Self-Organization in Ad Hoc Networks: Overview and Classification

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Abstract

Self-organization is a great concept for building scalable systems consisting of huge numbers of subsystems. The primary objectives are coordination and collaboration on a global goal. Until now, many self-organization methods have been developed for communication networks in general and ad hoc networks in particular. Nevertheless, the term self-organization is still often misunderstood or misused. This paper contributes to the ad hoc community by providing a better understanding of self-organization in ad hoc networks. Primarily, solutions for the medium access contol and the network layer are analyzed and discussed. The main contribution of this paper is a categorization of self-organization methodologies. Additionally, well-known methods in ad hoc networks are classified and some case studies are provided.

Index Terms

self-organization, ad hoc network, wireless sensor network, ad hoc routing, power-aware protocols, network layer, medium access control, clustering, bio-inspired networking

I. Introduction

Self-organization mechanisms can be found in every stretch of our every-day life [1]. From an academic point of view, self-organization was first analyzed in biological systems [2]. This research was soon extended to technical systems and engineering in general [3]. Self-organization can be summarized as the interaction of multiple components on a common global objective [4]. This collaborative work is done without central or decentral control. Instead, the interaction is done using a local context, e.g. the direct environment, that can be changed and adapted by each individual and, therefore, affects the behavior of other individuals. The primary objectives of self-organization are scalability, reliability, and availability of systems composed of a huge number of subsystems.

In computer networks, self-organization is especially important in ad hoc networking because of the spontaneous interaction of multiple heterogeneous components over wireless radio connections [5] without human interaction. This is especially the case in the areas of pervasive and ubiquitous computing. Eventually, self-organization is the only possible solution for many issues in this area but it definitely is not the universal remedy.

In this paper, we concentrate on self-organization mechanisms in general and corresponding methods available for ad hoc communication in particular. The contributions of this paper may be summarized as follows. The term self-organization is clarified focusing on ad hoc networks and the corresponding networking methodologies. Additionally, a categorization and classification scheme is provided that allows to distinguish different types of self-organization mechanisms and their applicability. In this context, existing self-organizing methods are analyzed and classified. Finally, several examples and case studies are provided to allow a better understanding of self-organization in ad hoc networks.

The remainder of the paper is organized as follows: in section II, the term self-organization is discussed as well as related concepts. Additionally, the main properties and their relationship to self-organization are depicted. In section III, a classification of different methodologies for self-organization in ad hoc networks is presented. It turned out that multiple dimensions need to be regarded. Several examples and case studies are provided in section IV. Issues solved by self-organization mechanisms as well as still open questions are discussed in section V. Finally, section VI concludes the paper.

II. Self-Organization in Ad Hoc Networks

A. Understanding Self-Organization

The main purpose of this section is to provide adequate definitions for self-organization and related terms in the context of ad hoc networks. Additionally, the term self-organization should be distinguished from manual or external control as well as from distributed systems that are based on global state information. Often, the term self-organization is used in conjunction with other so called *Self-X capabilities*:

- Self-healing - mechanisms that allow to detect, localize, and repair failures automatically; primarily distinguished by the cause of the failure, e.g. breakdown, overload, malfunction

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- Self-configuration - methods for (re-)generating adequate configurations depending on the current situation in terms of environmental circumstances, e.g. connectivity, quality of service parameters
- Self-management - capability to maintain devices or networks depending on the current parameters of the system
- Self-optimization - similar to self-management but focuses on the optimal choice of methods and their parameters based on the system behavior
- Adaptation - adaptation to changing environmental conditions, e.g. the changing number of neighboring nodes

All these terms can be summarized in *self-organization* for which we provide a proper definition adapted to the area of ad hoc networks in the following.

1) History and Overview: Self-organization is not an invention nor it was developed by an engineer. The principles of self-organization have been evolved in nature and we finally managed to study and apply these ideas to technical systems. First articles about self-organization date back in the early 1960ies. Ashby and von Foerster [1], [4] analyzed self-organizing mechanisms. Eigen [3] finally made the term self-organization popular in natural and engineering sciences.

Meanwhile, different strategies to control networked computers and devices have been developed. Starting with monolithic, centralized controlled systems, the demand for higher scalability and simplified deployment strategies was growing. The research domain of distributed systems is working on such solutions. Novel approaches lead to control and collaboration paradigms that show the same behavior as described for self-organizing systems [6]. In the area of ad hoc networks, multiple, possibly different solutions have been elaborated. A categorization and classification of these methods is provided in the next section. The common objective is to reduce global state information by achieving the needed effects based on local information or probabilistic approaches only. Most of these solutions are using (whether explicitly or implicitly) methodologies similar to biological systems. Even if the area of bio-inspired networking is a novel research domain, first summaries and overviews to such approaches are available [2], [7], [8].

2) Definitions: There are two main terms that will characterize and form the shape all self-organizing methodologies for ad hoc networks: *self-organization* and *emergence*. Unfortunately, there are no single, commonly agreed definitions for these terms available. Therefore, we will elaborate our own definitions that - in case of self-organization - will also lead to some classification of the different meanings of self-organization.

Definition 1 (Self-Organization): Self-organization is a process in which pattern at the global level of a system emerges solely from numerous interactions among the lower-level components of a system. Moreover, the rules specifying interactions among the systems' components are executed using only local information, without reference to the global pattern.

