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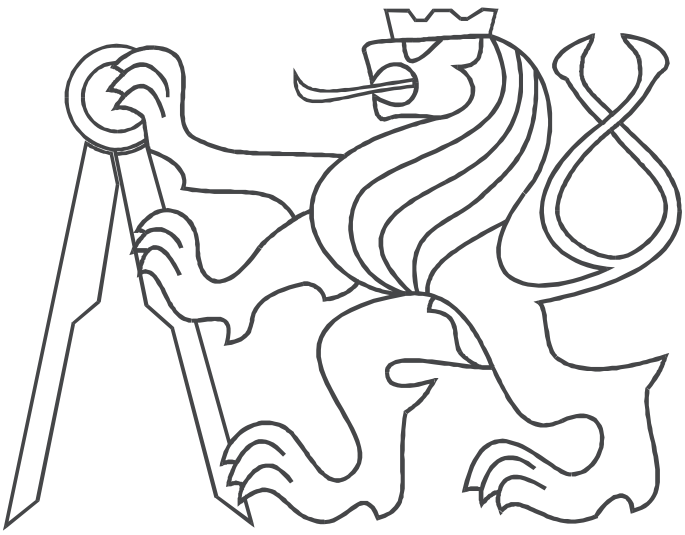

Doctoral Thesis Statement

Czech Technical University in Prague

Faculty of Electrical Engineering

Department of Control Engineering

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On Distributed and Real-Time Routing in Sensor Networks

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Abstract

The thesis is focused on in-network distributed and real-time routing algorithms for multi-hop sensor networks. The work aims mathematically derived algorithms which are based on the convex optimization theory and which are capable of computing an exact optimal solution e.g. in terms of the energy consumption. The work consists of three parts.

The first part is focused on centralized algorithms for real-time routing in sensor networks. Two routing algorithms are developed in this chapter. The first algorithm addresses problem with continuous data streams with a real-time constraints on communication delay. The second algorithm addresses problem, where the real-time data are send in messages with transmission periods significantly bigger than one hop communication delay. The both algorithms are based on a minimum-cost multi-commodity network flow model and use a network replication to include the real-time constraints. Solved by Linear Programming, they exhibit a very good performance, as is shown in our experiments. Surprisingly, the performance does not degrade even in the presence of an integral flow constraint, which makes the problems NP hard.

The second part of this work is focused on in-network distributed energy optimal routing algorithms for non-real-time data flow. Three distributed routing algorithms are mathematically derived in this part: *Two Loops Distributed Routing Algorithm* (TLDRA), *One Loop Distributed Routing Algorithm with Incremental flow update* (OLDRAi) and *One Loop Distributed Routing Algorithm with Optimal flow update* (OLDRAo). The algorithms are based on the proximal-point method and the dual decomposition of convex optimization problem. The algorithms compute an exact energy optimal routing in the network without any central node or the knowledge about the whole network structure, using only peer-to-peer communication between neighboring nodes. In contrast to other works in this area, the presented approach is not limited to strictly convex objective functions and it handles linear objective functions too. Proofs of the algorithms convergence are presented.

The third part of this work is focused on distributed routing algorithm for real-time data streams. The algorithm is based on the OLDRAo algorithm and on the routing algorithm for continuous data streams with real-time constraints from the two previous parts.

The behaviors of all presented algorithms have been evaluated on benchmarks for energy optimal routing in multi-hop sensor networks, using Matlab.

1 Introduction

1.1 Motivation

The communication systems and networks are one of the most important phenomena of the today's world. The almost whole word is connected and the communication systems are still evolving. Many communication systems are publicly well known such as the Internet, Cell phones, satellite networks etc. On the other side, many communication systems are not so well known, but they affect our lives not less, maybe more. There are e.g. the industrial networks, car systems, building control etc.

The development in the recent years is changing the configuration and the control of the communication systems. In many areas, the networks control is changing from the centralized control systems to distributed. Simultaneously, many communication systems are changing into so called multi-hop or switched communication, which increases data throughput and robustness. Examples of such systems are e.g. the Profinet, the switched Ethernet or the Sensor Networks.

