QoS Impact of Hierarchical Routing in Multi-channel Sensor Networks

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Abstract. Enabling integration of Wireless Sensor Networks (WSN) and smart objects with the Internet is an important milestone towards the so called Internet of Things. Providing these networks with QoS capabilities is crucial for emerging applications that have end-to-end requirements on the border wireless network domain. Impairments such as delays and losses are heavily influenced by the quality of the communication channels, the routing, the MAC protocol and the interactions of these influential factors. In this work we report on a hierarchical routing scheme for sensor networks with multi-channel radios aiming at improving QoS. The scheme decouples the aforementioned influences: The MAC-protocol is responsible for a scheduling in a set of nodes called a cluster. Neighboring clusters use different frequencies. The routing is done at the level of clusters. The (distributed) algorithms executed by the network nodes to support this architecture are evaluated against optimal solutions for clustering, frequency allocation and routing derived from Integer Linear Programming.

Keywords: wireless sensor networks, end-to-end delays, optimization, heuristics, clustering, routing.

1 Introduction

The use of the Internet Protocol (IP) in resource constrained devices such as smart objects and Wireless Sensor Networks (WSN) has changed the Internet landscape drastically. The integration of such networks to the Internet in the form of Internet of Things (IoT) enables vast and exciting possibilities for application domains, such as building and home automation, smart metering, industrial manufacturing and e-health logistics [1]. These new horizon also brings some technical challenges. Integrating WSN into Internet with applications such as monitoring, control, and interactivity, requires these networks to explore QoS improvement possibilities. In this work, we focus on WSN and the impact of hierarchical routing based on clustering and channeling to meet this goal in terms of delays and reliabilities.

Delays in WSN are influenced by the traffic arrival process at all of its nodes, by the reliability and losses of the communication channels, the MAC protocol and the

A. Timm-Giel et al. (Eds.): MONAMI 2012, LNICST 58, pp. 217–230, 2013.

routing. MAC protocols [2]–[5], and routing [6]–[8] have attracted a lot of interest over the last years. If the routing metric is traffic dependent then the influencing factors on the delay are consequently of stochastic nature and it seems to be hard, if not impossible, to devise a system with a predictable delay performance. This contribution proposes a layered architecture for sensor nodes which – like the MEMSIC® IRIS motes [9] – have the capability of supporting several radio frequency (RF) channels but use only one half-duplex transceiver. The idea behind this architecture is as follows: The network is decomposed into clusters. Each node is member of at least one cluster. Communication within a cluster can take place with a high reliability, i.e. sufficiently high signal-to-noise ratio and is based on a MAC protocol, e.g. IEEE 802.15.4. Neighboring clusters use different frequencies thereby to a large degree avoiding the problem of interference. Neighboring clusters overlap and a node being member of two clusters is elected as a “bridge” and has to connect these two clusters by alternating between the two RF channels at each cluster. The benefits expected from such architecture are:

- high reliability because the influence of interference is drastically reduced and losses will occur only as excessive delays – if at all,
- routing has to be organized only for the sequence of clusters to be visited and thus is of reduced complexity.

To this end this contribution tries to approach the objective of a predictable delay performance by deriving all system parameters from an optimization problem which has the objective to minimize average delay. This approach is divided into two steps, each of which involves an optimization problem:

- Clustering and frequency allocation
- Multi-commodity flow routing with a (cluster) load dependent metric

The rest of this paper is organized as follows: In Section 2 we present the related work on study and harnessing end-to-end delay in WSN. Section 3 explains the network and channel model used throughout this work. Sections 4 and 5 present the global optimization models and corresponding distributed heuristic algorithms, respectively. Section 6 shows delay measurements in selected traffic scenarios, for which we compare the aforementioned approaches of Section 4 and 5. Finally in Section 7 we wrap up our findings and suggest future work.

