Data Collection in Wireless Sensor Networks with Mobile Elements: A Survey

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Wireless sensor networks (WSNs) have emerged as an effective solution for a wide range of applications. Most of the traditional WSN architectures consist of static nodes which are densely deployed over a sensing area. Recently, several WSN architectures based on mobile elements (MEs) have been proposed. Most of them exploit mobility to address the problem of data collection in WSNs. In this paper we first define WSNs with MEs and provide a comprehensive taxonomy of their architectures, based on the role of the MEs. Then, we present an overview of the data collection process in such scenario, and identify the corresponding issues and challenges. On the basis of these issues, we provide an extensive survey of the related literature. Finally, we compare the underlying approaches and solutions, with hints to open problems and future research directions.

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1. INTRODUCTION

In recent years Wireless Sensor Networks (WSNs) have become an established technology for a large number of applications, ranging from monitoring (e.g., pollution prevention, precision agriculture, structures and buildings health), to event detection (e.g., intrusions, fire/flood emergencies) and target tracking (e.g., surveillance). WSNs usually consist of a large number of sensor nodes, which are battery-powered tiny devices. These devices perform three basic tasks: (i) sample a physical quantity from the surrounding environment, (ii) process (and possibly store) the acquired data, and (iii) transfer them through wireless communications to a data collection point called *sink node* or *base station* [Akyildiz et al. 2002].

The traditional WSN architectures are based on the assumption that the network is dense, so that any two nodes can communicate with each other through multi-hop paths. As a consequence, in most cases the sensors are assumed to be static, and mobility is not considered as an option. More recently, similar to the research trends in Mobile Ad Hoc Networks (MANETs) [Zhao and Ammar 2003] and Delay Tolerant Networks (DTNs) [Fall 2003], mobility has also been introduced to WSNs [Shah et al. 2003; Chakrabarti et al. 2003; Ekici et al. 2006]. In fact, mobility in

WSNs is useful for several reasons [Kansal et al. 2004; Anastasi et al. 2009a], as discussed below.

—*Connectivity*. As nodes are mobile, a dense WSN architecture may be not a requirement. In fact, mobile elements can cope with isolated regions, so that the constraints on network connectivity can be relaxed, also in terms of nodes (re)deployment. Hence, a sparse WSN architecture becomes a feasible option.

—*Cost*. Since fewer nodes can be deployed, the network cost is reduced in a mobile WSN. Although adding mobility features to the nodes might be expensive, in many cases it is possible to exploit mobile elements which are already present in the sensing area (e.g., trains, buses, shuttles or cars), and attach sensors to them.

—*Reliability*. Since traditional (static) WSNs are dense and the communication paradigm is often (ad hoc) multi-hop, reliability is compromised by interference and collisions. In addition, the message loss increases with the number of hops, which may be rather high. Mobile elements, instead, can visit nodes in the network and collect data directly through single-hop transmissions. This reduces not only contention and collisions, but also the message loss.

—*Energy efficiency*. The traffic pattern inherent to WSNs is convergecast, i.e., messages are generated from sensor nodes and are collected by the sink. As a consequence, nodes closer to the sink are more overloaded than others, and subject to premature energy depletion. This issue is known as the *funnelling effect* [Li and Mohapatra 2007], since the neighbors of the sink represent the bottleneck of traffic. Mobile elements can help reduce the funnelling effect, as they can visit different regions in the network and spread the energy consumption more uniformly, even in the case of a dense WSN architecture [Gandham et al. 2003; Wang et al. 2005].

However, mobility in WSNs also introduces significant challenges which do not arise in static WSNs. These challenges are described below.

—*Contact detection*. Since communication is possible only when the nodes are in the transmission range of each other, it is necessary to detect the presence of a mobile node correctly and efficiently. This is especially true when the duration of contacts is short.

—*Mobility-aware power management*. In some cases, it is possible to exploit the knowledge on the mobility pattern to further optimize the detection of mobile elements. In fact, if visiting times are known or can be predicted with a certain accuracy, sensor nodes can be awake only when they expect the mobile element to be in their transmission range.

—*Reliable data transfer*. As available contacts might be scarce and short, there is a need to maximize the number of messages correctly transferred to the sink. In addition, since nodes move during data transfer, message exchange must be mobility-aware.

—*Mobility control*. When the motion of mobile elements can be controlled, a policy for visiting nodes in the network has to be defined. To this end, the path and the speed or sojourn time of mobile nodes have to be defined in order to improve (maximize) the network performance.

In this paper we present a literature survey on WSNs with Mobile Elements (MEs). We will specifically focus on data collection, i.e., the process which makes the communication feasible between the sensor nodes and the sink. Indeed, there are many other issues which can be addressed by exploiting mobility in WSNs. Among them, the problem of sensing coverage and connectivity is definitely relevant [Ghosh and Das 2008; Ammari and Das 2010]. Interested readers may also refer to [Cortés et al. 2004; Schwager et al. 2009], which present ME control schemes specifically targeted for coverage purposes.

The rest of the paper is organized as follows. Section 2 introduces WSNs with MEs and provides a taxonomy of the network architectures, based on the role of the MEs. Section 3 presents an overview of the data collection process, and outlines the related issues. Each of such issues is then investigated in detail and comparatively reviewed in the subsequent sections. Specifically, contact detection and data transfer in WSNs with MEs are discussed in Sections 4 and 5, respectively. Section 6 presents routing to MEs, while motion control is covered in Section 7. Finally, Section 8 offers concluding remarks, with directions on open research issues.

2. WIRELESS SENSOR NETWORKS WITH MOBILE ELEMENTS

To better understand the specific features of Wireless Sensor Networks with Mobile Elements (WSN-MEs), let us first introduce the reference network architecture, which is detailed according to the role of the MEs.

The main components of WSN-MEs are the following.

—*Regular sensor nodes* (or just nodes, for short) are the sources of information. Such nodes perform sensing as their main task. They may also forward or relay messages in the network, depending on the adopted communication paradigm.

—*Sinks (base stations)* are the destinations of information. They collect data sensed by sensor nodes either directly (i.e., by visiting sensors and collecting data from each of them) or indirectly (i.e., through intermediate nodes). They can use data coming from sensors autonomously or make them available to interested users through an Internet connection.

—*Special support nodes* perform a specific task, such as acting as intermediate data collectors or mobile gateways. They are not sources nor destinations of messages, but exploit mobility to support network operation or data collection.

Note that mobility might be involved at the different network components. For instance, nodes may be mobile and sinks might be static, or vice versa. In any case, we define a WSN-ME as a network where at least one of the above-mentioned components is mobile.

Depending on the specific scenario, the support nodes might be present or not. When there are only regular nodes, the resulting WSN-ME architecture is *homogeneous* or *flat*. On the other hand, when support nodes are (also) present the resulting WSN-ME architecture is *non-homogeneous* or *tiered*. Furthermore, different from traditional WSNs, which are usually limited to be dense, WSN-MEs can also be sparse. As the network architecture strongly depends on the role of the MEs, we will analyze it in detail in the following section.

2.1 Mobile elements

This section introduces the different types of Mobile Elements (MEs) with increasing level of mobility, by focusing on architectural aspects.

2.1.1 *Relocatable nodes.* These are mobile nodes which change their location to better characterize the sensing area, or to forward data from the source nodes to the sink. In contrast with mobile data collectors (which are discussed in the next section), relocatable nodes do not carry data as they move in the network. In fact, they only change the topology of the network – which is assumed to be rather dense – for connectivity or coverage purposes. More specifically, after moving to the new location, they usually remain stationary and forward data along multi-hop paths. A WSN-ME architecture based on relocatable nodes is depicted in Figure 1. Although in theory ordinary nodes might be relocatable, in most cases special MEs (e.g., support nodes) are used.

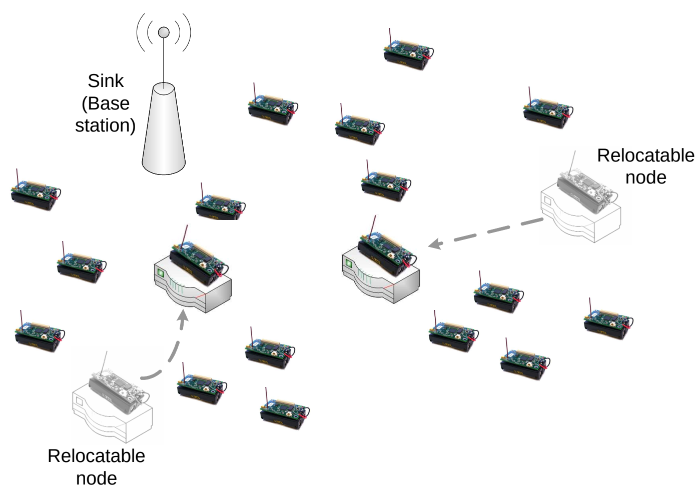


Fig. 1. Architecture of a WSN-ME with relocatable nodes.

A system with relocatable nodes targeted for topology management has been proposed in [Srinidhi et al. 2003]. In particular, special *Predefined, Intelligent, Lightweight tOpology managemenT* (PILOT) nodes are used to re-establish network connectivity for faulty links. In detail, PILOT nodes move to regions where the connection between nodes is unstable or failing, and act as bridges. As a consequence, they actively change the WSN topology in order to improve both communication reliability and energy efficiency. Algorithms for placement of relocatable nodes in the context of improving network connectivity have been investigated in [Wu and Yang 2005; Tang and McKinley 2006; Dini et al. 2008; El-Moukaddem et al. 2009].

Relocatable nodes can also be used to address the problem of sensing coverage. In this case, the primary concern is not ensuring network connectivity, but avoiding coverage holes – areas where the density of nodes is not adequate to properly characterize a phenomenon or detect an event. Approaches targeted for sensing coverage can focus on sensor deployment [Wu and Yang 2005; Wang et al. 2006;

Wang et al. 2007], sensor relocation and dispatch [Butler and Rus 2003; Wang et al. 2005; Yoon et al. 2008], or both [Wang and Hu 2008; Deshpande et al. 2009].