This definition of self-organization focuses on the emergence of patterns. Similar definitions can be found in the literature concerning well-studied methodologies in biological systems [2], [4]. The interaction of single components finally defines the behavior of the global system. Applied to ad hoc networks, self-organization can be seen as the interactions between nodes in the network leading to globally visible effects, e.g. the transport of messages from a source node to a sink node. Since we speak of the emergence of a pattern or a system behavior, the term emergence needs to be defined as well.

Definition 2 (Emergence): Emergent behavior of a system is provided by the apparently meaningful collaboration of components (individuals) in order to show capabilities of the overall system (far) beyond the capabilities of the single components.

Self-organization is often referred to as the multitude of algorithms and methods that organize the global behavior of a system based on inter-system communication. Most networking algorithms work like that. Therefore, self-organization in this context is not a new solution in this research area. Nevertheless, most of these algorithms are based on global state information, e.g. routing tables. In the networking community, it is commonly agreed that such global state is the primary source of scalability problems of the particular algorithms. Especially in the area of ad hoc networks, new solutions were discovered that show the properties of the new definition of self-organization. Most ad hoc routing algorithms as well as data centric data dissemination approaches are well-known examples [9].

B. Properties of Ad Hoc Networks

Ad hoc networks have become a major research domain during the last decade [5]. This trend is mainly forced by recent advances in microelectronics and wireless communications. Engineers have been enabled to develop a new generation of communication devices. Depending on the application scenario, different requirements have to be considered (see below).

All these applications have some common properties: the interconnected devices have to form a network in an ad hoc manner, i.e. spontaneously, have to maintain the network state and coordinate the information exchange. In some scenarios, the overall goal is pre-deployed in all single devices while others are mainly user-driven. The grade of interactivity greatly influences the possible solutions for controlling, i.e. organizing the network:

- No interactivity - the overall goal is provided either in form of a precise description or in terms of a desired behavior
- Little interactivity - the system can be (partially) controlled through user interactions
- High interactivity - there is no pre-defined goal, the system behavior depends on regular user interactions

All typical applications for ad hoc networks have high energy constraints in common [10], [11] whereas other resources must be specifically analyzed. In this paper, we consider the following three primary categories of ad hoc networks: wireless sensor networks (WSN), wireless personal area networks (WPAN), and spontaneously networked users (SNU):

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- WSN - Wireless sensor networks consist of devices that are able to measure various physical measures and to exchange the results with other sensors or to transmit them to a base station [12]. Usually, such sensor nodes are tiny devices operated by a battery. A micro controller and a low-power radio provide processing and communications capabilities [13]. Application scenarios range from disaster control and first responders to habitat monitoring and building monitoring [14]. The primary distinction of these scenarios lies in the deployment strategy and the data handling [15].
- WPAN - Wireless personal area networks have been developed to enable the exchange of information of various devices that an user is carrying. Developers consider entertainment and fun applications as well as assistance for elderly people, e.g. by monitoring heart rate and others and communicating the results to a physician. In this category, very heterogeneous devices with different capabilities have to interoperate towards a central (possibly multiple) objective. The devices are equipped with small micro controllers but others employ high-speed CPUs (PDAs etc).
- SNU - Spontaneously networked users form ad hoc networks on demand for exchanging data, having multimedia communications, and using entertaining applications such as multiuser games. Usually, such groups are composed of devices with higher processing capabilities and high-bandwidth communication facilities such as laptop computers and PDAs. The used applications range from groupware and other collaborative tools to high-dynamic multi-user games.

Table I summarizes the different constraints of these applications.

Requirement	WSN	WPAN	SNU
energy	high	high	low
processing power	high	medium	low
storage	high	medium	low
surrounding conditions	high	low	low
mobility	limited*	low	high
heterogeneity	limited*	high	low
security	low	high	medium
varying user demands	none	medium	high
formation of groups	no	high	high

TABLE I

IMPORTANCE IN AD HOC APPLICATIONS (* DEPENDING ON THE SCENARIO)

C. Self-Organization in Ad Hoc Networks

Questioning the problem of achieving an overall goal (regardless of the grade of interactivity) can be reduced to the question how to control all nodes in the ad hoc network. There have been various software engineering approaches developed for this purpose, e.g. middleware architectures were designed to overcome the most pressing questions.

At the beginning, the communication in wireless networks was inspired by well-known approaches from wired standards such as the Internet. Later, issues such as mobility [16], [17], high dynamics in terms of new devices joining a network and other devices leaving, and rapid changes of the environment have been identified. Such problems made a distributed configuration necessary. This configuration should be decentralized and organized based on local feedback loops, thus it evolves autonomously [18], [19]. Such processes are also known as self-organization [6], [7].

The most prominent issues to be solved using self-organization methods in ad hoc networks are

- *Scalability* - how many interacting nodes are supported with at worst a linear increase in the resource requirements?
- *Reliability* - is the reliability of connections influenced by the methodology itself?
- *Availability* - is the ad hoc network always available or are there special maintenance periods?

Primarily, the methodologies try to mitigate the need for centralized control or even to abandon it. The listed objectives must be addressed keeping the already mentioned constraints in mind such as energy, processing power, storage, and mobility.