1.1.1 Sensor Networks

The sensor networks are technology of future, which can significantly change the world as we know it. (for more detail see e.g. [14]) The rise of this technology is based on the recent development in the micro-electronic area. The main idea is to create a small and cheap devices, which are equipped with a microprocessor, a radio transceiver, some components to interact with the environment (typically sensors) and an energy source (typically battery). The sensor networks are meant to consist of hundreds or thousands of devices (usually called *motes* or *nodes*), which cooperate on given tasks. Primarily, the development was motivated by military applications such as battlefield monitoring. Today, they are used in many industrial and consumer applications, such as industrial process control, environment monitoring, home automation, traffic control etc.

The main challenges in the sensor networks lay in the strictly resource limitations such as limited energy, limited communication bandwidth or limited computational power. The limited resources are the main reason for the optimization in all levels of research. In this work we focus on the routing problems.

1.1.2 Routing in Sensor Networks

To save energy during the communication the nodes in sensor networks use multi-hop communication, which is a communication, where the messages are routed to their destinations through some other nodes, in order to decrease the transmission distance and save the energy (see illustration in Figure 1).

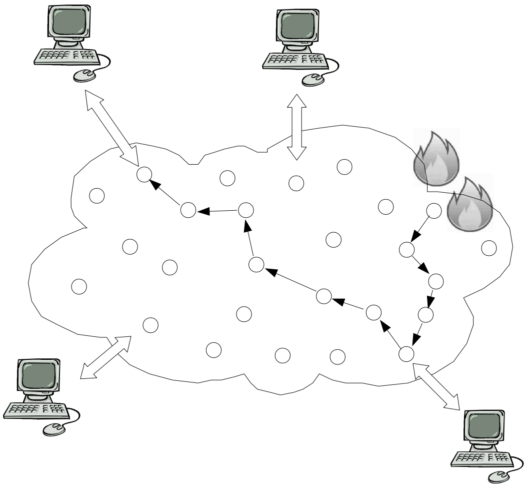


Fig. 1: Multi-hop communication

The routing algorithms can be categorized as on-line or off-line algorithms. The on-line algorithms choose the massage routing according to actual situation. The off-line algorithms use precomputed routing rules. The on-line algorithms are usually more simple, more robust in the case of network damage. On the other side the off-line algorithms are usually more effective in terms of energy consumption and communication bandwidth utilization [21].

A different categorization of the routing algorithms, important for this work, is into classes of centralized and distributed algorithms. The centralized algorithms are computed in a central computational point and then the routing rules are distributed into the network (e.g. [9]). The distributed algorithms are based on the cooperation of the individual nodes. The distributed algorithms are more robust against network damage. On the other side, to achieve the same optimality as the centralized algorithms they are more complicated and they are the challenges of the current research. The off-line routing algorithms can be both distributed or centralized.

1.1.3 Real-Time Routing

In many applications in sensor networks area such as industrial process control or fire detection, which are time-critical, a real-time communication is required. The objective of the real-time communication is to ensure that all the routed data are delivered to their destinations before their deadlines.

There are two main methods to model the communication delay in the sensor networks. The queuing delay, which is more suitable for networks using CSMA and similar medium access mechanism, where the communication delay is a function of data flow volume (e.g.[30]). And the constant communication delay, which is more suitable for networks with TDMA based medium access mechanism, where the communication delay depends on the number of communication hops and time slots schedule [9]. In this work, we focus on the constant communication delay, which is often used in the industry communication systems.

1.2 Related Works

Traditionally, routing problems for data networks are often formulated as linear or convex multi-commodity network flow routing problems e.g. [4, 11, 30, 7] for which many efficient solution methods exist [3, 27, 5, 19].

In [35], the multi-commodity problem formulation is used for simultaneous routing and resource allocation, which finds more efficient routing than the separated algorithms. One of the advantages of this method is that several objective functions and constraints can be put together. Using the same underlying model, we can easily combine the solution of different works focused on partial problems.

