### D. $k$-coverage for single sensor types

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. The $k$-coverage parameter $c_k^y$ indicates the magnitude of $k$. The function $\tau$ returns 1 if a certain point $x$ is withing the sensing radius of the type-$y$-sensor of node $v$. The function $\sigma$ indicates by how many active sensors a point $x$ is covered.

$$\tau(x, v^y) = \begin{cases} 1 & x \in A_v^y \\ 0 & x \notin A_v^y \end{cases}$$

$$\sigma(t, x) = \sum_{i=0}^{v(t)} \tau(x, v_i^y)$$

The $k$-coverage criterion is fulfilled if $\sigma$ is not smaller than the $k$-coverage parameter $c_k^y$ for all points in the region of interest. There are two variants depending on the kind of the region of interest: one for an area (equation 11) or volume, and one for targets (equation 12).

$$\zeta_k^y(t) \equiv \forall x \in R: \ \sigma(t, x) \geq c_k^y \tag{11}$$
$$\zeta_k^y(t) \equiv \forall p \in P: \ \sigma(t, p) \geq c_k^y \tag{12}$$

### E. Number of active nodes

At least a portion of $c_{an}$ times the number of existing nodes must be active at any time (sleeping nodes are not considered active).

$$\zeta_{an}(t) \equiv v(t) \geq c_{an} * n \tag{13}$$

### F. 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. This means that the parameter $c_{ln}$ can never be truly switched off because the true greater relation ensures that the lifetime of the sensor network is constrained to be at most the time of the failure of the last alive node. This has already been discussed as the *best case* for sensor network lifetime in the related work section.

$$\zeta_{ln}(t) \equiv u(t) > c_{ln} * n \tag{14}$$

### G. Availability (service disruption tolerance)

A service disruption of at most $c_{sd}$ seconds is tolerated. This parameter is included in the final lifetime definitions (equations 29 - 32).

### H. Latency

For each type of packet in the network, all packets of the type must arrive at a sink node within a period of $c_{la}$ after the initial sending.

$$\zeta_{la} \equiv \forall \text{packets} : \text{packet latency} \leq c_{la} \tag{15}$$

### I. Loss and error

At most a portion of $c_{lo}$ 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 $1 - c_{lo}$ packets must be correctly received by a sink node, i.e that the packet delivery ratio must be at least $1 - c_{lo}$.

$$\zeta_{lo} \equiv \frac{\text{lost packets} + \text{erroneous packets}}{\text{total packets}} < c_{lo} \tag{16}$$



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### *J. 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. The function $\chi(v_j, t)$ indicates if a node $v_j$ 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.

$$\chi(v_j, t) \equiv \exists b_i \in B(t) \wedge (v_j, b_i) \in V(t) \wedge \kappa(t, v_j, b_i) \tag{17}$$

One criterion to evaluate connectivity in a sensor network is to require that at least a certain portion of all active nodes have a connection to a base station.

$$\zeta_c(t) \equiv \exists V_c \subset V(t) : |V_c| \geq c_c * |V(t)| \wedge \forall v_c \in V_c : \chi(v_c, t) \tag{18}$$

Another criterion for connectivity is to include the coverage criteria in the definition. 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. [77].

For the connected coverage criteria it is useful to redefine the covered area $A^y(t)$ as $A^y_*(t)$. The difference between the two definitions is that $A^y(t)$ uses all active nodes, whereas $A^y_*(t)$ uses only those active nodes with a path to the sink.

$$A^y_*(t) = \bigcup_{\forall v_i \in V(t) : \chi(v_i, t)} A^y_{v_i} \cap R \tag{19}$$

Based on $A^y_*(t)$ and the previous definitions of area and target coverage in sections V-B and V-C, we can now define the criteria for connected area coverage $\zeta^y_{cac}(t)$ and connected target coverage $\zeta^y_{ctc}(t)$. 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.

