On the Lifetime of Wireless Sensor Networks

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Network lifetime has become the key characteristic for evaluating sensor networks in an application-specific way. Especially the availability of nodes, the sensor coverage, and the connectivity have been included in discussions on network lifetime. Even quality of service measures can be reduced to lifetime considerations. A great number of algorithms and methods were proposed to increase the lifetime of a sensor network—while their evaluations were always based on a particular definition of network lifetime. Motivated by the great differences in existing definitions of sensor network lifetime that are used in relevant publications, we reviewed the state of the art in lifetime definitions, their differences, advantages, and limitations. This survey was the starting point for our work towards a generic definition of sensor network lifetime for use in analytic evaluations as well as in simulation models—focusing on a formal and concise definition of accumulated network lifetime and total network lifetime. Our definition incorporates the components of existing lifetime definitions, and introduces some additional measures. One new concept is the ability to express the service disruption tolerance of a network. Another new concept is the notion of time-integration: in many cases, it is sufficient if a requirement is fulfilled over a certain period of time, instead of at every point in time. In addition, we combine coverage and connectivity to form a single requirement called connected coverage. We show that connected coverage is different from requiring noncombined coverage and connectivity. Finally, our definition also supports the concept of graceful degradation by providing means of estimating the degree of compliance with the application requirements. We demonstrate the applicability of our definition based on the surveyed lifetime definitions as well as using some example scenarios to explain the various aspects influencing sensor network lifetime.

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1. INTRODUCTION

With the proliferation of wireless sensor networks (WSN), completely new application domains for wireless ad hoc networks have emerged. From wildlife monitoring and precision agriculture to habitat monitoring and logistics applications, there is an increasing demand for developing more efficient sensor networks. Especially the characteristic features of WSN, such as the limitations in the available resources (energy, processing speed, storage), distinguish sensor networks from other ad hoc networks [Culler et al. 2004]. Besides these restrictions, WSN are also exposed to various requirements, for example the varying density of the node deployment, and possibly hazardous environmental conditions [Chong and Kumar 2003]. Many aspects concerning sensor networks have already been investigated [Akyildiz et al. 2002a], for example routing and data dissemination schemes [Akkaya and Younis 2005], self-organization issues [Dressler 2008], the efficient deployment of sensor nodes [Bai et al. 2006], and the interaction of sensor and actor networks (SANETs) [Akyildiz and Kasimoglu 2004], while others are still works in progress. This includes the study of *network lifetime* as a key characteristic of WSN.

Network lifetime is perhaps the most important metric for the evaluation of sensor networks. Of course, in a resource-constrained environment, the consumption of every limited resource must be considered. However, network lifetime as a measure for energy consumption occupies the exceptional position that it forms an upper bound for the utility of the sensor network. The network can only fulfill its purpose as long as it is considered alive, but not after that. It is therefore an indicator for the maximum utility a sensor network can provide. If the metric is used in an analysis preceding a real-life deployment, the estimated network lifetime can also contribute to justifying the cost of the deployment. Lifetime is also considered a fundamental parameter in the context of availability and security in networks [Khan and Misic 2008].

Network lifetime strongly depends on the lifetimes of the single nodes that constitute the network. This fact does not depend on how the network lifetime is defined. Each definition can finally be reduced to the question of when the individual nodes fail. Thus, if the lifetimes of single nodes are not predicted accurately, it is possible that the derived network lifetime metric will deviate in an uncontrollable manner. It should therefore be clear that accurate and consistent modeling of the single nodes is very important. However, a detailed discussion of all the different approaches found in the literature is beyond the scope of this article. The lifetime of a sensor node basically depends on two factors: how much energy it consumes over time, and how much energy is available for its use. Following the discussion by Akyildiz et al. [2002b], the predominant amount of energy is consumed by a sensor node during sensing, communication, and data processing activities. A sensor network consists of a number of these nodes. In such a network, the nodes communicate to form an ad hoc network and are thus able to transmit the collected sensor data to designated sinks. In principle, this is also true if in-network processing mechanisms are employed [Dressler et al. 2007; Krishnamachari et al. 2002].

Lifetime studies first came up because the recharging or replacement of batteries is not feasible in many scenarios (too many nodes, hostile environment, etc.), and thus the lifetime of the network cannot be extended infinitely. Naturally, lifetime was then discussed from different points of view, which led to the development of various lifetime metrics. Depending on the energy consumers regarded in each metric and the specific application requirements considered, these metrics may lead to very different estimations of network lifetime.

In summary, it can be said that although network lifetime is considered as one of the most important parameters for evaluating sensor networks or for algorithms to be used in sensor networks, there are still a large number of open issues. This finally motivated us to work on a general definition for sensor network lifetime that can be directly applied in analytical evaluation processes as well as in simulation models.

In this article, we discuss the need to refer to *network lifetime* as the key characteristic to evaluate the performance of sensor networks. We show that essentially all parameters can be reduced to lifetime considerations. Such parameters include coverage, connectivity, and node availability. Based on the analysis of previous lifetime definitions, we propose a more concise definition that can be used in all domains of sensor network research. Our model includes formal definitions of the lifetime aspects found in the surveyed papers, along with a number of new concepts. First, we introduce service disruption tolerance, which describes the ability of the network to cope with temporary failures of one or more of its requirements. Second, a time-integrated requirement specifies that it does not have to be satisfied at each point in time, but rather in the course of a certain time interval. Third, we introduce connected coverage as a combination of coverage and connectivity and show that this is a different requirement than connectivity and coverage on their own. Finally, our model inherently supports the concept of graceful degradation. For this, we provide means of estimating the degree of compliance with the application demands. The primary contributions of this article can be summarized as follows:

- *Analysis of existing lifetime definitions (Section 2)*. In this section, we provide a survey on network lifetime definitions as well as a comparison based on the selected parameters.
- *Overview of the parameters influencing network lifetime (Section 3)*. We summarize all parameters that affect the lifetimes of single nodes as well as the overall network lifetime. It will become obvious that application requirements have to be used to reflect the particular lifetime measures.
- *Concise redefinition of network lifetime (Section 4)*. We conclude the survey and the listed requirements with a formal definition of network lifetime that reflects all needed characteristics of typical sensor networks. Next to the well-known requirements such as node availability, coverage, or connectivity, we introduce the concepts of service disruption tolerance, time-integration, connected coverage, and graceful degradation. We also show how to include other measures such as the network quality, in the definition.

The developed metrics for network lifetime can be used to evaluate algorithms and methods in a comparable way, if the parameters used in the specific scenario are published. Lower bounds for specific parameters can be provided for estimating the degree of compliance with the application demands.

The remainder of the article is organized as follows. A survey of lifetime definitions is provided in Section 2. Afterwards, we discuss open issues and missing features in these lifetime definitions in Section 3. In Section 4, we present our more concise definition for sensor network lifetime. Its applicability is demonstrated in Section 5, based on the survey of lifetime definitions, as well as on an example. Finally, Section 6 concludes the article.

2. RELATED WORK ON NETWORK LIFETIME

In the literature, we can find a great number of relevant publications that address the problem of *sensor network lifetime*. Some papers employ network lifetime as a criterion that needs to be maximized, but never exactly define the term network lifetime. However, the majority of authors do state how network lifetime is defined in the context of their work. Obviously, this leads to a strong diversity of coexistent definitions. In this section, we summarize the most common definitions in the form of a survey of lifetime definitions.

2.1 Network Lifetime Based on the Number of Alive Nodes

The definition found most frequently in the literature is n-of-n lifetime. In this definition, the network lifetime T_n^n ends as soon as the first node fails, thus

$$T_n^n = \min_{v \in V} T_v,$$

with T_v being the lifetime of node v. Some authors exclude the sink nodes from the node set V to reflect the assumption that a power plug is available at the sink nodes [Madan et al. 2005]. T_n^n is a very convenient definition. It is easy to compute and the algorithms running in the network do not have to deal with topology changes. This is because in a network without mobile nodes—which is by far the most common case considered at the moment—the first node to fail results in the first topology change after the deployment. However, in most cases the lifetime calculated by this metric will be far too short for meaningful evaluation of sensor network applications. For example, consider a node that has several direct neighbors with the same sensing equipment. Most networks will be able to cope with the failure of one node in such a case but the metric cannot represent this kind of network redundancy. Therefore, the only case in which this metric can be reasonably used is if all nodes are of equal importance and critical to the network operation, as stated by Madan et al. [2005].

If n-of-n lifetime is to be used as a comparative metric, another objection usually holds. This definition favors WSN algorithms that ensure a maximum lifetime for each node: where the first node dies last. This means that algorithms that deplete the given energy most uniformly (where therefore most remaining nodes fail shortly after the first one) are possibly assigned a longer lifetime than those algorithms where a node may fail relatively early, but the network can still provide useful information for a long time after this event. The T_n^n metric is also not adequate for evaluating scenarios that consider hardware failures, because randomly distributed hardware failures might occur very early and thus distort the lifetime measure considerably. In spite of these arguments, many authors, for example, Wang et al. [2005], and Chang and Tassiulas [2000, 2004], adopt this metric without further consideration. Mhatre and Rosenberg [2004] state that n-of-n lifetime might be a conservative approach, especially for a system with single-hop communication.

A common variant of the T_n^n metric defines the network lifetime as the time until the fraction of alive nodes falls below a predefined threshold, β, or the time during which at least k out of n nodes are alive (k-of-n lifetime T_n^k). While this metric is better than n-of-n lifetime, it still lacks accuracy. Consider the case when $k' < k$ nodes at strategic positions (perhaps around the base station) fail and the remaining nodes now have no possibility of transmitting any data to the sink. Then the network should not be considered alive, but the metric does not recognize this until another $k - k'$ nodes have failed. Again, comparative evaluations cannot be performed using this metric as no statements are made as to where the nodes fail and whether the remaining nodes are still able to transmit data to the sink, or to sense events in the region of interest [Deng et al. 2005].

Hellman and Colagrosso [2006] define another metric based on the number of available nodes. They divide the set of nodes into critical and non-critical nodes and then allow for k node failures in the group of non-critical nodes and no failures at all in the group of m critical nodes. They name this approach m-in-k-of-n lifetime. Nevertheless, the objections as stated for k-of-n still apply.

Another variant of n-of-n lifetime is discussed in the context of clustering schemes [Chiasserini et al. 2002; Soro and Heinzelman 2005]. An important assumption for these approaches is that the cluster heads are chosen beforehand—probably as a set of special, more powerful nodes—and remain unchanged throughout the network lifetime. Then they define network lifetime as the time until the first cluster head fails (n-of-n cluster heads). This approach is very limited, as in most clustering schemes, cluster heads vary dynamically to balance the load between homogeneous nodes. In addition, all the constraints from the discussion of n-of-n lifetime also apply here.

Finally, it is possible to define network lifetime as the time until all nodes have been drained of their energy. This metric is very rarely used, for example in Tian and Georganas [2002], and then only as a best-case metric in combination with other metrics. This is due to the fact that the metric is far too optimistic to be useful. In most cases, a sensor network stops providing any useful service a long time before the last node finally fails.

In summary, it is evident that defining network lifetime solely based on the number of alive nodes is insufficient because neither the ability to communicate measurements nor the ability to sense events in the region of interest are incorporated into these metrics.

2.2 Network Lifetime Based on Sensor Coverage

Considering the specific characteristics of sensor networks, measuring the network lifetime as the time that the region of interest is covered by sensor nodes seems to be a natural way to define the lifetime. Coverage can be defined in different ways, depending on the composition of the region of interest and the achieved redundancy of the coverage. The region of interest can be a two-dimensional area or a three-dimensional volume where each point inside the area or volume has to be covered. This is often referred to as area or volume coverage. If only a finite set of target points inside an area has to be covered, the corresponding coverage problem is called target coverage. A third coverage problem, barrier coverage, describes the chance that that a mobile target can pass undetected through a barrier of sensor nodes [Cardei and Wu 2004].