2 Related Work

The sizes and traffic patterns of WSN make them suitable to establish hierarchies among the nodes, mostly grouping the nodes into clusters [10]–[11]. In this way, crucial tasks such as routing, information composition, channel access coordination, etc., are performed by a few nodes thereby simplifying the overall network behavior. In this work, we present the joint problem of clustering and channelization which ensures reliability for communications with the respective cluster coordinators. Moreover, the clustering not only groups nodes in the network, but also has to fulfill connectivity constraints to enable an inter-cluster multi-hop communication. The communication among clusters must go via bridge nodes, which due to having half-duplex single transceiver radios must alternate between clusters. The problem to assign channels is known as NP-Hard and is similar to the one in cellular networks [12]. Work towards time channelization has been addressed by [13] and [14], where the channel access is TDMA-based and a global synchronization is assumed. We do not assume such synchronization and favor RF-channelization to decouple the channel interference [15] across the network by imposing a limitation on the spatial reuse. Kaabi [16] discusses frequency channelization on the basis of multi-transceiver nodes. We assume common communication devices compliant with the IEEE 802.15.4 with only one transceiver. To address the problem of routing, we take the load-dependent metric of the expected waiting times of packets along queues in the clusters, following the classical approach and assumptions presented in [17], [18].

3 Network Model

The wireless sensor network is modeled as a graph with the set N of vertices representing the sensor nodes and where the edges represent bidirectional links. The existence of an edge in the graph will be determined by the channel model used, the transmission power and by the radiation pattern of the transceivers at the sensors. In our model, the nodes are assumed to be static and the links to have predictable expected behavior. This can be the case of industrial (manufacturing) applications where nodes are attached to machinery or to the walls forming a multi-hop network. Moreover, the sensors are equipped with transceivers that can be set to one out of several RF channel (IEEE 802.15.4 compliant devices).

3.1 Channel Model and Network Graph

We assume all nodes use the same transmission power P_t, and have omni-directional antennas. The channel is modeled as Log-distance Pathloss plus Log-normal Shadowing as presented in [19]. The model computes the received power as $P_r[dBm] = P_t - P_L$, where the loss is given by (1).

$$P_L(d) = 20\log_{10}\left(\frac{4\pi}{\lambda}\right) + 10n\log_{10}(d) + X_\sigma[dB] \tag{1}$$

The pathloss exponent is $n = 3$ and the shadowing component is characterized by zero mean and standard deviation $\sigma = 5dB$. The wavelength λ and the distance d are in meters. If the average received power is above a threshold that ensures reliable successful packet decoding, then the link is considered as part of the network.

The information of the existing links in the graph is stored in the neighborhood lists N_i, which contain all the nodes j that are connected to node i in the graph. These neighborhood lists are created by every node during an initialization phase via exchange of control messages. This information serves as the basis of the later organization of the network into clusters.

3.2 End-to-End Demand Requests

Nodes in the network have to satisfy demands, that is, send a series of packets, towards other nodes in the network. A demand is characterized by the source and destination nodes, as well as by the nature of the packet arrival process to take place. In this work we assume that a set D of end-to-end demand requests is given, described by their mean traffic intensity $\rho_d^{dem}, d \in D$, and their source and destination nodes. The traffic generated follows an ON/OFF model with Poisson distributed ON and OFF times, and constant bit rate (CBR) during the ON phase. A source selects a destination randomly for the ON period based on the information of the demand traffic intensity, from which a weighted selection can be made. The information of the demand intensities will be used at the second step of our solution approach, the routing problem, as will be explained later. The clustering and channelization problems are independent of the requested end-to-end demands, decoupling, and thus simplifying, the architecture definition from the usage-dependent routing task.

4 Optimization

We present in this section optimization models for the two steps in our proposed solution. In the next section we will consider distributed algorithms that will, up to some extent, follow the optimization framework.

A route in the proposed network consists of a sequence of clusters visited. At each cluster hosting neither the source nor the destination two transmissions take place:

- from entrance bridge (node) to a node named cluster head (in the center of the cluster)
- from the cluster head to the exit bridge (node).

These transmissions are scheduled by the MAC protocol IEEE 802.15.4 and are highly reliable due to a sufficiently high threshold for the signal-to-noise ratio enforced by the clustering algorithm.

4.1 Clustering and Frequency Allocation

Minimizing the number of clusters will also reduce the number of hops to the destination. Defining a clustering that minimizes the distances among nodes in the new clustered topology (aggregated over all node pairs in the network) is taken as an optimization objective. The purpose of the clustering is to divide the network into groups characterized by the 1-hop connectivity of every node in the group to a coordinator node (cluster head). The clusters themselves must build a connected covering on the network, and have specific frequency channels assigned for operations. The frequency allocation problem is similar to the well known frequency allocation problem in cellular networks, presented by [12], and is solved here jointly with the network clustering using an Integer Linear Programming (ILP) formulation.

