# Hex-MASCLE – Hexagon based Clustering with Self Healing Abilities

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***Abstract*— In large wireless sensor networks, low energy consumption is a major challenge. Hence, deployed nodes have to organize themselves as energy efficient as possible to avoid unnecessary sensor and transceiver operations. The energy conserving operations are limited by the task of the network, usually the network has to guarantee complete functionality during its lifetime.**

**The contribution of this paper completes the functionality-aware and energy-efficient clustering algorithm family MASCLE by two innovative algorithms. As already given by the MASCLE-algorithms, the proposed Hex-MASCLE algorithms combine advantages of temporal and spatial network fragmentation. In contrast to previous approaches, the shapes of the basic cells are given by regular hexagons, similar to honeycombs. In the present work, two possible versions for hexagon-based clustering with self-healing abilities are proposed and evaluated.**

**As result, the applying sensor network achieve a significant improve of network lifetime. Additionally, the algorithms are more fault-tolerant against localization errors.**

***Keywords-Wireless sensor networks; clustering; self-healing;***

## I. INTRODUCTION

Recent developments of small wireless communication, sensor and computer systems make it feasible to construct tiny sensor nodes for environment observation. Thereby, each node is equipped with sensors, wireless communication, battery and microcontroller. In scenarios like forest fire detection or precision farming, hundreds of these randomly deployed simple sensor nodes emerges as a wireless sensor network (WSN), which provides much more powerful phenomena detection ability than some complex single sensor systems could do.

However, a major requirement for sensor nodes is their independence from the observed environment. Hence, the energy resources for phenomena detection, computation and transmission are limited, and a node 'dies' after its resources are exhausted. In order to achieve the maximum possible network lifetime, the whole network has to act as energy-efficient as possible. Current researches increase the network lifetime by different node-based approaches, like energy efficient routing [1] or load balanced communication [2]. Another energy-aware WSN organization strategy is investigated in [3] and [4] with the cluster-based redundancy exploiting MASCLE (Mutual Assistance in a Cluster Environment) approach.

In this paper, we extend the idea of MASCLE by utilizing a new cell shape, a regular hexagon, to achieve the MASCLE capabilities and to outperform the preceding algorithms. As a result, we are able to present two approaches (Hex-MASCLE$^3$ and Hex-MASCLE$^4$) which differ in the number of phases and deactivated cells and cell size. Both algorithms reduces the number of required active nodes compared to 2-MASCLE or even 4-MASCLE. Similar to the fine grained assistance in 4-MASCLE, we are able to implement an assistance algorithm, which enables a self-healing of failed cells and leads to a further lifetime extension.

The remainder of the paper is organized as follows: Section II describes related work, Section III briefly introduces the preceding MASCLE-algorithms, Section IV presents our new clustering approaches. Section V investigates the new abilities of neighborhood assistance. Section VI compares characteristic parameters of Hex-MASCLE and former algorithms by simulations. The paper concludes in Section VII.

## II. RELATED WORK

A major challenge in outdoor scenarios of WSNs is the power consumption for communication combined with the limited energy of nodes. Hence, a goal in ongoing research is the increase of total lifetime of a network by a temporary deactivation of subsets of nodes. The challenge is to figure out the minimum number of required nodes for complete network functionality, i.e. complete sensor coverage of the environment to observe and multi-hop connectivity between all active nodes.

With clustering and covering, there actually exist two different basic strategies which allow a deactivation of nodes not required for a network with full functionality.

### *A. Clustering*

Mechanisms, which divide the network into groups of nodes which are closely located to each other are called clustering algorithms. Within each cluster, a clusterhead is

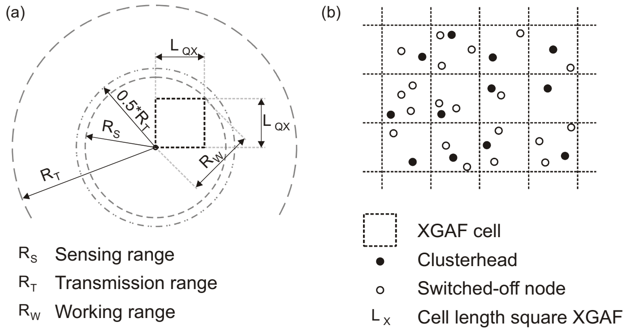

Figure 1. Square XGAF algorithm (a) Estimation of the maximum cell size (b) Application to a sensor network