There are two approaches to describe the degree of coverage redundancy that can be achieved by a given sensor network. The first approach requires that only a given percentage α, of the region of interest, is covered by at least one sensor. This is commonly called α-coverage. The second approach aims to achieve more redundancy, and thus requires that each point within the region of interest is covered by at least k sensors. This is termed k-coverage.

Several papers base their definitions of network lifetime on a coverage variant. Among these, the most common definition uses 1-coverage to define the lifetime as the time that the region of interest is completely within the sensing range of at least one sensor node—the region is covered by at least one node. This definition is adopted for target coverage in Cardei et al. [2005], and Liu et al. [2005b] and for area coverage in Bhardwaj et al. [2001], and Bhardwaj and Chandrakasan [2002].

A less strict variant of this definition is that only a fraction, α, of the region of interest needs to be covered. This definition can be found for example in Wu et al. [2005], Ye et al. [2002], and Zhang and Hou [2005a]. A stricter variant demanding that each point is covered by at least k nodes is adopted for example, in Mo et al. [2005].

Sensor coverage is often argued to be the most important measure for the quality of service a sensor network provides. There is a lot of ongoing research concerning coverage in sensor networks, often in the context of deployment strategies or scheduling algorithms. Good surveys can be found for example, in Cardei and Wu [2004] and Huang and Tseng [2005]. However, defining network lifetime solely based on the achieved coverage is not sufficient for most application scenarios because it is not guaranteed that the measured data can ever be transmitted to a sink node.

2.3 Network Lifetime Based on Connectivity

Another group of metrics takes the connectivity of the network into account. Connectivity is a metric that is commonly encountered in the context of ad hoc networks because there is no notion of sensor coverage in ad hoc networks and thus the ability to transmit data to a given destination is most important. The definition for ad hoc network lifetime given by Blough and Santi [2002] defines the lifetime as the minimum time when either the percentage of alive nodes or the size of the largest connected component of the network drop below a specified threshold. However, this definition only considers the size of the largest connected component in the network. This is clearly insufficient in WSNs where connectivity towards a base station is what matters most. This is reflected by Carbunar et al. [2006], who define connectivity as the percentage of nodes that have a path to the base station.

Baydere et al. [2005] and Yu et al. [2001] define the network lifetime in terms of the total number of packets that could be transmitted to the sink. While this number can serve as an indicator for the persistence of the network, it is very dependent on the actual algorithms used in the network. If, for example, data aggregation algorithms are used, the number of packets to be transmitted to the sink is reduced. However, these aggregated packets contain the same degree of information as the much higher number of non-aggregated packets. Therefore, the applicability of this metric in comparing the lifetimes of different network setups is limited. Especially when data aggregation algorithms are employed, this metric loses much of its expressive power. Another drawback is that the number of transmitted messages gives no clue as to how long, in time units, the network was able to measure its environment. Even if the traffic pattern produced by the sensing application is known, no conclusions can be drawn about the absolute lifetime because the pattern can be modified by packet loss or data aggregation. Similar considerations hold for in-network data processing [Dressler et al. 2007].

A third metric aiming at network connectivity defines the network lifetime in terms of the number of successful data gathering trips Olariu and Stojmenovic [2006]. In Giridhar and Kumar [2005] this is further confined to the number of trips possible "without any node running out of energy." This statement effectively reduces the definition to n-of-n lifetime, the difference being only that the lifetime is not given in time units, but in the number of data gathering trips. So, in addition to the drawbacks described for n-of-n lifetime, the drawbacks for the definition based on the total number of transmitted packets also apply.

Integrating connectivity in a network lifetime metric is certainly a good idea. However, it is important to consider connectivity towards a base station, not just connections between arbitrary sensor nodes. In addition, measuring the lifetime of a connected network in terms of numbers of transmitted packets is not comparable across different networks, and gives no indication of the absolute network lifetime.

2.4 Network Lifetime Based on Sensor Coverage and Connectivity

Due to the described limitations, several authors combine the coverage-based metrics with connectivity metrics. The network lifetime metric as defined in Wang et al. [2003] and Xing et al. [2005] gives the time when either the coverage or the connectivity drops below a predefined threshold. In this case, coverage is measured in terms of α-coverage as discussed before. Connectivity is measured in terms of the packet delivery ratio at the sink node.

Some authors completely hide details of their definition [Mhatre et al. 2005; Sha and Shi 2005; Cardei and Wu 2004] and define network lifetime for example as "the time interval that the network can perform the sensing functions and transmit data to the sink" [Cardei and Wu 2004]. In other terms, network lifetime is defined to be the time until either coverage or connectivity is lost. The exact definition of coverage and connectivity is left unspecified. Mhatre et al. [2005] do not measure the lifetime in traditional time units, but in the number of successful data gathering trips. We have already discussed the disadvantages of this approach.

Another interesting analysis of network lifetime can be found in a paper by Mo et al. [2005]. They define lifetime as the expectation of the interval during which the probability that connectivity and k-coverage are guaranteed is at least β. At that point, there are no big differences from the other approaches in this section. However, in contrast to most other definitions, Mo et al. [2005] allow for the variation of sensing ranges between sensor nodes. This is an important characteristic, as it is not to be expected that the sensing ranges in real-world deployments have exactly the same size on all the nodes.

2.5 Network Lifetime Based on Application Quality of Service Requirements

A number of researchers define network lifetime solely in terms of the application quality of service requirements. We appreciate this approach, especially when considering the fact that every design decision in a sensor network completely depends on the specific application the network is designated to perform.

For example, Kumar et al. [2005] state "We define the lifetime of a WSN to be the time period during which the network continuously satisfies the application requirement." Nevertheless, this illustrates the most important drawback of such a formulation; it is too abstract to be of any use in practical studies of WSNs. Although it covers every possible aspect by putting it all into the application requirements, the possible characteristics of application requirements are left unspecified.

Another definition in this domain is the time until "the network no longer provides an acceptable event detection ratio." as stated by Tian and Georganas [2002]. Although this definition is also quite vague, it does specify one application requirement, namely that of a specified ratio of event detections. However, the detection of events does not necessarily include the transmission of a corresponding report to a sink node. The definition therefore lacks a characteristic that is important for most sensor networks.

2.6 Network Lifetime as Defined by Blough and Santi

One definition of sensor network lifetime, namely that of Blough and Santi [2002], seems to provide a more concise meaning for the term than most others. They define the lifetime of a sensor network as the minimum of three points in time, each parameterizable with a constant ($0 \leq c_1, c_2, c_3 \leq 1$) to allow for flexible mappings of application requirements. The first time point, t_1, indicates the loss of connectivity in the network. Formally, t_1 is the time it takes for the cardinality of the largest connected component of $G(t)$ to drop below $c_1 \times n(t)$, where $G(t)$ is the communication graph of the network at time t, and $n(t)$ is the number of alive nodes at time t. The second time point, t_2, indicates how many nodes are still functional at time t, or more exactly, t_2 is the time it takes for $n(t)$ to drop below $c_2 \times n(0)$. The third time point, t_3, states the loss of α-coverage. t_3 is the time it takes for the volume covered to drop below $c_3 \times l^d$, assuming a region of interest of the form $R = [0, l]^d$, with $d \in \{1, 2, 3\}$.

So, in this definition, three aspects are combined to form one flexible measure of network lifetime: the number of alive nodes, connectivity, and coverage. Each of the three aspects can be left out by setting its corresponding parameter to zero.

Unfortunately, the definition also has its limitations. The coverage aspect, although very flexible in allowing a volume to be covered (and not just a two-dimensional area), does not allow for the possibility of covering only a set of target points. While target coverage could be reduced to volume coverage (by defining the region of interest as the smallest volume that includes all points from the target set), this would mean that the network has to cover a lot of empty space between the target points that could be ignored otherwise. The connectivity aspect only defines connectivity within the largest connected component of the communication graph. This does not necessarily include the sink nodes. So, with this definition of connectivity, the sink nodes could be oblivious to the events measured in the network after only a small number of nodes near the sink have failed and the remaining network still forms a large enough connected component. Finally, the definition includes no notion of mobility in the network. This can seriously affect the lifetime of a network and the evaluation of the network lifetime in a performance metric. All issues concerning mobility are discussed in more detail in the next section.

2.7 Summary

In summary, we provide a list of the discussed network lifetime definitions, each with a short outline of the definition and selected references that use or propose this definition in the literature:

(1) the time until the first sensor is drained of its energy [Chang and Tassiulas 2000; Duarte-Melo and Liu 2002; Giridhar and Kumar 2005; Lee et al. 2004; Madan et al. 2005; Mhatre and Rosenberg 2004; Shah and Rabaey 2002; Wang et al. 2005];

(2) the time until the first cluster head is drained of its energy [Chiasserini et al. 2002; Soro and Heinzelman 2005];

(3) the time there is at least a certain fraction β of surviving nodes in the network [Cerpa and Estrin 2004; Deng et al. 2005; Duarte-Melo and Liu 2002; Hellman and Colagrosso 2006; Tilak et al. 2002; Wieselthier et al. 2002];

(4) the time until all nodes have been drained of their energy [Tian and Georganas 2002];

(5) k-coverage: the time the area of interest is covered by at least k nodes [Mo et al. 2005];

(6) 100% coverage
  (a) the time each target is covered by at least one node [Cardei et al. 2005; Liu et al. 2005b];
  (b) the time the whole area is covered by at least one node [Bhardwaj et al. 2001; Bhardwaj and Chandrakasan 2002];

(7) α-coverage
  (a) the accumulated time during which at least α portion of the region is covered by at least one node [Zhang and Hou 2005a, 2005b, 2005c];
  (b) the time until the coverage drops below a predefined threshold α (until last drop below threshold) [Wu et al. 2005; Ye et al. 2002];
  (c) the continuous operational time of the system before either the coverage or delivery ratio first drops below a predefined threshold [Wang et al. 2003; Xing et al. 2005; Carbunar et al. 2006];

(8) the number of successful data-gathering trips [Giridhar and Kumar 2005; Mhatre et al. 2005; Olariu and Stojmenovic 2006];

(9) the number of total transmitted messages [Baydere et al. 2005; Yu et al. 2001];

(10) the percentage of nodes that have a path to the base station [Carbunar et al. 2006];

(11) expectation of the entire interval during which the probability of guaranteeing connectivity and k-coverage simultaneously is at least α [Mo et al. 2005];

(12) the time until connectivity or coverage are lost [Cardei and Wu 2004; Kansal et al. 2005; Mhatre et al. 2005; Sha and Shi 2005];

(13) the time until the network no longer provides an acceptable event detection ratio [Tian and Georganas 2002];

(14) the time period during which the network continuously satisfies the application requirement [Blough and Santi 2002; Kumar et al. 2005; Tilak et al. 2002; Wieselthier et al. 2002];

(15) $\min(t_1, t_2, t_3)$ with t_1: time for cardinality of largest connected component of communication graph to drop below $c_1 \times n(t)$, t_2: time for $n(t)$ to drop below $c_2 \times n$, t_3: time for the covered volume to drop below $c_3 \times l^d$ [Blough and Santi 2002].

