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Mobile Wireless Sensor Networks: Architects for Pervasive Computing

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1. Introduction

A mobile wireless sensor network owes its name to the presence of mobile sink or sensor nodes within the network. The advantages of mobile wireless sensor network over static wireless sensor network are better energy efficiency, improved coverage, enhanced target tracking and superior channel capacity. In this chapter we will present and discuss different classifications of mobile wireless sensor network as well as hierarchical multi-tiered architectures for such networks. This architecture makes basis for the future pervasive computing age. The importance of mobility in traditional wireless sensor network (WSN) is highlighted in this chapter along with the impact of mobility on different performance metrics in mobile WSN. A study of some of the possible application scenarios for pervasive computing involving mobile WSN is also presented. These application scenarios will be discussed in their implementation context. While discussing the possible applications, we will also study related technologies that appear promising to be integrated with mobile WSN in the ubiquitous computing. With an enormous growth in number of cellular subscribers, we therefore place the mobile phone as the key element in future ubiquitous wireless networks. With the powerful computing, communicating and storage capacities of these mobile devices, the network performance can benefit from the architecture in terms of scalability, energy efficiency and packet delay, etc.

For mobile wireless sensor networks, there are basically two sensing modes, local sensing and remote sensing. By allowing and leveraging sink mobility and sink coordination, mobile WSN can achieve the goal of lower and balanced energy consumption with the following features:

- Single-hop clustering. By allowing only single hop transmission between sensor and sink node, most previous multi hop relaying sensor nodes may become unnecessary. In fact, sensor nodes can enter sleep mode until the sink approaches. Therefore, the original energy budget for multi hop relaying can be saved.
- Sink mobility and coordination. For a delay tolerant application, single mobile sink in fact equals virtually multiple static sinks at different positions. Multi-sink deployment can bring more uniform energy dissipation, therefore the possibility of energy hole will be reduced and network coverage will be improved.

- Mobility-assisted positioning and identification. Sensor nodes can estimate their position by learning mobile sink's position, which can be periodically broadcasted. If each sensor node can be geographically identified, then it is feasible to use more energy-efficient routing method, such as the geographic based routing.
- Improved network scalability: This merit is achieved by lowering overhead of MAC/routing protocols at the vast majority of resource constrained sensor nodes, especially for high-density networks. Complexity of other network maintenance functions such as topology and connectivity control may also get reduced.
- Adaptive network configuration: This feature is achieved through adaptive network re-organization and varying-scale observation based on the observed dynamics of targets being sensed, both in spatial and temporal domains.
- Sacrificed message delay: This defect can mainly be attributed to the increased sensor-sink meeting delay. Methods such as increasing the density of sink nodes and controlling the trajectory of mobile sinks can offset relinquished performance. In these tiered networks, one shared design rationale is to keep the logics of sensor nodes as simple as possible, and move complex functions to the overlaying mobile elements with richer resources. We also notice that, some more recent work has commenced on applying methods including Delay Tolerant Networking (DTN) and peer-to-peer (P2P) information sharing for asynchronous message switching in challenged wireless sensor networks. Unfortunately, we have not found efficient inter-tier communication methods for such cross-tier optimization approaches.

At the same time, the delay performance cannot be improved by simply increasing sink velocity. When mobile sinks are moving too fast through the effective communication region of static sensors, there may not be sufficient long dialogue durations for the sensor nodes to successfully deliver potentially long packets to the mobile sink. In other words, with the increase of sink velocity, the outage probability of packet transmission will rise. We further address the issue of optimal multi hop forwarding strategy under predictable sink mobility, which includes the distance characteristics both in the case of multi hop and single hop communication model.

Energy conservation is regarded as one of the most significant challenges in wireless sensor networks (WSN) due to the severe resource limitations of sensor nodes [1]. In addition, the peculiar non uniform traffic pattern in wireless sensor networks can lead to increased traffic for those sensor nodes close to the sink node. Therefore an unbalanced energy dissipation pattern will be inevitable, and those critical sensor nodes close to the sink node will withdraw from the network earlier due to faster energy depletion. The withdrawal of sensor nodes around sink node has lead to the known "energy hole" problem. The network may consequently lose sufficient connectivity and coverage, if there is no supplementary sensor deployment. Methods such as in-network processing and deploying multiple sinks can only partly tackle this problem by sacrificing the information accuracy and increasing the infrastructure cost.

Different from these approaches for flat networks, we have addressed this problem by leveraging mobility and multi-radio heterogeneity to create a cellular-sensor hybrid system with clustered and tiered network architecture. By combing the rationales in previous approaches such as Data MULE [3] and TTDD [2], the mobile enabled WSN (mWSN [29]) enables both local and remote sensing by mobile phones extracting information of interest from the sensory environment. As illustrated in Figure. 1, there are three tiers in the mWSN architecture: sensor tier, mobile sink tier, and base station tier. At the sensor tier, sensor nodes as well as various RFID tags may be organized in a clustered fashion with mobile sinks as the cluster heads. At mobile sink tier, mobile sinks may coordinate locally or remotely to exploit the redundancy via short-range or long-range radios equipped with each mobile phone.

At the base station tier, gathered sensory information can be stored and forwarded to Internet by the base stations of cellular networks, which serves as the access points to Internet. mWSN will enhance the performance of network connectivity and coverage by connecting isolated "islands" of wireless sensor networks designed for different applications. As illustrated in Figure. 2, there are basically two sensing modes in mWSN. In the case of local sensing, after mobile sink sends the information query command, sensory information collected by fixed sensors will be firstly forwarded by mobile sink to the base station for information fusion, where the digital information can be parsed and translated into meaningful interpretations.

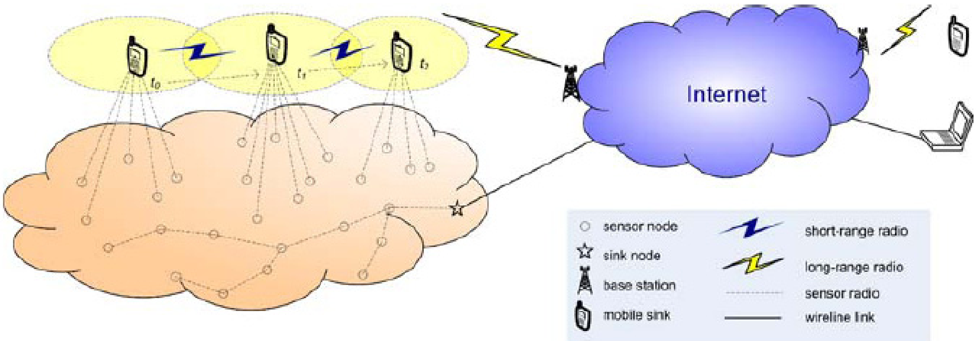

Fig. 1. Architecture Overview of Mobile enabled Wireless Sensor Network (mWSN).

In the case of remote sensing, the mobile sink will send the information query command to the base station, which will assign the sensing task to another mobile sink or fetch the information from a database of sensory information. The differentiation between local sensing and remote sensing may be based on the location information of sensors and mobile sink: if the location of a querying mobile sink is same with those of reporting sensors, it can be decided as a local sensing; otherwise, it should be a remote sensing.

Furthermore, with the knowledge of the remaining energy left at each sensor node, mobile sinks can choose the optimal path by circumventing the least energy sensor nodes [28]. The direct benefit of energy reduction is the lengthened network lifetime. As the route length can be reduced to one in mWSN, the scalability performance can also benefit from the hierarchical architecture of mWSN. However, the performance of packet delivery delay may be compromised, because packets have to be buffered before mobile sink approaches the sensor nodes.