$$\zeta^y_{cac}(t) \equiv \ A^y_*(t) \geq c^y_{cac} * |R|, y \in Y \tag{20}$$

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.

$$\zeta^y_{ctc}(t) \equiv \ \exists P_m \subset P \wedge |P_m| \geq c^y_{ctc} * |P| \wedge P_m \in A^y_*(t), y \in Y \tag{21}$$



### *K. Global coverage criteria*

The coverage criteria defined so far include area coverage, target coverage, $k$-coverage, connected area coverage and connected target 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 conjunctive combination of all single node criteria is fulfilled.

global area coverage: $$\zeta_{ac}(t) = \bigwedge_{\forall y \in Y} \zeta^y_{ac}(t) \tag{22}$$

global target coverage: $$\zeta_{tc}(t) = \bigwedge_{\forall y \in Y} \zeta^y_{tc}(t) \tag{23}$$

global $k$-coverage: $$\zeta_{k}(t) = \bigwedge_{\forall y \in Y} \zeta^y_{k}(t) \tag{24}$$

global connected area coverage: $$\zeta_{cac}(t) = \bigwedge_{\forall y \in Y} \zeta^y_{cac}(t) \tag{25}$$

global connected target coverage: $$\zeta_{ctc}(t) = \bigwedge_{\forall y \in Y} \zeta^y_{ctc}(t) \tag{26}$$

### *L. Definition of network lifetime*

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 conjunctive combination of all single criteria. Table II gives an overview of the parameters used in the criteria definitions, their ranges and which values can be used to turn each criterion off.

$$\zeta(t) \equiv \zeta_{ac}(t) \wedge \zeta_{tc}(t) \wedge \zeta_{k}(t) \wedge \zeta_{an}(t) \wedge \zeta_{ln}(t) \wedge \zeta_{la} \wedge \zeta_{lo} \wedge \zeta_{c}(t) \wedge \zeta_{cac}(t) \wedge \zeta_{ctc}(t) \tag{27}$$

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| parameter | meaning | range | off |
|---|---|---|---|
| $c^y_{ac}$ | area coverage | $[0, 1]$ | 0 |
| $c^y_{tc}$ | target coverage | $[0, 1]$ | 0 |
| $c^y_k$ | $k$-coverage | $[0, \infty]$ | 0 |
| $c_{an}$ | portion of active nodes | $[0, 1]$ | 0 |
| $c_{ln}$ | portion of alive nodes | $[0, 1]$ | 0 |
| $c_{sd}$ | service disruption tolerance | $[0, \infty]$ | $\infty$ |
| $c_{la}$ | maximum tolerable latency | $[0, \infty]$ | $\infty$ |
| $c_{lo}$ | maximum portion of packet loss or error | $[0, 1]$ | 1 |
| $c_c$ | portion of nodes with path to a sink | $[0, 1]$ | 0 |
| $c^y_{cac}$ | connected area coverage | $[0, 1]$ | 0 |
| $c^y_{ctc}$ | connected target coverage | $[0, 1]$ | 0 |

TABLE II
PARAMETERS

We then define $T$ to be the ordered sequence of all points in time where the aggregate criterion $\zeta(t)$ changes its value (from *true* to *false* or vice versa). We do this by checking $\zeta$ at time $t$ and at time $t - \epsilon$, i.e. just before time $t$.

$$T = \{t_i | (\zeta(t_i - \epsilon) \wedge \neg\zeta(t_i)) \vee (\neg\zeta(t_i - \epsilon) \wedge \zeta(t_i))\}, t_i < t_{i+1}, i \in \mathbb{N}_0 \quad (28)$$

To clarify the following definitions, we define $e$ to be the minimal index in $T$ after which a service disruption of more than $c_{sd}$ 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 $T$, i.e. $|T|$.

$$e = \begin{cases} \min(i \in [0, |T| - 1] : \neg\zeta(t_i) \wedge (t_{i+1} - t_i) > c_{sd}) & \text{if such } i \text{ exists} \\ |T| & \text{otherwise} \end{cases} \quad (29)$$

For further simplification, we define the periods of time during which the network is lively as $t^a_i$.

$$\forall i \in [0, e] : t^a_i = \begin{cases} t_{i+1} - t_i & \text{if } \zeta(t_i) \\ 0 & \text{otherwise} \end{cases} \quad (30)$$

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.