3. OPEN ISSUES AND GENERAL REQUIREMENTS

None of the discussed definitions of network lifetime reflects all the application demands and environmental influences. Typically, the real network lifetime is approximated under a set of very specific conditions. Therefore, the existing definitions are not applicable in a general context but in networks that meet the specified conditions. However, there are many more parameters

Table I. Summary of Requirements Influencing Network Lifetime

Mobility	—complicates analysis of network lifetime [Blough and Santi 2002] —improves sensor coverage [Batalin and Sukhatme 2002, 2003; Liu et al. 2005a; Low et al. 2005] —improves network connectivity [Cerpa and Estrin 2004; Wang et al. 2005] —influences clustering [Bandyopadhyay and Coyle 2003] —mobile sinks or mobile relays [Gandham et al. 2003; Jiang and Manivannan 2004; Wang et al. 2005] —combined effects [Dressler and Dietrich 2006]
Heterogeneity	—Some nodes have more battery power [Duarte-Melo and Liu 2002; Hellman and Colagrosso 2006; Lee et al. 2004; Liu et al. 2005a; Mhatre and Rosenberg 2004; Mhatre et al. 2005; Soro and Heinzelman 2005] —The amount of data each node must communicate varies [Hellman and Colagrosso 2006; Younis et al. 2004] —Nodes may have different types of sensors [Welsh et al. 2003] —Sensing radius is variable/some nodes have larger sensing radii [Lee et al. 2004; Lazos and Poovendran 2006; Mo et al. 2005; Zhang and Hou 2005a] —Some nodes have higher processing power and memory capacity [Lee et al. 2004; Soro and Heinzelman 2005] —Some nodes have longer transmission ranges/transmission range is variable [Mhatre and Rosenberg 2004; Xing et al. 2005] —The transmission power varies [Zhou et al. 2006]
Application characteristics	—distribution of subtasks —destination for data packets —node activity (sensing, processing, communication): by event, by request, regular intervals [Akyildiz et al. 2002b]
Quality of service	—general issues [Younis et al. 2004; Iyer and Kleinrock 2003] —collective QoS parameters [Chen and Varshney 2004] —coverage —exposure —connectivity —requirement of continuous service —observation accuracy —optimum number of sensors
Completeness	—interdependent measures —results not comparable because of incompatible lifetime definitions

influencing sensor network lifetime than just the aspects included in the existing definitions.

These parameters are outlined in the following. Additionally, we provide a short overview of the most important requirements in each category in Table I, together with some pointers to the literature, in order to summarize our discussion.

3.1 Node Mobility and Topology Changes

At the moment, most authors only consider networks with stationary sensor nodes. Some consider mobility as a chance for improving network functionality. Others also state that large-scale mobility complicates matters a lot. This indicates that mobility is indeed a very controversial subject in sensor networks. It offers chances as well as risks for the functionality of the network. However, whether chances or risks prevail, it should be clear that it is important to take mobility into account even in a stationary network.

The first reason we can give for this is that mobility can be simply regarded as a series of topology changes. With the movement of a node, some network links can break, others can be established, and the covered area may be altered. In turn, every topology change can be seen as a special case of mobility. As an example, consider node failures: some network links break when a node fails, and the area covered by sensors is altered in some way. The effects are nearly the same as with traditional mobility: node movements. So, even if the nodes themselves have no possibility of moving on their own, the network should be expected to be able to cope with node failures.

Another reason is that in every real-world deployment, there is an environment that affects the network in some way. Sensor nodes may roll down a hill or be moved—whether on purpose or accidentally—by external forces, for example, by animals kicking at them. These two examples, node failure and accidental mobility, demonstrate that mobility—topology changes—can occur even in a stationary network. A network that cannot cope with mobility at all will probably face a very short lifetime—and a definition of network lifetime that does not explicitly account for mobility at all will probably create wrong lifetime estimations.

The fact that node mobility and topology changes can complicate the analysis of network lifetime has already been mentioned by Blough and Santi [2002]. Consider one of the abstract definitions of lifetime, the definition by Kumar that measures lifetime as the time period during which the network continuously satisfies the application requirement. For example, what is the network lifetime if the network is considered alive from a starting time t_0 until time t_1, not alive until time t_2, alive again until time t_3, and not alive after that? Is it the time until t_1? Is it the sum of all the time periods during which the network is alive: the sum of $t_1 - t_0$ and $t_3 - t_2$? Or is it the time until t_3? Blough and Santi do not provide a solution for this question. We address this issue in Section 4.

In the literature, several approaches have been discussed to improve network behavior using mobility. Several authors investigate the improvement of sensor coverage over time by exploiting node mobility, for example, if there are not enough static nodes to cover the region of interest [Batalin and Sukhatme 2002; Batalin and Sukhatme 2003; Liu et al. 2005a; Low et al. 2005; Bisnik et al. 2006]. Others claim that mobile nodes can improve network connectivity by carrying data from one part of the network to another [Cerpa and Estrin 2004; Wang et al. 2005]. The influence of mobility on clustering algorithms is surveyed in Bandyopadhyay and Coyle [2003]. The effects on networks with mobile sinks or mobile relays are studied for example in Gandham et al. [2003], Jiang and Manivannan [2004], and Wang et al. [2005]. Even combined effects have been studied, such as the optimization of coverage and network lifetime using virtual movements, for example, dynamic node reprogramming [Dressler and Dietrich 2006].

3.2 Heterogeneity

About one-third of the papers reviewed for this survey do not state whether they consider homogeneous or heterogeneous nodes. While it is probably safe to assume that the authors are exploring homogeneous networks in these cases, it shows that the current level of awareness for node heterogeneity leaves a lot of room for improvement. Most of the authors dealing with heterogeneous nodes concentrate on just one type of heterogeneity. However, a short literature study revealed at least eight to ten types of heterogeneity that could have a significant impact on the functionality and lifetime of sensor networks.

The most common type of heterogeneity found in the literature today classifies the nodes in the network in two categories depending on their battery power. Most of the nodes are assumed to have a regular amount of energy, while a few nodes have a significantly larger energy reservoir at their disposal (or even unlimited energy). This type is mentioned for example in Duarte-Melo and Liu [2002], Hellman and Colagrosso [2006], Lee et al. [2004], Liu et al. [2005b], Mhatre and Rosenberg [2004], Mhatre et al. [2005], and Soro and Heinzelman [2005]. Many authors consider this in the context of clustering schemes, where the more powerful nodes are assumed to permanently perform the role of cluster heads. An important observation in this context is that nodes can become heterogeneous in terms of battery power simply because of differences in the discharge behavior of their batteries, depending on environmental factors, for example temperature differences in the region of the deployment.

Another variant is to presume that some nodes have to send a larger amount of data than others, for example because of different sensor types, as mentioned in Hellman and Colagrosso [2006] and Younis et al. [2004]. If the amount of data is the only criterion of interest, this type can be mapped to heterogeneity in the available battery power.

However, if sensor coverage is of importance, the different sensor types have to be considered explicitly because the coverage requirements have to be fulfilled by each type of sensor. Nodes with different types of sensors are considered in Welsh et al. [2003]. In Lee et al. [2004], Lazos and Poovendran [2006], Mo et al. [2005], and Zhang and Hou [2005a], nodes with varying sensing ranges, either due to environmental variations or due to sensor characteristics and sensor types are considered.

Powerful nodes with higher processing power and memory capacity are considered by Lee et al. [2004] and Soro and Heinzelman [2005]. They also consider nodes with different energy levels, which is reasonable because more powerful nodes, in terms of processing and memory, will usually be preferred as routers or data aggregators. In that case, more powerful batteries are often provided as well.

Varying transmission ranges are considered in Mhatre and Rosenberg [2004], Xing et al. [2005], and Zhou et al. [2006]. Mhatre and Rosenberg [2004] assume that some nodes (the cluster heads) will be capable of long-range transmissions reaching the base station in a single hop. In contrast, Xing et al. [2005] consider homogeneous nodes where the transmission ranges can vary and take irregular shapes due to environmental conditions. Zhou et al. [2006] take a similar approach and develop models to treat radio irregularity. They also consider varying transmission powers, resulting in varying transmission ranges, as a type of heterogeneity.

Sometimes, mobility is classified as a kind of heterogeneity as well. We discussed mobility issues in the previous section.

Taking into account all these different sources of heterogeneity in a sensor network, it should be obvious why it is important to consider heterogeneity for the analysis of network lifetime. Heterogeneous nodes can have an influence on network lifetime in many ways. For example, the lifetime could be prolonged by the network backbone that is provided by the more powerful nodes. The lifetime could also be shortened if some nodes gather much more data than others and then fail earlier due to necessary radio activity. Heterogeneity can also have an influence on the applicability of algorithms, especially of clustering schemes.

3.3 Application Characteristics

The application is the driving force of any sensor network. However, it is useful to distinguish between the overall application that a sensor network is made for, like monitoring environmental parameters in a building, and the programs running on each single sensor node. For example, it might benefit the overall application to split its duties into several tasks that are performed by different nodes. This leads to a heterogeneity of tasks in a network. Consider, for example, a number of nodes sensing temperature values and sending them to a local destination. In this example, the local destination is just another node for aggregating the data and for further forwarding to the base station. This approach is especially useful if the individual nodes do not have enough resources to perform both tasks simultaneously. In that case, the lifetime of the network strongly depends on the network's ability to provide an adequate distribution of all necessary tasks over the available sensor nodes [Dasgupta et al. 2003; Krishnamachari et al. 2002].

The destination for data packets that is used by the individual sensor nodes can affect communication patterns in the network. In addition to the simple cases with single fixed destinations either in the middle or at the edge of the network, multiple destinations at different places or even mobile sinks need to be considered as well. All variants potentially lead to different communication patterns in different regions of the network, thus influencing energy consumption. This effect has been studied for example in Solis and Obraczka [2004].

The final and possibly most important factor influencing network lifetime at the application level is the node activity in terms of sensor measurements, data processing, and communication [Akyildiz et al. 2002a]. In all cases, the activity can be triggered by events, for example, sending of data because sensor measurements exceed some threshold, it can be carried out at regular intervals, or it can be initiated by a request from another node. The frequency of energy-consuming actions will probably be quite different in the three cases.

3.4 Quality of Service

It has already been stated that the application is the driving force of every sensor network. It is to be expected that each application has different demands on the required services in the network and their quality of service parameters. A definition of network lifetime should take the QoS requirements of the application into account. Consequently, this leads to the central question of what the most common application requirements in sensor networks are. While the quality of service parameters for traditional networks have been thoroughly studied, there has been relatively little work on this topic in the context of sensor networks, for example, Chen and Varshney [2004] and Younis et al. [2004].

Traditional QoS measures include the delay (the response time and its components: transmission times, propagation delays, processing times, queuing delays, idle times), the jitter (the delay variation), the throughput and bandwidth, the loss and error rates (packet errors, bit errors), the resource consumption (processing, memory, bandwidth, power), the reliability (MTTF: mean time to first failure) and availability (downtime), and the overall costs (total cost of ownership, return on investment). The QoS requirements of sensor networks can be different from these traditional measures. End-to-end QoS measures are not as important as collective parameters. For example, Chen and Varshney [2004] state, “collective latency is defined as the difference between the time at which the first packet related to this event is generated by the source sensors and the time at which the last packet related to this event or the last packet used to make a decision arrives at the sink.”

Examples for additional QoS measures being, cited as important for sensor networks are the coverage, event detection ratio, and exposure (often stated as the main QoS parameters for sensor networks), connectivity (availability, latency, loss), requirements for continuous service (service disruptions up to a length of n are tolerated, indicates mission-criticality), the observation accuracy (measurement errors), and the optimum number of sensors sending information toward information-collecting sinks [Chen and Varshney 2004; Younis et al. 2004; Iyer and Kleinrock 2003]. Many of these parameters already appeared in the lifetime discussion. We see a deep relation between lifetime and quality of service in sensor networks. Therefore, we will integrate QoS directly in our lifetime definition.