The optimization problem is subject to the following constraints:

- the roles of member, bridge and cluster head are assigned,
- each node associates with a cluster,
- within a cluster the communications between members and cluster head are highly reliable, based on the link selection criterion as explained in Section 3.1,
- clusters using the same frequency channel should be sufficiently separated to mitigate the interference among them and ensure reliable communications between member nodes and their cluster head.

We now present the ILP model for the clustering and channelization. First, we introduce the parameters and variables used in the model.

Parameters

N	set of nodes in the network
N_i	1-hop neighbor set of node i
I_i	set of nodes that cannot use the same channel as i (interference set)
L	number of channels available for the frequency assignment
P	set of node pairs $P = N \times N$
p^{src}, p^{dst}	source and destination nodes of node pair p, respectively

Variables

$f_{ij}^{p} \in \{0,1\}$	flow from i to j
$h_i \in \{0,1\}$	$h_i = 1 \leftrightarrow$ node i is cluster head
$m_{ij} \in \{0,1\}$	$m_{ij} = 1 \leftrightarrow$ node i is member of cluster (head) j
$b_{ij}^{k} \in \{0,1\}$	$b_{ij}^{k} = 1 \leftrightarrow$ node k is bridge between cluster heads i and j
$x_i^l \in \{0,1\}$	head node i uses channel l
$y_{ij}^l \in \{0,1\}$	head nodes i and j use simultaneously channel l

Objective

$$Minimize \quad \sum_{i \in N} \sum_{j \in N_i} \sum_{p \in P} f_{ij}^{p} \tag{2}$$

Constraints

Connectivity Constraints

$$\forall i \in N,\ \forall p \in P: \sum_{j \in N_i} f_{ij}^{p} - \sum_{j \in N_i} f_{ji}^{p} = \begin{cases} 1, & i = p^{src} \\ -1, & i = p^{dst} \\ 0, & otherwise \end{cases} \tag{3}$$

From now on, we simplify the notations $\forall i \in N, \forall p \in P$ to $\forall i, \forall p$, respectively.

$$\forall i, j \in N_i, \forall p: \ f_{ij}^{p} \le m_{ji} + m_{ij} \tag{4}$$

$$\forall i, j \in N_i, \forall p: \; f_{ij}^{p} \le 2 - h_i + h_j \tag{5}$$

$$\forall i, j \in N_i, \forall p: \; f_{ij}^{p} \le h_i + h_j \tag{6}$$

Membership Constraints

$$\forall i, j \in N_i: \; h_i + h_j \le 1 \tag{7}$$

$$\forall i, j \in N_i: \; m_{ji} \le h_i \tag{8}$$

$$\forall i: \; 1 - h_i \le \sum_{j \in N_i} m_{ij} \le 2 \cdot (1 - h_i) \tag{9}$$

Bridging Constraints

$$\forall i, j < i: \; b_{ij}^{k} = m_{ki} \cdot m_{kj} \tag{10}$$

$$\forall i, j < i: \; \sum_{\substack{k \in N_i \\ k \in N_j}} b_{ij}^{k} \le 1 \tag{11}$$