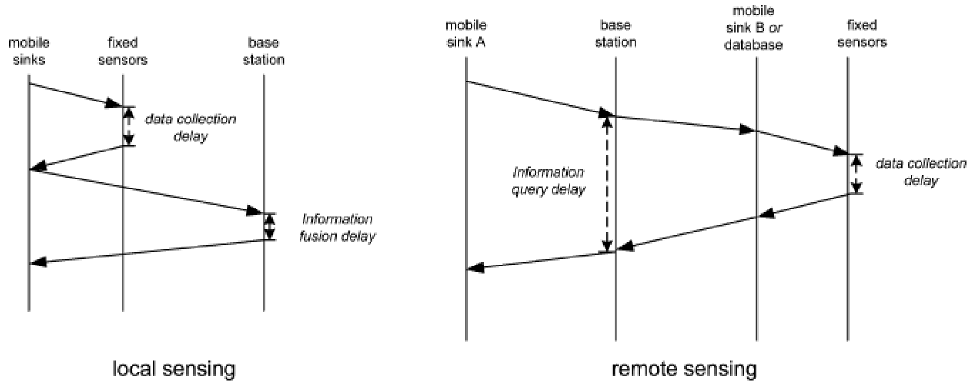

Fig. 2. Local Sensing and Remote Sensing in mWSN.

The concept of mobile wireless sensor network in the context of pervasive ubiquitous networks has emerged in recent years, although the genius of Marc Weiser envisaged this concept as early as in 1991 [31]. Along with the evolution of Wireless Sensor Networks (WSN) surfaced a new concept of presence of mobile sink or agents. Now, mobility in WSN is considered to be a blessing as opposed to problem. Their results confirm that mobility not only improves the overall network lifetime but also the data capacity of the network. Mobility can further address delay and latency problems. Most of the fundamental characteristics of mobile wireless sensor network are the same as that of normal static WSN. Some major differences, however, are as follows;

- Due to the mobility, mobile WSN has a much more dynamic topology as compared to the static WSN. It is often assumed that sink will move continuously in a random fashion, thus making the whole network a very dynamic topology. This dynamic nature of mWSN is reflected in the choice of other characteristic properties, such as routing and MAC level protocols and physical hardware.
- In most of the cases, it can be reasonably assumed that gateway sink has an infinite energy, computational and storage resources. The depleted batteries of mobile sinks can be recharged or changed with fresh ones and similarly mobile sink has access to computational and storage devices.
- The increased mobility in the case of mobile WSN imposes some restrictions on the already proposed routing and MAC level protocols for WSN. Most of the efficient protocols in static WSN perform poorly in case of mobile wireless sensor network.
- Due to the dynamic topology of mobile wireless sensor networks, communication links can often become unreliable. This is especially the case in hostile, remote areas where availability of constant communication channel for minimum QoS becomes a challenge.
- Because of the mobility involved, location estimation plays an important role so as to have an accurate knowledge of the location of the sink or node. Mobile wireless sensor networks have been shown to demonstrate enhanced performance over static wireless sensor networks. Because of the mobility of the sink, in general, much work can be shared by the mobile sink. Some of the advantages gained through mobile wireless sensor network over traditional sensor network are presented herewith.

Mobile Wireless sensor networks (Figure 1) are believed to have more channel capacity as compared to static WSN. The capacity gain has been calculated in case of mobile sink within WSN and has come out to be 3-5 times more than static WSN, provided the number of mobile sinks increases linearly with the growth of sensor nodes [32]. The other advantage of mWSN is its better targeting. Because, mostly the sensors are deployed randomly, as opposed to precisely, therefore there is often a requirement to move the sensor node for better sight or for close proximity. Also mobility helps in better quality of communication between sensor nodes. In a sparse or disconnected network, this property is especially helpful to maintain efficient network connectivity. Another advantage comes in the form of data fidelity**.** It is well known that the probability of error increases with increasing number of hops that a data packet has to travel. If we reduce the number of hops, this immediately reduces the probability of error. This not only increase the quality of data received but further reduces the energy spent at the static nodes by reducing the retransmissions required due to errors. Based on communication type, two kinds of mobile wireless sensor network exist at present. One is known as the infrastructure network in which the mobile unit is connected with the nearest base station that is within its communication radius to contact; as in the current mobile telephone system. The other one is called infrastructure-less mobile network, also knows as ad hoc network. No fixed routers are needed and all mobile units are capable of movement and still being able to self-organize and establish communication in an arbitrary manner. In this chapter we discuss the evolution of mobile Wireless Sensor Network and some of its characteristics which make the underlying network design considerations different from those of Wireless Sensor Networks. We present multi-tiered architectures for mobile wireless sensor networks, with an analysis on impact of mobility on delay and network connectivity. We then discuss the possible exciting technologies which could be integrated in future to work with WSN for ubiquitous computing. The chapter is organized in five sections. In the next section, we will present and discuss the multi-tiered architectures for mobile wireless sensor network based on overlay approach. In the third section, we will discuss the impact of mobility on the performance metrics of mobile wireless sensor networks. Fourth section will elaborate on some application scenarios of mobile wireless sensor networks in future pervasive world. The fifth section will discuss some of the existing enabling technologies for possible integration into mobile wireless sensor network for ubiquitous computing, followed by conclusion and references.

2. Hierarchical Architectures for Mobile Wireless Sensor Networks

Multi-tier architecture for traditional wireless sensor networks has been proposed in literature. We however present the multi-tiererd architecture for mobile wireless sensor network. A description of the ordinary planar wireless is presented, followed by the discussion of multi-tiered architecture for mobile wireless sensor network.

Planar Wireless Sensor Network: Typically, a Wireless Sensor Network (WSN) is composed of a large number of static nodes scattered throughout a certain geographical region. The sensory data is routed from the originator sensors to a remote sink in a multi-hop ad hoc fashion. In general, these sensor nodes have approximate energy conservation and transmission, sensing and caching capabilities, that is, they are homogeneous. A general example of planar wireless sensor networks is illustrated in Figure below.

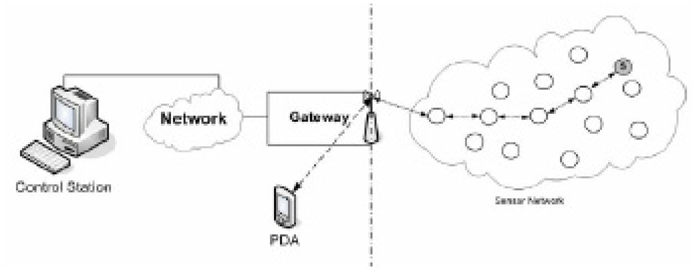

Fig 3. Typical planar Wireless Sensor Network

Using the ad hoc model, planar WSN would inherently pose some disadvantages on network performance. The throughput per node falls asymptotically with increasing nodes as $\theta\left(1/\sqrt{n}\right)$. When data is sent from one node to the next in a multi-hop network, there's a chance that a particular packet may be lost, and the odds grow worse as the size of the network increases. When a node sends a packet to a neighboring node, and the neighbor has to forward it; that takes energy. The bigger the network, the more nodes must forward data, and the more energy is consumed. The end result is: as the network grows, performance degrades.

Two-Tiered Sensor Network Architecture: In a two-tiered mobile-enabled wireless sensor network overlay, WSN utilizes mobile devices as the elements to construct the upper overlay. This owes to the development of microelectronic and wireless communication technologies resulting in the form of mobile phone, laptop and PDA.

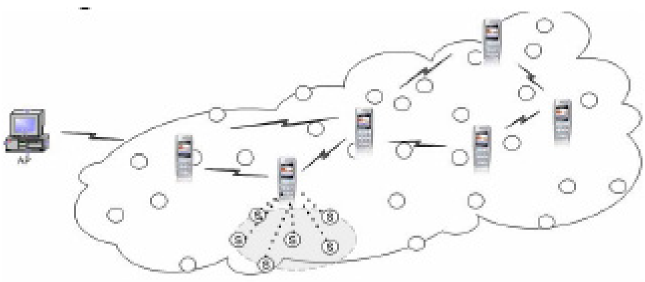

Fig. 4. Two-Tiered Sensor Network with Ad Hoc Configuration

Besides the basic ability of mobility, majority of these have the functions of processing complicated computing, caching and transmitting large number of information packet. These features enable these to be used in heterogeneous WSN and act as the elements of overlay structure. Based on the motivation mentioned above, we conceive the two-tier heterogeneous WSN architectures coupled with mobile overlay. Two brief illustrations are shown below in Figure 4 and Figure 5.