3.5 Completeness

Most of the existing lifetime definitions fail to consider multiple important aspects of sensor networks in a single step. For example, connectivity and coverage are often investigated independently, whereas these measures essentially influence each other. In general, we also agree on the advantage of analyzing specific application demands independently for a better understanding of the particular effects. Nevertheless, if different definitions are used that cannot be brought together in a final evaluation step, results become incomparable. This is a serious problem in sensor network research. Although it could be tempting to formulate a new definition of lifetime for each new network, this would certainly be less flexible and less comparable than a single definition incorporating many common application requirements.

4. A MORE CONCISE DEfiNITION

Based on the survey of lifetime definitions and the corresponding discussion of open issues, we now formulate our own definition in this section. The overall objective is to develop a definition that can be parameterized according to the application requirements but that also provides comparability between different optimization efforts of algorithms and methods in WSNs.

4.1 Prerequisites

The region of deployment is described by R. There can be different definitions for R, although the concrete specification is not relevant for the definition of network lifetime. Some possibilities include a rectangle ($R = [0, a_1] \times [0, a_2]$, $|R| = a_1 * a_2$), a cuboid ($R = [0, d_n]^n$, $|R| = \prod d_n$), or a circle ($|R| = \pi r^2$).

Each sensor node can be equipped with one or more sensors of different types. Therefore, we define the set of sensor types present in a network as $Y = \{y_1, \ldots, y_k\}$. The set of all existing sensor nodes is then called S^Y. The types of sensors available at each of the nodes is represented by the subsets $Y_i \subset Y$. It is important to note that each sensor node is associated to a subset of the set of sensor types. This means that there may be more than one sensor on a node, and there may also be zero sensors on a node. The total number of available sensor nodes is n.

$$S^Y = \left\{s_1^{Y_1}, \ldots, s_n^{Y_n}\right\}, \; Y_i \subset Y \tag{1}$$

$$|S^Y| = n. \tag{2}$$

Starting from the set of all sensor nodes S^Y, we define the set of all nodes that are alive at a certain time t as $U(t)$. In Equation (3) $u_i^{Y_i}$ is a sensor node from the set of all sensor nodes as defined here, which is equipped with the sensor types denoted by the subset Y_i, and whose energy is not yet depleted.

$$U(t) = \{u \mid u \in S^Y \wedge u \text{ alive at } t\}, |U(t)| = u(t). \tag{3}$$

Now we can define the set of nodes that are active at a time t, as $V(t)$. For a node to be active, it has to be alive (therefore $V(t)$ is a subset of $U(t)$), and it must not be in a sleep state.

$$V(t) = \{v \mid v \in U(t) \wedge v \text{ active at } t\}, |V(t)| = v(t). \tag{4}$$

The set of of nodes that are active at any time in the time interval $[t - \Delta t, t]$ is denoted as $W(t)$. If Δt is zero, $W(t)$ equals $V(t)$.

$$W(t) = \{w \mid w \in S^Y \wedge w \text{ active at any } t \in [t - \Delta t, t]\}, |W(t)| = w(t). \tag{5}$$

The set of sink nodes or base stations $B(t)$ is defined to be a subset of the existing nodes S^Y. In some network settings, sink nodes might be ordinary sensor nodes acting as base stations for other nodes. For this reason, the definition retains the possibility for a sink node to fail or sleep just like any other node. The set of sink nodes may vary over time, and it is also possible that there are no sink nodes present in the network at some point in time.

$$B(t) = \{b_1, \ldots, b_k\} \subset S^Y. \tag{6}$$

The communication graph of the network at a time t, is given as the undirected graph $G(t) = (V(t), E(t))$. This definition assumes that communication between two nodes is always possible in both directions. Apart from that, no assumptions are made about the communication ranges of the nodes. Note that only active nodes from the set $V(t)$ are included in the communication graph. In order to express the ability of two arbitrary nodes, m_i and m_j, to communicate at a time t, it is necessary to check if there exists a series of edges in $G(t)$ starting at m_i and ending at m_j. To express this formally, we renumber node, m_i as m_1, node m_j as m_n, and all nodes on the path between the two nodes accordingly. The ability of nodes m_1 and m_n to communicate at a time t can then be expressed as $\kappa(t, m_1, m_n)$. The number of hops needed for the communication is $n - 1$.

$$\kappa(t, m_1, m_n) \equiv \begin{cases} \forall i \in \{1, \ldots, n-1\} \ : m_i \in V(t) \wedge (m_i, m_{i+1}) \in E(t) & m_1 \neq m_n \\ 1 & m_1 = m_n. \end{cases} \tag{7}$$

The ability of two nodes to communicate in the time interval $[t - \Delta t, t]$ such that the links between consecutive hops become available successively within the time interval (support for delay tolerant networking) can be expressed as $\widehat{\kappa}([t - \Delta t, t], m_1, m_n)$. If $\Delta t = 0$, $\widehat{\kappa}$ is equal to κ.

$$\widehat{\kappa}([t - \Delta t, t], m_1, m_n) \equiv \begin{cases} \forall i \in \{1, \ldots, n-1\} \ : \ \begin{aligned}[t] & m_i, m_{i+1} \in V(t_i) \\ & \wedge (m_i, m_{i+1}) \in E(t_i) \\ & \wedge t_1, \ldots, t_n \in [t - \Delta t, t] \\ & \wedge t_i < t_{i+1}. \end{aligned} & m_1 \neq m_n \\ 1 & m_1 = m_n \end{cases} \tag{8}$$

The set of target points to be sensed by the network can be defined as $P^Y(t)$. Each target point can be sensed only by a certain collection of sensor types, denoted by the subsets $Y_i \subset Y$. It is possible that a target can be sensed by multiple sensor types. However, it is probably not very useful to have targets that cannot be sensed by any kind of sensor. Therefore, we require that Y_i is not the empty set in this equation. Target points outside the region of deployment R are not allowed.

$$P^Y = \left\{ p_1^{Y_1}, \ldots, p_m^{Y_m} | p_i^{Y_i} \in R \wedge Y_i \subset Y \wedge Y_i \neq \emptyset \right\}. \tag{9}$$

We define the area that is covered by all sensors of a certain type y, at a time t, as $A^y(t)$. In this equation, A_v^y denotes the area that is, covered by the sensor of type y of node v. The shape of this area can be arbitrary, representing the

Table II. Summary of the Criteria c_{**}

criterion	notation	additional parameters
portion of alive nodes	cl_{ln}, c_{ln}	
maximum tolerable latency	cl_{la}, c_{la}	latency l, interval Δt_{la}^{y}
delivery ratio	cl_{dr}, c_{dr}	interval Δt_{dr}^{y}
portion of nodes with path to a sink	cl_{cc}, c_{cc}	interval Δt_{cc}^{y}
area coverage	cl_{ac}^{y}, c_{ac}^{y}	multiplicity k_{ac}^{y}, interval Δt_{ac}^{y}
target coverage	cl_{tc}^{y}, c_{tc}^{y}	multiplicity k_{tc}^{y}, interval Δt_{tc}^{y}
barrier coverage	cl_{bc}^{y}, c_{bc}^{y}	multiplicity k_{bc}^{y}, interval Δt_{bc}^{y}
connected area coverage	cl_{ca}^{y}, c_{ca}^{y}	multiplicity k_{ca}^{y}, interval Δt_{ca}^{y}
connected target coverage	cl_{ct}^{y}, c_{ct}^{y}	multiplicity k_{ct}^{y}, interval Δt_{ct}^{y}
connected barrier coverage	cl_{cb}^{y}, c_{cb}^{y}	multiplicity k_{cb}^{y}, interval Δt_{cb}^{y}
service disruption tolerance	cl_{sd}, c_{sd}	disruption Δt_{sd}

sensing range of a sensor. This could be, for example, a circle centered at v or a circle section originating at v.

$$A^{y}(t) = \bigcup_{\forall v \in V(t)} A_{v}^{y} \cap R,\ y \in Y. \tag{10}$$

We are now ready to define a series of criteria that may influence network lifetime at least in some network settings. Each criterion can be excluded from the final definition of lifetime by setting its modification factor to zero. In the following equations, these parameters are denoted by c_{**}. Table II summarizes the parameters.

4.2 Graceful Degradation

If the network is considered not lively according to our definition of network lifetime, it is interesting to know to what degree the lifetime criteria are fulfilled, and which of the criteria is the main reason for the network failure. This is basically an analysis of lifetime bottlenecks, and can therefore be a very useful guideline when developing or deploying sensor networks, because it indicates the areas with the most room or need for improvement.

Graceful degradation is defined in the context of reliability measures for computing systems as the failure-free operation with decreased performance level [Beaudry 1978]. Most previous lifetime definitions allow for recognizing a network either as lively or non-functional and the lifetime is calculated accordingly. We intend to inherently design our lifetime description to support graceful degradation in the context of fault tolerant systems [Li et al. 2004; Zhou et al. 2005]. Soft limits are added to all the single verification parameters to reflect ranges instead of hard limits [Najjar and Gaudiot 1990].

In particular, the parameters c_{**} ($0 \leq c_{**} \leq 1$) indicate the soft upper bound above which the network is considered fully functional. The measure of interest is how good the network fulfills the criteria depending on their respective parameters. To measure the extent of this performance degradation, a hard lower bound is needed. Below this lower bound, the network is considered non-functional. For simplicity, the lower bound can be chosen to be zero. Of course, it is also possible to introduce additional parameters cl_{**} ($0 \leq cl_{**} \leq c_{**} \leq 1$) that indicate a different lower bound.

For each criterion, we define two functions. ψ_{**} indicates how well the criterion is fulfilled, resulting in values in the range $[0, 1]$. ζ_{**} is a measure of the quality of the fulfillment of a criterion, depending on the upper and lower bounds of the corresponding parameter. $\zeta_{**}(t) \geq 1$ means the criterion is fulfilled perfectly. If $\zeta_{**}(t) < 0$, the criterion is not fulfilled at all. Any value in the range $[0, 1]$ indicates the goodness of the fulfillment. For a linear degradation with an upper bound of c_{**} and a lower bound of zero, the amount of fulfillment for each criterion can be given by dividing ψ_{**} and the upper bound c_{**}. For linear degradation with a generic lower bound, a formula for calculating $\zeta_{**}(t)$ according to criterion $**$ is given in Equation 11 (in the following, we only provide the definition and calculation of ψ_{**} for each lifetime criterion $**$).

$$\zeta_{**}(t) = \begin{cases} \dfrac{\psi_{**}(t) - cl_{**}}{c_{**} - cl_{**}} & \text{if } c_{**} \neq 0 \wedge c_{**} \neq cl_{**} \\ \dfrac{\psi_{**}(t)}{c_{**}} & \text{if } c_{**} = cl_{**} \\ 1 & \text{if } c_{**} = 0 \end{cases} . \tag{11}$$

Equation 11 describes the degradation of the performance of each single criterion. To indicate the performance degradation of the whole network, we propose choosing the minimum of the single degradations. This is reasonable because the minimum indicates the worst-case performance, and also indicates which area needs to be improved the most (see Section 4.7).

4.3 Time-Integrated Criteria

The idea behind time-integrated criteria is that it is often sufficient if the fulfillment of a requirement is achieved in a certain time interval. For example, if 50% of the area is covered at one time in the interval, and the remaining 50% is covered at another time, the time-integrated area coverage is fulfilled, while classical area coverage is not. The same applies to many other criteria.

Therefore, we introduce an additional parameter Δt^{y}_{**} to accompany all criteria. Δt^{y}_{**} indicates the length of the time interval during which the requirements must be satisfied. If Δt^{y}_{**} is set to be zero, the time-integrated criterion equals the regular criterion.

