Locality Driven Congestion Control in Self-Organizing Wireless Sensor Networks

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Abstract - Congestion control is an essential task in communication networks. Especially in ad hoc and sensor networks, the task of bandwidth management and congestion control is very expensive. We propose a novel methodology for congestion control in sensor networks, which does not rely on the assumptions of topology knowledge, addressing, and bidirectional communication. Furthermore, an autonomous behavior of the intercommunicating nodes is guaranteed, i.e. a self-organizing behavior is achieved. This methodology is directly based on communication paradigms of sensor networks, which are dissimilar of the behavior of typical networks such as the Internet.

1 Introduction

During the last couple of years, many new application scenarios appeared inspired by the research on sensor networks [1], or in more general, ad hoc networks. In order to learn about the differences between sensor networks and other networks, the primary properties and capabilities of sensor networks should be listed. Sensor networks consist of a great many individual sensor nodes. Each node is working autonomously on a given task such as the examination of its environment [2]. The final goal is to show an emergent behavior of the global network, i.e. monitoring of a large area, using self-organization methodologies. To enable this task, the sensor nodes have to be able to collect sensor information, to forward them over an ad hoc network to a final destination such as a monitoring station [3]. Typically, each of these autonomously acting sensor nodes has very limited resources. Constraints are given on processing power, available memory, and communication bandwidth [6]. Additionally, the communication path is typically based on a radio link with high loss probabilities and short transmission ranges. Furthermore, energy consumption is an issue because sensor nodes are operating with an installed battery as the main power source and they are required to work uninterrupted for many months or even years. Therefore, operation and communication mechanisms were developed (and still work in progress), which show an energy-aware behavior.

For the communication, many protocols and implementations were developed in the last decade [9]. Most of these works are starting with commonly known methodologies and protocols known from the Internet technology. Unfortunately, sensor networks show only a few similarities to the Internet as discussed before. Typically, the following preconditions are used in most developments:

- all nodes are identical
- each node transmits its measurement data with the same constant data rate

These considerations are step-by-step evaluated and enhanced. For example, new models are focusing on event-driven transmission pattern, e.g. based on typical measurement scenarios in which some situations, e.g. measurement of very high temperatures, lead to increasing network utilization. In this paper, we focus on a very special capability, the congestion control in wireless ad hoc sensor networks. Congestion can appear in sensor networks because of many factors. First, the congestion behavior known from almost all packet networks can happen. This is, if too many packets arrive at a node while its input queue is flooded or if the output queue is overflowing because the node is no longer able to send any packets. Additionally, issues based on the wireless link have to be considered, e.g. if there is no transmission possible due to interferences on the radio. Finally, sensor nodes are often programmed sleep as often as possible for energy savings. Therefore, the routing changes frequently with time, which can lead to congestion in the network as well.

In this paper, we propose a congestion control methodology designed on the basis of studies of common sensor network behavior and of bio-inspired networking mechanisms, e.g. for self-organizing autonomous systems [5, 8]. Besides the description of the state-of-the-art and our new methodology, an outlook for further possible optimizations is included in this study.

2 Congestion Control in Sensor Networks

Currently known congestion control mechanisms are based on the following three procedures: end-to-end, path-based, and hop-by-hop. The main idea of end-to-end solutions is the embedding of congestion control mechanisms in a transport layer protocol. At the destination, it is possible to verify the number n of received packets out of N sent packets based on sequence numbers included in each packet. Mechanisms such as a provided window-size or feedback information can be used to inform the sender about congestion on the used path. The performance can be degraded if the path from the sender to the receiver is very long, which can quickly happen in large-scale sensor networks. The second approach is working on a path-based manner. If congestion occurs, it is being signaled back towards the sender hop-by-hop along the path. The difference to an end-to-end approach is the faster recognition of congestion. Nevertheless, the drawbacks from end-to-end solutions still hold. Finally, another approach employs hop-by-hop congestion detection and prevention [7]. The difference to path-based variants is that a backward path towards to the sender is no longer required. The only requirement is a bidirectional communication between two communicating nodes. This hop-by-hop mechanism does not focus on a particular transmission. It focuses on the detection of congestion and the transport of corresponding information to all neighbors. There, appropriate countermeasures must be taken in order to prevent any further congestion. Actions can vary from the random discard of new packets to the further signaling of the congestion situation towards the next neighboring nodes.