Figure 1 shows the evolution of system control from classical centralized control over distributed systems to pure self-organizing systems. In this context, we refer to centralized control in terms of external or manual coordination. Obviously, the scalability increases towards self-organized systems. More and more single devices can be put together to collaborate on a given (global) goal. One striking property of self-organization (corresponding to the provided definition) is the missing determinism of the algorithms. Each solution can be only evaluated by some quantiles.

We previously mentioned the major objectives for self-organization mechanisms in ad hoc networks: scalability, reliability, and availability. Besides these dominant targets, a number of further goals are addressed by particular solutions.

Mobility has a large impact on the behavior of ad hoc networks [17]. The convergence of employed mechanisms for routing and data dissemination must cover the changing topology [16], [20]. Optimization goals could be the *performance* or the *coverage*. Using non-deterministic methodologies to form an ad hoc network and to exchange data can have strong implications on the performance [21]. Similarly, the coverage must be improved while preventing any global state information at the same time [22], [23]. *Security* becomes even harder to achieve in self-organized systems mainly due to problematic key exchange and session handling [24], [25]. Cross-service solutions can lead to improved performance while providing

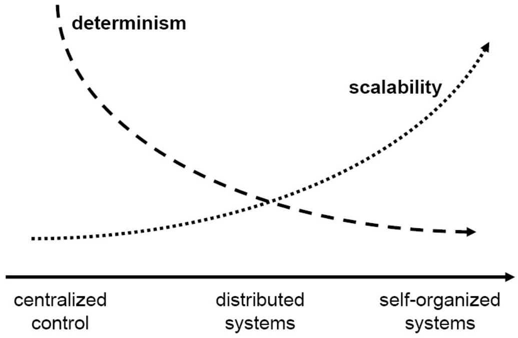

Fig. 1. Scalability vs. determinism in centralized controlled and self-organized systems

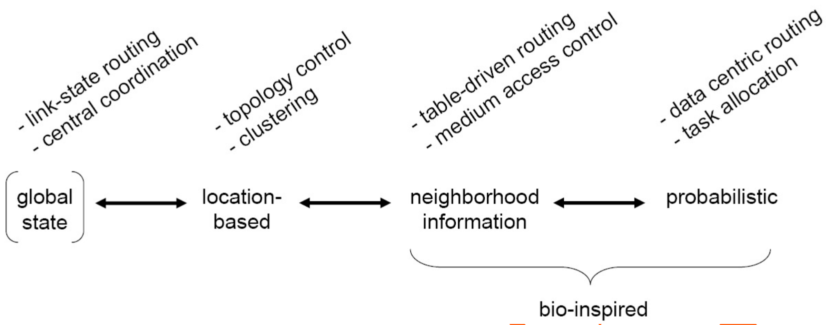

Fig. 2. Horizontal categorization of self-organization mechanisms in ad hoc networks

for example security services at the same time [26]. Finally, *coordination* between multiple devices must be organized [27]. For example, locality-based solutions have been considered [18], [28] as well as location-aware deployment and software management approaches [29], [30] and self-organized task allocation schemes [19].

In summary, self-organization in ad hoc networks is mostly addressed by either using local state information that is updated by feedback loops and neighborhood relationships, or probabilistic methods that are employed for taking the local decisions. Interestingly, biologically inspired approaches show many possible solutions that might influence the technical systems [31], [32].

III. Classification of Self-Organization Methods

Methodologies for self-organization in ad hoc networks can be categorized in multiple dimensions. In this section, we first provide a categorization of self-organization methods and secondly, try to classify some well-known mechanisms and ongoing developments. More detailed case studies are provided in the next section.

A. General Categorization

The categorization of self-organization methods in ad hoc networks opens a multidimensional space. In general, the methodologies can be grouped horizontally by their use of state information and vertically by their function in the protocol stack.

Figure 2 depicts the horizontal dimension. Reading the figure from the left, necessary state information to perform the particular algorithm is decreasing. As already mentioned, mechanisms in ad hoc networks try to avoid global state information in order to increase the scalability of the particular approach. The other categories are discussed in the following:

- *Location-based mechanisms* - Geographical positions or affiliation to a group of surrounding nodes, i.e. clustering mechanisms, are used to reduce necessary state information to perform routing decisions or synchronizations. Usually, similar methods as known for global state operations can be employed in this context. Depending on the size of active clusters or the complexity to perform localization methods, such location-based mechanisms vary in communication and processing overhead.
- *Neighborhood information* - Further state reduction can be achieved by decreasing the size of previously mentioned clusters to a one-hop diameter. In this case, only neighborhood information is available to perform necessary decisions. Usually, hello messages are exchanged in regular time periods. This keeps the neighborhood information up-to-date and allows the exchange of performance measures such as the current load of a system.
- *Probabilistic algorithms* - In some cases, it is useful to store no state information at all. For example, if messages are very infrequently exchanged or in case of high mobility, pure probabilistic methods can lead to optimal results. Statistical

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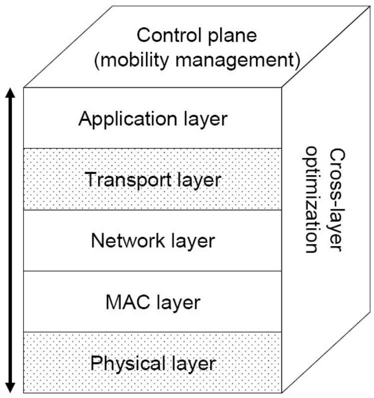

Fig. 3. Vertical categorization of self-organization mechanisms in ad hoc networks

measures can be used to describe the behavior of the overall system in terms of predicted load and performed operations. Obviously, no guarantee can be given that a desired goal will be reached.