4.4 Criteria

4.4.1 *Number of Alive Nodes.* The portion of alive nodes, including sleeping nodes, must be greater than c_{ln} times the number of existing nodes at any time. To constrain the lifetime of the sensor network to be at most the time of the failure of the last alive node, this parameter would have to be set such that one out of the n existing nodes must be alive: $c_{ln} = 1/n$. This has already been discussed as the *best case* for sensor network lifetime in the related work section.

$$\psi_{ln}(t) = \frac{u(t)}{n}. \tag{12}$$

4.4.2 *Latency.* For the latency criterion, it is required that at least a portion of c_{la} packets must have a shorter delay than the prespecified maximum latency l. This means that a certain portion of all packets must arrive at a sink node within a period of l seconds after the initial sending. The time-integrated latency criterion is somewhat stronger because it requires that in each time interval $T = [t - \Delta t_{la}, t]$, a portion of c_{la} packets must have a shorter delay than l. If Δt_{la} equals zero, $T = [0, t]$.

$$\psi_{la}(t) = \frac{\text{packets delayed less than } l}{\text{total packets received in } [t - \Delta t_{la}, t]}. \tag{13}$$

4.4.3 *Delivery Ratio.* At most a portion of $1 - c_{dr}$ packets of all data packets sent in the network may be lost or unusable due to packet loss or error. This is equivalent to demanding that at least a portion of c_{dr} packets must be correctly received by a sink node—that the packet delivery ratio must be at least c_{dr}. As before, time-integrated delivery ratio requires that the delivery ratio has to be greater than c_{dr} in each time interval $T = [t - \Delta t_{dr}, t]$.

$$\psi_{dr}(t) = \frac{\text{packets received correctly}}{\text{total packets sent in } [t - \Delta t_{dr}, t]}. \tag{14}$$

4.4.4 *Connectivity.* In basically all sensor networks, traffic flows from the individual sensor nodes towards one or more sink nodes. It is therefore not important to ensure connectivity between all sensor nodes, but rather to ensure connectivity towards the sink nodes. Following the recent discussion in the sensor networking community, the single base station model is changing to network-centric operation and control [Estrin et al. 1999; Dressler et al. 2007].

This leads to the requirement of supporting arbitrary communication among all the networked nodes. In the following, we use the notation of *sink nodes* for all destination nodes for ongoing communications at a given time t. In particular, the function $\chi(v, t)$ indicates if a node v has a connection to any active sink node in $B(t)$ at the time t. If there is no active sink node, the indicator function returns false because a connection to a sink node does not exist. In some cases, it is also useful to allow time-integrated connectivity. This means that the connectivity between two nodes is not fully available at one point in time, but becomes available successively in a time interval $[t - \Delta t_{cc}, t]$. If Δt_{cc} equals zero, the definition describes connectivity at a certain point in time.

$$\chi(v, t) \equiv \exists b_i \in B(t) \wedge \widehat{\kappa}([t - \Delta t, t], v, b_i). \tag{15}$$

A simple criterion to evaluate connectivity in a sensor network is to require that at least a certain portion, c_{cc}, of all active nodes have a connection to a base station.

$$\psi_{cc}(t) = \frac{|V_c(t)|}{|W(t)|}, V_c(t) \subset W(t), \forall v_c \in V_c(t) : \chi(v_c, t). \tag{16}$$

4.4.5 *Area Coverage.* Area coverage is a family of criteria, one for each type of sensor. The requirement is that the area covered by all sensors of type y must be greater than a certain portion of the deployment region. In other words, the fraction of the deployment region covered by type-y-sensors $A^y(t)/|R|$ must be greater than the parameter c^y_{ac}. This parameter may vary depending on the sensor type.

$$\psi_{ac}^{y}(t) = \frac{A^{y}(t)}{|R|},\ y \in Y. \tag{17}$$

4.4.6 *Target Coverage.* The target coverage criterion requires that for each type of sensor y, a certain portion c_{tc}, of all targets that can be sensed by type-y-sensors, must be within the area covered by those sensors. The set of targets that can be sensed by type-y-sensors is a subset of P^{Y} and denoted as P^{y}. In this definition, it is not relevant if the targets are stationary or mobile. At each point in time, the current position of the targets is evaluated. Between the evaluations, the target positions may be updated.

$$\psi_{tc}^{y}(t) = \frac{\left|P_{m}^{y}(t)\right|}{\left|P^{y}(t)\right|},\ P_{m}^{y}(t) \subset P^{y}(t),\ P_{m}^{y}(t) \in A^{y}(t),\ y \in Y. \tag{18}$$

4.4.7 *Barrier Coverage.* The barrier coverage criterion indicates if a region is covered sufficiently to ensure that an intruder passing through the region cannot do so undetected. The following definitions follow the ideas presented in Kumar et al. [2007]. In contrast to the other coverage criteria, barrier coverage requires information about the direction in which intruders will attempt to pass through the region. As the region of interest is not restricted to any particular shape, it is necessary to define sets of entry and exit points at the border of the region through which all intruders will pass. Depending on the shape of R, the entry and exit sets can be the sides of a rectangle, parts of a circle, or the top and bottom areas of a cube.

Then a crossing path l is defined as any path connecting a point from the entry set with a point from the exit set. Thus, the set of all crossing paths, L, represents all possible trajectories through the network that an intruder can take. A crossing path, l, is covered if it runs through the sensing radius of at least one sensor. A region is therefore considered to be barrier-covered if every crossing path is covered.

$$\psi_{bc}^{y}(t) = \begin{cases} 1 & \forall l \in L : \exists p \in l : p \in A^{y}(t) \\ 0 & \text{else} \end{cases}. \tag{19}$$

4.4.8 *k-Coverage.* The k-coverage criterion requires that each point in the region of interest has to be within the sensing range of at least k active sensors.

To include k-coverage in our definition, we extend the definitions for area, target, and barrier coverage with the additional parameters k_{**}^{y} and Δt_{**}^{y}. We also redefine the covered area $A_{k,\Delta t}^{y}(t)$ to indicate the k-coverage and time-integrated coverage of an area. The function $\tau(x, v^{y})$ returns a set containing the node v^{y} if a certain point x is within the sensing radius of its type-y-sensor, or an empty set if not. The function $\sigma(t, x)$ returns a set containing all active sensors covering a point x in the time interval $[t - \Delta t, t]$.

$$\tau(x, v^{y}) = \begin{cases} v^{y} & \text{if } x \in A_{v}^{y} \\ \emptyset & \text{else} \end{cases}$$

$$\sigma(t,x) = \bigcup_{\forall w^y \in W(t)} \tau(x, w^y).$$

We can now define the covered area $A^y_{k,\Delta t}(t)$ based on the function $\sigma(t,x)$.

$$A^y_{k,\Delta t}(t) = \{x \mid |\sigma(t,x)| \geq k^y, x \in R\}.$$

The k-coverage criteria for area and target coverage can now be defined by analogy to the case for $k = 1$. These new definitions degenerate to the equations in Sections 4.4.5 and 4.4.6 if $k^y_{**} = 1$ and $\Delta t^y_{**} = 0$. They can therefore replace the earlier definitions.

$$\psi^y_{ac}(t) = \frac{A^y_{k,\Delta t}(t)}{|R|}, y \in Y \tag{20}$$

$$\psi^y_{tc}(t) = \frac{\left|P^y_m(t)\right|}{\left|P^y(t)\right|}, P^y_m(t) \subset P^y(t), P^y_m(t) \in A^y_{k,\Delta t}(t), y \in Y. \tag{21}$$

A region is k-barrier covered, if all crossing paths through the region are k-covered. A crossing path is called k-covered if it runs through the sensing radii of at least k active sensors ($l \cap A^y_{v_i} \neq \emptyset$ for at least k active sensors). For $k = 1$, the following definition is equivalent to the previous one and can therefore replace the earlier one. Basically, the definition says that the number of sensors covering any point on each of the crossing paths needs to be greater than or equal to k.

$$\psi^y_{bc}(t) = \begin{cases} 1 & \forall l \in L : |\bigcup_{\forall x \in l} \sigma(t,x)| \geq k \\ 0 & \text{else} \end{cases}. \tag{22}$$

4.4.9 *Connected Coverage.* Another coverage-related criterion is to require connectivity for the covering nodes. This is a different constraint than connectivity and coverage on their own, because the nodes covering the area could be different from those able to communicate. This has already been mentioned by Thai et al. [2008].

As introduced here, we include the parameters k^y_{**} for k-coverage and Δt^y_{**} for time-integrated coverage. For the connected coverage criteria it is useful to redefine the covered area $A^y_{k,\Delta t}(t)$ as $\widetilde{A}^y_{k,\Delta t}(t)$. The difference between the two definitions is that $A^y_{k,\Delta t}(t)$ uses all active nodes, whereas $\widetilde{A}^y_{k,\Delta t}(t)$ uses only those active nodes with a path to the sink. To achieve this, we modify the definitions of τ and σ accordingly.

$$\widetilde{\tau}(x, v^y) = \begin{cases} v^y & \text{if } x \in A^y_v \wedge \chi(v,t) \\ \emptyset & \text{else} \end{cases}$$

$$\widetilde{\sigma}(t,x) = \bigcup_{\forall w^y \in W(t)} \widetilde{\tau}(x, w^y).$$

We can now define the connected covered area $\widetilde{A}^y_{k,\Delta t}(t)$:

$$\widetilde{A}^y_{k,\Delta t}(t) = \{x || \widetilde{\sigma}(t,x)| \geq k^y, x \in R\}.$$

Based on $\widetilde{A}^{y}_{k,\Delta t}(t)$ and the previous definitions of area and target coverage in Sections 4.4.5 and 4.4.6, we can now define the criteria for connected area coverage and connected target coverage. Both criteria are defined for a specific sensor type y, therefore resulting in a family of criteria for all the sensor types. For area coverage, the area covered by those active sensor nodes with a path to a sink must be greater than a specified portion of the whole area.

$$\psi^{y}_{ca}(t) = \frac{\widetilde{A}^{y}_{k,\Delta t}(t)}{|R|},\ y \in Y. \tag{23}$$

For target coverage, the portion of targets covered by active sensor nodes with a path to a base station has to be at least a specified percentage of all targets.

$$\psi^{y}_{ct}(t) = \frac{\left|P^{y}_{m}(t)\right|}{\left|P^{y}(t)\right|},\ P^{y}_{m}(t) \subset P^{y}(t),\ P^{y}_{m}(t) \in \widetilde{A}^{y}_{k,\Delta t}(t),\ y \in Y. \tag{24}$$

Connected barrier coverage can be defined accordingly.

$$\psi^{y}_{cb}(t) = \begin{cases} 1 \ \ \forall l \in L : |\bigcup_{\forall x \in l} \widetilde{\sigma}(t,x)| \geq k \\ 0 \ \ \text{else} \end{cases}. \tag{25}$$

4.4.10 *Global Coverage.* The coverage criteria defined so far include area coverage, target coverage, and barrier coverage, together with a version for connected coverage and parameters to indicate k-coverage and time-integrated coverage. However, each of these coverage criteria has only been defined for one type of sensor. Therefore, they have to be aggregated to cover all sensor types available in a network to indicate if the coverage criteria are fulfilled for each sensor type. This is done in the following equations. As can be seen, a global coverage criterion is only taken to be satisfied if the minimum of all single node criteria is fulfilled.

$$\text{global area coverage:} \qquad \zeta_{ac}(t) = \min_{y \in Y} \zeta^{y}_{ac}(t) \tag{26}$$

$$\text{global target coverage:} \qquad \zeta_{tc}(t) = \min_{y \in Y} \zeta^{y}_{tc}(t) \tag{27}$$

$$\text{global barrier coverage:} \qquad \zeta_{bc}(t) = \min_{y \in Y} \zeta^{y}_{bc}(t) \tag{28}$$

$$\text{global connected area coverage:} \qquad \zeta_{ca}(t) = \min_{y \in Y} \zeta^{y}_{ca}(t) \tag{29}$$

$$\text{global connected target coverage:} \qquad \zeta_{ct}(t) = \min_{y \in Y} \zeta^{y}_{ct}(t) \tag{30}$$

$$\text{global connected barrier coverage:} \qquad \zeta_{bt}(t) = \min_{y \in Y} \zeta^{y}_{bt}(t). \tag{31}$$

4.4.11 *Availability (Service Disruption Tolerance).* The service disruption criterion describes the ability of the network to tolerate malfunctions or failures of one or several requirements, to a certain extent. It can therefore be used to specify the required availability of the network. Its definition is introduced in Section 4.5.