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 $t^a_i$ defined above), stopping only when the criterion is not fulfilled for longer than $c_{sd}$ seconds.

$$Z_a = \sum_{i=0}^{e} t^a_i \quad (31)$$

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 $c_{sd}$.

$$Z_t = t_e \quad (32)$$



## VI. Applicability of the definition

### A. 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 $\zeta_{an}$ criterion (representing the number of active nodes), $\zeta_{la}$ (depicting the end-to-end latency of communications), and the tuple $\zeta_{cac}$ and $\zeta_{ctc}$ (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 II can not be represented easily in terms of our new definition. This is not due to inattention towards these definitions, but due to several other reasons which we will explain now.

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 re-formulated in terms of one of the connectivity metrics in our definition.

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| | |
|---|---|
| $A^y(t)$ | area covered by $y$-sensors at time $t$ |
| $A^y_*(t)$ | area covered by $y$-sensors with path to sink at time $t$ |
| $B(t)$ | set of base stations |
| $\chi(v,t)$ | indicates if $v$ has a connection to a base station at time $t$ |
| $e$ | 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 $t$ |
| $\kappa(t, m_1, m_n)$ | nodes $m_1$ and $m_n$ can communicate at time $t$ |
| $n = \lvert S^Y \rvert$ | number of existing sensor nodes |
| $P^Y$ | set of target points |
| $R$ | region of deployment |
| $\sigma(t,x)$ | indicates by how many sensors $x$ is covered at time $t$ |
| $S^Y$ | set of all existing sensor nodes |
| $\tau(x,v)$ | indicates if $x$ is covered by $v$ |
| $T$ | 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 $t$ |
| $Y = \{y_1, \ldots, y_k\}$ | set of sensor types present |
| $\zeta^y_{**}(t)$ | indicates if liveliness criterion ** is fulfilled at time $t$ for sensor type $y$ |
| $\zeta_{**}(t)$ | indicates if liveliness criterion ** is fulfilled at time $t$ |
| $\zeta(t)$ | indicates if the network is considered alive at time $t$ |
| $Z_a$ | accumulated network lifetime |
| $Z_t$ | total network lifetime |

TABLE III

SYMBOLS USED IN THE LIFETIME DEFINITION

| lifetime definition | $c^y_{ac}$ | $c^y_{tc}$ | $c^y_k$ | $c_{an}$ | $c_{ln}$ | $c_{sd}$ | $c_{la}$ | $c_{lo}$ | $c_c$ | $c^y_{cac}$ | $c^y_{ctc}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $n$-of-$n$ lifetime | 0 | 0 | 0 | 0 | **1** | $\infty$ | $\infty$ | 1 | 0 | 0 | 0 |
| $k$-of-$n$ lifetime | 0 | 0 | 0 | 0 | $\mathbf{\frac{k}{n}}$ | $\infty$ | $\infty$ | 1 | 0 | 0 | 0 |
| last node failure | 0 | 0 | 0 | 0 | **n** | $\infty$ | $\infty$ | 1 | 0 | 0 | 0 |
| 100% target coverage | 0 | **1** | 0 | 0 | 0 | $\infty$ | $\infty$ | 1 | 0 | 0 | 0 |
| 100% area coverage | **1** | 0 | 0 | 0 | 0 | $\infty$ | $\infty$ | 1 | 0 | 0 | 0 |
| accumulated $\alpha$-coverage | $\alpha$ | 0 | 0 | 0 | 0 | **n** | $\infty$ | 1 | 0 | 0 | 0 |
| $\alpha$-coverage (last drop) | $\alpha$ | 0 | 0 | 0 | 0 | $\infty$ | $\infty$ | 1 | 0 | 0 | 0 |
| $\alpha$-coverage (first drop) | $\alpha$ | 0 | 0 | 0 | 0 | **0** | $\infty$ | 1 | 0 | 0 | 0 |
| $k$-coverage | 0 | 0 | **k** | 0 | 0 | $\infty$ | $\infty$ | 1 | 0 | 0 | 0 |
| packet delivery ratio $\beta$ and $\alpha$-coverage | $\alpha$ | 0 | 0 | 0 | 0 | $\infty$ | $\infty$ | $\mathbf{1} - \beta$ | 0 | 0 | 0 |
| connectivity and $k$-coverage | 0 | 0 | **k** | 0 | 0 | $\infty$ | $\infty$ | 1 | $v(t)$ | 0 | 0 |
| Blough and Santi | $\mathbf{c_3}$ | 0 | 0 | 0 | $\mathbf{c_2}$ | $\infty$ | $\infty$ | 1 | 0 | 0 | 0 |