- *Bio-inspired methods* - Biologically inspired methods build a category that is composed of neighborhood-depending and probabilistic operations. All objectives are addressed by using positive and negative feedback loops. Positive feedback acts as an amplifier intensifying a reaction. Overload situations or over-reactions are counteracted using negative feedback. Many applications in ad hoc networks have been evaluated and published.

While the required state is reduced towards the probabilistic methods, the determinism or predictability of the algorithms is reduced as well. Therefore, the best solution for a particular application scenario must be chosen carefully by comparing all application requirements at once.

In contrast, figure 3 shows the layered system architecture. Depending on the particular layer, there are different kinds of self-organization issues. A common control plane coordinates and controls mobility questions and some additional cross-layer or cross-service issues have to be considered. Such cross-layer issues are for example energy, security, end-to-end performance, and coverage. Based on the given application scenario, particular mechanisms from different layers might interact to achieve a common goal, e.g. to reduce the necessary amount of energy, but they might also interfere with one another, e.g. by defining different sleep cycles at different layers to reduce the energy consumption. In this paper, we concentrate on the following mechanisms in ad hoc networks:

- *MAC layer* - Medium access control manages the access to the radio link. The primary purpose is the message exchange between directly connected nodes. Contention-based mechanisms dominate this layer. Additionally, synchronization between neighboring nodes is used to optimize the link sharing. To optimize the energy consumption as well as the achieved performance, sleep cycles must be managed. Self-organization mechanisms are employed to perform this step without the need of central management and pre-configuration.
- *Network layer* - End-to-end forwarding of data packets is provided by the network layer. Two very different tasks must be solved at this layer: routing and data forwarding. While routing might involve a huge amount of global state information, forwarding mainly addresses performance optimization, error control, and congestion handling. Many approaches have been developed that perform both tasks in a self-organized manner.
- *Application layer* - Besides the contents of the networked application itself, many coordination tasks must be organized: Which node should act as a master, which nodes should perform which part of the global task, etc. Task allocation schemes have been studied in various kinds of ad hoc networks that are based on self-organizing multi-agent systems of pure probabilistic approaches.

For both, horizontal and vertical differentiation, available methodologies for self-organization are discussed and summarized in the following subsection.

B. Classification of Self-Organization Methods

In this section, methodologies developed for ad hoc networks are classified in terms of employed self-organization mechanisms as defined in the depicted classification scheme. We follow the horizontal classification and discuss the mechanisms in vertical order.

1) Global State: Using global state information, optimal solutions can be calculated. The most prominent examples are optimal routing paths in terms of hop-count, quality of service, or utilization. Others try to address global synchronization issues for congestion-aware transport protocols. The group of self-organizing algorithms that collect and maintain global state information is large. Technical engineering solutions dominate this area that has evolved together with the distributed systems research. Basically, all these methods distribute their local state to all others and update it periodically.

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In MAC protocols, the optimal scheduling of sleep cycles can be calculated using such distributed state information. For example, mechanisms for delay efficient sleep scheduling [33] and energy efficient real-time medium access control [10] have been developed. Nevertheless, the maintenance of the perfect synchronization induces eminent scalability problems [34].

Similar to most Internet routing protocols, pro-active routing mechanisms have been developed for ad hoc networks first. All these protocols are based on periodic state exchange and can be grouped into distance vector based algorithms, e.g. DSDV (Destination-Sequenced Distance-Vector Routing) [35], link-state mechanisms, e.g. OLSR (Optimized Link State Routing) [36], and hierarchical approaches, e.g. HSR (Hierarchical State Routing) [37]. Considering the behavior of these algorithms, they always allow to find an optimal path through the network while differing in the convergence speed and the necessary amount of maintenance overhead. In ad hoc networks with high mobility or unfrequent data transmissions, the state maintenance is clearly too expensive.

Central controlled task allocation schemes fall into the same category of global state algorithms. For example, the open agent architecture (OAA) [38] makes use of centrally stored (and periodically updated) state information from all available nodes in the network to perform decisions where to run which task.

2) Location-based Mechanisms: Regionalizing global optimization algorithms is a first approach to improve the operation in ad hoc networks [39]. The explicit calculation of a route towards a destination can be prevented if the positions of the source, the neighboring nodes, and the destination are known [40]. Sometimes, the retrieval of such geographic information can be expensive, especially in mobile networks [41]. First solutions for location-aided routing in mobile ad hoc networks were proposed in [42]. Meanwhile, various alternatives have been developed using geographic positions for optimized routing decisions [43].