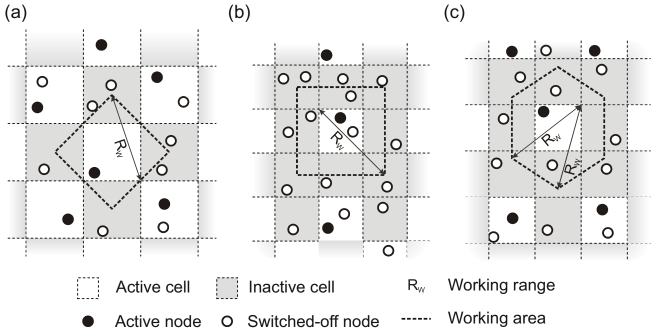

Figure 2. Applied MASCLE-algorithms (a) 2-MASCLE (b) Symmetric 4-MASCLE (c) Asymmetric 4-MASCLE

selected to takes the leading functions and may cause the remaining cluster-nodes to sleep. The amount of energy conservation depends on an efficient selection of clusterheads. On the one hand, it must be guaranteed that complete sensor coverage and radio connectivity is available in the network, on the other hand as few nodes as possible should be active to achieve this goal. The calculation of efficient clusters and clusterhead can be done range-based, probability based or position based [3-9]. Approaches which may ensure a full coverage are the versions of XGAF (Extended Geographical Adaptive Fidelity) [5], which clusters a WSN into a regular grid based on the position of each node. Not only the transmission range but also the sensing range of the nodes are used for calculating the geographical cluster size. In contrast to other clustering approaches like GAF (Geographical Adaptive Fidelity) [6] and (E)HGAF (Enhanced Hierarchical GAF) [7], it is guaranteed that each cluster member is able to sense the whole cluster and does not only serve as router between adjacent clusters. Based on this ability the maximum cell size depends on the maximum transmission and sensing range and is calculated in (1).

$$R_W = \min\,(R_S; R_T/2) \tag{1}$$

Here, $R_T$ is the transmission range, $R_S$ the sensing range and $R_W$ the working range, which denotes the maximum dimension of a cell. The estimation of the maximum cell size is shown in Figure 1(a), the application of XGAF to a WSN is depicted in Figure 1(b).

### B. Covering

As opposed to clustering algorithms, not a geographical but a temporal fragmentation of the network is done via covering strategies. The idea of covering is to split the networks into various numbers of groups, called covers. In contrast to clustering, each cover should contain nodes from all over the sensor-field. The aim is that each group is able to observe the entire environment without any holes. In addition, each node in a cover should be able to transmit its sensed information to the sink or to each other node of the cover, depending on the used routing algorithm and the purpose of the network. If the network is divided in covers which achieve this aim, only one cover has to be active at any point of time. In average, this deactivation if all covers beside one allows an reduction of *(n-1)/n* active nodes in the network, where *n* is the number of covers. In this case, the WSN would work in *n* phases with exactly one active cover in each phase. The phases are repeated periodically. Due to the deactivation, covering is able to increase its lifetime nearly by factor *n* compared to a network without applied covering algorithm. In [10], a probability-based covering algorithm is proposed. In this algorithm each node decides independently, which cover it belongs to by comparing a random number between 1 and *n* with the number of the actual active cover. The only requirements for each node are knowledge about the number of covers *n*, an existing random number generator, and synchronized clocks. The described algorithm is quite simple and is able to work without additional communication between any nodes but it has one crucial handicap. There is no guarantee that each group or at least one group covers the entire network. Hence, some parts of the environment may be left unobserved for a long period. Nevertheless, each observable part of the environment is observed at least one time during a full cycle of all phases. It is shown in [10, 11] that the algorithm in general performs well and is also able to deal with not exactly synchronized clocks. To achieve a uniform dispersal of the nodes onto all covers and hence to sensor coverage ability of each phase, several algorithms are introduced in [10, 11]. Although the high amount of communication limits the performance of these algorithms, the fundamental problem of covering is given by randomly deployed nodes. If the nodes are non-uniformly distributed, thin populated regions arise. This phenomenon forces the network to either reduce the number of covers *n* and build covers which are all capable of covering the entire environment, or accepting that some regions of the observed environment are only covered by a subset of covers. As an additional drawback, all of these algorithms only base upon the transmission range and do not take the sensing range into account. In the given references it is assumed that transmission and sensing range are equal.