One major difference between the two architectures described in Figure 4 and Figure 5 is the topology of the overlay networking. In the first structure, all the mobile agents, represented by the mobile phones, are self-organized into an ad hoc network. The topology of mobile overlay, which is random and temporary, has to depend on the relative positions of mobile agents, so it is possible only when the density of mobile devices is high enough. And the slower the mobile agents move, the more stably the overlay can be persisted. Some advanced wireless techniques, such as IEEE 802.11 and Bluetooth are suitable for constructing the wireless interconnected network.

But when the number of mobile phones is small, or the overlay belongs to a sparse network, the architecture mentioned above may not be viable. In this case, an alternative architecture presented in Figure 5 is more suitable. When each mobile phone gathers some data from the sensor nodes in its neighborhood, it doesn't forward it to the access point or other peers simultaneously, but only caches the data in its available memory. In order to avoid the data loss, the size of the memory in mobile agent should be kept large. The data loss is also decided by the average data generating rate from sensor nodes and the round trip time of the mobile agents, namely the maximum allowable delay of data delivery.

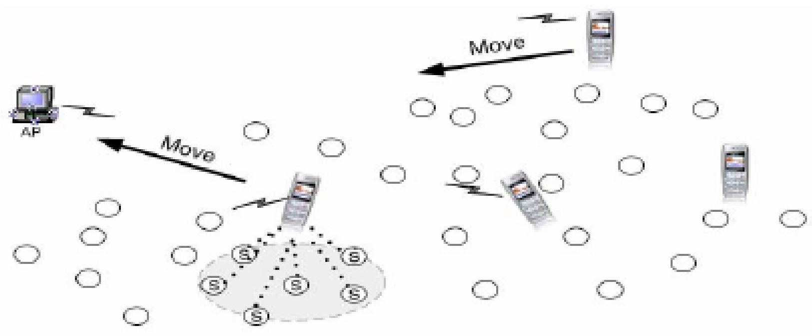

Fig. 5. Two-Tiered Sensor Network without ad hoc overlay

Three-Tiered Sensor Network Architecture: Combining the advantages of fixed access points and mobile agent serving as overlay elements together, we consider a three-tier heterogeneous mobile WSN that results from the introduction of ad hoc overlay and non-ad hoc overlay described above. It can be illustrated that if the *n* sensor nodes have a one-hop link to the nearest mobile agent, and forwarding is limited to the agent, to first order throughput scaling is achieved when the number of fixed access points exceeds $\sqrt{r}$, where $r < n$ is now the number of agents. This is because now the agents forward data for all the sensor nodes, therefore requirement on the number of access points relative to the two-tier hybrid network decreases. Thus, while agents may not reverse the scaling behavior, they can help reduce the number of access points and also lower the power consumption of the sensor nodes, both valuable resources in a variety of sensor applications. In addition to these general and theoretic networking issues, specifically for sensing applications, there are operational advantages to hierarchical heterogeneous layering that cannot be achieved with a "flat", homogeneous network of sensors, with its inherent limitations on power and processing capabilities. For instance, the mobile agents help preserve limited battery resources of sensors by eliminating the need for sensors to monitor communications from their neighbors. In data gathering networks, the medium layer offers the advantage of caching and forwarding compressed data to the destination. Thus for a variety of applications, it appears that a relatively small number of higher-level network elements with access to more power and better computing and communication capabilities could greatly improve the performance of the overall system in terms of throughput, reliability, longevity, and flexibility.

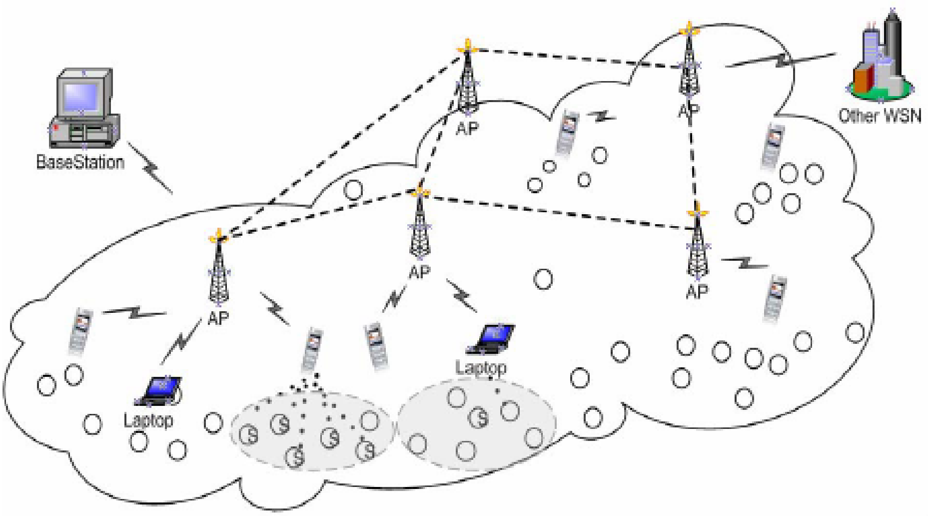

Fig. 6. A typical Three-Tiered Sensor Network Architecture

An example of such a three-tier hierarchical network is shown in Figure. 6. The lowest layer is a random deployed network composed of sensor nodes. These nodes are able to communicate immediately with upper layer agent in near range. They can also form an ad hoc network by communicating with each other, but it is not necessary. The most notable feature of medium layer is its mobility. The mobile agents move to anywhere at anytime if needed. They are responsible for gathering data from lower layer and then forwarding to upper layer. The behavior and collaboration of the mobile agents should be researched deeply so that the WSN performs well and achieves the best performance. The highest layer represents generally the fixed network consisted of some specific number of access points. This networking can be based on wired or wireless and can deploy some kinds of network models such as Mesh or ad hoc. The node of access points may be implemented by IEEE 802.11 AP, the base stations of cellular networks and so on. Meanwhile, this layer provides the network with the possibility of forming a large inter-city wireless sensor networks broadly. The relationship among the three layers is also described in Figure. 7 in which we can see that, many entries including mobile phones, vehicles, men, laptop and even animal, can act as mobile agents. But they have distinctive characteristics respectively, for instance, some are mobile controllable, some are mobile-predicted and some are random.

Two fashions to gather data from sensor nodes: At the lowest layer in the two or three-tier architecture mentioned above, there are two fashions to gather data from sensor nodes, as shown in Figure.8 and Figure.9. Here we will make some conclusions. The first fashion is that every sensor node is isolated. It doesn't communicate with its neighbors always and doesn't deliver received data until some mobile agent come close to it. This fashion does not depend on the topology of underlying network and it provides much energy conservation.

But the biggest disadvantage of this fashion lies in the poor-guaranteed latency of data delivery. The illustration is shown in Figure 7.
On the contrary to the isolated nodes fashion, sensor nodes can organize into an ad-hoc network at the initial phase. Data delivery and gathering can be done all the time. By this fashion, network performance is tightly dependant on the topology of underlying network. A perfect low latency can be achieved but maintaining and updating the network topology will consume much energy. The illustration of second kind of fashion is shown in Figure 8.

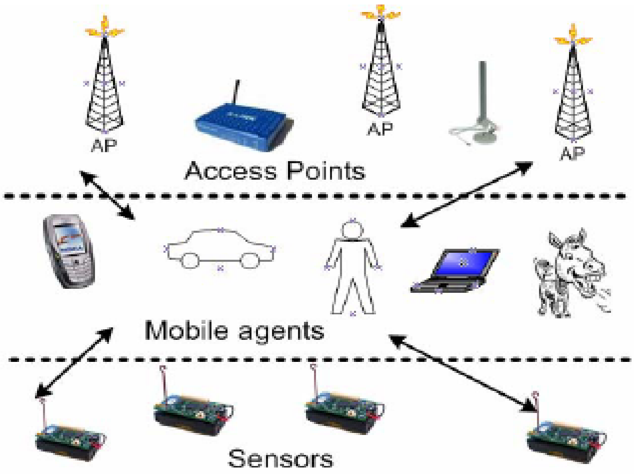

Fig. 7. A planar illustration of Three-tiered sensor network architecture

By observing the above architectures, one can predict that the ubiquitous environment of the future will comprise of both public and privately deployed sensor networks, which will enable the deployment of "smart services", accessible through advanced infrastructures, for instance, the capability-rich 3G mobile networks or open services gateways. In the following we discuss how such a sensor-based services model, which combines (mobile) telecommunication technologies and WSNs, can be realized. Figure 10 depicts the general architecture of a Sensor-Based Service (SBS) solution based on a 2.5G. or 3G network.