TABLE IV

MAPPING



The definition of Blough and Santi [31] 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 paper.

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 mapped entirely to coverage and connectivity criteria. Finally, the definitions targeting the application requirements are too abstract to find a specific representation.

### *B. Scenario-based comparisons of network lifetimes*

For the evaluation of the various network lifetime definitions surveyed in this paper, as well as our new definition, we used the setup described in [38]. To obtain sample data for the evaluation, we ran a simulation with 160 sensor nodes placed in an area of 400x400 $m^2$. The nodes used energy only for communication, and the power consumption values were taken from measurements on Mica2 nodes presented in [78]. The nodes only had a very small, randomly distributed supply of energy at their disposal. The nodes followed random sleep cycles and communicated regularly with a base station in the middle of the

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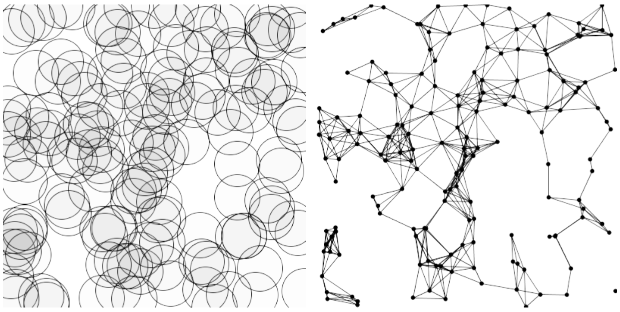

Fig. 1. Coverage and connectivity for the sample setup at time $t = 0$

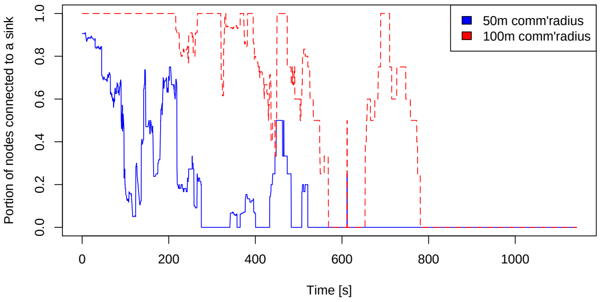


Fig. 2. Evolution of the connectivity criterion over time

simulation area during their awake periods. A number of sensor types was randomly selected from the three types available for each node.

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 30m and the communication graph for a communication range of 50m.

During the simulation, we recorded the positions of the nodes, their failure times, their sleep periods, and the types of sensors available on each node. We conducted only a single run of the simulation, as the purpose was not to obtain statistically significant simulation output, but to obtain sample values for the evaluation of the network lifetime definitions.

Figure 2 illustrates the interaction of sleep cycles and node failures in the sample setup on the basis of the connectivity metric. The portion of nodes with a path to a sink node was computed for communication radii of 50m and 100m.