Channelization Constraints

$$\forall i: \quad h_i \le \sum_{l} x_i^{l} \le h_i \tag{12}$$

$$\forall i, j, l: \; y_{ij}^{k} = x_i^{l} \cdot x_j^{l} \tag{13}$$

$$\forall i, j \in I_i, l: \quad y_{ij}^{l} = 0 \tag{14}$$

The objective function (2) represents the sum of all hop distances among all nodes in the network. This objective will try to form clusters that are close and well connected to other clusters via bridges. The rich connectivity via bridges shortens end-to-end path lengths in the network. This is a desirable property which chooses a convenient clustering independently from the demand information. The multi-commodity constraint, which also ensures a full multi-hop connectivity, is expressed by (3). Constraints (4)−(6) ensure that the path that a commodity flow follows on the network, goes through links connecting a head and a member and not two members or two heads. It is clear that members (and heads) in different clusters will use different RF channels, thus will be disconnected. However, in the model presented here, the intra-cluster communication is restricted to member or bridge node to the head. The membership is given by constraints (7)−(9). Two immediate neighbors should not be heads. Only a head can have members and a node can be a member of up to two clusters. When a node becomes member of two neighboring clusters, it becomes a bridge. Two clusters can share up to one bridge, as shown by (10) and (11). Constraints (12)−(14) deal with the channelization. Only heads are assigned a channel. Two heads that are within the interference set of each other cannot have the same channel. This set is defined as the 4-hop neighborhood, which ensures that two clusters using the same channel are separated more than 2 hops. The result of the clustering and channelization are the node roles, which determine the clustering in the network, and the channels on each cluster. As a final remark, constraints (10) and (13) are expressed as the product of two binary variables. Although a product is not a linear constraint, a straightforward linearization can be done (see [17]).

4.2 Routing

For the clustering a simple hop-count metric for the distance among node pairs was considered to be sufficient to produce a sensible clustering. For the routing, we take as input the result of the clustering and channelization step, and consider now the set *D* of end-to-end demands. An optimization problem formulation which tries to minimize the sum of the mean delays in all clusters *i* is proposed. This approach models a cluster as a (distributed) queuing system and relies on the Kleinrock's independence approximation [21] that arrivals at each cluster are all independent of each other.

We introduce the ILP model with its input parameters and variables.

Parameters

H	set of clusters *i* in the network
D	set of end to end demands *d*
R_d	set of routes *r* that connect the source and destination nodes of demand *d*
$\theta_{id} \in \{1,2\}$	intra-cluster traversed hops; it indicates the number of hops that demand *d* would require in cluster *i*. $\theta_{id} = 1$ only in case the cluster head is the source or destination of demand *d*
$\rho_d^{dem} \geq 0$	load introduced in the network by demand *d*

Variables

$w_i \geq 0$	mean waiting time for a packet to be transmitted at cluster *i*
$\rho_i^{clus} \geq 0$	traffic intensity at cluster *i*
$\delta_{id}^r \in \{0,1\}$	Kronecker symbol for which $\delta_{id}^r = 1$ indicates that route *r* of demand *d* transits via cluster *i* (link-path formulation [17]); otherwise $\delta_{id}^r = 0$

Objective

$$\text{Minimize} \quad \sum_{i \in H} w_i \tag{15}$$

Constraints

$$\forall i \in H: \quad w_i = \frac{1}{c_{clus}} \cdot \frac{\rho_i^{clus}}{1 - \rho_i^{clus}} \tag{16}$$

$$\forall i \in H: \quad \rho_i^{clus} = \sum_{d \in D} \sum_{r \in R_d} \rho_d^{dem} \theta_{id} \delta_{id}^r \leq 1 \tag{17}$$

The traffic intensities for demands and clusters are normalized with respect to the cluster capacity c_{clus}. This capacity is derived from a sequence of experiments with increasing load in a single cluster environment running just the IEEE 802.15.4 protocol. The onset of substantial losses was taken as the criterion to identify the capacity in the cluster.

The objective function (15) expresses the minimization of the mean waiting times at all clusters, which are seen as a distributed queuing systems. Constraint (16) equates the waiting times to the known formula of the average waiting time in an M/M/1 queue [18]. Note that although this constraint is not linear, the expression is convex on ρ_i^{clus}, and a piece-wise linear approximation can be used instead (see Fortz and Thorup's method [17]). Finally, constraint (17) expresses that the total traffic in a cluster is made up of the traffic of those demands whose routes are traversing the cluster, and that this traffic is bounded to the cluster capacity. The solution of this step is the set of routes that minimize the end-to-end delays according to the information of the demand intensities on an already clustered and channelized network. The traffic is not split into several routes.

5 Distributed Algorithms

The ideal migration path from a global optimization approach to a distributed algorithm would be a formal decomposition method of the global optimization problem to a set of smaller local ones to be solved at each node, with the assertion that the latter will converge to the former one. Unfortunately, the necessary conditions to make this feasible (like convexity of the problems involved) are not met here. We therefore introduce heuristics for the clustering and channelization step as well as for the routing, and will evaluate in Section 6 how close they get to the desired optimum.