All previously shown congestion control mechanisms for sensor networks are based on Internet technology and the lessons learnt during the developments in the last 30 years. There are a couple of requirements for a proper functioning of these mechanisms. First, an unambiguous addressing scheme is needed as well as complete topology information. An obvious requirement is the existence of a data path between a particular sender and a selected destination. In some cases, a deterministic routing protocol is also required. In practice, few of these requirements can be granted. In the following section, the behavior of typical sensor networks is being examined and the resulting properties are discussed.

3 First Enhancements

Sensor networks were primarily developed and deployed for monitoring environmental properties. For example, room or building supervision requires temperature information from many individual sensors, i.e. distributed measurements at many places are required to monitor the global temperature distribution. Typically, each sensor can send its information on a fairly regular basis, i.e. with a small but constant data rate. If dramatic changes are recognized, all the sensors discovering this anomaly will start sending traces about this event in a burst transmission. Congestion will obviously occur without implemented countermeasures (compare Fig. 1).

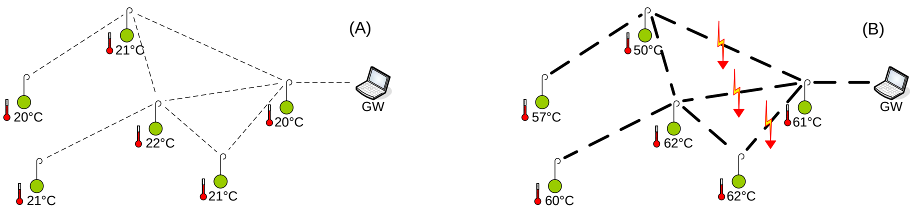

Fig. 1. Communication in a sensor network during standard operation (A) and during dangerous changes in the environment (B)

Similar or even worse situations can be expected in heterogeneous network environments employing different sensors for all tasks. Thus, the mentioned extreme situations will occur with an increasing probability. In summary it can be said that the intrinsic goals of data transmissions in sensor networks can be formulated as follows:

A message (data value) to be sent is given a priority. This priority depicts the importance of the particular task to achieve. Based on this priority, the message is forwarded to a percentage of the direct neighbors and to an even lower percentage of remotely accessible nodes. This process is repeated until the desired task is confirmed or the action is globally canceled. Therefore, a randomness factor is applied to the dispersion of information. This method was named feedback loop (a result of investigations in the research area of bio-inspired networking [8]) and is applicable in all kinds of sensor networks with unreliable data communication. It prioritizes messages that are more important such as shown in the example depicted in Fig. 2.

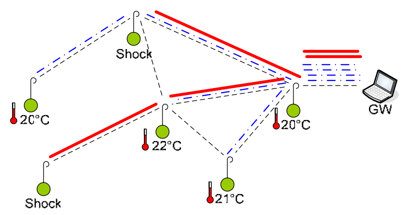

Fig. 2. Multiple sensors with different priorities

A more formal description of the data communication can be given as:

1. assign importance *I* to each event
2. calculate priority *P(I)* describing the distribution range
3. for all neighboring nodes N_n and previously known remote accessible nodes N_r, calculate an exponentially distributed weighting *W(N)*
4. forward message if $W(N)<P(I)$

This forwarding strategy can be directly applied to the described application scenarios. The algorithm ensures that high priority messages arrive at the destination with an increased probability but is has not completely solved the congestion problem. Thus, congestion can reduce the absolute probability of the successful delivery of a message or even decrease it dramatically. The study of this behavior led to a novel solution for congestion control, locality driven congestion control.