In order to demonstrate the impact of the various parameters, we evaluated the network lifetime varying one parameter at a time while switching the other parameters off. There were two exceptions to this: the parameter $c_k$ was varied together with the coverage parameters, and $c_{sd}$ was varied with all other parameters. The communication range was fixed as a circle with 50m radius, while the sensing range was a circle with a radius of 30m.

All criteria involving target coverage were evaluated with four different target placements: one scenario with only three targets in the middle and in two corners of the area, and three scenarios with ten randomly placed targets each.

In total, we computed the network lifetime for more than 3000 different parameter settings. The best case lifetime (i.e. the time of the last node failure) reachable in the sample setup was about 1150 seconds. For the figures below, the lifetime has been normalized to the interval $[0, 1]$.

### C. *Evaluation of existing definitions*

Figure 3 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. Figure 3 shows a box plot for each definition, indicating the median, the first and third quartile, and the minima and maxima of the achieved total network lifetimes. The same representation is used for all following figures as well.

In the context of the sample network, the definitions can result in very different network lifetimes varying roughly between 0 and 70% 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.

### D. *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. Figure 4 shows the resulting lifetimes for all evaluated parameter settings, split by tolerances of 0, 25, 50 and 100 seconds.



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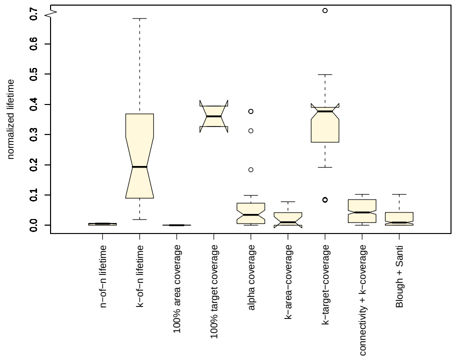


Fig. 3. Evaluation of existing network lifetime definitions

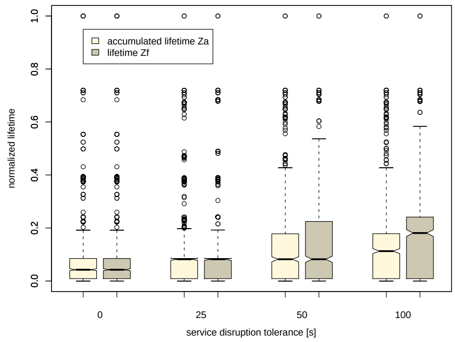


Fig. 4. Overall impact of service disruption tolerance

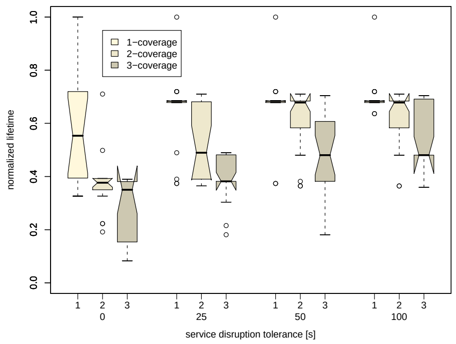


Fig. 5. Target coverage depending on service disruption tolerance and $k$-coverage

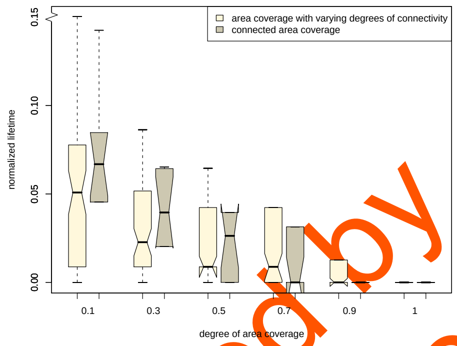


Fig. 6. Connectivity and area coverage vs. connected area coverage



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 depends strongly on the particular setup of a sensor network and should not be generalized from this figure.