4.5 Definition of Network Liveliness

We can now begin to integrate the presented definitions of single criteria into our final definition of network lifetime. First, we define an aggregate criterion, the liveliness of the network $\zeta(t)$ as the minimum of all single criteria $\zeta_{**}(t)$ calculated according to Equation 11.

$$\zeta(t) = \min(\zeta_{**}(t)). \tag{32}$$

The availability criterion indicates that a service disruption of at most Δt_{sd} seconds can be tolerated. To include this parameter in the lifetime definition, we first define T to be the ordered sequence of all points in time where the aggregate liveliness criterion $\zeta(t)$ crosses the border from perfect fulfillment ($\zeta(t) \geq 1$) to partial fulfillment ($\zeta(t) < 1$) or vice versa. We do this by checking ζ at time t and at time $t - \epsilon$: just before time t.

$$T = \{t_i | (\zeta(t_i - \epsilon) \geq 1 \wedge \zeta(t_i) < 1) \vee (\zeta(t_i - \epsilon) < 1 \wedge \zeta(t_i) \geq 1)\}, t_i < t_{i+1}, i \in \mathbb{N}_0. \tag{33}$$

In addition, we define $\psi_{sd}(t)$ to be the relation of the allowed service disruption (Δt_{sd}) to the maximal service disruption sd_{max} encountered at time t. $\psi_{sd}(t)$ will assume values in the range $[0, 1]$ if the service disruption exceeds the allowed tolerance, and values greater than one otherwise.

$$sd_{max} = max((t_{i+1} - t_i) : \zeta(t_i) < 1, i \in [0, |T| - 1]) \tag{34}$$

$$\psi_{sd}(t) = \begin{cases} \dfrac{\Delta t_{sd}}{sd_{max}} & sd_{max} > 0 \\ 1 & sd_{max} = 0 \end{cases}. \tag{35}$$

To clarify the following definitions, we define e to be the minimal index in T after which a service disruption of more than Δt_{sd} seconds follows. If such an index does not exist (for example if the service disruption tolerance is infinite), e is taken to be the last index in T: $|T|$.

$$e = \begin{cases} \min(i \in [0, |T| - 1] : \zeta(t_i) < 1 \wedge (t_{i+1} - t_i) > \Delta t_{sd}) & \text{if such } i \text{ exists} \\ |T| & \text{otherwise} \end{cases}. \tag{36}$$

For further simplification, we define the periods of time during which the network is lively as t_i^a.

$$\forall i \in [0, e] : t_i^a = \begin{cases} t_{i+1} - t_i & \text{if } \zeta(t_i) \geq 1 \\ 0 & \text{otherwise} \end{cases}. \tag{37}$$

4.6 Definition of Network Lifetime

We now propose two network lifetime metrics, both building on the previous definitions. Both metrics depict the network lifetime in seconds. The metrics probably become most expressive when used together.

(1) The first metric gives the *accumulated network lifetime* Z_a as the sum of all times that $\zeta(t)$ is fulfilled (these are exactly the intervals t_i^a), stopping

only when the criterion is not fulfilled for longer than Δt_{sd} seconds.

$$Z_a = \sum_{i=0}^{e} t_i^a. \tag{38}$$

(2) The second metric, the *total network lifetime* Z_t, gives the first point in time when the liveliness criterion is lost for a longer period than the service disruption tolerance Δt_{sd}.

$$Z_t = t_e. \tag{39}$$

4.7 Reduced Service Quality

With the inclusion of the service disruption criterion, our definition can already represent reduced service quality to a certain extent. However, this definition of network lifetime only takes into account the upper limit of each lifetime criterion. If we are interested in the lifetime that can be achieved if a criterion drops below its soft upper limit, but stays above a hard lower bound, we need to modify the definitions of T, sd_{max}, and $\psi_{sd}(t)$. Similar to T, let T' be the ordered sequence of all points in time where the liveliness criterion crosses the value 0—changes from partial fulfillment to no fulfillment or vice versa. Then we can calculate sd'_{max}, $\psi'_{sd}(t)$, and e' using T', resulting in a lifetime metric that allows for degraded service quality and periods of complete service disruptions.

$$T' = \{t_i | (\zeta(t_i - \epsilon) \geq 0 \wedge \zeta(t_i) = 0) \vee (\zeta(t_i - \epsilon) = 0 \wedge \zeta(t_i) > 0)\}, t_i < t_{i+1}, i \in \mathbb{N}_0 \tag{40}$$

$$sd'_{max} = max((t_{i+1} - t_i) : \zeta(t_i) = 0, i \in [0, |T'| - 1]) \tag{41}$$

$$\psi'_{sd}(t) = \begin{cases} \frac{\Delta t_{sd}}{sd'_{max}} & sd'_{max} > 0 \\ 1 & sd'_{max} = 0 \end{cases}. \tag{42}$$

4.8 Completeness and Extensibility

This definition of sensor network lifetime covers aspects found in the literature, as well as some further aspects we found to be useful for state-of-the-art sensor networks. The main advantages of this integrated definition are its comparability and its flexibility. The step-by-step application of single lifetime criteria in combination with the support for degraded service quality, and the final combination into a lifetime measure distinguishes this new lifetime definition from its predecessors.

While our definition covers many of the parameters related to network lifetime, we do not expect that every possible future application for wireless sensor networks can be covered by the current state of the definition. Therefore, we designed the definition to be relatively easy to extend with forthcoming criteria, by summarizing the criterion in a new $\psi_{**}(t)$ equation and adding the corresponding $\zeta_{**}(t)$ to all minimum equations.

An important point to note is that our definition is also easily applicable to networks where different parts of the network may need to satisfy different criteria. In that case, a good approach would be to separate the network into

Table III. Symbols Used in the Lifetime Definition: We Use Latin Letters for Definitions, and Greek Letters for Functions Indicating a Certain Property, Such as Liveliness

$A^y(t)$	area covered by y-sensors at time t
$\widetilde{A}^y(t)$	area covered by y-sensors with path to sink at time t
$A^y_{k,\Delta t}(t)$	area covered by k y-sensors in the time interval $[t - \Delta t, t]$
$\widetilde{A}^y_{k,\Delta t}(t)$	area covered by k y-sensors with path to sink in the time interval $[t - \Delta t, t]$
$B(t)$	set of base stations
e	minimal index in T before service disruption follows
$E(t)$	edges in communication graph at time t
$G(t) = (V(t), E(t))$	communication graph at time t
L	the set of all crossing paths through R
$n = \|S^Y\|$	number of existing sensor nodes
$P^Y(t)$	set of target points at time t
R	region of deployment
S^Y	set of all existing sensor nodes
T	sequence of points in time where liveliness criterion changes
$U(t)$	set of nodes alive at time t
$V(t)$	set of nodes active at time t
$W(t)$	set of nodes active at any time in the interval $[t - \Delta t, t]$
$Y = \{y_1, \ldots, y_k\}$	set of sensor types present
Z_a	accumulated network lifetime
Z_t	total network lifetime
$\chi(v, t)$	indicates if v has a connection to a base station during the time interval $[t - \Delta t, t]$
$\kappa(t, m_1, m_n)$	nodes m_1 and m_n can communicate at time t
$\widehat{\kappa}([t - \Delta t, t], m_1, m_n)$	nodes m_1 and m_n can communicate in the time interval $[t - \Delta t, t]$
$\sigma(t, x)$	gives a set containing all nodes covering the point x at any time during the time interval $[t - \Delta t, t]$
$\widetilde{\sigma}(t, x)$	gives a set containing all connected nodes covering the point x at any time during the time interval $[t - \Delta t, t]$
$\tau(x, v^y)$	gives a set containing node v if v covers x, and an empty set otherwise
$\widetilde{\tau}(x, v^y)$	gives a set containing node v if v is connected and covers x, and an empty set otherwise
$\psi^y_{**}(t)$	indicates how good criterion ** is fulfilled at time t for sensor type y
$\psi_{**}(t)$	indicates how good criterion ** is fulfilled at time t
$\zeta^y_{**}(t)$	indicates to what degree liveliness criterion ** is fulfilled at time t for sensor type y
$\zeta_{**}(t)$	indicates to what degree liveliness criterion ** is fulfilled at time t
$\zeta(t)$	indicates to what degree the network is considered alive at time t

its different parts and evaluate the lifetime for each part separately. The parts could even overlap to some extent. Combining the lifetime measures from the different parts can be done similarly to the combining of the single criteria, for example by using the minimum.

5. APPLICABILITY OF THE DEFINITION

To analyze the applicability and usability of our new definition, we first describe the mapping from existing lifetime definitions and some selected sensor network applications to parameter settings of our definition in Sections 5.1 and 5.2. We then use a discrete-event simulation to evaluate the lifetimes achievable

Table IV. Mapping of the Existing Definitions and a Few Common Applications Scenarios to the New Definition. Values of the Additional Parameters are Given Only Where they Differ from their Default Value

lifetime definition	c_{ln}	c_{la}	c_{dr}	c_{cc}	c_{ac}^{y}	c_{tc}^{y}	c_{bc}^{y}	c_{ca}^{y}	c_{ct}^{y}	c_{cb}^{y}	c_{sd}
n-of-n lifetime	$\mathbf{1}$	0	0	0	0	0	0	0	0	0	0
k-of-n lifetime	$\frac{\mathbf{k}}{\mathbf{n}}$	0	0	0	0	0	0	0	0	0	0
last node failure	0	0	0	0	0	0	0	0	0	0	0
100% target coverage	0	0	0	0	0	1 k=1	0	0	0	0	0
100% area coverage	0	0	0	0	1 k=1	0	0	0	0	0	0
accumulated α-coverage	0	0	0	0	α k=1	0	0	0	0	0	1 $\Delta t=\mathbf{n}$
α-coverage (last drop)	0	0	0	0	α k=1	0	0	0	0	0	1 $\Delta t=\infty$
α-coverage (first drop)	0	0	0	0	α k=1	0	0	0	0	0	1 $\Delta t=0$
k-area coverage	0	0	0	0	1 k=$\mathbf{k}$	0	0	0	0	0	0
packet delivery ratio β and α-coverage	0	0	β	0	α k=1	0	0	0	0	0	0
connectivity and k-area coverage	0	0	0	$\frac{\mathbf{v(t)}}{\mathbf{n}}$	1 k=$\mathbf{k}$	0	0	0	0	0	0
Blough and Santi	$\mathbf{c_2}$	0	0	0	$\mathbf{c_3}$ k=1	0	0	0	0	0	0
habitat monitoring	0	0	0	1 Δt=24h	0	0	0	0	0	0	1 Δt=24h
smart building	0	0	0	1 Δt=24h	0.9 k=1 Δt=1h	0	0	0	0	0	1 Δt=1h
human physiological data	0	0.95 Δt=1s	0.95	1	0	0	0	0	0	0	0
intrusion detection	0	1 Δt=2s	0.95	0	0	0	0	0	0	1 k=5	0

with the existing definitions (Section 5.4), the lifetimes for common application scenarios (Section 5.5), and the effects of the new criteria on network lifetime (Section 5.6).