5.1 Clustering and Frequency Allocation

This algorithm is solved by the network at the initialization phase. And its results are used as inputs for the routing step. As output of the algorithm each node should be either: head, member or bridge, and heads will have a channel assigned in a greedy fashion taking into account the channel assignment in the neighborhood. In extensive experiments with different randomly generated networks and different number of nodes we found that the number of clusters exceeded the results from the global optimization by at most 15-20%.

In the following we explain the principles behind the heuristic which basically aims at a feasible solution of the problem rather than an optimal one, i.e., the algorithm fulfills the constraints of the presented optimization model, such as global inter-cluster connectivity and interference avoidance, but do not explicitly address a global hop-distance minimization in the clustered and channelized topology.

Every node exchanges control messages only with its 1-hop neighbors until the whole network enters a steady state in which neither roles nor channels are assigned or updated. The possible roles a node can take and their allowed update transitions are depicted in Fig. 1. Head, member and bridge are regarded as stable roles, whereas head candidate and orphan as transient roles. If a node uses a transient role, it will try to update to any other stable role allowed by the transition diagram. The transitions occur at each update round of the heuristic computation.

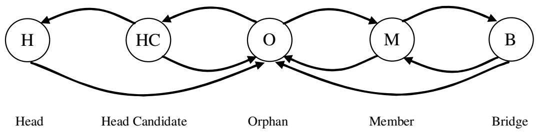

Fig. 1. Node roles and allowed transitions

Each node evaluates a set of rules periodically until it either reaches a stable role or a watchdog timer indicates that the clustering failed. In this work we accept networks where all nodes acquire stable roles and allow enough time for this.

The process assumes the selection of an initiator node, referred to as the “anchor”. This node is distributedly selected in a similar manner as the root node in spanning tree bridges [22], where the node with the highest ID is chosen as root. To achieve this, each node broadcast locally its own address ID or the highest one it has heard. After a while, all nodes know the ID of the anchor, which starts the heuristic being a head himself. All the other nodes start as orphans and update their roles according to the following rules:

- The anchor is a cluster head using the first channel. It starts the clustering by broadcasting its information and remains in that state for the rest of the process.
- An orphan node will primarily try to become member of any cluster head in its immediate vicinity. If there is no head around but only member nodes, then it decides to become a head candidate to extend the clustered architecture, provided the clustered neighborhood allows the allocation of a non-conflicting channel.
- A member node checks for head candidates around and tries to become a bridge to that head candidate. If its own head gave up its role, the member becomes orphan.
- A bridge checks its two heads and depending on whether one or both have ceased of being cluster heads, the bridge will become a member or orphan. Otherwise, it remains committed as bridge between the clusters.
- A head candidate that realizes that a node is bridging it to the current clustered architecture becomes cluster head. Otherwise, it becomes orphan.
- A head checks if it connected to the anchor via its bridges. This ensures proper cluster connectivity. Otherwise, it becomes orphan.

The idea is that nodes around the anchor form the first cluster. Then nodes in the 1-hop neighborhood of this first cluster organize the second group of clusters and channel assignment. Once the nodes in this second tier reach stable roles, they greedily commit to their roles. The process goes on with the subsequent external tier. The global cluster connectivity is guaranteed by keeping (at least) the connectivity to the anchor node via multiple clusters.

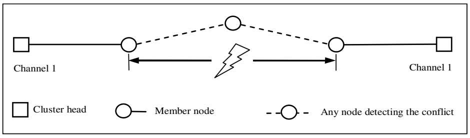

Fig. 2. Interference situation

Two clusters are considered to interfere when they (i.e., any of their members) are within 2-hops distance. This means that cluster heads should be more than 4-hops away. The situation is illustrated in Fig. 2. When the complete network achieves a valid and stable clustering and channelization the process enters into the next phase: routing of demands.