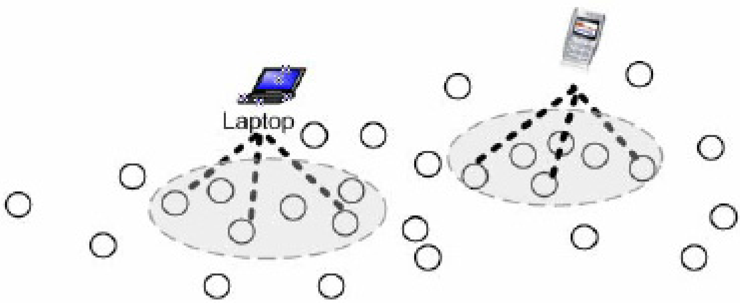

Fig. 8. Gathering data from isolated sensor nodes

The main modifications to the traditional network architecture will be:

The deployment of sensor networks in the monitored fields: A typical modern sensor network consists of sensor nodes and a gateway node. The gateway node has more processing, energy and communication capabilities than the other nodes and is a connecting link between the sensor network and other networks (e.g. mobile network or Internet). Hence, this node should be capable of communicating with the mobile network infrastructure, either directly (GSM/GPRS modem) or indirectly (Internet modem and Gateway GPRS Support Node - GGSN).

An application platform for the lifecycle management of the services and the handling of the remote sensor networks:

This platform is responsible for the creation, deployment, and management of the SBS and the WSN. Furthermore, this platform, as a central component of the overall architecture, can handle all the relevant charging and payment issues. Such platform should be open and support the largest possible number of underlying sensor network technologies.

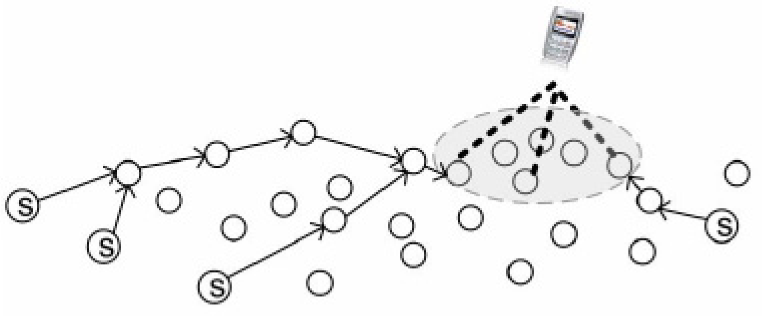

Fig. 9. Gathering data from connected sensor nodes

An open Sensor API for the communication between the WSN and the platform:

The accumulated experience from the wireless networking applications dictates the standardization and adherence to open public APIs for the interaction between the applications and the network elements.

Since the WSN can be regarded as a network element, the support of de facto standards for the WSN handling (i.e., sensor data retrieval) by the platform seems both crucial and feasible. Such an API could be the Parlay/OSA (Open Services Access). The only extension that would be required is the addition of a Sensor SCS (Service Capability Server) to the Parlay/OSA specification. Surely, the ongoing WSN research activity and the diversity in the WSN implementations introduce problems on such SCS standardization, but we can expect that the specific domain will be more clear and stable in a few years. The aforementioned enhancements to the network are not so extensive and have limited impact, because they do not make any unrealistic assumptions on the capabilities of the existing core network and do not imply any alterations to the existing mobile terminal equipment. Thus, the value added services based on such a solution, could experience a fast market penetration with minimal infrastructure investment.

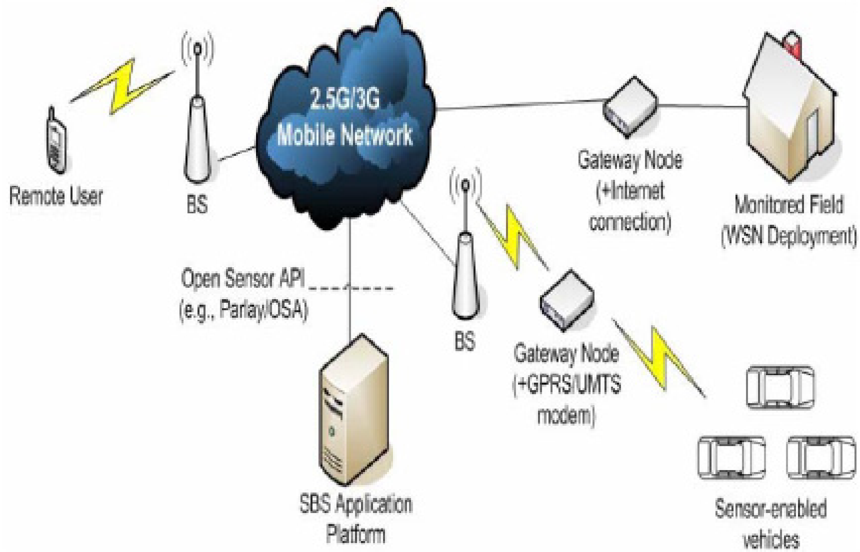

Fig. 10. Enabling Sensor-Based Services in mobile networks

3. Performance Influence from Sink Mobility in Single-hop mWSN

The existing approaches exploiting sink mobility can be categorized with respect to the property of sink mobility, communication/routing pattern, and sink amount. According to the obtainable knowledge about sink mobility, there are basically three kinds of sink mobility: random, predictable, and controlled sink mobility. In terms of the hop-count between sensors and sink, there are mainly two communication/routing patterns: single-hop and multi hop forwarding. The hop-count between sensors and sink has also defined the cluster radius in clustered wireless sensor networks. Majority of related work studied the mobility of single sink. However, a joint optimization is possible if coordination among multiple sinks is feasible. Table 1 lists the related work by comparing different approaches of leveraging sink mobility. Note here Mobile Base Station (MBS) and Mobile Data Collector (MDC) in [12] are with the same meanings as multihop and single-hop forwarding, respectively. For random sink mobility [2–10, 18], sensors can only choose to immediately deliver data to approaching mobile sinks, which leads to significant packet dropping due to insufficient sensor-sink communication duration. For predictable sink mobility [16–17, 19–21], sensors can learn the trajectory pattern of mobile sinks in spatial and temporal domains, based on which sensor topology can be adaptively reorganized. For instances, sensors can decide the transmission schedule which can maximize the opportunity of successful data transmission, and we can design routing strategies for more balanced load among sensors. For controlled sink mobility [11–15, 22–27], the optimization problem can be generally classified into two categories: finding the optimal sink trajectory, i.e. the rendezvous based solution or traveling salesman problem that aims to minimize mobile sink visiting time for all the sensor nodes; mWSN for Large Scale Mobile Sensing finding the optimal sink location, i.e. to optimally place multiple sinks or relays in order to minimize the energy consumption and maximize network lifetime.

It is well known that the traditional definition for a wireless sensor network is a homogeneous network with flat architecture, where all nodes are with identical battery capacity and hardware complexity, except the sink node as the gateway to communicate with end users across Internet. However, such flat network architecture inevitably leads to several challenges in terms of MAC/routing design, energy conservation and network management. In fact, as a kind of heterogeneity, mobility can create network hierarchy, and clustering is beneficial to improve network scalability and lifetime.