Figure 5 shows how service disruption tolerance and $k$-coverage influence the lifetime achievable if target coverage is the only criterion. The exact amount of target coverage required is varied between 0 and 1 inside each of the box plots. If the targets are required to be covered by more than one sensor, the lifetime of the network decreases significantly, in some cases by more than 20% of the maximum achievable lifetime. On the other hand, allowing for some amount of service disruption can increase the network lifetime by approximately the same amount. As an example, compare the lifetime for 2-covered targets without service disruption tolerance with the lifetime for 3-covered targets with 25 seconds of service disruption tolerance. The medians of both lifetimes are nearly equal, demonstrating that a tolerance towards service disruptions can compensate higher requirements in other parts of the system to some extent.

### *E. 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 if 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.

Figure 6 shows the network lifetime depending on varying degrees of area coverage. The light boxes represent all cases where there were requirements on the connectivity next to the coverage requirement, whereas the dark boxes represent the

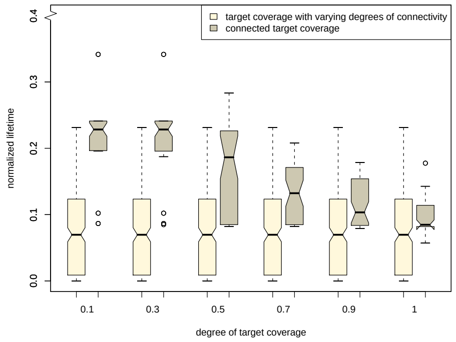


Fig. 7. Connectivity and target coverage vs. connected target coverage

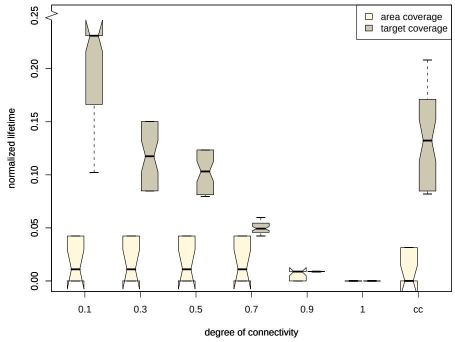


Fig. 8. Connectivity and coverage vs. connected coverage at coverage = 0.7

cases with the connected area coverage requirement. The connectivity required for the light boxes was varied between 0 and 1 for each box. Figure 7 shows the same plot for target coverage instead of area coverage. Figure 8 shows the network lifetime depending on connectivity with the coverage requirements for area coverage (light boxes) and target coverage (dark boxes) fixed at 0.7. The two rightmost boxes show the lifetime achieved with connected coverage fixed at 0.7.

The combination of target coverage and connectivity does not depend on the required level of target coverage, as figure 7 illustrates. This means that connectivity is always a stronger requirement than target coverage. For area coverage, figure 8 demonstrates that the combination of area coverage and connectivity does only depend on connectivity for very large values of area coverage. Therefore, area coverage is in most cases a stronger requirement than connectivity. These observations are probably only valid for the sample setup and not in general. However, they lead to the assumption that in many networks, one of the criteria is a stronger requirement than the other, so that the lifetime only depends on either coverage or connectivity. The connected coverage criteria do not show these dependencies. Therefore, they produce more accurate estimates of network lifetime.

As seen in figures 6-8, 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.



## VII. Conclusion

Motivated by the emergence of network lifetime as the key characteristic of sensor networks that covers typical properties of these networks such as node availability, sensor coverage, and connectivity as well as more sophisticated quality of service properties, several papers have been written that propose algorithms to increase the network lifetime in specific scenarios. We surveyed lifetime definitions in the literature, outlined advantages and drawbacks, 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 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 based on a comparison with the related work as well as using a simple example scenario.

Currently, the definition allows to recognize a network either as lively or non-functional and the lifetime is calculated accordingly. If the need for graceful degradation in the context of fault tolerant systems arises [79], [80], the lifetime definition can be enhanced to support this as well by modifying the single verification parameters to reflect ranges instead of hard limits [81].

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