On the other hand, clustering mechanisms have been studied to enhance the performance in ad hoc networks while reducing the necessary amount of energy at the same time [44]. The primary idea is to group nodes around a clusterhead that is responsible for state maintenance and inter-cluster connectivity. Clustering is a crosscutting technology that can be used in nearly all layers of the protocol stack. Examples for efficient clustering algorithms are passive clustering [45], which reduces the necessary overhead for maintaining the structure of the clusters, and on-demand clustering [46], which mitigates the need for permanent maintenance of clusters by creating them on-demand.

The primary goal for employing clustering algorithms is always to reduce the maintenance overhead as needed for global state methods. Obviously, this allows to reduce the energy consumption on a global level while reducing the possible performance as seen in global state mechanisms only a little. LEACH (Low-Energy Adaptive Clustering Hierarchy) [47] and its competitor HEED (Hybrid, Energy-Efficient, Distributed Clustering Approach) [48] are examples for power-aware cluster-based communication approaches for ad hoc networks. Routing algorithms make also use of efficient clustering mechanisms [49]. A typical example is the Zone Routing Protocol (ZRP) [50].

3) Neighborhood Information: Compared to cluster maintenance or even global state, neighborhood information can be gathered quite easily (usually, it is also used as a starting point for maintaining clusters or global state). The basic idea is to periodically exchange some hello or sync messages that include all necessary information for the particular algorithm to take decisions based on its local state and the state of its neighbors. The overhead for maintenance functionality is drastically reduced but there is no way for providing optimal solutions (end-to-end communication paths, global allocation schemes, etc.).

In the medium access control layer, sync messages are employed to synchronize all neighboring nodes to a common sleep cycle [33], to organize the message exchange using RTS/CTS , or to provide enhanced performance solutions such as adaptive listening. The most prominent MAC protocol in the wireless ad hoc domain is IEEE 802.11 [51]. It features RTS/CTS-based solutions for the hidden/exposed terminal problems, adaptive sleep cycles, and energy-control using overhearing techniques. More specialized for wireless sensor networks is the S-MAC (Sensor MAC) protocol [52], [53]. In addition to the mechanisms established in IEEE 802.11, adaptive listening has been integrated that allows for an enhanced performance while enabling maximized overhearing periods at the same time. The Power Control MAC Protocol [54] is an energy-aware extension to typical contention-based MAC protocols. It adapts the transmission power to the current needs in the networks.

In the network layer, there are two very different approaches based on neighborhood information: re-active routing protocols and data-centric communication methods (also known as objectivity-driven). Re-active routing protocols do not keep global routing tables up-to-date. Instead, they only manage neighborhood relationships. On demand, i.e. if messages have to be transmitted, routing information is gathered by flooding route requests through the network in order to find a suitable path towards the destination. Several optimizations in terms of adjustable caches for previously determined route information allow a fine-tuning of the algorithms depending on the application scenario. Well-known examples are AODV (Ad-Hoc On Demand Distance Vector Routing) [55], [56] and its successor DYMO (Dynamic MANET On Demand) [57]. In contrast, data-centric communication methods prevent the calculation of routing paths and employ interest distributions instead. The class of diffusion algorithms can be classified into neighborhood information. While multiple diffusion algorithms have been developed during the last few years, directed diffusion [27], [58] is still the best known approach. Other variants of directed diffusion try to optimize particular aspects such as the minimization of the energy consumption [59] or the inclusion of geographical information in GEAR (Geographical end Energy-Aware Routing) [60]. CADR (Constrained Anisotropic Diffusion Routing) [61] is a form of diffusion algorithm that optimizes both, energy and transmission latency.

Task allocation schemes based on local information and on-demand decision taking show an improved behavior in terms of

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necessary state maintenance. Multi-agent systems usually employ centralized control mechanisms that are based on a auction system. An example for this group of coordination schemes is Murdoch [62].

4) Probabilistic Algorithms: The category of probabilistic algorithms intents to keep no state information at all. Therefore, it shows the best behavior is very few messages per time have to be transmitted because the overhead due to state maintenance is negligible. The overhead for actual transmitting messages can be much higher. There cannot be an optimal path from a source towards a sink; probabilistic algorithms are used instead. In MAC protocols and congestion-aware communication mechanisms, stochastic distributions and random delays are employed to prevent the global synchronization effect. For routing and data dissemination in ad hoc networks, probabilistic algorithms are often used to prevent pure flooding of messages through the whole network. A comparison of data dissemination protocols in ad hoc networks is, for example, provided in [63], [64].

Without routing tables, information exchange in communication networks can be organized by flooding the messages through the entire network. Optimized flooding strategies [45] try to prevent the forwarding of duplicates of the packet by using a maximum time-to-live or sequence numbers. The probability that a message will arrive at a destination is very high even in case of mobility and error-prone wireless channels. On the other hand, the overhead due to message transmissions into unessential parts of the network increases with the network size. Gossiping [65] and rumor routing [66] as alternatives to flooding have been developed to cope with this problem. Probabilistic parametric routing [67] and weighted probabilistic data dissemination schemes [28] further improve the behavior of these algorithms. The optimization goal is the overhead due to unnecessary messages compared to the probability of reaching the final destination. This group of algorithms can be extended to probabilistic lightweight group communication [68] and task allocation schemes as well.