5.1 Mapping of Existing Definitions

Nearly all definitions of network lifetime existing in the literature can be represented with our definition. In Table IV, we provide parameter settings that reproduce the most common definitions described in the related work section. As can be seen, most of the criteria we employ in our lifetime definition have already been used in the literature—while not in such a comprehensive way. Other parts such as the ζ_{la} criterion (depicting the end-to-end latency of communications), the time-integrated coverage criteria, and the tuple ζ_{ca} and ζ_{ct} (representing the area and target coverage, respectively, under connectivity constraints) have been introduced to complete the definition according to the specific requirements in sensor networks.

However, some of the definitions of network lifetime discussed in Section 2 cannot be easily represented in terms of our new definition. This is not due to inattention towards these definitions, but due to other reasons, which we will now explain.

The definition targeting the failure of the first cluster head is not representable because there is no explicit notion of cluster heads in our definition. However, as cluster heads are mostly responsible for maintaining the connectivity to the base stations, this metric can be reformulated in terms of one of the connectivity metrics in our definition.

The definition of Blough and Santi [2002] is represented in the last line of Table IV. However, this representation is only partial, as their connectivity metric "largest connected component" is missing. This is intentional because that metric does not incorporate application-specific requirements such as the need for a particular base station. It should be replaced by a connectivity metric representing connectivity to a sink node.

The definitions measuring the lifetime in terms of the total number of packets arrived at the sink or the number of successful data-gathering trips are not representable. This is because they do not give the lifetime in terms of a comparable time unit, but in terms of a number that can vary greatly depending on the algorithms employed. This has already been discussed earlier in this article.

The remaining definitions can in principle be represented in terms of our definition, but are given too vaguely to derive precise numbers for their parameter settings. These definitions include the one targeting *connectivity* and *coverage*. We provide metrics for both connectivity and coverage, but as the authors did not specify the details, there is a broad range of possible representations for this definition. The definition based on the event detection ratio can be entirely mapped to coverage and connectivity criteria. Finally, the definitions targeting the application requirements are too abstract to find a specific representation.

5.2 Mapping of Sensor Network Applications

To further evaluate the applicability of our definition, we analyzed sensor network applications as surveyed in Akyildiz et al. [2002a], Arampatzis et al. [2005], and Khemapech et al. [2005]. Concerning the importance of different lifetime criteria, most of the application scenarios can be grouped into two main classes with two subclasses each.

The first main class comprises mission critical applications that have to fulfill very strong requirements throughout their lifetime. Examples include the detection of forest fires, floods, nuclear/chemical/biological attacks, intrusion detection, or battlefield surveillance. In these applications, service disruptions cannot be tolerated, while connected coverage as well as low latencies and loss rates are required. In some cases, it is also necessary to require a certain number of alive nodes.

Table V. Sensor Network Applications

Class	Application Examples	Lifetime Aspects
Critical, coverage	Forest fire detection, flood detection, nuclear/chemical/biological attack detection, battlefield surveillance, intrusion detection	$c_{ca}/c_{ct}/c_{cb}$, c_{ln}, c_{la}, c_{lo}
Critical, no coverage	Monitoring human physiological data, military monitoring of friendly forces, machine monitoring	c_{cc}, c_{ln}, c_{la}, c_{lo}
Noncritical, coverage	Agriculture, smart buildings, habitat monitoring (sensors monitor the inhabitants in a region)	$c_{ac}/c_{tc}/c_{bc}$, c_{cc}, c_{sd}
Noncritical, no coverage	Home automation, habitat monitoring (sensors are attached to animals and monitor their health and social contacts)	c_{cc}, c_{sd}

The second main class includes non-critical applications that are nevertheless quite useful and nice to have. This comprises for example agricultural settings, climate control in office buildings, and home automation. Typical requirements in these applications are coverage and connectivity, together with a relatively high tolerance towards service disruptions.

The two subclasses are applications with and without coverage requirements. Applications without coverage requirements are typically those applications where the sensor nodes are directly attached to their targets, and therefore coverage is guaranteed as long as the sensor node is alive. Example applications include habitat monitoring, monitoring of human physiological data, machine monitoring, and the monitoring of friendly forces and equipment in military situations. The requirements in these applications include at least connectivity and alive nodes. In some cases, low latency and loss are also required, while in other cases, a certain amount of service disruption can be tolerated. Table V gives an overview of the discussed application classes.

While these applications are widely discussed in the sensor networks community, only very few of the papers we surveyed for this work mention which application scenarios could benefit from their work. In most cases, the intended application scenario is merely paraphrased by a rough description of the application, the node distribution, and the intended traffic patterns. Therefore, we will discuss one application example from each of the four classes in detail, referencing the surveyed papers where applicable. The derived parameter settings are summarized in the bottom part of Table IV.

Application Example: Habitat Monitoring. Consider a habitat monitoring scenario where sensor nodes have been attached to several animals to monitor their health and social contacts to other animals. One or more base stations have been set up at places where the animals regularly pass by, for example, at a common watering place. The sensors are required to gather data from their animals regularly, but it is deemed sufficient if the data is transmitted to a sink once a day. It can also be tolerated if no data arrives on some days. Then, the relevant parameters could be set as $c_{cc} = 1$, $\Delta t_{cc} = 1$ day, $c_{sd} = 1$, $\Delta t_{sd} = 1$ day. This means that all nodes need connectivity to a base station at least once a day, allowing for outages of one day.

Application Example: Intrusion Detection. In a sensor network deployed to detect and track intruders, such as is considered in Kumar et al. [2005], it is important that the desired course of the fence is covered by several nodes to rule out bogus measurements. Kumar et al. [2005] consider only coverage and latency to define the lifetime of the network, resulting in the following parameter setting: $c_{bc} = 1, k_{bc} = 5, c_{la} = 1, l = 2, c_{sd} = 0$. This may need to be extended to cover connectivity and the packet loss rate. Therefore, we propose extending the parameter settings like this: $c_{cb} = 1, k_{cb} = 5, \Delta t_{ca} = 0, c_{la} = 1, l = 2$ s, $c_{dr} = 0.95, c_{sd} = 0$; we include connected barrier coverage as well as a low loss rate.

Application Example: Smart Buildings. In a smart building scenario, sensor nodes are deployed to monitor the climate inside a building. If the measurements of environmental parameters like temperature or humidity deviate from the desired values, actions can be initiated for climate control. The network may be required to cover at least 90% of the building and to ensure that sensor readings are delivered to the central control unit at regular intervals. The corresponding lifetime parameters could be set to $c_{ac} = 0.9, k_{ac} = 1, \Delta t_{ac} = 1$ hour, $c_{cc} = 1, \Delta t_{cc} = 1$ hour, $c_{sd} = 1, \Delta t_{sd} = 1$ hour. This means that the control instance can act upon fresh sensor readings at least once every hour, allowing for outages of one hour. In contrast, Shah and Rabaey [2002] require that all nodes are alive, $c_{ln} = 1$, for a smart building scenario, which is less flexible.

Application Example: Human Physiological Data. Monitoring human physiological data is a highly critical application, because certain variations in the measured data, like a sudden drop of the pulse must be acted upon immediately. It is therefore important that the nodes are always connected to a base station, and can transmit data with low latency and loss. This could be expressed as a parameter setting of $c_{cc} = 1, \Delta t_{cc} = 0, c_{la} = 0.95, l = 1$ s, $c_{dr} = 0.95, c_{sd} = 0$.

5.3 Evaluation of Network Lifetime: Simulation Scenario

For the evaluation of the various network lifetime definitions surveyed in this article, as well as our new definition, we use a setup similar to the one described in Xing et al. [2005]. To obtain sample data for the evaluation, we ran simulations with 100 sensor nodes placed in an area of 300 × 300 m using the simulation tool OMNeT++. The nodes use energy for communication and sensing, and the power consumption values were taken from measurements on Mica2 nodes as presented in Landsiedel et al. [2005]. Two types of sensors are deployed on the nodes. 75 nodes are equipped with a cheap sensor (in terms of energy consumption). Measurements from these sensors are gathered every 10 s and sent to the base station in one small packet. The remaining 25 nodes have a sensor with high energy consumption and a sampling rate of 60 s. Three large packets are needed to transmit these data to the base station. To realize multi-hop communication towards the sink, the nodes are equipped with a protocol stack consisting of the 802.11 physical and MAC layers, and the DYMO routing protocol. The nodes have only a very small supply of energy

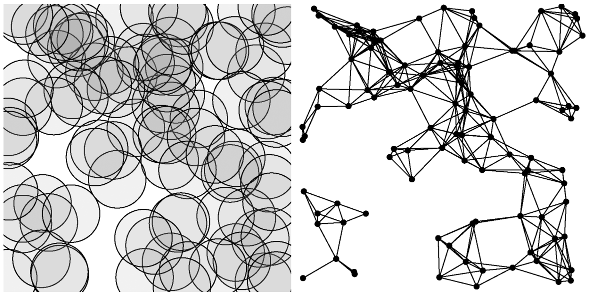

Fig. 1. Coverage and connectivity for a sample replication at time $t = 0$.

at their disposal, which fixes the best case lifetime (the time of the last node failure) of the network at about 40 minutes. For our figures, the lifetime has been normalized to the interval [0, 1].

To demonstrate the effects of mobility, we simulate two different scenarios: one with only static nodes, and one with 10% mobile nodes. Figure 1 shows the distribution of the nodes in the sample setup at time $t = 0$, as well as the initial coverage with a sensing radius of 30 m and the communication graph for a communication range of 50 m. During the simulation, we recorded the positions of the nodes, their failure times, the latencies and loss rates for all application traffic, and the types of sensors available at each node. We conducted ten replications of each simulation scenario to obtain statistically significant simulation output.

5.4 Evaluation of Existing Definitions

Figure 2 shows a box plot for each definition, indicating the median, the first, and third quartiles, and the minima and maxima of the achieved total network lifetimes. The same representation is used for all following figures as well.

The left part of Figure 2 shows an evaluation of the existing definitions of network lifetime in the context of our sample setup. For each definition with a direct mapping to our definition, as shown in Table IV, we computed the network lifetime with varying parameters. In the context of the sample network, the definitions can result in very different network lifetimes varying roughly between 0 and 100% of the best case lifetime. In addition, there is a high variance of the resulting lifetime depending on the actual values of the parameter setting used for each definition. This illustrates how difficult it is to compare network lifetimes obtained with different, and possibly custom, lifetime definitions.

5.5 Evaluation of Sensor Network Applications

The right part of Figure 2 shows an evaluation of the sensor network application scenarios presented here. The parameter settings have been varied over a range of acceptable values for each scenario. The lower part of Table IV shows one sample parameter setting for each scenario. It is evident that the requirements for the scenarios lead to very different estimations of network lifetime. Another

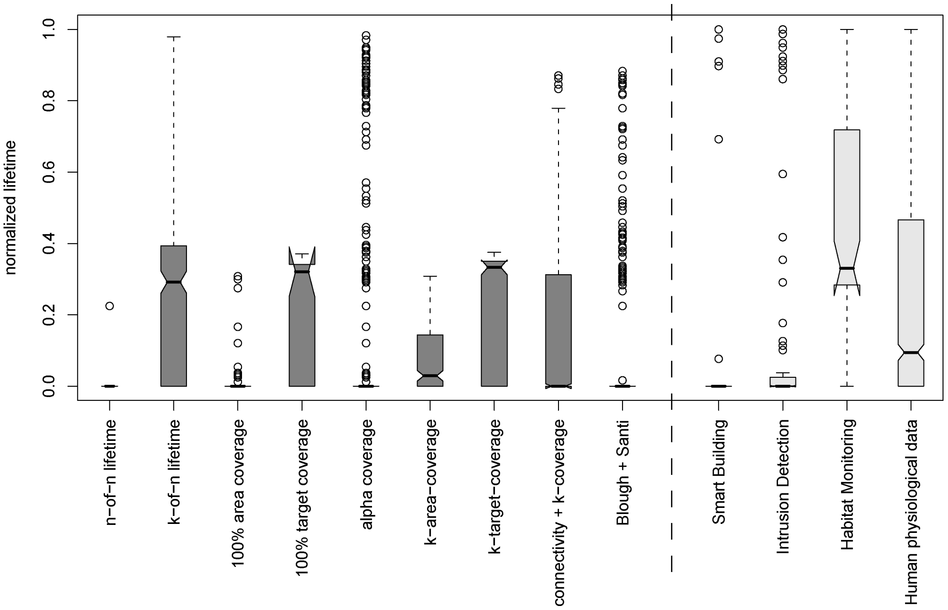

Fig. 2. Evaluation of existing network lifetime definitions and selected sensor network applications.