Relocatable nodes provide a *mobility-assisted* approach to WSNs, in the sense that MEs are not actively exploited for data collection. Therefore, in the following we will not discuss further solutions based on relocatable nodes. We will instead detail actual *mobility-based* approaches where MEs are actively used for data collection.

2.1.2 *Mobile Data Collectors (MDCs).* These are mobile elements which visit the network to collect data generated from source nodes. Depending on the way they manage the collected data, MDCs can be either *mobile sinks* or *mobile relays*.

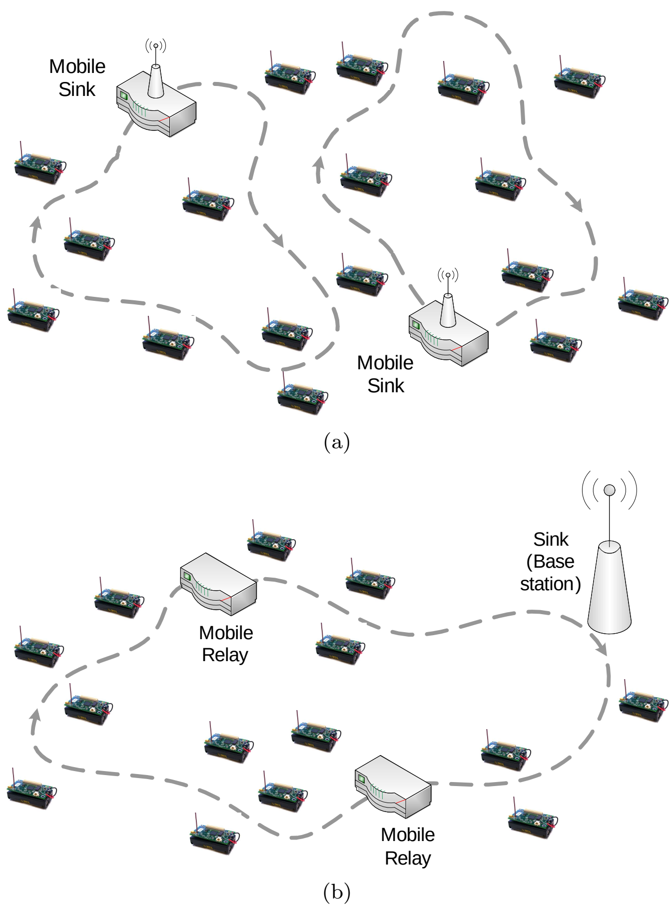


Fig. 2. Architectures of WSN-MEs with MDCs: (a) mobile sinks and (b) mobile relays.

Mobile Sinks (MSs). These are mobile nodes which are the destination of messages originated by sensors, i.e., they represent the endpoints of data collection in WSN-MEs. They can either autonomously consume collected data for their own purposes or make them available to remote users by using a long range wireless Internet connection. The MS-based WSN-ME architecture is depicted in Figure 2(a).

MSs have been considered in the existing literature [Wang et al. 2005; Rao et al. 2008]. In these cases, ordinary sensor nodes are static and densely deployed in the sensing area. One or multiple MSs move throughout the WSN to gather data coming from all nodes. Note that the path between the source nodes and the MSs is multi-hop, although the actual path changes with time, since the position of the MS is not fixed.

A different approach targeted for data collection in urban scenarios has been considered in [Anastasi et al. 2010]. In this case, people act as MSs by collecting environmental data (such as pollutants concentration and weather conditions) for their own purposes. The reference WSN scenario is represented by a sparse WSN where multiple MSs can be in contact with a single sensor node at the same time.

Mobile Relays (MRs). These are support nodes which gather messages from sensor nodes, store them, and carry the collected data to sinks or base stations. They are not the endpoints of communication, but only act as mobile forwarders. This means that the collected data move along with them, until the MRs get in contact with the sink or base station. The MR-based WSN-ME architecture is depicted in Figure 2(b).

MR-based data collection in WSNs has been proposed in the data-MULE system [Shah et al. 2003; Jain et al. 2006]. In detail, the data-MULE system consists of a three-tier architecture, where the middle tier is represented by relays, called *Mobile Ubiquitous LAN Extensions* (MULEs). Sensor nodes – which are supposed to be static – wait for a MULE to be in contact before starting communications. Then the MULE collects data and moves to a different location, eventually passing by the base station, where the gathered data are stored and made available to remote users.

Similar approaches have also been used in the context of opportunistic networks (see [Conti et al. 2008] for a detailed survey). One of the most well-known approaches is given by the message ferrying scheme [Jun et al. 2005; Zhao et al. 2004]. Message ferries provide the service of message relaying in sparse and mobile ad hoc networks. Message ferries move around in the network area and collect data from sources. They carry the stored data and forward them toward the destinations. Thus, message ferries can be seen as a moving communication infrastructure which enables data transfer in sparse wireless networks.

2.1.3 *Mobile peers.* Unlike MDCs, which are either sinks or special relay nodes, mobile peers are ordinary mobile sensor nodes in WSN-MEs. Since they can be both originator and relays of messages in the network, their interactions are symmetrical because the sink itself might also be mobile. When a peer is in the communication range of the base station, it transfers its own data as well as those gathered from other peers while moving in the sensing area. A WSN-ME architecture based on mobile peers is depicted in Figure 3. In this case the network is homogeneous and rather sparse.

Mobile peers have been successfully employed in the context of wildlife monitoring

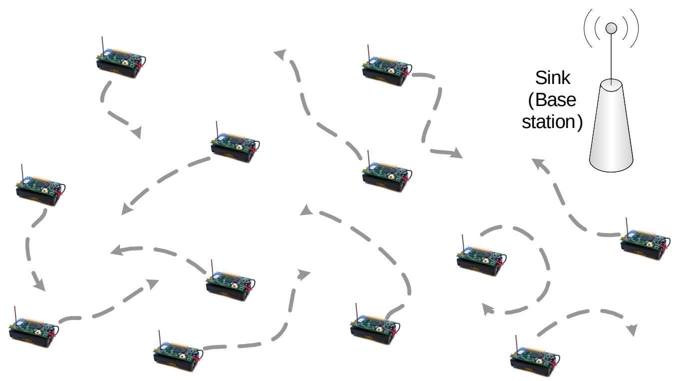


Fig. 3. Architecture of a WSN-ME with mobile peers.

applications, such as tracking of zebras in the ZebraNet project [Juang et al. 2002] or whales in the SWIM system [Small and Haas 2003; Haas and Small 2006]. Sensor nodes are attached to animals and act as peers, so that not only do they generate their own data, but also carry and forward all data coming from other nodes which they have been previously in contact with. When mobile peers get close to a base station, they transfer all the gathered data. Data which have already been transferred to a base station are flushed by peers in order to save storage.

Mobile peers can also be used for opportunistic data collection in urban sensing scenarios [Campbell et al. 2006; Campbell et al. 2008]. Sample applications include personal monitoring (e.g., physical exercise tracking), civil defense (e.g., hazards and hotspot reporting to police officers) and collaborative applications (e.g., information sharing for tourism purposes). In this context, sensors are not used mainly for monitoring the environment, but are rather exploited to characterize people in terms of both interactions and context (or state) information. An example is represented by handheld mobiscopes [Abdelzaher et al. 2007] where handhelds devices – such as cell phones or PDAs – gather data from the surrounding environment and report them to servers, which provide services to remote users.

Since most of the issues in the context of WSN-MEs based on mobile peers are similar to classic DTNs, we will not focus on these topics. Interested readers may refer to [Conti et al. 2008] for additional information.

3. OVERVIEW OF DATA COLLECTION IN WSN-MEs

In this section we will outline the different phases of the data collection process and point out the main issues involved. For convenience, without loss of generality, we will refer to the scenario shown in Figure 4, where a contact occurs between an ME and a static sensor node. The description can be easily extended to the case where sensor nodes are also mobile.

With reference to Figure 4, the ME is in *contact* with a sensor when they can reach out each other through wireless communications. In general, a contact happens when two or more nodes are in their mutual communication range. The amount of time the nodes are in contact is defined as the *contact time*. We define the *contact area* of a node as the region where that node can possibly be in contact

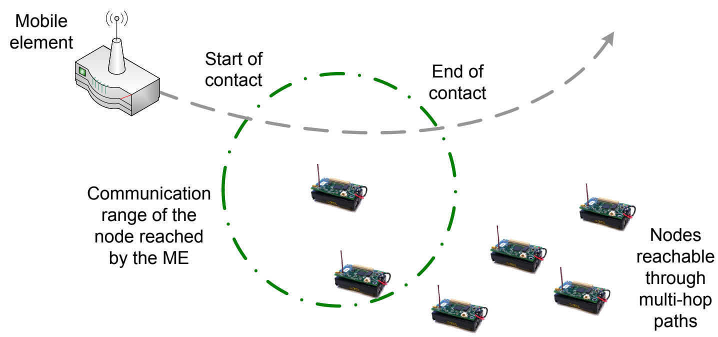


Fig. 4. Representative scenario for data collection in WSN-MEs.

with other nodes, for example the dashed circle in Figure 4. Since nodes cannot communicate unless they are in contact, we define *discovery* as the process which allows a node to detect a contact, i.e., the presence of an ME in its communication range. On the other hand, we define *data transfer* as the message exchange between nodes which are in contact. Note that this definition of data transfer covers only single-hop transmissions, which may involve two or more nodes, where at least one is mobile. We also define the *residual contact time* as the amount of time which is actually used for data transfer during a contact. The residual contact time is generally shorter than the contact time, since a node has to discover the presence of an ME before starting the message exchange. Finally, we indicate as *routing* the process of data forwarding toward an ME, i.e., the selection of the path or the sequence of pair-wise message transmissions to the intended destination.