5) Bio-inspired Mechanisms: The turn to nature for solutions to technological questions has brought us many unforeseen great concepts. This encouraging course seems to hold on for many aspects in technology. Basically, positive and negative feedback loops have been studied in different domains of biology that can be adapted and transferred to ad hoc networking. General optimizations for wireless sensor networks have been studied [69] as well as communication paradigms in WSN [70], [71].

Swarm intelligence, i.e. the behavior of individuals in a group that is working on a common overall goal, was used to improve routing decisions and collaboration issues [72]. Ant-based routing algorithms for ad hoc networks have been proposed [73] as well as the use of swarm intelligence for task allocation [74]. Both are based on the idea of pheromone markers for collaborative foraging. Additionally, adaptive solutions based on genetic algorithms for routing [75] and quality of service provisioning [76] have been proposed.

Other approaches in the area of bio-inspired networking try to reduce the message overhead by using mechanisms known from cell and molecular biology [77]. The main idea is to adapt the inter- and intracellular signaling pathways using cellular transmitters, e.g. hormones [78]. For example, the blood pressure is regulated by complex feedback loops between multiple hormonal transmitters secreted by cells of different organs. It was shown that these feedback loops can be adapted to communication and control in sensor/actuator networks [71].

IV. Case Studies

Three case studies are provided in this section as examples for self-organization mechanisms categorized and depicted previously. The selection of these examples does not quality one of these approaches to be one of the best in its category. The discussed case studies were chosen only for their straightforwardness concerning the employed self-organization algorithms.

A. MAC Layer - PCM

Power control is an important issue in MAC protocols. Most schemes vary the transmit power to reduce the overall energy consumption. In addition to providing energy saving, power control can potentially be used to improve spatial reuse of the wireless channel. The Power Control MAC (PCM) protocol [54] is an extension to typical contention-based MAC protocols. It transmits the RTC/CTS handshake messages with the maximum available power p_{max}. The RTS/CTS handshake is used to determine the required transmission power $p_{desired}$ that is used for the subsequent DATA/ACK transfer. The signal level of the received RTS is used for the calculation of $p_{desired}$ in combination with some well-known minimum received signal strength Rx_{thresh} that is necessary for correctly decoding the messages. The principles are shown in detail in figure 4.

The transmission power is calculated using the following formula (whereas p_r denotes the received power level):

$$p_{desired} = \frac{p_{max}}{p_r} * Rx_{thresh} * c \quad (1)$$

Therefore, the calculation is based on locally available information only by observing the neighboring environment. However, it was shown that this scheme can degrade network throughput and can result in higher energy consumption than when using IEEE 802.11 without power control. PCM proposes some enhancements that do not degrade throughput and yield energy saving.

The problem is that there are nodes that can sense the signal of the RTS/CTS exchange but cannot decode it because the signal level is too weak (nodes A and H in figure 4). During the DATA/ACK period, these nodes do not sense a signal any longer.

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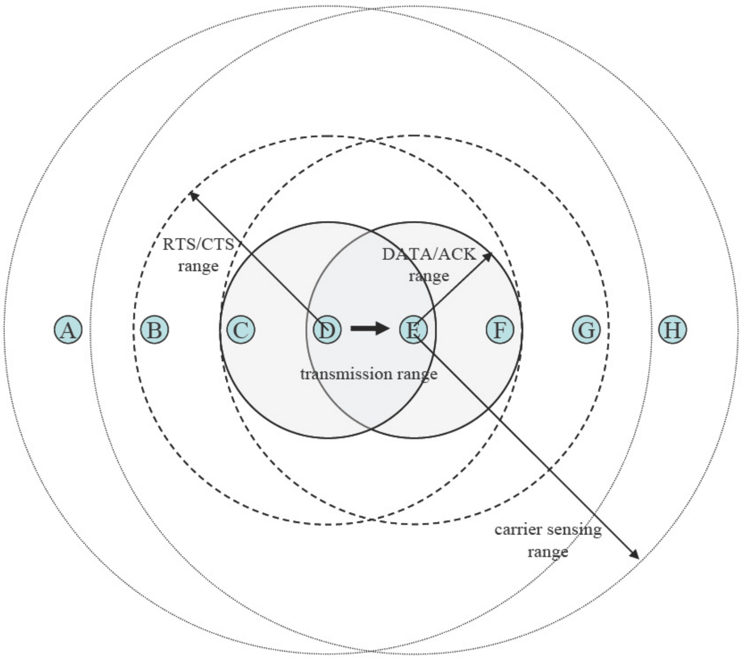

Fig. 4. Transmission ranges of the power control MAC protocol

Therefore, they may initiate their own RTS/CTS exchange which results in a collision with the still ongoing data transmission. The power control MAC protocol addresses this issue by varying the signal level of the data transfer by periodically increasing it to p_{max} allowing distant nodes to sense the signal of the ongoing transmission. The period can be adapted to the carrier sensing algorithm in order to optimize the behavior of the protocol.

In summary, it can be said that the PCM is a good example for achieving optimal throughput by reducing the necessary transmission energy to a minimum. It does so using neighborhood information only, i.e. the knowledge extracted from monitoring and analyzing the surrounding behavior and conditions. Therefore, node mobility is supported as well as changes of the network topology.