	References	Random, predictable, or controlled sink mobility	Single-hop or multihop forwarding	Single-sink or multiple sinks
Data MULEs, SENMA, DFT-MSN	[3–6]	Random	Single-hop	Multiple
CarTel, Message Ferry	[7–10]	Random	Multihop	Multiple
Mobile Element Scheduling	[11, 12]	Controlled	Single-hop	Single
AIMMS	[13–15]	Controlled	Multihop	Single/multiple
Predictable Mobile Observer	[16]	Predictable	Single-hop	Single
SEAD	[17]	Predictable	Multihop	Multiple
TTDD, EARM	[2, 18]	Random	Multihop	Single
HLETDR, Joint Mobility and Routing	[19, 21]	Predictable	Multihop	Single
Base Station Relocation, Maneuverable Relays	[22–27]	Controlled	Multihop	Multiple

Table 1. Comparison of Leveraging Sink Mobility in Wireless Sensor Network

Intuitively, increasing the sink velocity v will improve the system efficiency, since in unit time interval the mobile sink can meet more sensors and gather more information throughout the sensor field. However, we should carefully choose this parameter as explained below. On one hand, the higher the mobile sink velocity, the higher the probability for static sensors is to meet mobile sinks. On the other hand, when mobile sinks are moving too fast across the effective communication region of static sensors, there may not be a sufficient long session interval for the sensor and sink to successfully exchange one potentially long packet. In other words, with the increase of sink velocity, the “outage probability” of packet transmission will rise. Therefore, finding a proper value for sink velocity must be a tradeoff between minimizing the sensor-sink meeting latency and minimizing the outage probability.

3.1. Sensor-sink Meeting Delay

Suppose the network consists of m mobile sinks and n static sensors in a disk of unit size. Both sink and sensor nodes operate with transmission range of r. The mobility pattern of the mobile sinks $M_i(i=1,\ldots m)$ is according to “Random Direction Mobility Model”, however, with a constant velocity v. The sink’s trajectory is a sequence of epochs and during each epoch the moving speed v of M_i is invariant and the moving direction of M_i over the disk is uniform and independent of its position. Denote Q_i as the epoch duration of M_i, which is measured as the time interval between M_i 's starting and finishing points. Q_i is an exponentially distributed random variable, and the distributions of different Q_i (i=1, ..., m) are independent and identically-distributed (i.i.d) random variables with common average of $\overline{Q}$. Consequently the epoch length of different L_i 's are also i.i.d random variables, sharing the same average of $\overline{L} = \overline{Q}v$.

Assume a stationary distribution of mobile sinks, in other words, the probabilities of independent mobile sinks approaching a certain static sensor from different directions are equal. Specifically, the meeting of one static sensor N_j (j=1, ..., n) and one mobile sink M_i is defined as *Mi* covers *Nj* during an epoch. Since M_i will cover an area of size $\pi r^2 + 2rL_{i,k}$ during the k-th epoch, then the number of epochs X_i needed till the first sensor-sink meeting is geometrically distributed with average of (Theorem 3.1 of [30]), with the cumulative density function (cdf) as

$$F_{x_i}(x) = \sum_{x_k \leq x} p(1-p)^{k-1}$$

In the case of multiple mobile sinks, the sensor sink meeting delay should be calculated as the delay when the first sensor-sink meeting occurs. Thus the number of epochs *X* needed should be the minimum of all X_i (i=1, ..., m), with the cdf as

$$F_x(x) = 1 - \left[1 - F_{x_i}(x)\right]^m \cong \sum_{x \leq x} mp(1-p)^{k-1}$$

Denote $\overline{X}$ as the average of X, the expected sensor sink meeting delay will be

$$\overline{D_1} = \overline{X} . \frac{\overline{L}}{v}$$

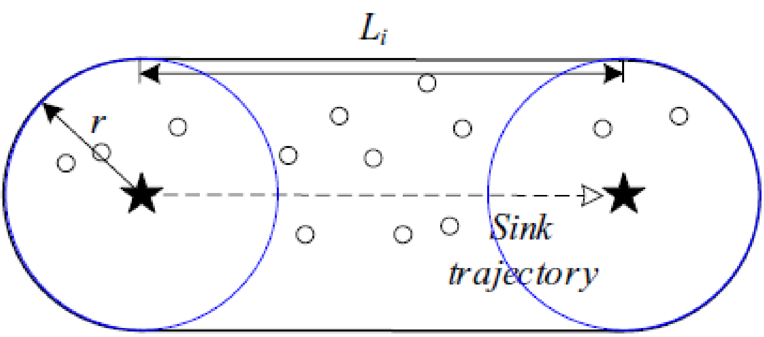

Fig. 11. Illustration of computing the distribution of sensor sink meeting delay.

This result gives us some hints on choosing the parameters to minimize the sensor-sink meeting delay. If we increase the radio transmission range *r*, or increase the number of mobile sinks *m*, or increase the sink velocity *v*, the sensor-sink meeting delay can get reduced. However, the above analysis has implicitly neglected the time consumed by packet transmission during each sensor-sink encounters. If the message length is not negligible, the message has to be split into several segments and deliver to multiple sinks.

3.2. Large Message Delivery Delay

In case of packet segmentations, the split packets are assumed to be sent to different mobile sinks and reassembled. Message delivery delay can be mainly attributed to the packet transmission time, while the packet re-sequencing delay is out of the scope of our study. Assume each sensor will alternate between two states, active and sleep, whose durations will be exponential distributed with a mean of $1/\lambda$. Thus the message arrival is a Poisson process with arrival rate λ. For constant message length of *L*, constant channel bandwidth *w*, the number of time slots required to transmit a message is T=*L/w*. Then with a service probability $p = m\pi r^2$, the service time of the message is a random variable with Pascal distribution (Lemma 1 of [6]). That is, the probability that the message can be transmitted within no more than *x* time slots, is

$$F_x(x) = \sum_{i=0}^{x-T} \binom{T+i-1}{T-1} p^T (1-p)^i$$

Such a Pascal distribution with mean value of $T/p = L/\pi mwr^2$. Under an average Poisson arrival rate λ and a Pascal service time with $\mu = p/T = \pi mwr^2/L$, data generation and transmission can be modeled as an M/G/1 queue. Then the average message delivery delay can be expressed as follows:

$$\overline{D_2} = \frac{1}{\lambda}\left[\rho + \frac{\rho^2 + \lambda^2\rho^2}{2(1-\rho)}\right]$$

where $\rho = \lambda/\mu$. For simplicity, we neglect the impact of arrival rate and set λ =1, thus

$$\overline{D_2} = \frac{1}{\mu - 1} = \frac{1}{\frac{\pi mwr^2}{L} - 1}$$

This result shows that, by decreasing message length *L*, or increasing transmission range *r* and number of mobile sinks *m*, the message delivery delay can be reduced. We have designed simulations to verify our analysis. One thousand five hundred sensor nodes have been deployed in a 10,000x10,000-m region. The data generation of each sensor nodes follows a Poisson process with an average arrival interval of 1s. By varying the ratio of sink velocity against transmission radius, and by varying the number of mobile sinks, we can evaluate the performance of average message delivery delay and energy consumption, as illustrated in Figure. 12 and Figure. 13.

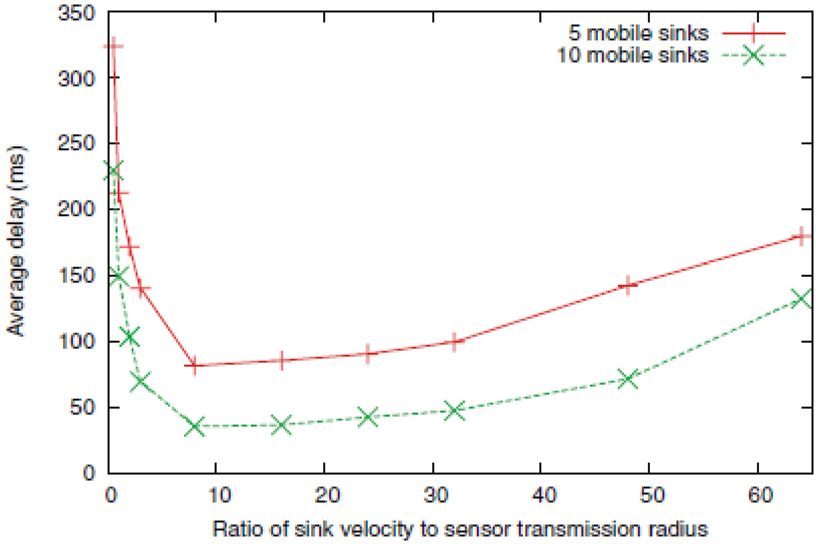

Fig. 12. Average message delivery delay under different scenarios by varying the number and velocity of mobile sinks.