On the basis of the discussion above, three main phases associated with the data collection in WSN-MEs emerge: *discovery*, *data transfer* and *routing to MEs*. Each phase has its own issues and requirements which we briefly investigate below.

—*Discovery* is the first step for collecting data in WSN-MEs, since the presence of the ME in the contact area is generally unknown at sensors. The goal of discovery protocols is to detect contacts as soon as they happen, and with a low energy expenditure. In other words, discovery should try to maximize the number of detected contacts, and also the residual contact time, while minimizing the energy consumption. Discovery will be considered in Section 4.

—*Data transfer* immediately follows discovery. The goal of data transfer protocols is to get the most out of the residual contact time, that is, to maximize the throughput – in terms of messages successfully transferred per contact – while minimizing the energy consumption. Data transfer will be discussed in Section 5.

—*Routing to MEs* is actually possible only when the density of the network is enough to allow (even partial) multi-hop routes[1]. This is true for dense WSN-

[1]Actually messages can be opportunistically forwarded during contacts even when the network is sparse, such as in [Juang et al. 2002; Haas and Small 2006]. Since this case is not very different to what happens in DTNs (as already mentioned in Section 2.1.3), we will not address it in the

MEs, where routing to ME is always possible. Actually, this can happen even with more sparse WSN-MEs, where nodes can organize as disconnected clusters. In this case, routing is possible only when an ME is in contact with at least one node in the cluster. However, some nodes can be elected as bridges and act as gateways between the cluster nodes and the ME. In both cases, the goal of routing is to find the best multi-hop paths – in terms of both delivery ratio and low energy consumption – towards either the ME or a node which can be in contact with the ME. Routing to MEs will be considered in Section 6.

3.1 Impact of mobility

In the previous discussion we abstracted from the specific characteristics of mobility, even though we addressed the presence of MEs in the data collection scenario. However, different kinds of mobility can significantly impact on the phases of data collection. The aspect of mobility which has the most significant impact on the data collection process is *controllability*, depending on whether the motion of the ME is autonomous or not.

There are two main patterns for *uncontrolled mobility*: deterministic and random. The *deterministic* mobility pattern is characterized by the regularity in the contacts of the ME, which enters the communication range of sensor nodes at specific (and usually periodic) times. This can happen when the ME is placed on a shuttle for public transportation, as in [Chakrabarti et al. 2003]. On the other hand, the *random* mobility pattern is characterized by contacts which take place not regularly, but with a distribution probability. For instance, Poisson arrivals of an ME have been investigated in [Somasundara et al. 2006], while random direction ME mobility has been considered in [Poduri and Sukhatme 2007]. In general, a node should perform discovery continuously, so that it can increase the chance of detecting contacts. However, when some knowledge on the mobility pattern of nodes can be exploited, the node can restrict discovery to the instants where the probability of an ME being in proximity is high. This aspect will be discussed in Section 4.2.

Different from the former case, *controlled mobility* exploits nodes which can actively change their location, because they can control their trajectory and speed. As a consequence, motion becomes an additional factor which can be effectively exploited for designing data collection protocols specific to WSN-MEs. It should be noted that controlled mobility can make some issues related to data collection less relevant. For instance, the discovery problem can be somewhat simplified, since MEs can be instructed to visit (individual) nodes at specific times. In addition, the duration of contacts is also less problematic, since the MEs can stop at nodes until they have collected all buffered data. Anyway, different problems arise in this context, mainly related to how to schedule ME arrivals at sensors – which includes defining both the trajectory and the speed of the ME – while satisfying certain quality of service constraints (such as minimizing latency and buffer overflows) and keeping the energy consumption as low as possible. Motion control will be discussed in Section 7.

Figure 5 summarizes the different aspects of data collection in WSN-MEs and

following, but rather focus on routing to MEs.

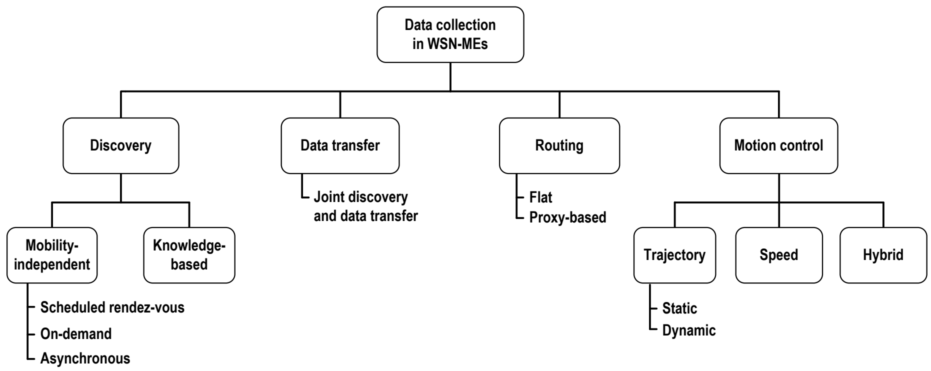


Fig. 5. Taxonomy of the approaches for data collection in WSN-MEs.

illustrates a taxonomy of the approaches used in the different phases. In the following sections we will analyze the different aspects in detail by surveying the main proposals presented in the literature.

4. DISCOVERY

Discovery allows nodes to detect the presence of the ME while it is in the contact area. Since communication is possible only during contacts, discovery should not only be able to correctly detect the presence of the ME, but should also be timely, so that the contact time can be fully exploited.

Indeed, contacts need to be detected even when they occur very infrequently. In order to reduce the energy consumption due to discovery, two complementary approaches can be used. First, it is possible to design (general) mobility-independent low-power protocols, which can detect MEs irrespective of their mobility pattern. Second, it is also possible to exploit some knowledge on the mobility of nodes, so that sensors can be active only when the ME is expected to be in contact. We detail these two approaches separately below.

4.1 Mobility-independent discovery protocols

Mobility-independent discovery protocols can be subdivided into different schemes: *scheduled rendez-vous*, *on-demand*, and *asynchronous*.

Scheduled rendez-vous schemes assume that sensor nodes and MEs agree on a specific instant at which they will be in contact. This may happen when the MEs follow a very strict schedule, so that sensors know exactly when the ME will enter the contact area, and can thus wake up at pre-defined times. In [Chakrabarti et al. 2003], for instance, MEs are assumed to be on board of public transportation shuttles which visit sensor nodes according to a tight schedule. As an alternative, nodes can just define a network-wide active time and wake up accordingly, so that they can contact the neighboring nodes which are available at that time. This kind of approach is adopted in ZebraNet [Zhang et al. 2004], where nodes are synchronized through a Global Positioning System (GPS). Scheduled rendez-vous protocols are rather simple to implement, because they only consist of the exchange or derivation of schedules, and very energy-efficient. Obviously, such approaches require strict synchronization, or that the mobility of the ME is accurate enough to obey schedules. However, this assumption is rather strong and difficult to hold in practice, unless the motion of the ME can be controlled somehow. This limits the applicability of scheduled rendez-vous schemes to practical scenarios.

On-demand schemes are based on the idea that the static node can wake up as a result of a process initiated by the ME. To this end, two main approaches can be used. In the first approach, nodes use multiple radios [Schurgers et al. 2002a; Yang and Vaidya 2004]: a long-range and high-power radio is used for data communication, while a low-range low-power radio is used for awaking nodes. As the wakeup radio is low-power, the static sensor can continuously monitor the related channel (also known as paging channel) for activity. The ME sends a tone or a message to the paging channel. As soon as the static sensor detects activity on the channel, it powers up the data radio and starts communicating with the ME. A different approach exploits a radio-triggered activation, similar to Radio Frequency IDentification (RFID) systems [Gu and Stankovic 2005; Ansari et al. 2008]. In this case, the ME sends wakeup messages (or signals) which have enough energy to trigger the activation of the static sensor node. Specifically, the energy provided by the wakeup message is used at the sensor node to generate an interrupt, which, in turn, enables the radio transceiver.

Although these methods have been originally proposed in the context of traditional (static) WSNs, they are very appealing also in the context of WSN-MEs, because they can significantly reduce the energy consumption of sensor nodes. In addition, they allow a very timely detection of MEs. However, they have some disadvantages. First, both low-power radios and radio-triggered emitters have a very short coverage range, restricted to a dozen meters in most cases. This can be a very limiting factor in a large number of applications, as the distance of the ME from static sensors may not always be that short. In addition, they require special hardware support, which is not available on currently off-the-shelf commercial platforms.

Finally, *asynchronous* schemes define sleep/wakeup patterns such that nodes can communicate without explicitly agreeing on their activation instants. One of the most common variants of asynchronous schemes in the context of WSN-MEs is based on periodic listening [Jain et al. 2006; Anastasi et al. 2008; 2009b]. More specifically, the ME sends periodic discovery messages, while the static node cyclically wakes up and listens for advertisements for a short time. If it does not detect any discovery message it can return to sleep, otherwise it can start transferring data to the ME [Schurgers et al. 2002b]. To ensure that the sensor can receive a discovery message independent of its sleep/wakeup schedule, the discovery parameters and the duty-cycle have to be properly defined [Anastasi et al. 2009a]. The same scheme can be extended to exploit multiple radios or multiple channels, like in [Zhao et al. 2004]. In this case, the ME still uses the approach based on discovery messages, but replicates it over multiple channels. For instance, when two channels are available, the ME can use a high transmission power for the *far discovery* channel, and a low transmission power level for the *near discovery* channel. The sensor can use a very low duty-cycle for the far discovery channel. As soon as the presence of the ME has been detected, the sensor switches to the near discovery channel with a higher duty-cycle. This scheme is a compromise between discovery latency and energy efficiency, since the sensor can take advantage of discovering the ME when it is far away, and start communicating only when it is in close proximity.