B. Topology Control and Clustering - LEACH

LEACH (Low-Energy Adaptive Clustering Hierarchy) [47] is a clustering-based protocol that utilizes randomized rotation of local cluster base stations (clusterheads) to evenly distribute the energy load among the sensors in the network. Energy load is defined in this context as the utilization in terms of awakness plus needed transmission energy. LEACH uses localized coordination to enable scalability and robustness for dynamic networks, and incorporates data fusion into the routing protocol to reduce the amount of information that must be transmitted to the base station. The primary goal is to equally distribute the energy load to all available nodes and to enhance the lifetime of the entire network. In [47], simulations were conducted that show that LEACH can achieve as much as a factor of 8 reduction in energy dissipation compared with conventional routing protocols. In addition, LEACH is able to distribute energy dissipation evenly throughout the sensors, doubling the useful system lifetime for the networks that were simulated.

The operation of LEACH is broken up into rounds, where each round begins with a set-up phase, when the clusters are organized, followed by a steady-state phase, when data transfer occurs. The election process works as follows. At the beginning of a round, each node decides whether or not to become a clusterhead. This decision process depends on only a single pre-defined value, the desired percentage P of cluster heads in the network, i.e. the number of clusters to be created. Each nodes elects itself to be a clusterhead with a certain probability. For this, each node choses a random number n between 0 and 1. If the number is less than a threshold $T(n)$, the node will become a clusterhead for the current round r. This threshold is calculated as follows (G denotes the set of nodes that have not been clusterhead in the last $1/P$ rounds):

$$T(n) = \begin{cases} \frac{P}{1-P*(r mod 1/P)} & \text{if } n \in G \\ 0 & \text{otherwise} \end{cases} \quad (2)$$

Therefore, at round 0, each node has a probability P of becoming clusterhead. The probability of the remaining nodes must be increased because there are fewer nodes left for becoming clusterhead in round $r + 1$. Finally, the cluster-head nodes broadcast their status to the other nodes in the network. Based on this information, each node determines to which cluster it wants to belong by choosing the clusterhead for which the communication energy can be minimized.

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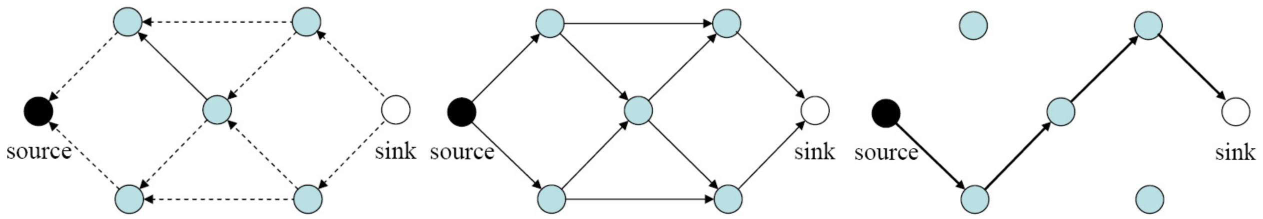

(a) interest propagation (b) gradient setup (c) data delivery

Fig. 5. Interest and data propagation usind in directed diffusion

In summary, it can be said that LEACH operates on locally taken decisions that are broadcasted to all neighboring nodes. Based on the local decision and some (local) communications, the nodes organize themselves into a larger compound for energy-aware operations. Therefore, LEACH combines multiple mechanisms for self-organization: probabilistic algorithms (choice of becoming clusterhead) and neighborhood information (set-up of the clusters). This combination together with location information (the clusters are used for efficient data communication), LEACH provides an optimized behavior for communication in ad hoc networks based on self-organization methods. Obviously, in order to minimize the overhead, the steady state phase should be long compared to the set-up phase. Mobility is supported by LEACH, whereas new nodes have to be synchronized to the current round. Node failures may lead to less clusterheads being elected than desired.

C. Routing and Data Dissemination - Directed Diffusion

Address-based routing depends on globally unique addressing schemes as well as on pro-actively or re-actively created and maintained routing tables for path calculations. Instead, directed diffusion [58] is a data-centric communication approach. The mechanism was developed for use in wireless sensor networks in which nodes can coordinate to perform distributed sensing of environmental phenomena. All nodes in a directed diffusion-based network are application-aware. This enables diffusion to achieve energy savings by selecting empirically good paths and by caching and processing data within the network.

Basically, directed diffusion consists of two different mechanisms: interest distribution and data propagation. Using naming methods, interest can be described in the form "I am looking for all measures of temperature higher than 20°C in the area [10,10,300,200]". Such interest is diffused through the network as shown in figure 5 (a). Intuitively, this interest may be thought of as exploratory; it tries to determine if there are any sensor nodes that detect the requested measures. Such interest messages are renewed periodically to keep them up-to-date. Each node in the network that forwards this interest message sets up a gradient towards the source of the interest, i.e. the sink node (figure 5 (b)). A special reinforcement process is employed to weight the gradients based on their qualities, e.g. loss ratio or hop count. If a sensor node receives the message that actually can provide the requested data, it will finally start to measure for example the temperature and to transmit the results along the chosen gradient towards the sink as depicted in figure 5 (c).