## III. MASCLE-Algorithms

This Section briefly presents the already developed MASCLE-algorithms and their basic abilities.

### A. 2-MASCLE

The basic approach, which combines temporal and spatial network fragmentation and aspires to complete network funcionality, is 2-MASCLE [3]. Similar to XGAF, the nodes are clustered by a regular grid but with 20% smaller cell size. This reduction guarantees that any node of a cell is able to communicate with orthogonal neighbors in 2-cell distance. Additionally, it guarantees a sensor coverage of one quarter of each orthogonal adjacent cell. The area, each node of a cell is able to cover with its sensor, is called working area *AW*. In

TABLE 1
Algorithm Properties

| Algorithm | Max. Cell Area $R_S \leq R_T/2$ | Working Area | Phases $N$ |
| --- | --- | --- | --- |
| Square XGAF | $AC_{SX} = 0.5R_W^2$ | $AW_{SX} = 0.5R_W^2$ | 1 |
| Hexagon XGAF | $AC_{HX} = 0.65R_W^2$ | $AW_{HX} = 0.65R_W^2$ | 1 |
| 2-MASCLE | $AC_{2M} = 0.4R_W^2$ | $AW_{2M} = 0.8R_W^2$ | 2 |
| Symmetric 4-MASCLE | $AC_{4MS} = 0.22R_W^2$ | $AW_{4MS} = 0.89R_W^2$ | 4 |
| Asymmetric 4-MASCLE | $AC_{4MA} = 0.28R_W^2$ | $AW_{4MA} = 1.11R_W^2$ | 4 |
| Hex-MASLCE[3] | $AC_{HM3} = 0.37R_W^2$ | $AW_{HM3} = 1.11R_W^2$ | 3 |
| Hex-MASCLE[4] | $AC_{HM4} = 0.29R_W^2$ | $AW_{HX} = 1.15R_W^2$ | 4 |

2-MASCLE, the chosen working area allows that 4 orthogonal adjacent cells of a 2-MASCLE cell cover its middle cell with any of their nodes in collaboration. This leads to the ability of temporal cluster fragmentation into two groups in a checkerboard pattern. Hence, half of cells belongs to the first group and the other half belongs to the second group. 2-MASCLE applied to a sensor network and the resulting working area $AW_{2M}$ are depicted in Figure 2(a), the maximum cell size is given in TABLE 1.

### B. 4-MASCLE

An enhanced clustering algorithm which combines spatial and temporal network fragmentation is 4-MASCLE. Here, the size of the square cells is chosen in the way that only one of four cells has to be active to guarantee full network functionality. The two evaluated versions, symmetric and asymmetric 4-MASCLE, differs in the arrangement of active cell. This leads to a different cell size and different size and shape of the resulting working area. The algorithms are depicted in Figure 2(b) and Figure 2(c), the maximum cell size is given in TABLE 1.

### C. Phase change

As depicted in Figure 2, only a part of the network is required to be active. All other cells are allowed to switch into a sleep mode, and even clusterheads of sleeping cells are allowed to sleep. In fact, the sleeping cells consumes nearly no energy compared to active cells. Here, at least the clusterheads have to be online permanently to sense their environment and enable a fast message routing from phenomenon acquiring nodes to the sink. Inside a cell, the clusterhead can be exchanged with a simple role change algorithm to achieve an energy balance between the nodes of a cell.

To balance the energy consumption between all available cells, a phase change algorithm is implemented in each MASCLE-algorithm. In fact, each possible active group assigns itself to a number. In 2-MASCLE, one group assign itself to the number *0* and the other one to number *1*. In 4-MASCLE, the numbers *0*, *1*, *2* and *3* are allocated to the cells. With knowledge about the *X*- and *Y*-distance from a reference point and the applied cell size, each cell is able to estimate the group it belongs to by simple modulo operations.

