) and internal nodes form a pyramid scheme for (in-network) aggregation and (pipelined) data stream processing.

There are numerous advantages of MSNs over their stationary counterparts. In particular, MSNs offer: (i) *dynamic network coverage*, by reaching areas that have not been adequately sampled; (ii) *data routing repair*, by replacing failed routing nodes and by calibrating the operation of the network; (iii) *data muling*, by collecting and disseminating data/readings from stationary nodes out of range; (iv) *staged data stream processing*, by conducting in-network processing of continuous and ad-hoc queries; and (v) *user access points*, by enabling connection to handheld and other mobile devices that are out of range from the communication infrastructure.

These advantages enable a wide range of new applications whose data management requirements go beyond those of stationary WSNs. In particular, MSN system software is required to handle: (i) *the past*, by recording and providing access to history data; (ii) *the present*, by providing access to current readings of sensor data; (iii) *the future*, by generating predictions; (iv) *distributed spatio-temporal data*, by providing new means of distributed data storage, indexing and querying of spatio-temporal data repositories; (v) *data uncertainty*, by providing new means of handling real world signals that are inherently uncertain; (vi) *self-configurability*, by withstanding "harsh" real-life environments; and (vii) *data and service mash-ups*, by enabling other innovative applications that build on top of existing data and services.

In light of the above characteristics, the most predominant data management challenges that have prevailed in the context of MSNs include:

*In-Network Storage:* The absence of a stationary network structure in MSNs makes continuous data acquisition to some sink point a non-intuitive task (e.g., mobile nodes might be out of communication range from the sink). In particular, the absence of an always accessible sink mandates that acquisition has to be succeeded by in-network storage of the acquired events so that these events can later be retrieved by the user. Mobile devices usually utilize flash memory as opposed to magnetic disks, which are not shock-resistant and thus are not appropriate for a mobile setting. Consequently, a major challenge in MSNs is to extend local storage structures and access methods in order to provide efficient access to the data stored on the local flash media of a sensor device while traditional database research has mainly focused on issues related to magnetic disks.

*Flexible and Expressive Query Types:* In a traditional database management system, there is a single correct answer to a given query on a given database instance. When querying MSNs the situation is notably different as there are many more degrees of freedom and the underlying querying engine needs to be guided regarding which alternative execution strategy is the right one, typically on the basis of target answer quality and resource availability. In this context, there are additional relevant parameters that include: (i) *Resolution:* physical sensor data can be observed at multiple resolutions along space and time dimensions; (ii) *Confidence:* more often than not, correctness of query results can be specified only in probabilistic terms due to the inherent uncertainty in the sensor hardware and the modeling process; (iii) *Alternative models:* in some cases, several alternative models apply to a single scenario. Each alternative typically represents a different point in the efficiency (resource consumption) and effectiveness (result quality) spectrum, thereby allowing a tradeoff between these two metrics on the basis of application-level expectations. The prime challenge is to define new declarative query languages that make use of these new parameters while allowing a highly flexible and optimizable implementation. Additionally, approximate query processing with controlled result accuracy becomes vital for dynamic mobile environments with varying node velocities, changing data traffic patterns, information redundancy, uncertainty, and inevitable flexible load shedding techniques. Finally, in order to have an efficient and optimized implementation of query types, MSNs will need to consider cross-layer optimization since all layers of the data stack are involved in query execution.

*Efficient Query Routing Trees:* Query routing and resolution in stationary WSNs is typically founded on some type of query routing tree that provides each sensor with a path over which answers can be transmitted to the sink. In a MSN, such a query routing tree can neither be constructed in an efficient manner nor be maintained efficiently as the network topology is transient. The dynamic nature of the underlying physical network tremendously complicates the interchange of information between nodes during the resolution of a query. In particular, it is known that sensing devices tend to power-down their transceiver (transmitter-receiver) during periods of inactivity in order to conserve energy [2]. While stationary WSNs define transceiver scheduling approaches, such as those defined in TAG [9], Cougar [16] and MicroPulse [1], in order to enable accurate transceiver allocation schemes, such approaches are not suitable for mobile settings in which a sensor is not aware of its designated parent node in the query tree hierarchy. Consequently, nodes are not able to agree on rendezvous time-points on which data interchange can occur.

*Purpose-Driven Data Reduction:* The amount of data generated from MSNs can be overwhelming. Consequently, a main challenge is to provide data reduction techniques which will be tuned to the semantics of the target application. Furthermore, data reduction must take into account the entire spectrum of uses, ranging from real-time to off-line, supporting both snapshot and continuous queries that take advantage of designated optimization opportunities (e.g., multi-query) especially targeted for mobile environments. Finally, it must also consider the inherently dynamic aspects of these environments and the possibility of in-network data reduction (e.g., in-network aggregation).