Accordingly, directed diffusion operates on local requirements in form of interests, their diffuse distribution through the network, and temporary state maintenance in form of gradients. Depending on the number of nodes and the number of active interests, the utilization of the network is very low or comparable to other routing approaches. Directed diffusion allows to switch between different design choices for the implementation or even their runtime-change to adapt to changing environments. For example, the interest propagation can employ pure flooding, directed flooding based on the location, or directional propagation using previously cached data. Data propagation can be implemented in form of single path delivery of probabilistic multipath forwarding. Additionally, data caching or aggregation algorithms can be employed for robustness and data reduction. This example shows again that multiple self-organization mechanisms can be successfully coupled to build a communication protocol that makes efficient use of the available resources. Because there is no addressing scheme needed and the interest information is periodically updated, directed diffusion supports mobility as well as additional or failing nodes.

D. Summary

Table II summarizes the self-organization mechanisms used by the excamples in the case studies as well as their capabilities.

V. Solved and Open Issues

It was shown that there are self-organization mechanisms available in ad hoc networks actually solving many well-known problems. Depending on the category within the solution space and the particular application scenario, the speed-up can be different. The following issues should be mentioned as examples.

- *Manageability* - The manageability of large-scale networks is drastically increased because of the prevention of global state maintenance. Nodes try to identify their environment by just looking at it. Therefore, little or even none central management is necessary to keep the network operational.

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Example	Self-organization mechanisms	Capabilities
PMC	MAC layer	energy control
	neighborhood information	mobility support
LEACH	network layer	energy control
	neighborhood information	load control
	probabilistic algorithms	mobility support
	topology control	
Directed diffusion	network layer	load control
	local environment	mobility support
	probabilistic algorithms	situation-aware communication

TABLE II

SUMMARY OF SELF-ORGANIZATION MECHANISMS USED BY THE EXAMPLES IN THE CASE STUDIES

- *Scalability* - Hopefully, only linear or less overhead is induced by increasing the network size. Self-organization helps to reduce the overhead required for state maintenance and operational overhead. Depending on the chosen methodology and the network behavior (traffic, network size), networks are allowed to increase to very large-scale dimensions.
- *Overhead* - As mentioned before, the overhead caused by maintenance and protocol overhead can be reduced by employing various self-organization mechanisms. It is important to keep analyzing the globally visible overhead. In case of preventing the maintenance of global state information, it will always involve some amount of additional work to perform the desired operation such as routing in an ad hoc networks. On a global point of view, there should be a reduction of necessary overhead visible if the right mechanisms for the particular applications have been chosen and they are properly configured.
- *Reliability* - The reliability of a network as visible to an application depends on many parameters. At this place, we do not consider the reliable communication of a transport protocol but the ability of the network to dynamically react on node or link failures and the employment of using multiple paths simultaneously. Basically, reliability is provided based on the inherent capability of self-organization mechanisms to adapt to changing environments.

On the other hand, some problems are still unsolved or might even appear by introducing self-organization. In the following, we discuss the some examples of still open issues. These can be seen as starting points to conduct further research on self-organization and ad hoc networking.

- *Controllability* - As shown in figure 1, the predictability of the behavior of a self-organizing system might rapidly decrease while increasing its scalability. This problem is directly related to the controllability of the system. Network management solutions as known so far cannot be successfully employed in self-organizing ad hoc networks. Therefore, one can believe that the network is operating well but its is hard to prove the availability or even the achieved quality.
- *Cross-mechanism interference* - The composition of multiple mechanisms for self-organization in ad hoc networks can lead to unforeseen effects. For example, two different energy-aware methods implemented at the MAC and the network layer might interfere and lead to either reduced throughput or reliability or to much higher energy consumption compared to the non-optimized behavior. Cross-layer design and cross-method validation techniques are needed to identify such interferences and to eliminate them.
- *Software development* - Developing ad hoc applications demands new software engineering approaches. Multiple questions have to be considered at once: where to run which (part of the) application and how to distribute data and activity over the network. Recent examples that have to be elaborated more clearly are policy-based approaches and profile matching techniques.
- *System test* - The test of the systems and the installed software components becomes a complex task. It is not possible to create a lab environment showing exactly the properties of the desired deployment scenario. The same holds for field tests because it is not possible to predict future conditions influencing the ad hoc network. System test approaches must be changed to incorporate the unpredictable environment.

VI. CONCLUSION

In conclusion, it can be said that self-organization mechanisms create many new and exciting application areas for ad hoc communications. Especially, the main objectives of large scale wireless ad hoc networks scalability, reliability, and availability are addressed and novel solution spaces are opened. Nevertheless, it must be mentioned that the employment of the discussed mechanisms has to be bought for high costs. The predictability of the communication methodologies is reduced by employing self-organization methods. Therefore, self-organization cannot be seen as a universal remedy. A proper analysis of the particular application and its requirements is necessary in order to choose adequate mechanisms.

In this paper, a general definition and classification of self-organization mechanisms in ad hoc networks was presented. Based on this categorization and clarifying case studies, we encourage other researchers to continue and intensify their studies on ad hoc network communication in general and self-organization mechanisms in particular. Possible interactions with interdisciplinary research domains should be carefully investigated in order to find and adapt well-studied solutions to the ad hoc community.

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