5.2 Routing

To obtain a load-aware routing, cluster heads periodically measure the traffic intensity ρ_d^{clus} of their cluster and disseminate this information to all other cluster heads in a broadcast manner. Although the traffic is generated by the nodes according to the mean intensity of the demands, it follows an ON/OFF model that matches the mean values but that makes the routing a dynamic process. On the adaptation, load is balanced to follow less congested (less costly) routes. The clusters are now be seen as "edges" in a logical graph and have a corresponding expected delay to traverse through them. The bridge nodes now look for the shortest route using Dijkstra's algorithm that traverses the least loaded clusters, i.e., via the shortest edges in the new simplified logical graph. The metric announced by the cluster heads is proportional to the mean delay as given in (18). Thus the modeling approach is the same as the one leading to the optimal problem (15−17) and the results are expected to closely follow those of the proposed ILP model.

$$m_i = \frac{1}{c_{clus}} \cdot \frac{\rho_d^{clus}}{1-\rho_d^{clus}} \tag{18}$$

6 System Simulation

Simulations are carried out on the Network Simulation System OMNeT++ version 4.1 [23]. The chosen wireless simulation framework is MiXiM [24]. MiXiM is a set of libraries that provide the basis for physical modeling of wireless transmissions and operations up to MAC layer. Further, the module for IEEE 802.15.4 developed by Rousselot et al [25] was extended and used in the solution approach presented. In the following experiments the topology is generated randomly [20], transmission power is set to 1 mW and the packet size is assumed to be constant (40 Byte), which makes a packet transmission time to be around 1.3 ms.

In a first set of experiments we wish to observe the performance of the distributed algorithm for clustering and channelization with respect to the optimal solution based on the ILP model of Section 4.1. Fig. 3 shows the number of clusters found by the ILP model and by the distributed algorithm averaged over 10 experiments per point. The 90% confidence interval for a Student's t−Distribution is likewise shown.

It can be seen that the distributed algorithm follows closely the results of the optimal solution for the number of clusters formed in the network. We turn our attention to the hop distances among all nodes in the elicited architecture for both approaches. These values are captured by the objective values of the ILP model for clustering and channelization. We take the resulting architecture from the distributed algorithm and determine the aggregated hop distance among all possible node pairs. The normalization of such metric with respect to the optimal values is shown in Fig. 3 (See right-most vertical axis).

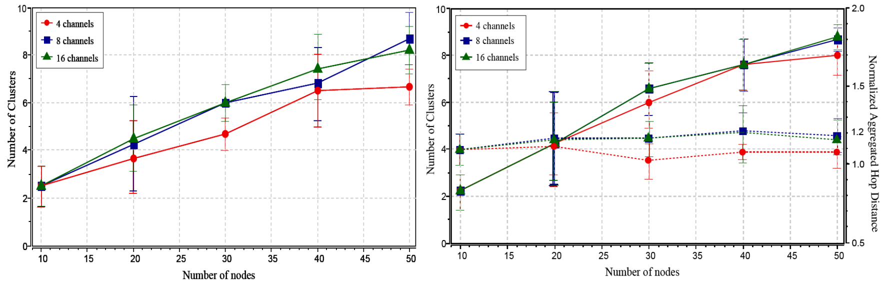

Fig. 3. (Left) Optimal number of clusters found by the ILP model for clustering and channelization for different numbers of channels available and nodes in the network. (Right) Results for the distributed algorithm. Dashed lines show the normalized objective value of the distributed solution with respect to the optimum value.

These results show that for the observed networks sizes from 10 to 50 nodes, the distributed algorithm keeps the aggregated end-to-end hop distances in the network up to 20% above the optimum. Although the hop distance cannot fully describe the end-to-end delays that packet incur during its advance towards their destination, this is a sensible metric directly associated to the total number of clusters that the shortest path between two nodes should traverse, and the fact that it is load-independent makes it possible to decouple it from the routing phase.

We now show the results for a 100-node network which meets the constraint of being connected in the sense of full (multi-hop) reachability using reliable wireless links. Packet transmission requests are generated in a Poisson process in each node following the ON/OFF model, the intensity of which corresponding to the values laid down in the demand intensity vector ρ_d^{dem}. In our experiments we consider that every node generates an aggregated normalized demand $\rho_{Node}^{dem} = \sum_d \rho_d^{dem}$ and distinguish between low load and high load scenarios:

- *Scenario 1*: Each node generates $\rho_{Node}^{dem} = 0.001$ (low load).
- *Scenario 2*: Each node generates $\rho_{Node}^{dem} = 0.0125$ (high load).

