Optimization and control problems in wireless ad hoc networks

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Abstract. Recent advances in technology have enabled the development of low cost, low power and multi functional computation devices. These devices networked through wireless bring the idea of mobile ad hoc networks and wireless sensor networks into reality. In this paper[1] we discuss the optimization and control problems related to ad hoc networking topologies and communication. The short description of wireless ad hoc and sensor networks is provided. The focus is on energy conservation techniques and algorithms for computing the optimal transmitting ranges in order to generate a network with desired properties while reducing sensors energy consumption.

1 Introduction to wireless ad hoc networks

Wireless networks are becoming very popular method of transmitting data, [11]. Wireless transceivers are being installed in many devices such as printers, PDAs, laptops, etc. Majority of networks, currently being in use requires fixed infrastructure, such as access points, in order to function properly. Network nodes that find themselves out of the infrastructure range are unable to communicate with other network nodes. Hardware required to enable wireless communication in an area may be expensive or difficult to deploy, which may limit possible applications of wireless networks. Currently research effort is directed toward designing technology, that enables wireless communication in an area which does not have any pre-deployed infrastructure.

1.1 Wireless ad hoc network

Wireless ad hoc networks consist of autonomous nodes which organize themselves into a network without any need to rely on external infrastructure. Additionally it is assumed that nodes participating in ad hoc networks can be mobile and single hop communication between each pair of nodes may not be possible. Ad hoc networks may consist of various devices such as laptops, cellular phones, PDAs, etc.

Communication protocols used in modern wireless networks, such as IEEE 802.11 or Bluetooth (IEEE 802.15.1), are able to function in an ad hoc mode, but several key problems need to be solved before any practical implementation of the ad hoc networking paradigm is possible. The main such problems are:

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- *Energy Conservation*, nodes participating in an ad hoc network are usually battery powered, small size devices. Since power available to network nodes is limited, it should be used as efficient as possible.
- *Low-quality communication*, quality of communication over a wireless channel may depend of external factors, such as terrain structure. Some of these conditions may also be time varying, like weather conditions.
- *Constrained Resources*, resources available to network nodes are limited. Main constraints are battery power and network bandwidth.
- *Time varying topology*, each node participating in an ad hoc network may leave the network at any given time, because of various reasons like lack of power. On the other hand at any given time a node may join the network. Considering network nodes as mobile devices may complicate network topology even further.

1.2 Wireless sensor network

Wireless sensor network is the type of wireless ad hoc network, which consists of large quantity of identical, wireless sensors. Each sensor is a miniature device containing sensing unit, battery unit, CPU and a radio transceiver. Transceivers used in this kind of networks are usually characterized by short range, low transmission rate and very low power consumption. Wireless sensor networks are usually homogeneous and consist of stationary (or quasi stationary) nodes. Communication scheme in wireless sensor networks is usually many-to-one, sensors transmit data to a favored node responsible for relaying information gathered from sensors to a network operator.

1.3 Wireless ad hoc networking scenarios

Wireless ad hoc networks may be deployed in various environments and be trusted with different tasks [7, 11, 13]. The purpose of the network existence is a vital factor, which needs to be considered when designing the network. Other networking protocols need to be utilized in building-wide network, used to provide PDAs with the Internet access and other protocols will be utilized in a sensor network used to detect a fire of a forest. In order to design an ad hoc network capable of performing an entrusted task, following information is required: *geographical location of each node*, *possible transmission ranges* (if node's transmit power level may be modified), *estimated number of network nodes*, *number of nodes that can be lost before the network is considered disabled*, *purpose of the network* (maximization of network life time, maximization of network throughput, etc.).

2 Sensor networks design and exploration

The optimal location of sensors has already been recognized in many practical applications. Let us consider the environmental protection system consisting of measurement devices for air quality monitoring. The goal of our system is to provide forecasts of expected levels of pollutant concentrations in the given spatial domain. The problem is to calculate the optimal sensors location in order to obtain good quality forecast.