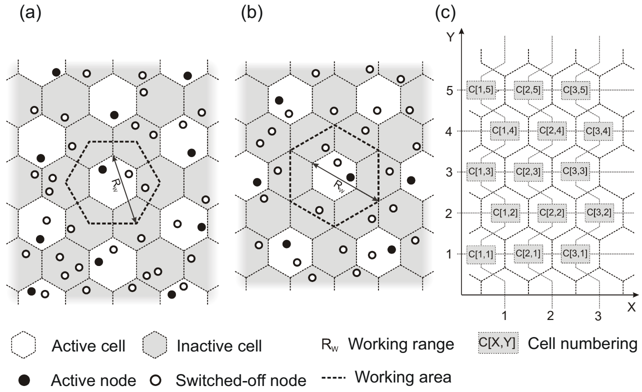


Figure 3. Hexagon MASCLE algorithm (a) Version with 3 phases (b) Version with 4 phases (c) Cell numbering

To apply the phase change, the overall time is divided into phases, each with duration *T*. During each point in time *t*, a clusterhead of each cell is able to check the actual phase $P_{act}$ by applying equation (2).

$$P_{act} = mod\ (\lfloor t/T \rfloor; N) \tag{2}$$

The number of phases *N* depends on the actual algorithm and is given in TABLE 1 for each presented algorithm.

### D. Assistance mechanisms

Due to the fact, that the working areas of MASCLE cells overlap each other, it is imaginable to replace a cell with a couple of neighbors without losing network functionality. This possibility is utilized by MASCLE with its assistance mechanisms – a failed or empty cell is covered by a number of required neighbor cells. The examination whether a cell is failed and which are the most efficient assistance strategies is done during each phase change. More details are given in [3] and [4].

## IV. HEXAGON-MASCLE

As shown in [5], hexagon XGAF achieves mostly better network characteristics than square XGAF. This inspired us to develop a MASCLE approach based on hexagonal cells, arranged as done in honeycombs or cellular networks. In this paper, two versions of Hex-MASCLE have been investigated, which differ in the arrangement of active cells. Hence, a difference in cell size, size of the working area and number of phases is required. Both versions are explained in the following.

### A. 3-Phase Hexagon-MASCLE

The first version, called Hex-MASCLE[3], was developed to apply a 3-phase based cell scheduling system. To achieve such a clustering, the working area of each cell must be able to cover the area of overall 3 cells. The maximum resulting cell size is achieved, if the arrangement of active and sleeping cells is repeated every second cell row. In each first row, every third cell is activated, while the other ones remain in a sleep mode. In each second row, also only every third cell is switched on, but shifted by 1.5 cells compared to each first row. The resulting arrangement and the resulting working area is shown in Figure 3(a), the resulting cell size is given in TABLE 1. To estimate the according phase, the cells are numbered as applied

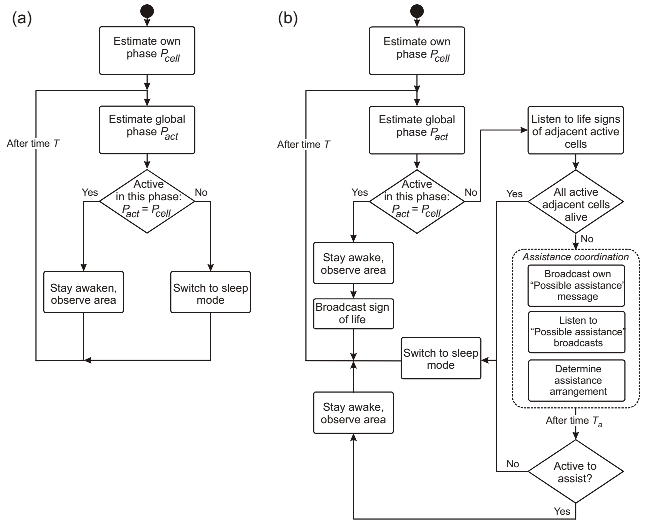


Figure 4. Hexagon-MASCLE scheduling algorithm (a) without neighborhood assistance (b) with neighborhood assistance

in Figure 3(c). With this numbering, each node of each cell is able to calculate its own phase $P_{cell}$ with equation (3).