As can be found in Figure. 12, it coincides with our expectation that the more mobile sinks deployed the less delay for message delivery between sensors and sinks. Besides, the simulation results are identical with our analysis on choosing the proper speed for mobile sinks. When the sink mobility is low, the sensors have to wait for a long time before encountering the sink and delivering the message. When the sink moves too fast, however, although the sensors meet the sink more frequently, they have to have the long messages sent successfully in several successive transmissions. In fact, there exists an optimal velocity under which the message delivery delay will be minimized. Average energy consumption is illustrated in Figure. 13. By different cluster size, we mean the maximal hop count between the sensor and mobile sink. It is worthy noting that when the cluster size is small (1 or 2), the average energy consumption will almost remain constant irrespective of the number of mobile sinks.

In other words, more deployed mobile sinks will not lead to further reduced energy consumption. However, when messages can be delivered to a mobile sink multiple hops away then the number of mobile sinks will have influence on the energy consumption: the more mobile sinks, the less energy will be consumed. In fact, the energy consumption in mWSN is more balanced compared with static WSN, which means the remaining energy of each sensor node is almost equal. It is easily understood that more balanced energy consumption will lead to more robust network connectivity and longer network lifetime.

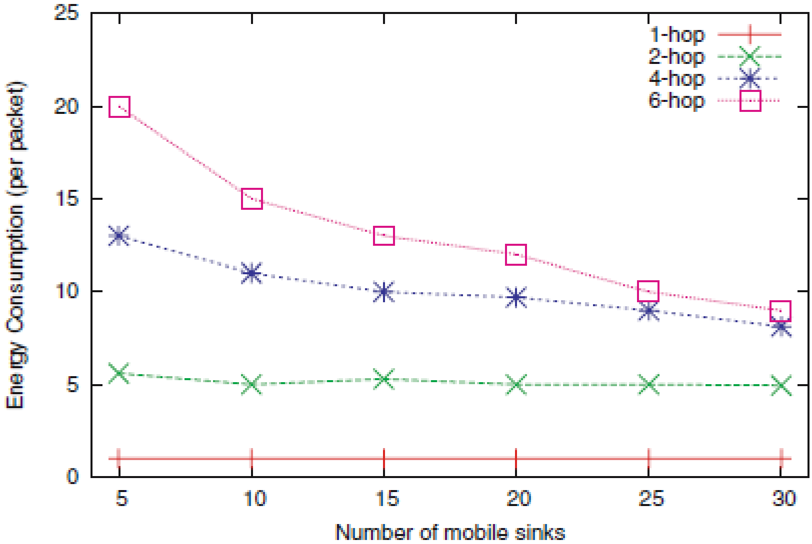

Fig. 13. Average message delivery delay under different scenarios by varying the cluster size and member of mobile sinks.

3.3. Outage Probability

In the above subsection, we have calculated the service time distribution for one sensor node (with multiple mobile sinks). However, while moving along predefined trajectory one mobile sink may potentially communicate with several sensor nodes simultaneously. In order for a successful packet delivery, we are interested in finding the relationship between such parameters as packet length *L* (number of time slot required is T=l/*w*), transmission range *r*, sink velocity *v*, and outage probability p_{outage}. Here we only qualitatively describe the relationship between p_{outage} and *r*, *v*, *T*. To guarantee the packet transmission completed in duration *T*, we first defined a zero-outage zone, as illustrated by the shaded region H in Figure 14. Nodes lying in H will be guaranteed with zero outage probability, because the link between sensor & sink remains stable for duration of *T* with probability 1. Intuitively, if H is viewed as a queuing system, then the larger the area of H, the higher the service rate, thus the lower the average outage probability. The border arc of H is the intersected area of two circles with radius *r*, and the width of H is determined by *(2r-vT)*. Therefore, the goal of enlarging the area of H can be achieved via increasing *r*, or decreasing *v* or *T*. With constant packet length (i.e. constant *T*), we can choose to increase *r* or to decrease *v*. However, increased *r* will require for larger transmission power, therefore, it is more energy efficient by decreasing sink velocity *v*. Some preliminary simulation results can verify the expectations on the parameter tuning methods. With 3,000 sensor nodes and one mobile sink in a 10,000x10,000-m region, when the sink velocity is 15 m/s and transmission range is 80 m, the outage percentage statistics have been shown in Figure. 15. One can find that, as analyzed above, the larger the transmission range r is, or the shorter the packet length T, is, the lower the outage percentage will be.

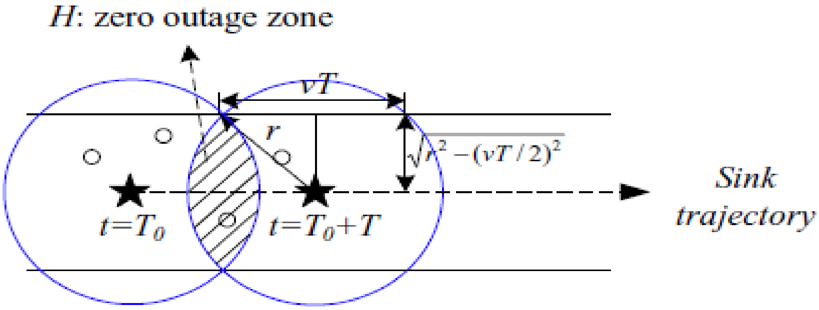

Fig. 14. Illustration for computing the relationship between zero-outage probability and r

It has been shown by Biao et. al. in [29] that with high probability, the average duration d until which a mobile sink first enters the field of sensor node S is given by,

$$d \leq \frac{4\log m}{crv}\sqrt{\frac{1}{m}}$$

where, the constant $c(c<1)$ is a scaling factor defined in [33,34], r is the communication radius of the sensor node, v is the velocity of the mobile sink, m is the number of mobile sinks present in the network Likewise, to calculate the impact of velocity of mobile sink on message delay an equation is

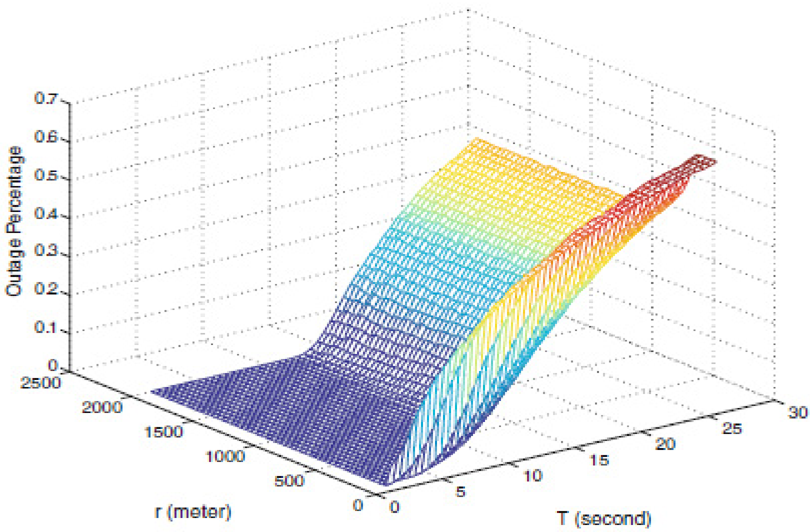

Fig. 15. Outage probability vs. r and T

derived as a Pascal distribution with Poisson arrival rate λ, and a Pascal service time $\mu = p/s$, where s is the number of time slots required to transmit a message of length L within a channel bandwidth of w. Another term p, is the service probability of a sensor node within the coverage of at least one mobile sink, and is given by,

$$p = \frac{crv\sqrt{m}}{4\log m}$$

we define the ratio of the packet arrival rate to the service time as $\rho = \lambda/\mu$, and similarly replace the value of pascal service time to study the impact of sink mobility on delay; the equation is given by,

$$\mu = \frac{wr\sqrt{\pi}\,p}{Lv}$$

The average message delivery delay can then be expressed as,

$$D = \frac{1}{\lambda}\left(\rho + \frac{\rho^2 + \lambda^2\rho^2}{2(1-\rho)}\right)$$