Several aspect can be considered in sensor location problem. It depends on the network purpose and type of sensors, i.e. stationary (motionless) and spatially movable or scanning sensors. The goal recognized in many application domains is to perform coverage and exploration of an unknown, unstructured and dynamic environment. The coverage problem can be defined as the maximization of the total area covered by sensors. Graph models and covering methods (branch and bound global optimization techniques [6]) can be applied to solve the considered problem. In [3] the graph model-based algorithm LRV (Least Recently Visited) for the cooperative system comprised of mobile robots and a static sensor network is proposed. The algorithm is able to perform coverage and exploration of dynamic environment, while deploying and maintaining an active infrastructure. The branch and bound optimization methods can be applied to determine the initial sensors location that covers the given area. The covering method for Lipschitz functions optimization that assumes the application of Dirichlet sets to cover the domain can be used. The detailed description of the idea together with the algorithm is presented in [4].

Another problem that can be considered is to design a network of observation locations in a spatial domain that is used to estimate unknown parameters of a distributed parameter system. We can distinguish the situations where one has many stationary sensors and activates only some of them during a given time interval, or alternatively has only several mobile sensors. Different approaches are proposed in literature. The application of branch and bound techniques to calculate the optimal location of sensors where one is given a finite number of possible sites at which to locate a sensor and cost constraints allow only some proper subset of them to be selected is presented in [13]. The exemplary procedure replacing less informative sensor locations with those which furnish more information is proposed in [10].

3 Nodes localization in ad hoc networks

Self-organized ad hoc networks usually consists of a set of sensors with initially unknown location information. Location estimation is very valuable in ad hoc networks. It allows using many geographic-aware routing, multicasting and energy conservation algorithms. Overhead associated with geographic-aware routing protocols is usually significantly smaller than overhead associated with non geographic-aware routing protocols. When no information about node location is available, performing route discovery procedure usually requires flooding the whole network with route request messages. On the other hand, when information about location of target node is available, route discovery procedure does not need to flood the whole network, it is sufficient to send route request messages to nodes located "closer to destination".

The simplest, but most expensive way to determine the node location is equipping each node with a GPS adapter. This solution comes with a cost of GPS adapter multiplied by the number of network nodes, as well as energy cost of powering the GPS adapter by each network node. To decrease the cost of network design the approach in which only a few sensors with known locations are considered is proposed. Network nodes, which location is known are called *"anchors"*. Location of anchors may be obtained by installing GPS adapters on these nodes or by simply placing these nodes in locations with known coordinates. Location of other nodes, called *"non-anchors"*, is unknown. Localization algorithms that estimate the locations of *"non-anchors"* by using knowledge of the absolute positions of *"anchors"* and such measurements as distance and bearing are applied.

The available literature [5, 2, 1] provides the overview of the measurement techniques in sensor networks localization and one-hop or multi-hop connectivity-based and distance-based algorithms. In the networks where a centralized information architecture exists (i.e. traffic monitoring, health monitoring, environmental monitoring) the centralized versions of the algorithms are proposed, otherwise the distributed localization is suggested. Recently the application of stochastic optimization to solve the distance-based localization task has became popular. The goal is to solve the optimization problem formulated as follows:

$$\min_{\hat{x},\hat{y}} \left\{ J = \sum_{i=m+1}^{m+n} \sum_{j \in N_i} (||\hat{x}_i - \hat{x}_j|| - d_{ij})^2 \right\} \tag{1}$$

where m denotes the number of anchors, N_i the neighborhood of node i, $\hat{x}_i$ the estimate of the node i location, d_{ij} the measured distance between nodes i and j.

Well known global optimization techniques, such as Monte Carlo, controlled random search, simulated annealing or genetic algorithms are proposed to solve (1) [5, 1].

4 Energy conservation problem

Nodes in an ad hoc network are usually battery powered and have limited amount of power at their disposal. Each battery powered device, participating in an ad hoc network needs to manage its power in order to perform its duties as long and as effective as possible.

Communication protocol designers need to keep in mind that nodes in an ad hoc network are often trusted with duties other than just participation in the ad hoc network. Every network node, apart from providing network connectivity, needs to perform other tasks. It may be even more desirable to withdraw some nodes from the network, just to let them use their power to perform their other duties. Hence the need to conserve nodes energy.

Energy conservation problem appears also in the infrastructure based wireless networks. Infrastructure of these networks is usually powered from power grid and is not constrained by amount of available energy. It is possible to use power conserving strategies based on utilizing large amount of the base station power in order to preserve power of battery powered devices. Such approach is not valid in an ad hoc networking scenario, due to lack of fixed infrastructure elements.