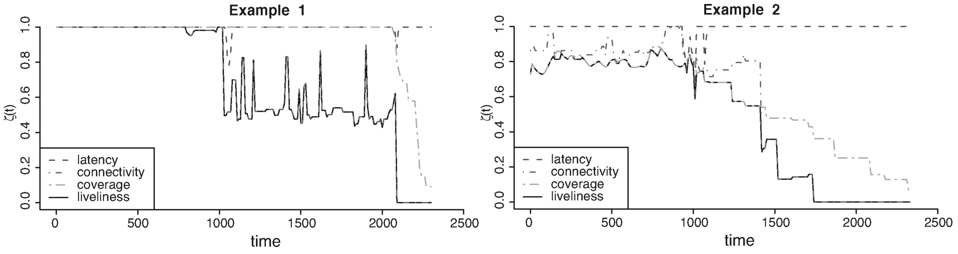

Fig. 3. Sample plots of the liveliness criterion and its parameters over time.

point that is easily visible is that none of the existing definitions are able to adequately represent the scenarios. Consequently, this result underlines the requirement for our new application-specific lifetime definition.

5.6 Evaluation of New Criteria

In this section, we evaluate the impact of the new criteria introduced in this article. Due to space constraints, we only give short illustrations of the effects the criteria may have, rather than a full study of these effects.

Figure 3 shows how the liveliness of the network depends on the underlying criteria. The application requirements in both examples include the same constraints on latency, connectivity, and coverage; the only difference is that they are based on different replications of our simulation scenario. It can be seen that the connectivity constraint is effectively bounding the liveliness in the left graph (Example 1), so that the liveliness deviates from 1 whenever

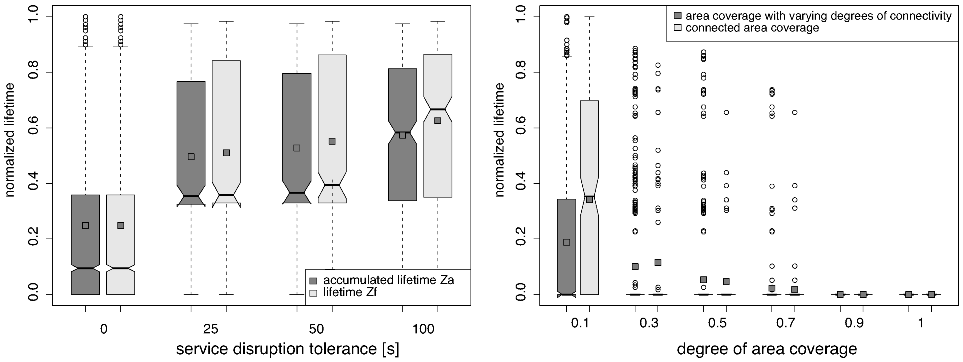

Fig. 4. Left: Overall impact of service disruption tolerance; Right: Connectivity and area coverage vs. connected area coverage. The red squares in each box denote the mean value.

the connectivity constraint is violated. In contrast, the liveliness in Example 2 never even reaches the value 1. There is also no single constraint that is stronger than the others: at some point in time, the liveliness is bounded by each of the three criteria. This illustrates how the network liveliness works as a function of the application requirements. It also shows that it is important to use all known requirements for the calculation of the network lifetime because the requirement bounding the lifetime may not be known in advance, or it may not even exist (as in Example 2).

5.6.1 *Impact of Service Disruption Tolerance.* To evaluate the impact of the service disruption tolerance parameter we introduced into the definition, we first analyze how the total lifetime, Z_t, and the accumulated lifetime, Z_a, behave depending on the length of the service disruption tolerance. The left part of Figure 4 shows the resulting lifetimes for all evaluated parameter settings, split by tolerances of 0, 25, 50, and 100 s. Both lifetime metrics increase with increasing service disruption tolerance. Following from the definition of the metrics, Z_t is only equal to Z_a if the service disruption parameter had no effect, either because it was zero, or because the first service disruption period was already longer than the parameter allowed. In all other cases, Z_t is greater than Z_a. The figure also demonstrates that the classic lifetime metrics without service disruption tolerance can yield lifetimes that are significantly too low if the network application allows for some amount of service disruption.

In about 65% of the evaluated cases with nonzero lifetime and service disruption tolerance, tolerating some amount of service disruption led to a higher value of the lifetime metrics. The difference between the accumulated lifetime Z_a and the total lifetime Z_t indicates how long the network was not lively during the lifetime indicated by Z_t, and therefore shows the magnitude of the non-lively periods that were tolerated. As could be expected, with increasing service disruption tolerance, increasingly large non-lively periods are tolerated. However, the exact amount of this increase strongly depends on the particular setup of a sensor network and should not be generalized from our experiments.

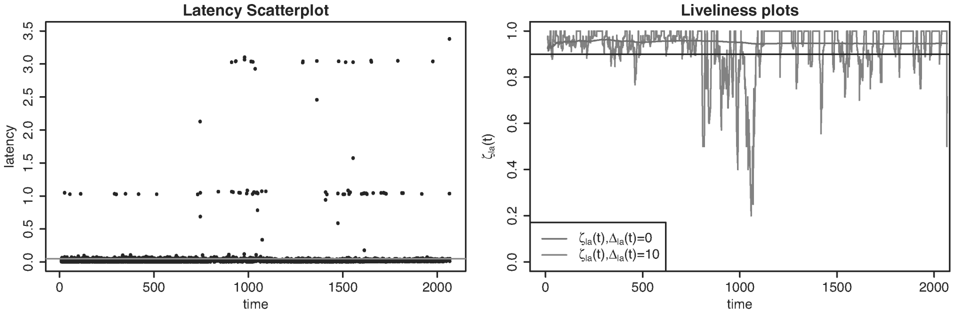

Fig. 5. Evaluation of latency vs. time-integrated latency.

5.6.2 *Evaluation of Connected Coverage Criteria.* Another new aspect in our definition of network lifetime is the introduction of the connected coverage criteria. While we assume that this metric is a stronger constraint than connectivity and coverage on their own, the evaluation must provide hints as to whether this is really the case. To ensure that the evaluation is not influenced by other parameters, only parameters related to connectivity and coverage were varied in this section.

The right part of Figure 4 shows the network lifetime depending on varying degrees of area coverage. The dark boxes represent all cases where there were requirements on the connectivity next to the coverage requirement, whereas the light boxes represent the cases with the connected area coverage requirement. The connectivity required for the dark boxes was varied between 0 and 1 for each box.

As seen in Figure 4, the lifetimes calculated with the connected coverage criteria are different from the lifetimes with the two single criteria: connectivity and coverage. However, there is no evidence that connected coverage generally results in higher or lower lifetimes.

Connected coverage will result in a higher lifetime if the connectivity percentage requirement is not fulfilled, but there are a few nodes with a connection to a base station providing the required coverage. Connected coverage will result in a lower lifetime if the set of nodes providing connectivity is at least partially different from the set of nodes providing coverage, so that not all of the covering nodes can find a path to a base station.

5.6.3 *Evaluation of Time-Integrated Criteria.* Figure 5 provides an illustration of the effects that the time-integration parameter may have on a criterion. For this example, we assume that the network is required to deliver 90% of all data messages in less than 50 ms ($c_{la} = 0.9, l = 0.05$). The left part of the plot shows the latency values gathered in the simulation, and the grey line indicates the threshold of 50 ms. The right part shows the calculated liveliness in two variants, one without time integration, and the other with the time-integration parameter set to 10 s.

It can easily be seen that without time integration, the requirement seems to be fulfilled over the entire time. However, the evaluation with $\Delta(t) = 10$s shows that there are indeed some points in time where the requirement is not

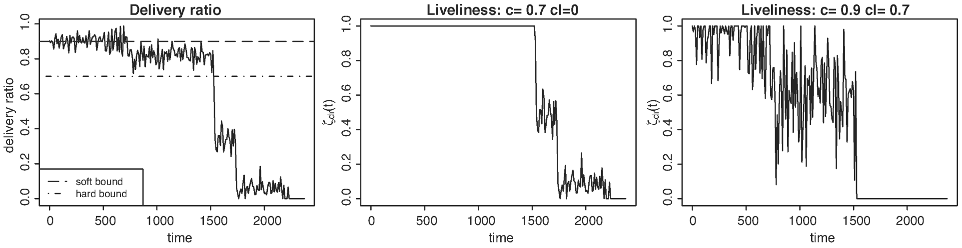

Fig. 6. Influence of upper and lower bounds on the liveliness: according to a selected measurement (delivery ratio), the liveliness measure is plotted for two different upper/lower bound values.

fulfilled. Therefore, for the latency and delivery ratio requirements, the time integration parameter results in a stronger demand on the network. It should be noted that this behavior may vary depending on the specific requirement: in conjunction with coverage or connectivity, time-integration may lead to a reduced demand on the network.

5.6.4 *Evaluation of Graceful Degradation.* Figure 6 illustrates the effect that upper and lower bounds may have on the liveliness of a single criterion, but also on the global liveliness. The plot on the left depicts the message delivery rate as measured during a simulation run. It also shows the locations of the upper and lower bounds at 0.9 and 0.7, respectively. The middle plot shows an evaluation of the liveliness criterion, ζ_{dr}, if only the hard lower bound is taken into consideration. For a user or an administrator of a network, the only useful information contained in this plot is whether ζ_{dr} has the value 1 or not—whether the network is fully functional or not. The rightmost plot shows the evaluation with an additional soft upper bound. It contains much more information because it also indicates when the network drops below a specified warning level, allowing the administrators to take early precautionary measures against complete network failure.

6. CONCLUSION

In this article, we reviewed the existing definitions of network lifetime as proposed in the literature. It turned out that most papers—especially those proposing algorithms to increase the lifetime of sensor networks—are built on differing lifetime definitions. We outlined advantages and drawbacks of the existing definitions, and summarized additional requirements. This way, we emphasized the need for a more general and concise definition for accumulated and total network lifetime, that is formal and applicable in various domains. Our new definition of sensor network lifetime is composed in a modular way, enabling the incorporation of different aspects for different application scenarios. The definition comprises metrics that have been used in the literature before, such as node availability, sensor coverage, and connectivity. We also introduced a number of new metrics that we have found to be useful in the context of sensor network applications, including connected coverage, time-integration, and service disruption tolerance.

A major benefit of our definition is that it can indicate the level of performance degradation in addition to the network lifetime according to a fully functional network. The definition can be used for analytical evaluation as well as for simulation models to evaluate specific algorithms in a comparable way. Thus, the definition results in more precise estimates of network lifetime, and can represent application requirements for very different sensor network settings. We demonstrated the applicability of our definition based on a comparison with the related work, a short study of sensor network applications, as well as using a simple example scenario.

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