4.2 Knowledge-based power management

In the previous section, we have discussed general approaches for ME discovery which do not rely on the specific mobility pattern of the MEs. The efficiency of the discovery process can be further improved by exploiting some knowledge on the mobility pattern of the ME, such that the sensor node can perform discovery only when the ME is likely to be in contact, and then sleep for the rest of the time. To this end, suitable mechanisms have to be defined in order to derive the mobility pattern of the ME. Since sensor nodes start with no prior knowledge on the mobility pattern, they have to learn it by observing the arrivals of the ME.

A general framework for knowledge-based power management in DTNs has been proposed in [Jun et al. 2005]. Three different power management modes are defined. In the *dormant* mode nodes sleep since they do not expect to be in contact with others, while in the *searching* mode nodes try to discover potential contacts. Finally, in the *contact* mode nodes are awake and communicate with their neighbors. Within this context, the authors propose power management policies – in terms of transitions between the different modes – targeted for scenarios where different degrees of knowledge about contacts are available: no-knowledge, partial and complete knowledge. We characterize approaches suitable for different mobility patterns below.

Even in the case where mobility is deterministic, visit times may be unknown to sensors so that they have to predict when actual contacts will occur. In [Gao et al. 2010], the authors initially perform a learning phase where they check the presence of the ME by using an asynchronous discovery protocol. Specifically, the ME continuously emits beacon messages, while static nodes perform periodic listening. Once the ME has been discovered, sensors store the time of contacts, which are then used to derive the schedule of ME visits. As for random mobility, sensor nodes still have to learn when contacts will take place, however they have to consider that the contacts are not deterministic. When available, some prior knowledge on mobility can be exploited, i.e., where a probabilistic characterization of the mobility pattern is available in a specific scenario. This is the approach used in [Jun et al. 2005], where statistical information about the mean and the variance of contacts is exploited. Otherwise, a characterization of the mobility pattern can be derived online.

Obviously, when the mobility pattern is completely random, it is hard to predict contacts, and nodes can only continuously perform contact detection. In [Poduri and Sukhatme 2007], the time needed for mobile peers to form a connected backbone (called coalescence time) is characterized, under the assumption that nodes move according to a random direction mobility model. The authors find upper and lower bounds for the coalescence time, which are related to both the communication range and the number (N) of mobile peers. Specifically, the upper bound of the coalescence time is shown to be $O(\frac{1}{\sqrt{N}})$. In some cases, the contact opportunities can be so scarce and short that additional measures are needed to effectively support data collection. To this end, two mechanisms are proposed in [Eisenman et al. 2008], with specific reference to WSNs with mobile peers and uncontrolled human mobility. The basic idea behind them is that nodes can obtain a quantity of interest even when they are not equipped with an adequate sensor. They can either exploit readings made available from other peers (*sensor sharing*), or exploit alternative sensed quantities – e.g., accelerometer rather than GPS data for measuring slopes – when available (*sensor substitution*).

In both deterministic and random mobility patterns, contacts can be either *stationary* or *dynamic*. In the first case, they are usually periodic, thus repeating in a given time, usually referred to as *epoch*. In the latter case, contacts usually show a certain periodicity, but their period or trend can change from time to time. On one hand, for stationary mobility patterns, the learning phase can be performed only once (after the sensors have been deployed), since the arrival pattern does not change with time. On the other hand, dynamic mobility requires continuous monitoring, so that the sensor nodes can adapt to changing operating conditions.

In [Baruah et al. 2004], the nodes which are in contact with the MEs (called proxies) are exploited to keep track of its traversal, and are responsible for making the information on ME arrivals available to the rest of nodes in the network. More specifically, proxies store the arrival times of the ME and derive the corresponding mean and variance by using plain averaging or exponential smoothing. This approach is justified by two main factors. First, maintaining the time series of ME arrivals in order to derive their distribution has huge storage requirements. Second, averaging and smoothing help to cope with variations in the mobility pattern.

Approaches to ME discovery based on reinforcement learning, a form of unsupervised learning in the field of artificial intelligence [Kaelbling et al. 1996], are considered in [Dyo and Mascolo 2008; Di Francesco et al. 2010] for sparse WSNs. In [Dyo and Mascolo 2008] mobile sensor nodes act as peers, and can perform three different actions, namely, awake, sleep, or change their duty-cycle to a different value. When a node is awake, it scans for neighbors and uses the number of encountered neighbors as the reward of discovery. More in detail, each day is split in a number of time slots and the reward is obtained by using an exponentially weighted moving average (EWMA) filter. A balanced strategy is proposed to set the duty-cycle, so that a given daily energy budget of nodes is spread proportionally to the likelihood of the ME of being in contact in a specific time slot. A similar approach is exploited in [Di Francesco et al. 2010] for the scenario where an ME collects data from sparsely deployed static sensor nodes. The major advantage of reinforcement-based approaches is that they can adapt to different mobility models without any a priori knowledge, even when some parameters (like the speed or the time between subsequent contacts) change with time.

4.3 Discussion

Although several discovery schemes have been proposed in the literature, most of them have been originally designed for static WSNs [Schurgers et al. 2002a; Yang and Vaidya 2004: Gu and Stankovic 2005: Ansari et al. 2008]. Whereas they can also be applied to WSN-MEs, many of them have not been evaluated in the specific context of mobile nodes. In fact, most of the schemes proposed for WSN-MEs are based on periodic listening. It would be interesting to evaluate the performance of on-demand schemes based on radio-triggered activation, or rendez-vous schemes exploiting multiple radios (and/or channels), in the specific scenario of WSN-MEs.

A common assumption behind knowledge-based approaches to discovery is that contacts are rather periodic [Chakrabarti et al. 2003]. It seems there is only limited research in the field of actually deriving the arrival times of an ME, as well as the duration of contacts. This is especially useful when synchronous schemes are used, and no a-priori information on contacts is available. To this end, machine learning techniques [Bishop 2007] specifically targeted for sensor nodes might be used.

Most of the existing solutions to the discovery problem assume that discovery is performed for each potential contact, in order to improve the detection efficiency. However, in some cases, discovery might not be very useful. Consider the scenario where a sensor node generates messages quite slowly with respect to the frequency of the ME contacts. In this case, the sensor might choose to perform discovery less frequently, by deliberately missing some contacts, while still being able to transfer buffered data. This problem, referred to as communication scheduling [Bolöni and Turgut 2008], has not been fully exploited so far.

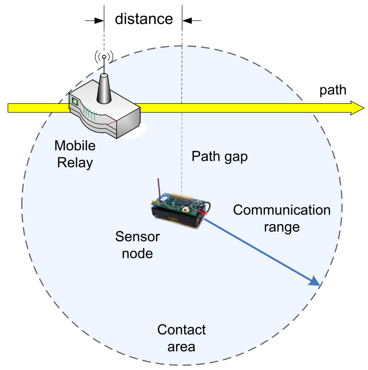
Finally, all proposed solutions rely on using the radio for discovery purposes. Since during contacts nodes are in general also physically close to the ME, mechanisms which are not radio-based can also be exploited, such as passive infra-red sensors, microphones, or ultra-sonic rangers. This area of research seems to be rather unexplored so far.

5. DATA TRANSFER

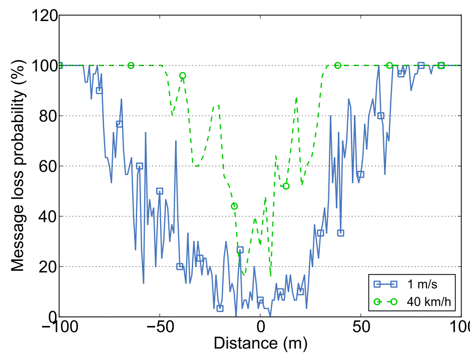
After the presence of an ME has been detected, actual data transfer has to be accomplished by using a data collection protocol. By data transfer, we mean the communication process between an ME and its one-hop neighbors[2]. As a consequence, data transfer protocols have to be aware of the issues which result from mobility. In fact, the communication process is affected not only by channel conditions, but also by the distance between the source and the receiver, which changes with time based on their speed.

A few approaches in the literature have characterized the way mobility affects communications between an ME and static sensor nodes. Experiments carried out in [Kansal et al. 2004] have shown that a robotized ME moving slowly – ranging from 30 to 150 cm/s – can collect an amount of data which is actually independent of the speed. The situation is much different, however, when MEs can move at higher speeds. This happens in urban scenarios like the one considered in [Anastasi et al. 2007a], where an ME moves along a street to collect data from static sensors as shown in Figure 6(a). In that paper, different distances between the static sensors and the ME are considered, as well as different speeds for the ME (such as 1 m/s for pedestrians, in addition to 20 and 40 km/h for cars and buses). In this context the message loss is shown to have a sort of parabolic trend while the ME is in the transmission range of the static sensor, as illustrated in Figure 6(b). Note that the message loss function is somewhat symmetrical, and reaches the minimum value

[2]The different problem of routing to MEs, limited to the case where MEs are MDCs, will be considered in Section 6.



(a)



(b)

Fig. 6. (a) Reference scenario and (b) message loss experienced between a static node and an ME moving at different speeds, from [Anastasi et al. 2007a].

when the ME is closest to the static sensor. This minimum value does not depend significantly on the speed of the ME, while it is greatly affected by the trajectory (i.e., the path gap) of the ME. The impact of duty-cycle for energy conservation during data transfer is also investigated in [Anastasi et al. 2007a]. The authors show that the number of transferred messages is not marginal for low duty-cycles (below 5%) even when the ME moves at high speed.