Radio transceiver is able to operate in four modes with different levels of energy needed for powering the transceiver. Possible modes are as follows:

Send Data – radio transceiver is sending data to other nodes (requires most energy). Some transceivers allow to use several fixed power levels while sending data, which potentially allows to conserve power while sending a message to a nearby node.

Receive Data – transceiver is receiving data (requires moderate amount of energy).

Idle – transceiver neither sends nor receives data, but is turned on and is ready to send or receive data.

Sleep – transceiver neither sends nor receives data (transceiver is not powered).

Power save protocols attempt to save nodes energy by putting its radio transceiver in the sleep state. Utilization of these protocols comes at a cost of reducing network bandwidth and may possibly disrupt the flow of data in an ad hoc network, because the sleeping node is unable to send or receive data. These protocols try to save power, while minimizing impact on the network throughput and route selection. Due to different purposes of the network different protocols are provided [8, 14, 9].

4.1 Synchronous power save

In this scenario it is assumed that nodes periodically wake up to exchange data packets. The sleep cycles of all nodes has to be globally synchronized. Another issue is adjusting length of sleep and wake phases, so that energy saved is maximal and impact on throughput is as low as possible.

4.2 Topology based power save

In this approach a subset of nodes which topologically covers whole network is selected. Nodes belonging to this set are not allowed to enter the sleep state because they are responsible for relaying traffic in the network. Other nodes are required to be periodically awake in order to receive incoming traffic. The power save protocol should be capable of buffering traffic destined to the sleeping nodes and forwarding data in partial network defined by the covering set. Nodes in the covering set need to stay in the idle state and therefore are forced to use much more power, than nodes out of the covering set. The covering set membership needs to be rotated between all nodes in the network in order to maximize the life time of the network.

A subset of nodes topologically covering the network is usually based on a *dominating set*. A dominating set of network is a subset of nodes, such that each node in the network is either in the dominating set, or a neighbor of a node in a dominating set. If a dominating set is a connected subgraph of the network, it is a great choice to serve as a routing backbone for the network.

Algorithms used to find a dominating set of a network should utilize information about power available to the nodes. Nodes with the least amount of power should be excluded from a dominating set whenever possible.

Span Protocol Span protocol [12] utilizes a routing backbone based on a dominating set of nodes. In this algorithm nodes make local decisions on whether to sleep or to join a forwarding backbone as a *"coordinator"*. The coordinators are capable of buffering traffic destined to sleeping nodes outside of backbone and are periodically elect from all nodes in the network. Each node periodically broadcasts messages that contain its status, current coordinators and neighbors.

The election algorithm was designed to achieve four goals: every node is in radio range of at least one coordinator, all nodes share the task of providing global connectivity roughly equal, the number of coordinators is minimal, the election of coordinators is decentralized and based only on the local information. The algorithm operates in two phases. In the first phase the possibility of including nodes to a set of coordinators is tested. A given node can become a member of this set if it discovers using only information gathered from local broadcasts that at least two its neighbors cannot reach each other either directly or via one or two coordinators.

In the second phase each non-coordinator periodically determines if it should become coordinator or not and announce its intent to become coordinator. In the case when multiple nodes decide to become coordinator at the same time announcement contention may occur. This contention is resolved by delaying announcements with randomized back-off delays, $delay = [(1 - \frac{E_r}{E_m}) + (1 - \frac{C_i}{\binom{N_i}{2}}) + R] \cdot N_i \cdot T$, where N_i denotes a number of neighbors of node i , C_i number of nodes that would be connected if i become a coordinator, E_r remaining power at node i, E_m maximal power at node i, R random value, T round trip delay for a small packet.

None of the nodes is a permanent member of a coordinator set. A node withdraws when it discovers that every pair of its neighbors is able to reach each other directly or via one or two coordinators. It can still be used to forward packets but the coordinator announcement algorithm treats it as a non-coordinator. After a node has been a coordinator for some time, it marks itself as a tentative coordinator and stays tentative for some amount of time. The tentative coordinator mechanism allows to rotate a coordinator set membership fairly among all nodes.

GAF Protocol Geographic Adaptive Fidelity (GAF) [15] selects nodes responsible for relaying traffic in the network based on their geographical positions. In order to function properly, the GAF protocol requires nodes to know their geographical position. This information may be obtained from GPS, or other location system.