$$P_{cell} = mod\ (C[X] + mod(C[Y]; 2); 3) \quad (3)$$

## B. 4-Phase Hexagon-MASCLE

A second possible solution for a self-assisting cell structure is to apply a 4-phase based cell scheduling. This version is abbreviated with Hex-MASCLE$^4$. The maximum resulting cell size is achieved, if each fourth cell row behave identical. In each first row, every second cell is active, while the other ones remain in a sleep mode. Each second row is completely switched off. In each third row, every second row is switched on, but compared to each first row, the active cells are shifted by 1 cell. Each fourth row is completely deactivated. The resulting arrangement and the resulting working area is shown in Figure 3(b), the resulting cell size is given in TABLE 1. To estimate the according phase, the cells are numbered as given in Figure 3(c). With this numbering, each node of each cell is able to calculate its own phase $P_{cell}$ with equation (4).

$$P_{cell} = \mathrm{mod}\left(C[X] + \left\lfloor\frac{C[Y]}{2}\right\rfloor; 2\right) * 2 + mod(C[Y]; 2) \quad (4)$$

## C. Algorithm workflow

Just as done in previous MASCLE algorithms, only one node of each cell (the clusterhead) of the actual phase have to be active during each point in time. Due to the restricted cell size, it is not important where the active node is located. In each cell, a simple role changing protocol can decide which node is assigned to the clusterhead. The flow chart of the algorithm from a cell's point of view is given in Figure 4(a).

# V. NEIGHBORHOOD ASSISTANCE

Due to the fact that each populated cell guarantees a coverage of parts of adjacent cells and their working areas, assistance mechanisms can be applied to heal a failed or unpopulated cell. To achieve such self-healing behavior, we modified our cell scheduling algorithm as shown in Figure 4(b). After each period $T$, a cell is not allowed to switch to or remain in sleep mode without receiving an "alive" message of all adjacent cells, which have to be active in the successive phase. If all necessary "alive" messages were received, the cell is allowed to switch to sleep mode for the duration of the next period $T$. If the "alive" message of a normally active cell is not received, this cell is declared as failed cell. To maintain complete sensor coverage, the adjacent cells of the failed cell have to recognize whether they are required to assist the failed cell.

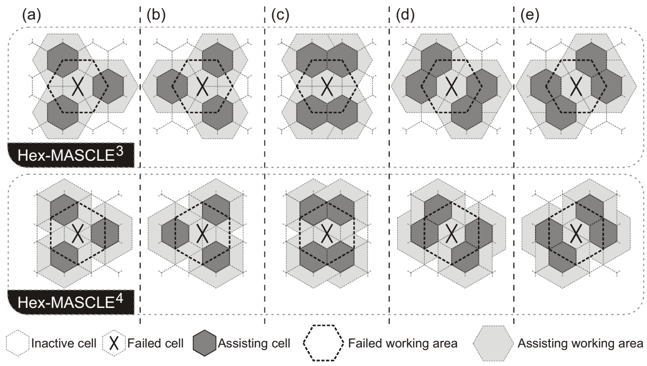


Figure 5. Assistance in Hexagon-MASCLE (a-b) with 3 adjacent cells, (c-e) with 4 adjacent cells. From left to right: Preferred assistance arrangements

It has to be considered, that not only the cell area, but the whole working area of the failed cell has to be assisted to guarantee unlimited network functionality in the following period. The simplest solution for healing a failed cell is the activation of all 6 adjacent cells. However, this activation implies additional energy consumption of the surrounding cells. Certainly, a complete assistance with fewer cells leads to fewer active cells and therefore an increased network lifetime. Therefore, our developed assistance algorithms aspire to assist with as few cells as possible. Due to the given cell size, and size and shape of the working areas, the possible assistance strategies with direct neighbors are identical for Hex-MASCLE$^3$ and Hex-MASCLE$^4$. Although Hex-MASCLE$^4$ provides assistance possibilities with more distant neighbors, we focused on assistance via direct neighbors to keep the algorithm simple and avoid multi-hop message exchange between assisting cells.