Several papers have been performed in the area of real-time routing in multi-hop wireless sensor networks. In [15], a well known soft real-time communication protocol SPEED, is presented. The protocol uses the speed of the message propagation to set priorities of the messages. Several works use relation between message propagation speed and transmitting energy to balance trade-off between energy consumption and communication delay. In [13], a protocol called RPAR is presented, in [6] a protocol called EDEM is presented or in [34] a distributed cross-layer routing mechanism is presented.

There are papers which modify the geographical routing into time aware form [1, 10]. In [24] an algorithm based on direct diffusion which balances node energy utilization is presented. In [20] the authors deal with real-time communications over cluster-tree sensor networks, where they evaluate the end-to-end communication delay. In [8], the authors assume nodes in hexagonal cells and use inter-cell and intra-cell communication in single directions to ensure the real-time behavior. The protocol presented in [33] uses the distance from the last transmitting node to avoid data collisions and the data is sent in communication waves. However, none of these algorithms can ensure real-time and energy optimal routing, especially in high loaded networks.

There are several works, which focus on the decomposition of network optimization problems described by strictly convex optimization. A systematic presentation of the decomposition techniques for network utility maximization (NUM) is presented in [29, 28, 12]. The authors present several mathematical approaches to structural decomposition of the NUM problems and classify them. In [18, 17, 26] the authors use the dual decomposition to decompose cross-layer optimization problems into optimization of separated layers. The presented approaches lead to structural decomposition (e.g. to routing layer, capacity layer...) which is not suitable for derivation of the in-network distributed algorithm. In [16] a general distributed algorithm for strictly convex optimization problems with common parameter for all nodes is presented.

The decomposition of an optimal routing problem is presented e.g. in [32, 25], where the authors have focused on the node-path formulation of the routing problem and use the dual decomposition to find the distributed algorithm. The presented algorithms can be described as a negotiation between the source node and the path load. This approach is suitable for problems with a small number of communication paths. However, in sensor networks routing problems, where many possible communication paths exist, we have to find a different way to distribute the routing algorithm.

Beside the ad-hoc real-time routing algorithms SPEED, RPAR and others, which route the data according to actual parameters (like time remaining to the deadline, message priority, network load etc.), there are several works, which focus on the algorithm distributed from their centralized mathematical description and use the precomputed routing paths. Some of the easy algorithms are based e.g. on the Dijkstra's algorithm, or on the network flooding principles (see e.g. [21]). The more sophisticated algorithms are based on the convex optimization theory and use the decomposition methods to derive their distributed version.

In [36] the authors use the network flow problem formulation in node-link form with strictly convex objective function to derive the distributed routing algorithm. Further, the authors extend the algorithm to optimize a queuing delay which is strictly convex function of the total flow routed through the links. This approach ignores the constant communication delay, which is independent on the volume of the routed flow. In case of a high flow fragmentation this approach cannot ensure the messages deadlines satisfaction. Moreover, the queuing delay optimization cannot be used in the case of pre-scheduled communication based on the TDMA principles (e.g. GTS allocation in IEEE 802.15.4).

In [2] the authors derive a distributed routing algorithm, where they minimize communication delay, which is caused by computation in the nodes. The authors focus on the time needed for the messages decoding and encoding in the nodes to check and regenerate the corrupted data. The objective function of this problem is linear. The authors use the quadratic approximation of the objective function to derive the distributed algorithm.

In contrast with all the papers about real-time routing in sensor networks referenced here, our approach ensures the real-time and energy optimal routing for all communication demands even in high loaded networks.

All the in-network distributed algorithms referenced here are limited to strictly convex objective functions and fail in the case of linear objective functions. According to our knowledge, this work is the first one, which addresses and solves the problem of the dual decomposition of NUMs for problems with linear objective functions.

2 Aims of the Doctoral Thesis

The main goal of this thesis is to bring a new knowledge into the area of in-network distributed and real-time routing algorithms for multi-hop sensor networks. The work aims mathematically derive algorithms which are based on the convex optimization theory and which are capable of computing an exact optimal solution e.g. in terms of the energy consumption.

The goals of the thesis are:

1. Develop a centralized algorithm for real-time routing in multi-hop sensor networks.
2. Derive in-network distributed routing algorithm for non-real-time data flow in multi-hop sensor networks.
3. Derive in-network distributed routing algorithm for real-time data flow in multi-hop sensor networks.