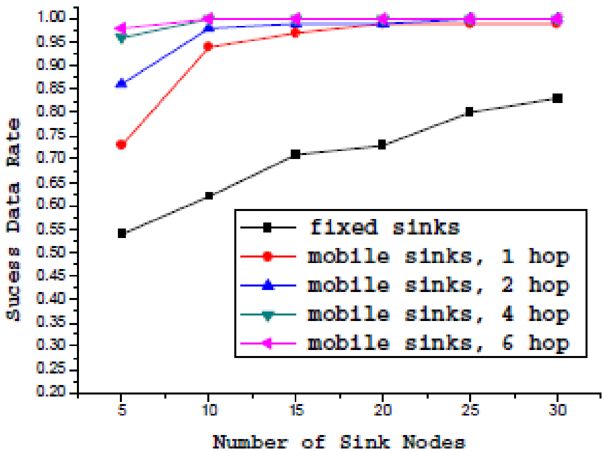

Fig. 16. Data success rates in loose-connectivity network

For simplicity, we neglect the impact of arrival rate and set $\lambda = 1$, thus

$$D = \frac{1}{\mu - 1}$$

The above equation therefore implies that on one hand, large v can improve the service probability p, on the other hand it increases the required times of mobiles sinks reaching it in order to finish a message transmission. Both sides of the impacts should be considered when choosing the appropriate velocity value of mobile sinks. The impact of mobility of the sink on the performance metrics of network connectivity is further highlighted in Figure 16. A comparison of data success rates between fixed sinks and mobile sinks in spare network is also presented herewith. In this case, the data success rate produced by mobile sinks is much better than that by fixed sinks. One of the advantages of mobile sinks is that they can move to such sensor nodes that are disconnected from others.

4. Future Application Scenarios

The possible application scenarios for traditional wireless sensor networks, which are envisaged at the moment, include environmental monitoring, military surveillance digitally equipped homes, health monitoring, manufacturing monitoring, conference, vehicle tracking and detection (telematics) and monitoring inventory control. Since, mobile wireless sensor networks are a relatively new concept; its specific, unique application areas are yet to be clearly defined. Most of its application scenarios are the same as that of traditional wireless sensor networks, with the only difference of mobility of mobile sink, preferably in the form of mobile phones. We, however, envisage a space where sensors will be placed everywhere around us, a concept of ubiquitous network, where different promising technologies will work together to help realize the dream of late Marc Weiser. We propose that with these sensors placed everywhere, a single individual mobile phone can enter into a "session" with the "current sensor network" in which he or she is present. A mobile phone will have the necessary interfaces available to allow it to communicate with the heterogeneous world. In most of the cases, this mobile phone will "enter" into the network as one of the mobile sinks. This way, a mobile phone can enter into the session anywhere at any time; at airport, railway station, commercial buildings, library, parks, buses, home etc. We will now discuss some of the possible application scenarios in ubiquitous computing age as a motivation for future work. This follows that we need to develop smart sensors and mobile phones to be able to take part in these applications. Mobile phones will be expected to have multiple radios to support multiple, heterogeneous technologies existing today. We believe that mobile WSN will be able to address multitude of applications, once the "world" gets smart.

Smart Transport System: One way in which mobile wireless sensor networks can help is through implementing an intelligent traffic system. With the sensors placed frequently around the city, these sensors can monitor and analyze the current traffic system at these areas at a given time. This information is delivered back to a central gateway or sink, having a link to different mobile phone operators, which in turn can provide this "traffic help" service to its customers, on demand.

Security: Similarly, with these sensors placed everywhere in and around the city, these very sensors can be used to implement security system in daily life. On an individual basis, a mobile phone of a person can enter into a "session" with the already present sensors in the area. In this way, it can keep a track of his belongings, car and even kids. Mobile enabled wireless sensor networks can help to monitor the environment, both external and internal. For internal environment monitoring, buildings can be made “smart building” to constantly monitor and analyze the environmental situation.

Social Interaction: One other possible scenario in ubiquitous computing is that of social interaction. There is a rapid increase in number of mobile subscribers in the world. We believe that with the possible integration of RFID tags and WSN, mobile phones can act as sinks to have a “social interaction” among peers who share the common interest. People can place their digital tags at their places of choice, or among their friends. Similarly, this combination of RFID tags and WSN can help mobile phones users in using their mobile phones as “single” tool to carry out all their tasks, be it shopping, billing, information gathering, guidance, social interaction, etc. By entering into a “session” with existing sensors or WSN in a particular area, the mobile phone user can get the necessary information on his mobile phone, like the location of his friends/relatives, the time table/schedule of the events taking place, environmental conditions etc. With the help of little initial information about the user, it is also possible to enter into any area, shop around, buy digital tickets and simply walk off, all with electronic billing. The same idea can be implemented in the form of e-voting in elections ranging from company elections to elections on much larger scale. “Context Aware” computation will be a significant key player in helping mobile WSN in social areas. Coupled with the superior image recognition techniques built in, people can interact with each other and with the environment. This single advancement in technology can have an enormous application potential, more than what we can imagine at the moment.

Health: One area which is already showing such signs of applications of ubiquitous computing is health monitoring. Emerging developments in this area are providing the means for people to increase their level of care and independence with specific applications in heart monitoring and retirement care. In recent years, one area of increasing interest is the adaptation of “micro grid” technology to operate in and around the human body, connected via a wireless body area network (WBAN). There are many potential applications that will be based on WBAN technology, including medical sensing and control, wearable computing, location awareness and identification. However, we consider only a WBAN formed from implanted medical sensors. Such devices are being and will be used to monitor and control medical conditions such as coronary care, diabetes, optical aids, bladder control, muscle stimulants etc. The advantages of networking medical sensors will be to spread the memory load, processing load, and improving the access to data. One of the crucial areas in implanting sensors is the battery lifetime. Batteries cannot be replaced or recharged without employing a serious medical procedure so it is expected that battery powered medical devices placed inside the body should last for ten to fifteen years. Networking places an extra demand on the transceiver and processing operations of the sensor resulting in increased power consumption. A network placed under a hard energy constraint must therefore ensure that all sensors are powered down or in sleep mode when not in active use, yet still provide communications without significant latency when required.

Miscellaneous Scenarios: We focus to concentrate on creating a smart world where a single user mobile phone can perform a multitude of applications. We envisage a scenario, where wireless sensor networks will be placed every where around the “smart” city and a person’s mobile phone can just enter and leave the network as humans. Suppose a person goes into the shopping mall. With the already installed sensors and RFID tags installed over there, his mobile phone can interact with the environment. A user looks for his product of choice and is concerned about the price; he can just inquire through his mobile phone the price of the same item in other stores, at internet or even from the manufacturer. This will be made possible by having subscribed service from other retailers, distributors, internet sites or manufacturers. With the enormous growth of RFID, it is very much expected that every single item will have its own unique RFID tag, and with the help of grid computing and advanced database systems, it is not unreasonable to think of a data repository of this magnitude. For the huge number of sensor data collection, XML, which is good for firewalls and human readable, will help make sense of complex, huge senor data. We believe that sensor networks will populate the world as the present Internet does. For example, think of buildings covered with small, near invisible networked computers, which continually monitor the temperature of the building and modify it in relation to the amount of people in the building, thus saving energy. Or sensors buried in the ground, monitoring areas prone to earthquakes and landslides and providing vital feedback, which could prevent human loss and mass destruction.