As shown in Figure 5(a-b), Hex-MASCLE provides 2 assistance arrangements by activating 3 adjacent cells and 3 assistance arrangements by activating 4 adjacent cells, as shown in Figure 5(c-e). All other activations of adjacent cells would either be not sufficient to cover the failed working area or contain redundant activated cells. To select one of the available assistance arrangements, all populated cells around the failed cell broadcast a "possible assistance" message during the period $T_a$ ($T_a << T$) of the assistance coordination. The chosen cell size of Hex-MASCLE guarantees a mutual listening of all possible assisting cells. Hence, each possible assistant cell recognizes which adjacent cells of the failed one are available and is able to determine the remaining possible assistance arrangements. Therefore, each cell can decide autonomously whether it is required to assist the failed cell by selecting the most efficient possible assistance arrangement. The 'efficiency' of the assistance arrangements is given by the

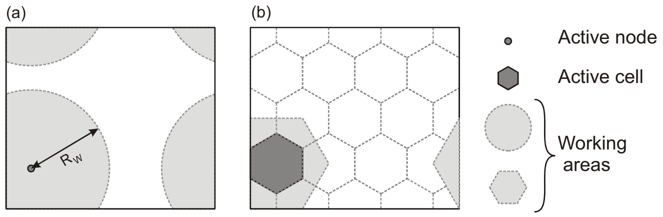


Figure 6. Simulation area without edge effects. Working area of (a) a single sensor node, (b) Hex-MASCLE[3]

order in Figure 5 and decreases from left to right. Hence, an arrangement with as less active cells as possible is preferred and selected. Indeed, arrangements with an equal number of active cells have the same efficiency, but we ordered them arbitrarily to give all nodes a preset for the arrangement selection. If no arrangement is available, all remaining adjacent cells stay awake to assist the cell, but without guaranteed network functionality.

## VI. Simulation and Results

To demonstrate the advantages of our presented approaches, we compare Hex-MASCLE to XGAF, the covering-algorithms and the preceding MASCLE algorithms. To maintain statements about lifetime, number of necessary and active nodes, we utilize a self contained simulation area, which avoids the impact of edges, as shown in Figure 6.

The simulation parameters are given in TABLE 2. Although an area of 1000m*1000m does mostly not exactly fit to the cell sizes, all results are normalized to this simulation area. For example, number of deployed nodes always means number of deployed nodes inside the evaluated area.

Network functionality depends on sensor coverage and connectivity. While the connectivity of nodes is less critical than the coverage, i.e. nodes may find other neighbors to get connected to the network, we decide to set the sensing range $R_S$ as critical range for the working range $R_W$. Thus, the network functionality correlates with its coverage ability. Furthermore, we assume in our simulations that the amount of energy for intra cluster rotation, nodes in sleep mode, and the assistance coordination is negligible compared to the amount of energy a node consumes during the time it has to be active. For a further simplification, we assume that period $T$ is equal to the lifetime of an completely active node based on its battery charge, as required in tracking scenarios, for example. Additionally, in the case of the MASCLE algorithms, the phase $P_{act}$ changes after each period. With the given assumptions, we compared the algorithm with each other on terms of required nodes, network behavior during runtime and maximum lifetime of the sensor network.

TABLE 2
Simulation Environment

| Property | Value |
|---|---|
| Simulation tool | MATLAB® |
| Evaluated area | 1000m*1000m |
| Transmission range $R_T$ | 120m |
| Radio model | Unit disc |
| Sensing range $R_S$ | 56m |
| Simulated networks | 500 |
| Lifetime of a node | approx. 91h* |
| Deployed nodes for lifetime simulations | 10000/km$^2$ |

*Lifetime for an active Mica2 mote [12], idle listening mode and a typical battery charge of 5200mAh

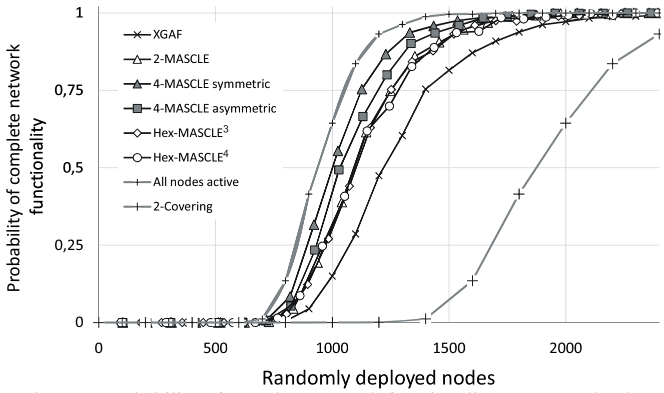


Figure 7. Probability of complete network functionality versus randomly deployed nodes

### A. Required nodes

The first simulation investigates the minimum number of required nodes to achieve complete network functionality. To achieve this, various networks with different numbers of deployed nodes were investigated and the number of networks with complete sensor coverage during the first phase were counted. The result is given in Figure 7. As apparent, both Hex-MASCLE versions are not able to perform as good as symmetric 4-MASCLE. Reasons are the smaller cell size and the resulting high number of assistance arrangements of symmetric 4-MASCLE cells – Symmetric 4-MASCLE offers more than twice the arrangements as Hex-MASCLE does. However, both Hex-MASCLE versions are able to compete with 2-MASCLE and outperform XGAF in this network characteristic.