Several works have evaluated the data transfer phase in WSN-MEs by using a simple message loss model and data transfer process. For instance, in [Chakrabarti et al. 2003], a circular communication range and no message loss during a contact are assumed. Similar conditions are assumed in [Shah et al. 2003], where an analytical model is developed to characterize the performance – in terms of data success rate and buffer requirements at sensors – of data collection using an ME. Under the same assumptions, a stop-and-wait protocol is used for data collection in [Kansal et al. 2004; Somasundara et al. 2006]. Note that, since the static sensors in general may not know when the contact time ends, a timeout since last received message is used as the end of contact indication. Since a stop-and-wait approach is not efficient as for communications, a window-based *Automatic Repeat reQuest* (ARQ) scheme is investigated in [Anastasi et al. 2007b]. The authors consider a scenario where sensor nodes have a limited number of messages to transfer during each contact and assume the the realistic message loss model derived in [Anastasi et al. 2007a]. It is analytically shown that, by using a window larger than one message, it is possible to improve the number of successfully transferred messages, while reducing the energy expenditure of the sensors. The authors also derive the optimal transmission schedule, based on the number of buffered messages and the message loss pattern.

5.1 Impact of discovery

The approaches mentioned so far only consider the data transfer phase, i.e., they do not consider the impact of the discovery phase on the subsequent operations. A joint characterization of discovery and data transfer is given in [Jain et al. 2006], which extends the previous work in [Shah et al. 2003]. More specifically, the authors in [Jain et al. 2006] consider the single-radio asynchronous discovery protocol based on periodic listening (already introduced in Section 4.1) and model the ME arrivals as a Poisson process. However, since it is assumed that messages cannot be lost during contacts, no specific data transfer scheme between the sensors and the ME is considered. Analysis and simulation are performed for multiple MSs in order to characterize the energy expenditure of nodes, as well as latency and data success rate of data collection. The authors derive a stability condition (such that buffered data at sensors do not arbitrarily grow with time) based on different parameters, including the ME arrival rate and the message generation rate at sensors. They show that the amount of successfully collected data is modest (less than 60%) when the stability condition is barely satisfied. In addition, they found that mobility patterns with bursty ME arrivals perform worse than others where contacts are more regular.

A simulation analysis is performed in [Anastasi et al. 2008] by using a message loss model derived from [Anastasi et al. 2007a]. Here a single-radio asynchronous discovery protocol based on periodic listening is used, while the data transfer protocol is a window-based ARQ with selective retransmission [Kurose and Ross 2009]. The performance evaluation is performed under saturation conditions, i.e., when the sensor node is always ready to send data to the ME. First, the impact of different parameters (e.g., the duty-cycle) is considered to evaluate the contact miss rate and the residual contact time. Then, the throughput and the overall energy consumption per message correctly transferred to the ME are derived. The obtained results show that the duty-cycle adopted in the discovery phase significantly impacts on the energy consumption per collected message, depending on the uncertainty of ME arrivals. In detail, a low-duty-cycle is not always the most energy-efficient option, especially when ME arrivals are predictable with a certain accuracy. An analytical model for data collection, under the same conditions of [Anastasi et al. 2008], is given in [Anastasi et al. 2009b], which also considers the case where an ME has only a limited number of messages (called *bulk*) to transfer at each contact. To this end, the authors derive the probability of bulk reception and the associated average transfer latency.

Data delivery to one or more MEs simultaneously present in the contact area is also investigated in [Anastasi et al. 2010] in the context of sparsely deployed sensor nodes transferring chunks of data to multiple MEs. The authors refer to urban applications where people (acting as MEs) download environmental data (e.g., air quality, temperature, and so on). In this case the communication is successful only if the entire amount of data coming from sensors is correctly received by at least one ME. In order to improve data dissemination, the *Hybrid Interleaved data transfer protocol* (HI) is introduced. The HI scheme exploits an encoding technique suitable for WSN nodes [Rizzo 1997] to add redundant information to the source data. Encoded data are then split into blocks which are interleaved before being sent. The stream of data is finally broadcast to MEs, which can recover the original information even when they receive only a subset of the encoded data. An acknowledgement scheme is also used to notify sensors that the entire chunk of data has been correctly decoded at the ME. The HI scheme is shown to perform better than a window-based ARQ scheme with selective retransmission, even when a single ME is in contact with one sensor node.

5.2 Discussion

The scope of data transfer to MEs is quite broad. However, most solutions proposed in the literature either consider: (i) a dense WSN, where a custom MAC protocol is used for data collection between an ME and multiple static sensor nodes; or (ii) a sparse WSN, where communication typically occurs between a single static node and one or at most a very limited number of MEs. On one hand, MAC protocols specifically targeted for data transfer between multiple static sensors and MEs have been only marginally addressed, as in [Venkitasubramaniam et al. 2004] which present an opportunistic-ALOHA MAC for WSNs exploiting aerial vehicles as MSs. On the other hand, the suitability and the performance of MAC protocols commonly used in WSNs, like the IEEE 802.15.4 standard [IEEE 802.15.4 2006], should be better characterized when MEs are involved.

Despite having received wide attention in the context of DTNs and MANETs, schemes based on encoding [Pelusi et al. 2007] seem to be rather unexplored in the context of WSN-MEs, with the exception of [Anastasi et al. 2010], where sensor nodes exploit erasure coding to transfer data to multiple MSs. This aspect should be investigated further, especially in highly dynamic mobile scenarios.

Recently, joint discovery and data transfer have been evaluated in depth. However, most of the solutions available in the literature evaluate the performance only with reference to a single or a few metrics. Approaches capable of incorporating different quality of service parameters are still lacking. To this end, solutions providing integrated and adaptive resource management have not been proposed in the literature yet.

6. ROUTING TO MOBILE ELEMENTS

In this section we discuss approaches for routing messages toward MEs, with focus on MDCs. This implies that the network is dense enough to allow either a full ad hoc multi-hop or a hybrid (partial multi-hop) communication paradigm. We assume that the ME is not controllable, so that the routing protocol has to adapt to the motion of the ME. Routing techniques which jointly exploit motion control will be considered in Section 7.

There are two main classes of routing techniques for uncontrollable MEs, namely, *flat routing* and *proxy-based routing*. In both cases the routing paths to the ME are adaptively computed and updated, so that it can be reached while traversing the network. *Flat routing* is characterized by the fact that all nodes behave the same way, and, hence, there are no sensors with special roles. *Proxy-based routing*, on the contrary, elects a number of proxies or gateways among sensor nodes. Proxies bridge communications between the static sensors and the ME.

6.1 Flat routing

Several routing protocols for WSN-MEs have originated from well-known solutions originally conceived for traditional dense networks with static nodes. However, there exist solutions specifically conceived for WSN-MEs. For convenience, we will start discussing protocols which have been extended to WSN-MEs, and then present the remaining approaches.

A modification of the Optimized Link State Protocol (OLSR) [Clausen and Jacquet 2003], a proactive protocol for ad-hoc networks, has been proposed in [Dantu and Sukhatme 2009] for robot networks where nodes act as mobile peers. The main idea behind the proposed solution is to exploit cues related to the mobility of nodes, in order to stabilize routes. The first cue is related to the direction of movement, and basically consists of an angular difference estimation between the neighboring nodes. The second one is related to the position of nodes. Routes are selected by using a stability metric, which estimates how long a link will last. Stability is obtained from the direction, or from both direction and position whenever both cues are available. The proposed approach is shown to reduce route switches of 10% when only the direction cue is considered, and of 20% when both position and location cues are exploited, with respect to the unmodified OLSR protocol.

Directed Diffusion (DD) [Intanagonwiwat et al. 2003] is one of the most famous approaches for data dissemination in static WSNs, and consists of three main phases. During the first phase, the sink initiates the propagation of an interest, which is a query message referring to a specific event. In the second phase, the interest is disseminated into the network, and gradients are set up on the basis of how each node is willing to receive and forward data. As a result, multiple paths from sources to the sink are set up. The last phase consists of a reinforcement, so that only one or a few paths are established for data propagation. The original DD scheme has been devised for static WSNs, therefore it is not suitable for WSN-MEs. A modification of DD addressing MEs is proposed in [Kansal et al. 2004] where two mechanisms are introduced to cope with mobility. The first one gives a higher priority to the interest propagation coming from MEs, with respect to static nodes. This helps reduce useless data propagation to intermediate nodes when the ME is actually approaching the sender. The second mechanism exploits acknowledgement messages during message exchange: since the ME usually remains in the communication range only for a small time, acknowledgement-based communication can better react to the ME going out of reach during transfers.

Similar to the previous case, the *MintRoute* protocol [Woo et al. 2003] has also been extended to WSN-MEs. The original MintRoute protocol used for static WSNs builds a tree structure for data collection, where the paths are evaluated by using a metric which tries to minimize the number of (re)transmissions. During network operations, MintRoute continuously evaluates link quality and re-computes the routing tree, if needed. A modification of MintRoute, called *MobiRoute* and specifically targeted for WSNs with an ME, has been proposed in [Luo et al. 2006]. Three mechanisms are introduced to cope with node mobility. The first one exploits beacon messages and timeouts to detect broken links due to the ME moving out of range. The second mechanism limits the tree re-construction phase to reduce the overhead, and tolerates temporary sub-optimal routing paths. The last mechanism uses bandwidth throttling and data buffering to mitigate the data loss generated by the ME while moving. Simulation results show that, with respect to the original MintRoute approach, MobiRoute can improve the network lifetime while keeping a satisfactory delivery ratio.

The *Energy-Aware Routing to Mobile gateway* (EARM) [Akkaya and Younis 2004] has been specifically devised for an ME which moves along a piece-wise linear path. At first, initial energy-efficient routes to the ME are obtained by using any routing protocol available for WSNs. Then, while the ME moves throughout the network, routes are updated under the constraint of minimizing the associated overhead. Nodes can increase their transmission power to a certain extent, in order to cover the ME while going out of reach. When the ME cannot be reached any more, routes are extended by exploiting part of the old neighboring nodes as intermediate forwarders, whenever possible, and as long as the associated overhead can be tolerated. Otherwise, re-routing is performed. Simulation results show that EARM obtains a 20% longer network lifetime with respect to continuous re-routing, at the cost of a slight increase in the end-to-end delay.