4 Locality Driven Congestion Control

The proposed solution is based on common demands on the behavior of sensor networks. A requirement on the congestion control mechanism is that it maintains control even if some links get temporarily saturated. The limitation of the bandwidth of the traffic flows might not be sufficient. For example, high priority messages must be handled other than standard measurements. Additionally, it the network is responsible that no transmission starves due to congestion control. Our approach, locality driven congestion control, covers both constraints. The principle procedure is to examine the saturation of a link and the local congestion behavior, respectively. This knowledge can be estimated based on the number of successfully received messages *N* during the last time interval *T*. The algorithm can be written as follows:

```
For each message M
  update message counter N(M,T)
  identify importance factor I_M
  calculate probability P(N,I_M)
  if exponentialDist(P,T)=TRUE
        forward message M
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The methodology works as follows. Each node maintains a counter representing the number of messages received in the last time interval. The algorithm is working independently on each node in the sensor network providing a self-organizing and adaptive congestion control. Concentrating on a single node, the following parameters are calculated in order to estimate a forwarding probability of a message:

1. The arrival rate λ of messages is used for estimating the congestion. The counter N, i.e. the number of messages received in the last interval T, represents this rate. It is updated with every received message M as a function of M and T.
2. Each message contains an importance factor I_M. It is used as the primary decision element for congestion control, i.e. the forwarding probability.
3. Using I_M and N, the forwarding probability $P(N,I_M)$ is calculated. This function is used to control the number of messages per time based on their priority.
4. Finally, an exponential distribution of outgoing messages is calculated in order to ensure that P is large enough to match the parameters of the outgoing channel. Thus, the saturation of the outgoing link is included to transmit as much messages as possible but to prevent congestion on this forwarding channel.
5. Based on the wireless transmission, the system is able to observe the saturation of the radio link. Thus, the parameters can be directly adapted to current situation.

The main advantage of the locality driven congestion control mechanism is the self-organization of all sensor nodes leading to an emergent behavior of a complex system. Each node in the network autonomously runs the same algorithm based on local knowledge and no inter-node communication is necessary for congestion control requirements. No assumptions on given topology information or addressing schemes are required and, in addition, nearly no state information must be managed except the number of successfully received messages in the last time interval.

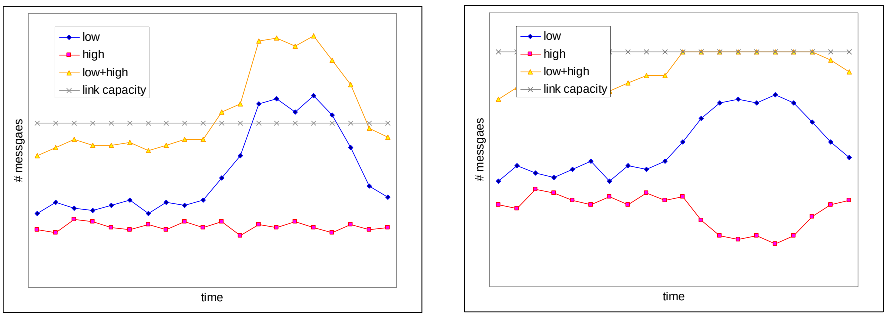

Fig. 3. Arrival rate (left) and departure rate (right) of messages at a node. The link gets congested during the operation as depicted by the overstepping of the link capacity. The outgoing link is fully saturated but not congested

An example is provided based on two message types, a low priority and a high priority message. In Fig. 3 (left), the arrival rate of messages at a selected node is shown. It can be obviously seen that the total number of messages exceeds the link capacity. Using the proposed algorithm, the forwarding of the messages can be organized preventing congestion patterns as shown in Fig. 3 (right). The optimization can be done at each node individually. Thus, only local information is required for the processing. Optimized values for the link saturation, i.e. the maximum number of packets to transmit over the radio link depends on the given application scenario. It is one of the parameters, which must be carefully controlled in order to achieve a high throughput in addition to a properly working congestion control.

5 Conclusions

In this paper, an approach for congestion control was presented designed for the typical behavior of commonly known sensor networks. The advantages of the algorithm are its independency of topology and addressing schemes. In fact, it does not require any kind of addressing of path information. An implication of this behavior is the absence of state information, which must be maintained in other congestion control mechanisms. The procedure was motivated by studies of biological mechanisms for self-organization such as the signaling pathways in cell and molecular biology [4]. Additionally, we are about to implement the algorithm in a lab environment consisting of Mica2 motes to compare experimental effects with analytical and simulative results.

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