For both scenarios we have measured packet delays and have averaged their values over all flows of the scenario. The experiments were conducted for four cases:

DSDV Flat: Destination Sequenced Distance Vector (DSDV) [6] routing in a flat single-channel network

Hier. Optimal: clustering and hierarchical routing according to the results obtained from the global optimization

Hier. Distributed: clustering and hierarchical routing according to the results obtained from the distributed algorithms

Dist. Rout/Opt. Clus.: distributed hierarchical routing over optimal clustering

DSDV routing is a simple non-hierarchical routing using single channel which tries to minimize hop distance. We wish to compare the impact of the hierarchization against such a routing to establish the value of the QoS gain against no hierarchy at all. As seen in Fig. 4, the tendency to avoid high amount of losses which are observed with a flat routing is maintained in the scenarios for the optimal and distributed cases, thereby supporting the basic idea leading to our approach. However, it is also obvious, that the latter suffers from a poorer performance for lower delay values. The reason for this lies in the suboptimal clustering found by the distributed algorithm. When the distributed algorithm for the routing runs over the optimal clustering, the results become close to the expected performance.

On the other hand, even for the optimal case for clustering and routing, we observe significant delays compared to DSDV flat routing. The reason for this behavior is twofold: First, the routing via the cluster heads sometimes generates "unnecessary" hops which increase delays. Secondly, the scheduling within a cluster, in particular the communication between cluster head and bridges, which due to their dual homing in two clusters sometimes are unavailable, creates quite a control overhead, the mechanisms of which have to be tuned to optimal parameter settings of the MAC layer. Although opportunistic receptions within the clusters help to reduce the unnecessary hops, the results improve marginally.

The gap between optimal and distributed curves (approx. factor of 2-3) indicates that the clustering algorithm in the distributed approach has room for improvements. The positive impact of the proposed solution is evident for the high load scenario. When the flat routing DSDV has very high (30%) losses, the hierarchical routing reduce them to 5% (even in the optimal case), and avoid large delays for the 25% recovered traffic.

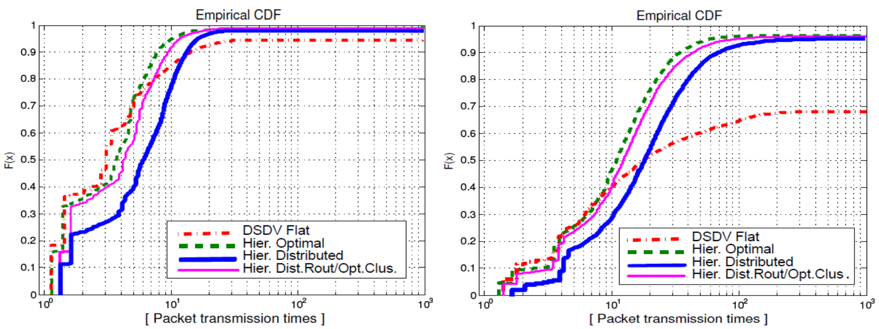

Fig. 4. (Left) Scenario 1: Cumulative distribution functions of the average delay for low load and for the 4 cases. (Right) Scenario 2: Distribution of the average delay with high load.

7 Conclusions and Future Work

We have shown that hierarchical routing in a sensor network with multi-channel capability will lead to a reduction of large delays and losses in WSN, which extends the QoS support for emerging services as these networks become more integrated to the incoming Internet of Things. We have presented results for an optimal cluster-based routing as well as for distributed algorithms of clustering, frequency allocation and routing. As practical wireless sensor networks are not suited for approaches based on centralized optimal solutions, we have tried to derive a heuristic using the optimization model as base. It comes not as a surprise that the global optimization algorithms perform better than the distributed ones. However, also the global optimization algorithms do not meet the low delay values found with the non-hierarchical routing for scenarios of low load. With high loads, the hierarchy shows better results in terms of end-to-end delays and losses, which indicates the applicability of the solution for the proposed scope, such as distributed manufacturing monitoring. A gap in the results between the distributed algorithms and the optimum was observed. The reason – and therefore also the topic for future work – lies in the scheduling overhead, the interaction between the scheduling at cluster level and the MAC layer, and the MAC parameter optimization, to speed up the two-hop forwarding within a cluster. Finally, to further improve the hierarchy against flat networks, a clustering algorithm which pursues the optimization of the objective function in a more formal context is expected to deliver better results.

Acknowledgments. The authors gratefully acknowledge the support of this work by the German Research Foundation (DFG).

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