### B. Runtime behavior

The second simulation investigates the number of active nodes over the time a network is alive and demonstrates the impact of the assistance algorithms to the network behavior. In Figure 8, it can been seen that the nodes with applied XGAF algorithm perform as traditionally expected: A certain part of the network is active and depletes until the next time step. In the next time step, another fraction of nodes is activated and depletes its energy. After round about 10 time steps, XGAF has more than 60% depleted nodes, and there already exist cells

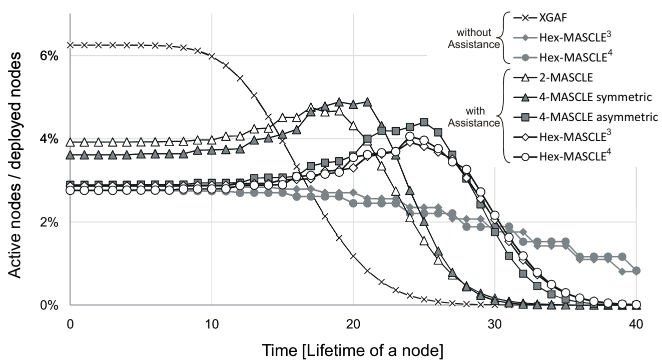


Figure 8. Active nodes versus runtime of the network

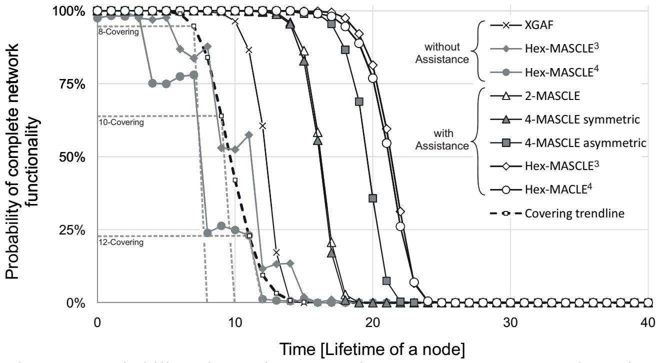

Figure 9. Probability of complete network coverage versus network runtime

which are not longer populated. Hence, the fraction of active cells becomes smaller until all nodes of the network are dead. Furthermore, it can been seen that both Hex-MASCLE versions without applied assistance perform similar to XGAF. The main difference is the ratio of active nodes at time step 0. Furthermore, in Hex-MASCLE$^3$ without assistance, the number of active nodes only changes significantly every third time step, which is reasoned by the allocation of nodes into three phases. Similarly, the change in the percentage of active nodes of Hex-MASCLE$^4$ is only performed every fourth step.

The MASCLE-algorithms with assistance behave completely different. Instead of continuous decrease of active nodes, the number of active nodes even increases during runtime. In the occurrence of a failed cell, each MASCLE algorithm tries to heal the cell by activating additional cells. Of course, this additional activation increases the energy exhaustion of adjacent cells. Finally, the assistance leads to a faster node wastage and therefore a fast decrease of active nodes after a maximum of active nodes is achieved. However, the assistance ability has direct impact to the most important network characteristic, the lifetime.

### *C. Lifetime*

In contrast to earlier WSN-clustering and routing algorithms, we assume a 'living' network not as a network with a certain number of remaining nodes, which is often applied to compare networks. In most WSN-application it is unimportant how many nodes are left, but it is absolutely important that complete network functionality can be achieved, that means that phenomena everywhere in the network can be detected and furthermore each acquiring node is able to reach the sink at any time. From this point of view, a network lives until the first coverage hole emerges in the network.