The GAF protocol uses the term of *"node equivalence"*. Two nodes are equivalent when they are equally useful as relays in communication between other nodes. Problem of finding equivalent nodes is nontrivial, nodes equivalent in communication between pair of nodes do not have to be equivalent in communication between another pair of nodes.

Problem of finding equivalent nodes is addressed by introducing a grid which divides the spatial domain, where nodes are distributed. The grid is constructed so that all nodes in a grid square ale equivalent with respect to providing connectivity to any adjacent grid square. Such construction of the grid is possible when each node in a grid square is in transmission range of every node in adjacent grid squares, which implies grid size of $R/\sqrt{5}$, where R is the nodes transmission range.

Nodes may switch between one of the three states: *active*, *discovery* and *sleep*. In the active state a node is responsible for relaying traffic on behalf of its grid square. After spending some time in the active state, a node withdraws to the discovery state allowing other nodes in the same grid square to enter the active state. A node in the active state additionally periodically announces its state.

In the discovery state nodes exchange discovery messages, trying to detect other nodes in the same grid square and grid ID. After spending some time in the discovery state a node switches to the active state. Entering the active state may be suppressed by hearing an announcement from the "higher ranking" nodes.

Nodes in the active and discovery states may switch to the sleep state whenever they find another equivalent capable of taking over routing operations. When a node enters the sleep state, it cancels all pending timers, and powers down the radio. After spending some time in the sleep state node turns on its radio and enters the discovery state.

The decision which node (in the same grid square) should enter the active state is based on a *"ranking function"*. The default ranking function tries to maximize a network life time. The node with the highest rank is supposed to enter the active state and handle all routing operations on behalf of its grid square. Ranks are assigned based on several factors, like:

Node state – nodes in the active state have higher rank than nodes in the discovery state, which is the reason why no more than node per grid square is in the active sate.

Expected Lifetime – nodes with higher expected lifetime have higher rank.

It is possible to use different ranking functions, if necessary. All timers may also be used to tune a performance of the protocol.

The GAF protocol is intended for use in wireless sensor networks. No mechanism is available for buffering traffic destined to sleeping nodes, it is assumed that data sinks never enter the sleep state. There is also no guarantee that each grid square has an active node at any given time.

5 Topology control

Topology control is defined in [11] as *"the art of coordinating nodes' decisions regarding their transmitting ranges, in order to generate a network with desired properties (e.g. connectivity) while reducing node energy consumption and/or increasing network capacity."*

Motivation behind topology control is that power required for transmitting a data package between two network nodes is proportional to d^{α}, where d denotes the distance between nodes and $\alpha \geq 2$. Transmission of data package to the distance of d requires power proportional to d^2. Lets assume that instead of performing direct transmission, a relay node is used. In such case two transmissions need to be performed: from a source node a to a relay node b (distance d_1) and from a relay node b to a destination node c (distance d_2). Lets consider a triangle abc, also let α be an angle at vertex b. By elementary geometry we have:

$$d^2 = {d_1}^2 + {d_2}^2 - 2d_1 d_2 \cos\alpha$$

When $\cos\alpha \leq 0$, total amount of energy spent to transmit a data package is smaller when a relay node is used.

It is generally more efficient to perform several short range transmissions, than one long range transmission. Short range transmissions use less power than long range transmission and cause less interference in a network, hence increasing a network bandwidth.

Topology control assumes that nodes are capable of controlling power utilized to transmit data. Main problem is to assign per-node transmit power level in order to minimize power drained from the network, while maintaining network connectivity.

5.1 Topology control in the OSI stack

Topology control protocols are responsible for providing the routing protocols with the list of the nodes' neighbors, and making decisions about the ranges of transmission power utilized in each transmission. The OSI network model assumes that routing task is dealt with the network layer. On the other hand all functions and procedures required to send data through the network are stored in the OSI data link layer. Therefore the topology control layer is placed partially in the OSI network layer and the OSI data link layer, as presented in Figure 1.

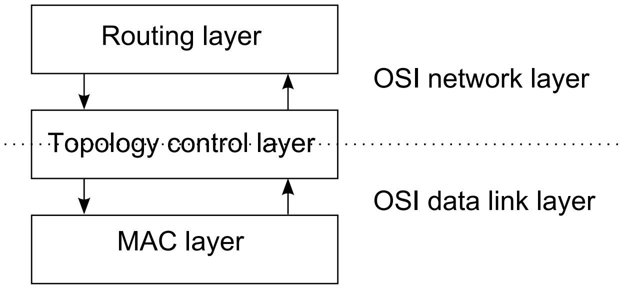

Figure 1. Placement of topology control layer in the OSI stack

5.2 Topology control protocols

Topology control protocols may utilize various information, like signal strength, location of nodes or direction from which the signal was received. Based on these information topology control techniques may be divided, as depicted in Figure 2.