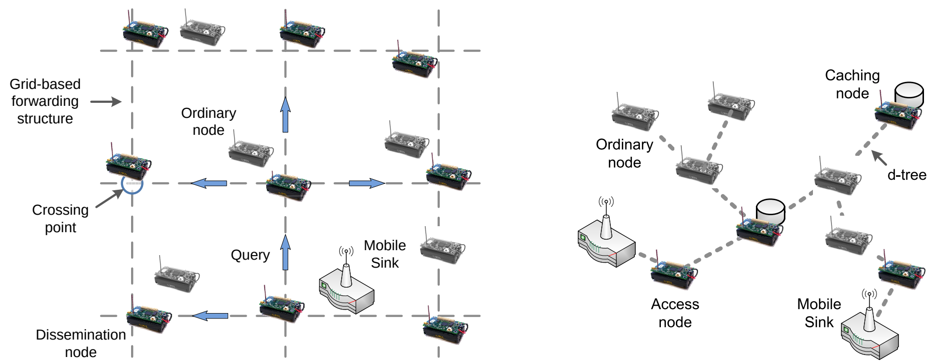
The *Weighted Entropy DAta diSsemination* (WEDAS) protocol introduced in [Ammari and Das 2005] also targets WSN-MEs, and exploits an information-theoretic approach. Forwarders are selected between the source nodes and the ME (which is assumed to move according to the random waypoint model) on the basis of two different parameters: the remaining energy at sensor nodes and the position of the ME. Here, both parameters are estimated and tracked, so that sensors can derive how they evolve with time. Hence, the concept of entropy – in terms of the uncertainty of the considered parameters – is applied for deriving the routing paths by weighting the remaining energy and the estimated position of the ME. Then an optimization problem is formulated in order to find the forwarders among the nodes with the minimum weighted entropy.

6.2 Proxy-based routing

Proxy-based routing protocols select a number of (static) sensor nodes called *proxies* – also referred to as *gateways*, *anchors* or *rendez-vous points* – which are in charge of collecting data from a specific region of the WSN. When the ME is in proximity or a few hops away, the proxy starts transmitting data to it. Note that proxy-based approaches can be used in both dense and moderately sparse WSNs. In the following, we will discuss first solutions which are limited to dense WSN-MEs, and then approaches which are (also) suitable to sparse WSN-MEs.

Two-Tier Data Dissemination (TTDD) [Luo et al. 2005] proactively builds an overlay grid-based forwarding structure to route data to MEs. The intersections of grid lines are called crossing points, while squares are referred to as cells (Figure 7(a)). Upon sending a message, a source node first establishes itself as a crossing point, then it starts sending announcements to the four adjacent intersections. The location of crossing points is exploited to reduce the data propagation in the network: only the node closest to the destination intersection will process the announcement message and repeat the procedure. This recursive propagation of announcements elects the dissemination nodes, which will operate as proxies, and establishes the routing paths. The ME starts the data collection process by flooding a query message to its local cell. The dissemination nodes then propagate the query along the grid and get the data back from sources. The assumption behind TTDD is that nodes are aware of their location and exploit geographic routing.

A similar approach is followed by *Scalable Energy-efficient Asynchronous Dissemination protocol* (SEAD) [Kim et al. 2003], which builds and maintains a dis-



(a) (b)

Fig. 7. Sample proxy-based routing protocols: (a) Two-Tier Data Dissemination (TTDD) and (b) Scalable Energy-efficient Asynchronous Dissemination protocol (SEAD).

semination tree (d-tree, for short) not only for routing, but also for data caching. The MEs can join the d-tree by sending a subscription query to their closest neighbor. This neighbor will become the access node of MEs, i.e., the node acting as a bridge between the MEs and the rest of the network (Figure 7(b)). Upon receiving a subscription query, the access node starts building the d-tree recursively. This building phase jointly determines the branch locations and the optimal position of the caching nodes, so as to minimize the communication overhead and the related energy consumption. The d-tree is recomputed dynamically as the ME moves through the network. When the hop distance between the ME and its access nodes exceeds a given threshold, a new access node is selected and the corresponding d-tree is built. This threshold is a tradeoff between latency and energy expenditure for updating the d-tree. SEAD is proved to perform better than other common data dissemination protocols such as Directed Diffusion and TTDD. A modified version of SEAD, called *DElay-constrained minimum-Energy Dissemination* (DEED), is proposed in [Kim et al. 2005] with focus on low-latency data collection.

A solution based on reinforcement learning has been proposed in [Baruah et al. 2004] for a scenario where an ME collects data in a relatively dense WSNs. To this end, the *Hybrid Learning-Enforced Time Domain Routing* (HLETDR) is introduced. The nodes which can communicate directly with the ME are selected as proxies. Proxies keep track of ME arrivals and derive a reinforcement, which is calculated as the probability of the ME being in the vicinity, under the assumption that its mobility pattern distribution is Gaussian. This reinforcement value is then propagated by the MEs to the rest of the network through multi-hop paths. During propagation, reinforcement is used by nodes to update the forwarding probabilities to their neighbors. The notion of time domain is also exploited, so that a temporal characterization is added to the routing process. The proposed solution is shown to be energy-efficient and robust to node failures by a simulation study.

The *Maximum Amount Shortest Path* (MASP) data collection strategy has been proposed in [Gao et al. 2010] for an ME moving along a constrained path. The sensor nodes which are at a one-hop distance from the ME are elected as proxies, and they collect data from the rest of the network through multi-hop routing. Proxies with a short contact time may become bottlenecks in the network, especially when they have to transfer a lot of messages. Therefore, MASP assigns nodes to proxies according to their contact time length, so as to maximize throughput while keeping the energy consumption low. To this end, an Integer Linear Programming (ILP) model is proposed and solved by using a genetic algorithm. In order to implement the MASP scheme, a two-phase data collection protocol is defined for both ME discovery and data gathering. MASP can also support relatively sparse WSNs as well as multiple MEs. Simulation results show that MASP can effectively increase the throughput and balance the energy consumption, thus outperforming the commonly adopted Shortest Path Tree approach.

A solution for moderately sparse sensor networks has been investigated in [Somasundara et al. 2006]. More specifically, the authors consider a network of disconnected groups of nodes, called *clusters*, which are visited by an ME. A node is elected within each group as a cluster head, in order to manage the inter-cluster data collection and the subsequent transmission to the ME. The cluster organization is initiated by the ME, which broadcasts a beacon message while traversing the network. Nodes which are one-hop neighbors of the ME are elected as cluster heads. These nodes propagate the beacon messages in the cluster, so that the shortest paths to the other nodes are established. Nodes can change their cluster membership in case they can reduce their hop distance to the ME. To improve data transfer during contacts, data coming from a cluster are pre-cached at the cluster head by using the Directed Diffusion protocol [Intanagonwiwat et al. 2003]. Data collection is initiated by the ME which periodically broadcasts a POLL message. Cluster heads then transfer data by using an acknowledgement-based retransmission scheme.

6.3 Discussion

A comparison of approaches for routing to MEs is given in Table I. Despite the number of solutions proposed in the literature, several schemes share a number of shortcomings. For instance, many approaches rely on centralized solutions. Although centralized solutions may be still convincing in the specific context, where the ME has much more computational power than ordinary nodes, decentralized solutions are more appealing [Somasundara et al. 2006; Gao et al. 2010], especially when multiple MEs are used. In addition, many solutions assume that the location of nodes is somewhat known, for instance by using a GPS [Kim et al. 2003; Luo et al. 2005]. Unfortunately, this assumption does not hold in practice, since GPS devices are costly and power-hungry. Even though GPS might be restricted to MEs (which can be used as anchors), mobility poses significant issues related to how to derive correct (up-to-date) location information.

A different aspect is related to the assumptions which are used to simplify the analysis, but that in most cases are too simplistic and do not apply to practical scenarios. Actually, these assumptions should be more carefully evaluated, and contrasted with experiments in more realistic scenarios. For instance, in [Vlajic and Stevanovic 2009] it is shown by simulations that there is only a limited advantage in using MEs rather than static sinks when the IEEE 802.15.4 standard is used as

Table I. Comparison of approaches for routing to MEs.

Solution	ME role	Number of MEs	Network type	Mobility pattern	Metric of interest
EARM [Akkaya and Younis 2004]	MS	Single	Dense	Linear	Energy
WEDAS [Ammari and Das 2005]	MS	Single	Dense	Random	Energy
HLETDR [Baruah et al. 2004]	MS	Single	Dense	Random	Energy
OLSR$^+$ [Dantu and Sukhatme 2009]	Peer	Multiple	Both	Random	Reliability
MASP [Gao et al. 2010]	MS	Multiple	Both	Linear	Reliability
DD$^+$ [Kansal et al. 2004]	MR	Single	Sparse	Fixed	Energy
SEAD [Kim et al. 2003]	MS	Multiple	Dense	Random	Energy
DEED [Kim et al. 2005]	MS	Multiple	Dense	Random	Latency
TTDD [Luo et al. 2005]	MS	Multiple	Dense	Random	Energy
MobiRoute [Luo et al. 2006]	MS	Single	Dense	Fixed	Reliability
[Somasundara et al. 2006]	MS	Single	Sparse	Fixed	Reliability

the MAC protocol. In fact, the overheads due to mobility management (e.g., node association and route maintenance) overcome the benefits of a mobile WSN.

7. MOTION CONTROL

As already mentioned, node mobility can be either controllable or not. When mobility is not controllable, sensor nodes can only conform to the way the ME moves throughout the network. Clearly, the mobility pattern of the ME significantly impacts the optimal data collection scheme. In [Chatzigiannakis et al. 2006], different data collection strategies are considered: passive (poll-based, initiated by the ME), partial multi-hop and full multi-hop. The data collection schemes are evaluated by simulation for different variants of randomized and deterministic ME mobility patterns. The obtained results show that, when latency is not critical, the most energy-efficient option is given by the ME traversing the whole network. Otherwise, a fixed trajectory with partial multi-hop data collection can achieve low latency at the expense of a higher energy consumption and message loss.