5. Related Technologies for Ubiquitous Computing

In this section, we will highlight some of the existing enabling technologies which are believed to function along with WSN for the ubiquitous computing paradigm. Some of the exciting combinations are Mobile IPv6, RFID, P2P and grid technology. P2P and Grid technology are already believed to play a significant part in realizing the ubiquitous network dream. Grid and P2P systems share a number of common characteristics and it is now considered that they are both converging towards creating overlay infrastructures that support sharing resources among virtual communities that will also reduce the maintenance cost. We believe that the grid technology will be especially helpful in handling and managing the huge amount of sensor data that these future ubiquitous heterogeneous sensor networks will produce. However, a lot of issues remain to be solved to truly integrate these technologies, the biggest of which is mobility. On the other hand, a number of network owners will be ready to share information gathered by their networks (for example traffic status at their current location) for mutual benefit of all involved parties or will deploy networks with the sole intention of providing services to interested users and charging for them. In such environment where sensor networks come and go in an ad-hoc manner, deployed by numerous unrelated service operators, it will be impossible to establish a long lasting subscriber operator relationship between sensor networks and their users. Users will not know about the existence of sensor networks in a certain area in advance nor will know what type of services discovered networks provide. Instead, depending on their current requirements and needs, users will have to use ad hoc mechanisms to search for required services and available networks. Obviously, as variety of sensors and network types is enormous, both service discovery and communication protocols have to be very flexible and capable of supporting different types and formats of sensor data and services. A description of different related enabling technologies is now presented.

Mobile IPv6: There exist some characteristics of IPV6 which are attractive to WSN in its possible integration. We believe that the advantages that we will accrue from IPv6 are enormous and include some of the followings:

Enlarge address space: This means IP can increasingly mount up without considering short of addressing resource. With the possible integration of different technologies, Mobile IPv6 will help solve the addressing problem.
Identification and security: This improvement makes IPV6 more fit to those commercial applications that need sensitive information and resources.
Access Control: We can make identification and add some access control according to different username. IPV6 also proposes force management about consistency that can prevent the data from modifying during the transmission and resist the rebroadcast aggression. IPV6 also protect the aggression by other services like encryption, ideograph etc.
Auto-configuration: IPV6 supports plug and play network connection. Although we have seen the common issues about IPV6 and WSN, there still exist some questions to be solved. Embedded applications are not considered in IPV6 initially, so if we want to realize IPV6 in WSN we must do effort to the size of the protocol stack. We do not need to realize high layer stack in each wireless sensor node from the aspect of OSI. Power consumption is another issue. But if we want to apply IPV6 in WSN, we must reduce its power consumption. This can be realized through using duty-cycle model.
RFID Technology*:* RFID tag is the key device for the actualization of "context awareness", which is essence of ubiquitous computing and can recognize "data carriers" by electronic wave without physical contact. Auto-ID lab's EPC (Electronic Product Code) numbering code is based on 96-bit system, which is believed to be large enough to put electronic tag for every grain of rice on this planet earth. Contact-less chips in RFID do not have batteries; they operate using the energy they receive from signals sent by a reader. In context of integration of RFID technology into wireless sensor networks, probably, the most prominent integration application will be in the field of retail business. RFID, already, has been making a major breakthrough in the retail business, with giants like Wal-Mart beginning to embrace it. Although, RFID can be incorporated on its own in different application areas, it has some disadvantages, which are the main reasons for research community to pursue research in integration of RFID with WSN. Some of the disadvantages which make room for integration of RFID with WSN are

- Inability of RFID to successfully track the target object (customer) within a specified working space (department floor, exhibition etc.).
- Deployment of RFID systems on already existed working spaces. For example, if we have to deploy RFID on a department floor, it will be prohibitivel y expensive to do so.

In this regard one scheme is to implement the combined RFID and WSN technologies in enhancing the customer relationship management for a retail business. Mobile RFID has already started getting attention with Nokia incorporating it into its mobile phone, thus creating the first GSM phone with RFID capabilities. The kit uses the 13.56MHz radio frequency range at the very short range of typically 2-3cm using the ISO-14443A standard, and has 2 Xpresson RFID reader shells, 20 RFID tags, and the software for the phone (Nokia 5140) tag reading. The kit is best suited for applications with 1-20 users.
GRID Technology: Grid Computing delivers on the potential in the growth and abundance of network connected systems and bandwidth: computation, collaboration and communication over the advanced web. At the heart of Grid Computing is a computing infrastructure that provides dependable, consistent, pervasive and inexpensive access to computational capabilities. The main driving force behind grid computing is the desire to take advantage of idle resources in a network and use these in intensive computations. With

a grid, networked resources -- desktops, servers, storage, databases, even scientific instruments – can be combined to deploy massive computing power wherever and whenever it is needed most. We believe that with the huge amount of sensor data that future heterogeneous wireless sensor networks will produce, grid technology can be efficiently used to manage and store this magnitude of data. Technicalities at software and hardware level remain to be solved. Grid computing, at the moment, is not thought to be directly integrated into the WSN, but works as a third party in touch with the network base station or gateway. Playing a direct role can be wireless grid; technology to support less data intensive applications. Wireless grid technology has already got boost by some good progress in availability of compatible hardware. Wi-Fi technology and WLAN are supposed to play a key role in making wireless grid a reality. The wireless grid architecture represents a combination of high-performance WLAN switches with structured WLAN distribution systems and is believed to be a key development for the industry. One of the possible architecture is to employ densely deployed Wi-Fi radios with powerful centralized control to deliver predictable wired-LAN-like performance with the flexibility of WLANs. As the current wireless grid, with the help of WLAN standards already can support high data rate of 54 Mbps, it is therefore well set to integrate into the future densely deployed wireless sensor networks.

Mobile P2P: Mobile P2P can be simply defined as transferring data from one mobile phone to another. Some of the limitations that become challenges for mobile P2P to be implemented are low efficiency (in terms of CPU and Memory), low power, low bandwidth and billing issues. This concept basically presents the peer-to-peer networking concept that is widely in use today in fixed communication networks, but mapped to mobile environment. Each sensor network presents a peer node capable of working and providing information independently of other peers, but also of communicating with other nodes and sharing available information with them. Collaboration of completely uncoordinated and nomadic networks on execution of a common task in a mobile environment is obviously not easy to implement. Different types of information and services, various data formats and application requirements, connectivity of and ability to discover sensor networks connected to different mobile networks are some of the most interesting issues. An idea can be to expose the WSN to a P2P network and enable the UPnP (Universal Plug n Play) Gateway to discover remote sensor nodes through the P2P substrate and to instantiate UPnP proxies for them to ensure client connectivity.

6. Conclusion

Mobile enabled Wireless Sensor Network (mWSN) has been proposed to realize large-scale information gathering via wireless networking and mobile sinks. Through theoretical analysis it is established that by learning the mobility pattern of mobile sinks, d_{char} based multi hop clustering scheme can forward the packets to the estimated sink positions in a timely and most energy-efficient way. Besides, the less strict the packet deadline is, the more energy saving is achieved. In addition, the mobility's influence on the performance of single-hop clustering has been investigated. It is found that sink mobility can reduce the energy consumption level, and further lengthen the network lifetime. However, its side effects are the increased message delivery delay and outage probability. The same problems will remain by tuning the sink density or coverage (i.e. sink amount and transmission range), so the conclusion is that sink mobility and sink density are permutable, since sink mobility increase its spatial redundancy similar with deploying multiple sinks.

In this chapter, we have further presented multi-tier architecture for the mobile wireless sensor network as a key element of future ubiquitous computing paradigm. The multi-tier architecture has been discussed in previous research for traditional wireless sensor network; however we consider the multi-tier architecture in mobile WSN, with a special emphasis on integration into a pervasive network. The detailed architectural implementation is presented in this chapter, followed by an analysis of the impact of mobility on performance related issues in WSN. The hierarchical multi tiered architecture is believed to perform efficiently and is also scalable to large network size. We have further discussed some of the future application scenarios for this ubiquitous computing age along with a description of some of the related existing technologies which play a significant role in the proposed architecture.

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