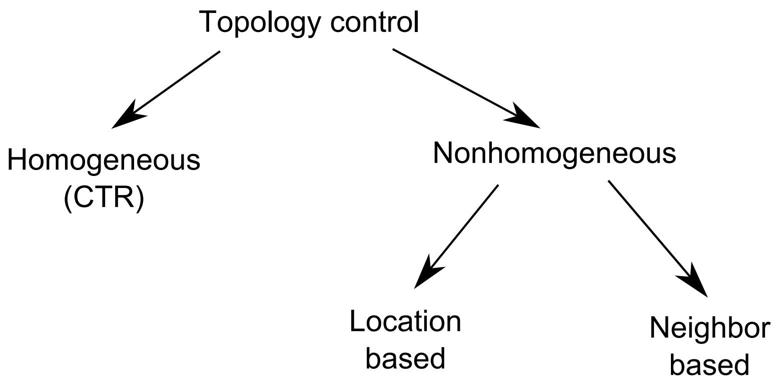

Figure 2. A taxonomy of topology control techniques

Homogeneous topology control assumes that each node uses the same value of transmission power, which reduces the problem to simpler task of finding the minimal level of transmit power such that certain network property is achieved.

Location based topology control assumes that nodes are able to determine their exact position. LMST (Localized Minimum Spanning Tree) [11] belongs to this group of protocols. It operates in three phases:

***Information exchange*:** Each node sends a broadcast message, at maximum power, containing its ID and location information.

***Topology construction*:** Each node determines a set of its neighbors, calculates euclidean distance to every neighbor and finally creates a Minimum Spanning Tree based on its neighbors and computed distances (edge weights in the MST).

Final network topology is derived from Local MST created by all nodes. Neighbor set of each node consists of nodes, which are its direct neighbors in its Local MST. Unfortunately, created topology may contain unidirectional links. Two approaches are proposed: it is assumed that all of them are bidirectional links, all unidirectional links are removed.

Determination of transmit power level : Transmission power required to reach every neighbor in a given topology is calculated based on the broadcast messages transmitted in the information exchange step. Each broadcast message is transmitted at the maximum power. Based on the measurements of power of the broadcast messages and knowledge about power level used when transmitting the message, it is possible to compute power level needed to reach the target neighbor.

5.3 Neighbor based topology control

In this approach we assume that no information about location of nodes is available but each node can determine set of its neighbors and build an order on this set. Order may be based on round trip time, link quality or signal strength. Several techniques are provided in [11].

The exemplary one – the KNeigh protocol assumes that each destination node can estimate a distance to a source node based on signal parameters of received message. It operates in three phases.

***Phase 1*:** The identification messages are exchanged. These messages are sent at maximum transmit power and contain nodes' identification strings. Each node determines its set of neighbors. A distance to each neighbor is derived from signal properties of messages.

***Phase 2*:** Each node selects k closest neighbors and broadcasts a list of these neighbors at maximum power. Unidirectional links are detected based on these messages. In the original implementation of the protocol these links are removed from further consideration. The method similar to applied in LMST protocol is used to set the transmit power level of each node.

***Phase 3*:** Optimization phase. The energy inefficient links are removed from topology. The following method is applied to select them: Whenever there exists a node c which is a direct neighbor of both nodes a and b, nodes a and b are direct neighbors and communication between nodes a and b through node c is more energy efficient than direct transmissions, then link between a and b is removed from the topology.

Although the KNeigh protocol is very simple and lightweight, its usage may potentially results in topology which *does not guarantee* preserving original network connectivity in the worst case.

6 Summary

The paper provides the short overview of the optimization and control problems in wireless ad hoc static and mobile networks. Several well-known schemes, methods, optimization algorithms and protocols that can be applied to solve location, localization and topology control tasks were briefly described. A list of open research problems in the area of ad hoc networks is provided and discussed in the extensive literature and has became a hot debate nowadays.

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