On the other hand, when mobility is controllable, the ME movements can be designed so as to achieve specific goals and optimize given performance parameters. As already mentioned in Section 1, we are considering here solutions which actively exploit motion control for data collection. The different problem of coordinated control of multiple mobile peers is considered in [Yao and Gupta 2009], where a backbone is formed in order to maintain connectivity among group of nodes, as well as to obtain a specific target formation.

Clearly, a controlled ME gives more flexibility for designing a data collection scheme. In this context, several robotized MEs have been developed, such as Robomote [Dantu et al. 2005], NIMS [Pon et al. 2005] and the PackBot system [iRobot Corporation 2010] used in [Kansal et al. 2004; Somasundara et al. 2006]. Mobility can be characterized by means of *trajectory*, the path followed by an ME during its movements, and *speed*. Approaches targeted for controlling the MEs can define either or both of these two parameters. Details related to the different classes are given in the next subsections.

7.1 Trajectory control

Trajectory control can be subdivided into two different categories. On one hand, *static trajectory control* refers to the definition of a path which does not change with time. On the other hand, *dynamic trajectory control* refers to the definition of a policy which can change the trajectory of the ME on-the-fly, in order to satisfy specific constraints on data collection, such as timeliness.

In general, trajectory control can be used for both sparse and dense wireless sensor networks. In many cases, when the network is moderately dense and partial multi-hop data forwarding can be afforded, some solutions jointly consider mobility and routing so as to further improve the performance of data collection.

7.1.1 *Static trajectory.* Many solutions available in the literature have addressed the design of a static trajectory for MEs. For instance, [Luo and Hubaux 2005] consider a single ME which collect data from a circular dense WSN. The authors show that, when a shortest path routing is used, the optimal ME mobility strategy consists of moving at the border of the sensing area. Based on this finding, they jointly consider mobility and routing for energy conservation. In this case the ME can still move in a circle, but with a shorter radius with respect to the sensing area. Nodes in the inner circle can use shortest path routing, while others follow a hybrid forwarding scheme. The nodes first route messages circularly until the minimum distance from the destination is reached. Then they forward data along the shortest path.

A different approach is taken in [Gandham et al. 2003] where the *Base Station Location* (BSL) problem is formulated for multiple MEs which can move to a limited number of locations called feasible sites. The ME locations are first derived by using integer linear programming. Then a flow-based routing protocol is applied to energy-efficient communication. In [Xing et al. 2008a], a *Rendez-vous Design* (RD) approach similar to the proxy-based routing (cfr. Section 6.2) is applied by jointly considering the motion control of an ME. Several mobility patterns are considered, depending on whether the ME can move freely or not. The problem, restricted to the case where the ME movements are constrained, is also analyzed in [Xing et al. 2008b], which considers multi-deadlines for data collection and also multiple MEs.

Several solutions devise a trajectory defined as a closed polygonal chain. This approach is used by the *Partitioning Based Scheduling* (PBS) algorithm presented in [Gu et al. 2005]. The PBS scheme derives the trajectory of the ME in different phases, in order to avoid message loss at sensors due to buffer overflows (originated by a low ME speed). During the partitioning phase, nodes are grouped based on distance and buffer overflow times. On the other hand, during the scheduling phase the trajectory is defined. First, the paths within each group are calculated as solutions to the Traveling Salesman Problem (TSP). Then the group paths are concatenated so as to obtain the complete trajectory in the network. A path planning algorithm of the same class, called *SenCar*, is presented in [Ma and Yang 2006], with emphasis on load balancing. More specifically, the authors start from a linear path and derive an ME turning point depending on the energy expenditure due to data collection. Then they elect clusters where multi-hop routing is used for nodes which are not one-hop neighbors of the ME. The process adds a turning point at a time, then updates the network topology accordingly so as to re-evaluate the energy expenditure, until latency or timing constraints are satisfied. The proposed solution is extended in [Ma and Yang 2007] to tackle disconnected networks and obstacles on the ME path. A similar solution, formulated in the context of the *Data Mule*

Scheduling (DMS) problem, is presented in [Sugihara and Gupta 2008] for sparse WSNs with only single-hop communications, and then extended in [Sugihara and Gupta 2009] for a hybrid multi-hop communication scheme.

The *Network Assisted Navigation* (NAN) problem is introduced in [Rao et al. 2008]. It aims at finding an ME trajectory so that all nodes can be reached in a single hop. This is done by creating a logical overlay topology of Navigation Agents (NA). In detail, NAs act as anchor nodes such that the ME can reach all nodes in a single hop while passing by the NAs. Then a distributed TSP is solved to compute the path along the NAs. Finally, a distributed navigation system and a data collection scheme are defined. The proposed solution is shown to have a low latency and a high delivery ratio, and its performance is close to a centralized solution exploiting a complete knowledge on the network topology. The *Network Assisted Data Collection* (NADC) problem is considered in [Rao and Biswas 2008; 2010] as en extension over NAN. In this case, a hop-bound factor k can be specified, so that data can be forwarded up to k hops. An extensive analysis of the impact of k is considered in [Rao and Biswas 2010]. It is easy to see that the NADC problem corresponds to the NAN problem when $k = 1$.

7.1.2 *Dynamic trajectory.* Dynamic trajectory control can be further classified into *on-demand* and *priority-based* approaches. *On-demand* schemes basically change the trajectory of the ME as soon as an event is detected by the static nodes. An example of this approach in the context of delay tolerant networks is represented by the *Node-Initiated Message Ferrying* (NIMF) [Zhao et al. 2004]. An ME starts moving along a default route, while periodically broadcasting its location. A node can send a request to the ME in order to be visited. Upon receiving a request, the ME modifies its trajectory by visiting the requesting node, and then goes back to the original (default) route. A similar approach, specifically designed for WSN-MEs and targeted for surveillance applications, is given by *iMouse* [Tseng et al. 2007]. Static sensors are deployed over a sensing area and sample the quantity of interest, for example, light and temperature for detecting fires. When an anomaly is detected in the sensed values, the base station is informed by static nodes, and special MEs equipped with cameras are dispatched to visit the location (called emergency site) where the event took place. The MEs visit the emergency site and take a snapshot of the event with more accuracy, then report the collected data to the base station. More specifically, the base station schedules the visits of the MEs at the emergency sites in order to maximize their residual energy. An implementation of the system is also provided in [Tseng et al. 2007], along with experimental and simulation results.

Priority-based schemes depend on the constraints on buffer overflow times at sensors, or latency due to data collection. The *Mobile Element Scheduling* (MES) problem is introduced in [Somasundara et al. 2004] for WSNs where nodes operate with different sampling rates. The issue with MES is how to schedule the ME movements to prevent buffer overflows at source nodes. The MES problem is different from the TSP, since at each MES cycle nodes can be visited more than once (depending on the overflow times), and it is also shown to be NP-hard. Therefore, a number of heuristics are defined, such as different variants of the Earliest Deadline First (EDF) scheduling. The original scheme targeted for a single ME is extended to multiple MEs in [Somasundara et al. 2007].

A different priority-based scheme is represented by the *Multi-hop Route to Mobile Element* (MRME) algorithm proposed in [Gu et al. 2006] as an extension to PBS [Gu et al. 2005] for supporting urgent messages. An Urgent Message (UM) is a message which has to be collected by an ME within an amount of time Δ since it has been generated. UMs are assumed to be generated rather infrequently with respect to ordinary messages. UMs can be serviced as regular messages at nodes which have an overflow time less than Δ, according to the PBS algorithm; otherwise explicit mechanisms are needed. One option is given by artificially reducing the overflow time to Δ. A different option consists of relaying data to a sensor which has an overflow time less than Δ before the ME arrives in its contact area. Finally, a hybrid approach combining the two aforementioned solutions can also be applied.

7.2 Speed control

In the simplest form of speed control, which can be referred to as *stop and communicate*, the ME traverses the network by following a fixed path and visits a single node at a time. Hence, when the ME enters the communication range of a sensor which has messages to send, it stops there and collects all buffered data. Depending on the path and the message generation rate at source nodes, the duration of contacts can change with time, so that the duration of a path traversal can be variable as well. This affects the latency of the data collection process, which in this case is strictly related to the time needed by the ME to visit the entire network (*tour*).

Latency-sensitive data collection in scenarios where the speed of an ME can be controlled is investigated in [Kansal et al. 2004], where different algorithms are experimentally evaluated. The first algorithm is *Stop to Collect Data* (SCD), which is similar to the stop and communicate approach. Let T be the maximum time that the ME can spend for a tour, which is tightly related to the maximum latency which can be afforded by the application. Let s be the constant speed of the ME, such that all nodes in the network can be visited in at most time T. The SCD algorithm specifies that the ME can either move at speed $2s$ or stop. Since a complete tour at speed $2s$ requires a time $T/2$ to be completed, the ME can spend the remaining time ($T/2$) for collecting data at sensor nodes. This time is uniformly distributed among the N nodes which have been discovered in the network, hence the time the ME stops at each sensor is $T/(2N)$. Despite its simplicity, the SCD algorithm performs better (in terms of collected messages) than a scheme where the ME moves with a constant speed.