*Perimeter Construction and Swarm-Like Behavior:* In many types of MSNs, new events are more prevalent at the periphery of the network (e.g., water detection and contamination detection) rather than uniformly throughout the network (which is more typically for applications like fire detection). This creates the necessity to construct the perimeter of a MSN in an online and distributed manner. Additionally, many types of MSNs are expected to feature a swarm-like behavior (The term *Swarm (or Flock)* refers to a group of objects that exhibit a polarized, non-colliding and aggregate

motion.). For instance, consider a MSN design that consists of several rovers that are deployed as a swarm in order to detect events of interest (e.g., the presence of water) [18]. The swarm might collaboratively collect spatio-temporal events of interest and store them in the swarm until an operator requests them. In order to increase the availability of the detected answers, in the presence of unpredictable failures, individual rovers can perform replication of detected events to neighboring nodes. That creates challenges in data aggregation, data fusion and data storage that have not yet been addressed.

*Enforcement of Security, Privacy and Trust:* Frequent node migrations and disconnections in MSNs, as well as resource constraints raise severe concerns with respect to security, privacy and trust. Additionally, the cost of traditional secure data dissemination approaches (e.g., using encryption) may be prohibitively high in volatile mobile environments. As such, research on encryption-free data dissemination strategies becomes very relevant here. This includes strategies to deliver separate and under-defined data shares, secure multiparty computation and advanced information recovery techniques.

*Context-Awareness and Self-Everything:* Providing a useful level of situational awareness in an unobtrusive way is crucial to the success of any application utilizing MSNs as this can be used to improve functionality by including preferences from the users but can also be used to improve performance (e.g., better network routing decisions if the exact topology is known). Note that context is often obvious in stationary WSN deployments (i.e., a specific sensor is always in the same location) but in the context of a MSN additional data management measures need to be taken into account in order to enable this parameter. Additionally, it is crucial for them to be "plug-and-play" and self-everything (i.e., self-configurable and self-adaptive) as application deployment of sensors in the field is famously hard, even without the mobility aspect which is introducing additional challenges. Finally, a crucial parameter is that of being adaptive both in how to deal with the system issues (i.e., how to adapt from failures in network connectivity) and also with user-interface/application issues (i.e., how to adapt the application when the context changes).

## Key Applications

MSN Data Management algorithms, architectures and systems will play a significant role in the development of future applications in a wide range of disciplines including the following:

*Environmental and Habitant Monitoring:* A large class of MSN applications have already emerged in the context of environmental and habitant monitoring systems. Consider an ocean monitoring environment that consists of *n* independent surface drifters floating on the sea surface and equipped with either acoustic or radio communication capabilities. The operator of such a MSN might seek to answer queries of the type: "*Has the MSN identified an area of contamination and where exactly?*". The MSN architecture circumvents the peculiarities of individual sensors, is less prone to failures and is potentially much cheaper. Similar applications have also emerged with MSNs of car robots, such as CotsBots [3], Robomotes [5] or Millibots [10], and MSNs of Unmanned Aerial Vehicles (UAVs), such as SensorFlock [1], in which devices can fly autonomously based on complex interactions with their peers. One final challenging application in this class is that of detecting a phenomenon that itself is mobile, for example a brush fire which is being carried around by high winds.

*Intelligent Transportation Systems:* Sensing systems have been utilized over the years in order to better manage traffic with the ultimate goal of reducing accidents and minimizing the time and the energy (gasoline) wasted while staying idle in traffic. Since cars are already equipped with a wide range of sensors, the generated information can be shared in a vehicle-to-vehicle network. For example the ABS system can detect when the road is slippery or when the driver is hitting the brakes thus this information can be broadcasted to the surrounding cars but also to the many cars back and forth, as needed, in order to make sure that everybody can safely stop with current weather conditions and car speeds.

*Medical Applications:* This class includes applications that monitor humans in order to improve living conditions and in order to define early warning systems that identify when human life is at risk. For instance, Nike+ is an example for monitoring the health of a group of runners that have simple sensing devices embedded in their running shoes. Such an application would require embedded storage and retrieval techniques in order to administer the local amounts of data. Applications in support of the elderly and those needing constant supervision (e.g., due to chronic diseases like diabetes, allergies, etc.) are another example in which MSN data management

techniques will play an important role. Wellness applications could also be envisioned, where a health "dose" of exercise is administered according to ones needs and capabilities. Another area are systems to protect soldiers on the battlefield. SPARTNET has recently developed wearable physiological sensor systems that collect, organize and interpret data on the health status of soldiers in order to improve situational and medical awareness during field trainings. Such systems could be augmented with functionality of detecting and reporting threats that are either derived from individual signals (e.g., when a soldiers personal health monitor shows erratic life-signals) and from correlated signals that are derived from multiple sensors/soldiers (e.g., by recognizing when a small group of soldiers is deviating away from the expected formation). Finally, disaster and emergency management are another prime area where MSN data management techniques will play a major impact.

*Location-Based Services and the Sensor Web:* The last group of challenging motivating applications is that of real-time location-based services, for example a service that can report whether there are any available parking spaces or a service that can keep track of buses moving and report how delayed a certain bus is. Many of these services become more powerful with the integration of data from the *Sensor Web* (i.e., live sensor data) with the *Web* (i.e., static content available online) and the *Deep-web* (i.e., data that is stored in a database, but are accessible through a web page or a web service).

## Cross-references

- ▶ Mobile and Ubiquitous Data Management
- ▶ Sensor Networks
- ▶ Spatial Network Databases
- ▶ Stream Data Analysis

## Recommended Reading


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# Mobile Wireless Sensor Network Data Management

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