A simulation of this network characteristic is displayed in Figure 9. It can been seen that square XGAF as an representative for an clustering algorithm without assistance performs worst and similar to the random based covering algorithms. Furthermore, one can see that both versions of Hex-MASCLE with assistance are able to outperform the already developed MASCLE algorithms by at least 10% in terms of lifetime. Interestingly, Hex-MASCLE$^4$ is not able to outperform Hex-MASCLE$^3$, which is reasoned in the similarity of both algorithm and the identical assistance arrangements. Although both Hex-MASCLE algorithms perform similar in terms of lifetime, in reality Hex-MASCLE$^3$ would be preferred due to the larger cell size, which correlates with a higher tolerance to inaccurate localization.

## VII. Conclusion and Outlook

In the proposed work we introduced two extensions of a cell based clustering approach on the basis of regular hexagons. Like the predecessors 2-MASCLE and 4-MASCLE, both Hex-MASCLE versions utilize the idea of temporary deactivation of nodes on the cluster level. The inter cluster rotation of our approaches are described as a three phase cycle (Hex-MASCLE$^3$) or four phase cycle (Hex-MASCLE$^4$). The intra cluster rotation, however, is left open and may be realized by any common scheduling algorithm. Similar to the preceding MASCLE algorithms, we introduced self healing algorithms as an aspect of our clustering strategy. As shown in section VI, the modified cell shapes as well as the implemented assistance algorithm lead to fewer active nodes and a longer network lifetime than the predecessors.

Although we investigated the most important resulting WSN characteristics, several points have been left open, which will be investigated in future work. An essential question will be to evaluate the networks behavior in case of imprecise localization, which represents the conditions in practice.

## References


[1] X. Hong, M. Gerla, H. Wang; "Load Balanced, Energy-Aware Communications for Mars Sensor Networks", Proceedings of Aerospace Conference, 2002

[2] M. Ma, Y. Yang; "Adaptive Triangluar Deployment Algorithm for Unattended Mobile Sensor Networks", IEEE Transactions on Computers, Vol.56, No.7, July 2007

[3] J. Salzmann, R. Behnke, D. Lieckfeldt, D. Timmermann; "2-MASCLE – A Coverage Aware Clustering Algorithm with Self Healing Abilities", Proceedings of Intelligent Sensors, Sensor Networks and Information Processing, ISSNIP, Melbourne, Australia, 2007

[4] J. Salzmann, R. Behnke, M. Gag, D. Timmermann, "4-MASCLE – Improved Coverage Aware Clustering with Self Healing Abilities", International Symposium on Multidisciplinary Autonomous Networks and Systems, Brisbane, Australia, 2009

[5] J. Salzmann, R. Behnke, D. Timmermann, „Tesselating Cell Shapes for Geographical Clustering", 10th IEEE International Conference on Computer and Information Technology (CIT 2010), pp. 2891-2896, ISBN: 978-0-7695-4108-2, Bradford, United Kingdom, June 2010

[6] Y. Xu, J. Heidemann, D. Estrin; "Geography-informed Energy Conservation for Ad Hoc Routing", In Proc. 7th Ann. Intl. Conf. on Mobile Computing and Networking, Rome, Italy, 2001

[7] T. Inagaki, S. Ishihara; "A Scheme for Expanding Grid Size of Geographical Adaptive Fidelity", Fourth International Conference on Networked Sensing Systems; Braunschweig, Germany, 2007

[8] M. Liu, J. Cao, G. Chen, X. Wang; „An Energy-Aware Routing Protocol in Wireless Sensor Networks", MDPI Sensors 2009, 9, 445-462

[9] J. Salzmann, R. Behnke, J. You, D. Timmermann,"Free-CLASH – Improved Localization Free Clustering in Large Wireless Sensor Networks", The International Workshop on Scalable Ad Hoc and Sensor Networks, St. Petersburg, Russia, 2009

[10] Z. Abrams, A. Goel, S. Plotkin, "Set k-cover Algorithms for Energy Efficient Monitoring in Wireless Sensor Networks, "Proceedings of Information Processing in Sensor Networks 2004, Berkeley, USA, 2004

[11] C. Liu, K.Wu, V.King; "Randomized Coverage-Preserving Scheduling for Wireless Sensor Networks" , 4th International Networking Conference, Waterloo, Canada, 2005

[12] "MPR-MIB Users Manual," 2004, Available: http://www.xbow.com