The second algorithm also proposed in [Kansal et al. 2004] is *Adaptive Speed Control* (ASC). Different from the previous case where the speed is changed only according to the number of encountered nodes, ASC exploits additional statistics collected during each path traversal, which include the percentage of collected data with respect to buffered messages. Nodes are classified into different groups, depending on the level of the collected data, such as low, medium or high. The ME stops at the nodes with a low percentage of collected data, while it moves with speed s when it is in contact with the nodes with a medium level of collected data. The ME moves with speed $2s$ with the rest of the nodes. The time spent by the ME at sensors is chosen such that the ME can still complete a tour in at most time T. The ASC algorithm is shown to have a good performance when the network is sparse. However, it performs worse than the SCD algorithm when the network is connected and sensor nodes contend for sending messages to the ME. To this end, the ASC algorithm has been revisited in [Somasundara et al. 2006] for partially multi-hop WSNs. Nodes are first organized into clusters, so that they send their messages to the cluster-head, which in turn communicates with the ME when it passes by. The speed of the ME is changed according to the level of congestion in different zones of the network. Congested zones are represented by the sets of nodes which lie in a high density region, have a very short contact time or experience a very low channel quality. Depending on the level of congestion in each zone, the ME slows down or even stops so as to accommodate data transfer.

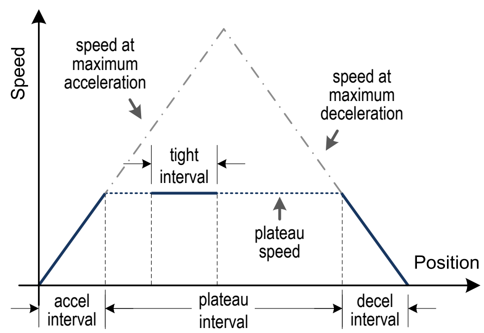


Fig. 8. The heuristic speed control algorithm from [Sugihara and Gupta 2010].

The issue of speed control has also been considered in [Sugihara and Gupta 2010] within the DMS problem initially introduced for trajectory control [Sugihara and Gupta 2008]. Given a static ME path, is it possible to derive the instants where the ME and the sensors are in contact. By considering only these intervals, the speed control problem can be reduced to one-dimensional scheduling, which is however still NP-hard. To this end, a heuristic algorithm is proposed, where three different speed profiles are used: accelerate at the maximum acceleration, move at constant speed (called plateau speed) and decelerate at the maximum deceleration. The time periods spent in each state are called accel interval, plateau interval and decel interval, respectively (Figure 8). The algorithm starts by considering the entire interval which is needed for a complete traversal of the network. Then it maximizes the plateau speed until it finds a tight interval, i.e., an interval during which a set of tasks – such as data transfer from a number of nodes – can be completed. After such an interval has been found, the process repeats for the sub-intervals where the speed has not been yet determined, i.e., the ones which do not include the accel, the decel and the tight interval already derived in the previous steps. The procedure ends when the speed of the ME has been allocated for the entire interval needed for the network traversal. The algorithm is shown to be fast and near-optimal by means of analysis and numerical experiments.

7.3 Hybrid schemes

Instead of defining separately the path and the speed of the MEs, both approaches can be applied at the same time. A class of solutions is based on the *move and sojourn* approach. Here, the ME starts from a specific location and move to some other destination, where it stops for a given time for collecting data. Hence, both the trajectory (*move*) and the visiting times (*sojourn*) of the ME are defined in this case. This scheme has been considered in [Wang et al. 2005] for a single ME. The reference network is rather dense, so that nodes – which are assumed to be homogeneously distributed along a bi-dimensional grid – can reach the ME through multi-hop paths. Furthermore, the authors assume that all nodes in the network have the same transmission range, and that shortest path routing is used. Based on these assumptions, a linear programming formulation of the problem is defined, with the objective of maximizing the network lifetime. Both analytical and simulation results are provided, showing five-fold improvements over solutions where a static sink is used.

The model in [Wang et al. 2005] has been extended in [Basagni et al. 2008] so that the uniform distribution of nodes along a grid is no longer assumed: the sink can move to a number of specific locations, called feasible sites, without any specific constraint. Different from [Wang et al. 2005], the cost due to sink relocation – e.g., latency and energy expenditure due to routing release and setup – is also kept into consideration. In addition to the more precise formulation, [Basagni et al. 2008] also presents the *Greedy Maximum Residual Energy* (GMRE) heuristic. The main idea behind GRME is that the ME should move first to the feasible site which is surrounded by the nodes with the higher residual energy in the network. In order to support the selection of the new location, a sentinel node is selected around each feasible site. Sentinels characterize the energy levels of surrounding nodes and answer the queries coming from the ME. Then the ME uses the information provided by sentinels to decide its movements.

An extension over [Wang et al. 2005] is also given in [Papadimitriou and Georgiadis 2006]. First, there are no restrictions on how nodes are arranged in the sensing field. In addition, the model supports transmission ranges different for each node, and thus can be used even when power control techniques are adopted. Finally, the problem of movement scheduling is evaluated jointly with routing. Due to the joint scheduling and routing optimization, the network lifetime is two times the one which can be obtained from the algorithm in [Wang et al. 2005]. Joint scheduling and routing is also investigated in [Gatzianas and Georgiadis 2008] under almost the same conditions as [Papadimitriou and Georgiadis 2006]. However, different from [Wang et al. 2005; Papadimitriou and Georgiadis 2006] which propose centralized solutions, the linear programming model here is solved in a distributed way. To this end, the authors provide a distributed algorithm for computing the new locations and the sojourn times of the sink.

7.4 Discussion

A comparison of the approaches targeted for mobility control is given in Table I. Although the topic has been extensively evaluated in the literature, proposed solutions – both theoretical and practical ones – have several limitations. In fact,

Table II. Comparison of approaches targeted for mobility control.

Solution	ME role	Number of MEs	Network type	Mobility pattern	Joint routing	Metric of interest
GRME [Basagni et al. 2008]	MS	Single	Dense	Unconstr.	No	Reliability
BSL [Gandham et al. 2003]	MS	Multiple	Dense	Unconstr.	Yes	Energy
PBS [Gu et al. 2005]	MR	Multiple	Sparse	Unconstr.	No	Reliability
MRME [Gu et al. 2006]	MR	Multiple	Sparse	Unconstr.	No	Reliability
SCD, ASC [Kansal et al. 2004]	MR	Single	Sparse	Constr.	No	Reliability
[Luo and Hubaux 2005]	MS	Single	Dense	Unconstr.	Yes	Energy
SenCar [Ma and Yang 2006]	MS	Single	Dense	Both	Yes	Energy
SenCar$^+$ [Ma and Yang 2007]	MS	Single	Both	Both	Yes	Energy
[Papadimitriou and Georgiadis 2006]	MS	Single	Dense	Unconstr.	Yes	Energy
NAN [Rao et al. 2008]	MS	Single	Sparse	Unconstr.	No	Latency
NADC [Rao and Biswas 2010]	MS	Single	Both	Unconstr.	Yes	Latency
MES [Somasundara et al. 2004]	MS	Single	Dense	Unconstr.	No	Latency
ASC$^+$ [Somasundara et al. 2006]	MR	Single	Sparse	Constr.	No	Reliability
MES$^+$ [Somasundara et al. 2007]	MS	Multiple	Dense	Unconstr.	No	Latency
DMS-path [Sugihara and Gupta 2008]	MR	Single	Sparse	Unconstr.	No	Latency
DMS-path$^+$ [Sugihara and Gupta 2009]	MR	Single	Dense	Unconstr.	Yes	Latency
DMS-speed [Sugihara and Gupta 2010]	MR	Single	Sparse	Unconstr.	No	Latency
RD [Xing et al. 2008a]	MS	Single	Dense	Both	Yes	Energy
RD$^+$ [Xing et al. 2008b]	MS	Multiple	Dense	Constr.	Yes	Latency

many approaches rely on strong assumptions which generally do not hold in practice, such as the linear path considered in several papers [Somasundara et al. 2006]. Furthermore, in nearly all cases – with the relevant exceptions of [Ma and Yang 2007; Sugihara and Gupta 2009] – obstructions and physical obstacles are not considered, so that the applicability of the solutions to real scenarios is rather limited. In addition, only a few distributed schemes have been proposed so far [Gatzianas and Georgiadis 2008].

More practical solutions (which have been actually deployed) also have several limitations. In fact, mobile robots such as the one in [Dantu et al. 2005] are really slow – their speed is in the order of a few centimeters per second – and also have issues with some terrain conditions (e.g., slopes or hollows), even though advances in technology are improving their performance in both directions [iRobot Corporation 2010]. Solutions exploiting unmanned aerial vehicles [Venkitasubramaniam et al. 2004] seem promising, but their speed might be too high and motion control too limited. Micro aerial vehicles [Wu et al. 2004] and flapping robots [Deng et al. 2006] are gaining increasing attention in the research community, but more efforts are needed in order to get feasible solutions which can be effectively applied to WSNs.

8. CONCLUSIONS

In this paper we have extensively characterized data collection in Wireless Sensor Networks with Mobile Elements (WSN-MEs). First we provided a general definition of WSN-MEs, then we presented a comprehensive taxonomy of their architectures, based on the role of the MEs. Furthermore, we discussed in depth the data collection process and highlighted its main challenges. We finally analyzed each topic by a comparative survey of the approaches available in the literature. Our analysis also provided hints for open research problems.

Mobility has brought a breakthrough in WSNs, traditionally bound to scenarios where nodes are static and densely deployed. The distinctive features related to mobility in WSNs have clearly emerged, especially if compared to mobile ad-hoc or delay tolerant networks. However, some issues have not been clearly identified nor addressed, and the solutions proposed so far in the literature have not exploited the potential of approaches specifically targeted for WSNs to the full extent.

Routing to MEs and mobility control have been more thoroughly analyzed in the literature. This might be explained on the basis of previous work related to these topics in the context of wireless networks and robotics. On the other hand, it seems that discovery and data transfer have not been deeply investigated for the specific WSN-ME scenario, despite similar problems have already been considered in the context of mobile ad-hoc or delay tolerant networks.

As a general remark, there are only a few implementations on real scenarios [Somasundara et al. 2006; Small and Haas 2003; Haas and Small 2006]. An experimental evaluation on testbeds and real deployments is an aspect that requires more in-depth investigation. In addition, comprehensive solutions which can be applied out-of-the box to specific application scenarios have yet to be proposed.

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