3 Main Results of Thesis

3.1 Multi-Commodity Network Flow Model

The work in this thesis is based on the multi-commodity network flow model, which is used as an underlaying model to describe the routing problem by mathematical equations (see e.g.[4, 11, 30, 7]). The model is formulated by Linear Programming in node-link form as:

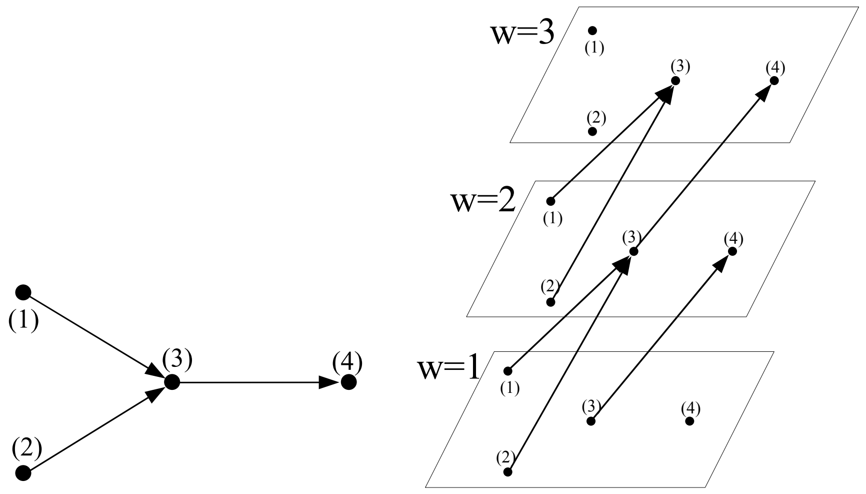
$$\begin{array}{rcll} \min\limits_{x} & \vec{c}^T\vec{t} & & \\ \textbf{subject to:} & & & \\ A^-\vec{x}^{(m)} + \vec{s}_{out}^{(m)} & = & A^+\vec{x}^{(m)} + \vec{s}_{in}^{(m)} & \forall m \in \mathcal{M} \\ \vec{t} & = & \sum\limits_{m\in\mathcal{M}} \vec{x}^{(m)} & \\ D\vec{t} & \leq & \vec{\mu} & \\ \vec{x}^{(m)} & \geq & \vec{0} & \forall m \in \mathcal{M} \end{array} \tag{1}$$

The vector $\vec{c} > 0$ is a column vector of the energy consumption per sent data unit. The $\mathcal{M}$ denotes set of all communication demands in the network. The column vector $\vec{s}_{in}^{(m)} \geq \vec{0}$ denotes the flow coming into the network, the $\vec{s}_{out}^{(m)} \geq \vec{0}$ denotes the flow leaving the network and the $\vec{x}^{(m)} \geq \vec{0}$ denotes the flow routed through the network for demand m. The vector $\vec{t} \in \mathcal{R}^L$ denotes the total flow for each link over the network. The matrices A^+ and A^- are incidence matrices for incoming and leaving links defined as:

$$A^+_{n,l} = \begin{cases} 1, & l \in \mathcal{I}(n) \text{ (link } l \text{ enters node } n) \\ 0, & \text{otherwise} \end{cases} \tag{2}$$

$$A^-_{n,l} = \begin{cases} 1, & l \in \mathcal{O}(n) \text{ (link } l \text{ leaves node } n) \\ 0, & \text{otherwise} \end{cases} \tag{3}$$

The matrix D and the column vector $\vec{\mu}$ describe the capacity constraints. If there is a separate capacity for each communication link, matrix D is the identity matrix of size



(a) Original graph (b) Expanded graph for 2 hops

Fig. 2: Intuitive presentation for the graph replication.

$[L \times L]$ and $\vec{\mu} \geq \vec{0}$ consists of the link capacities. For the node capacities the $\vec{\mu} \geq \vec{0}$ is column vector of the node capacities and matrix D is

$$D_{n,l} = \begin{cases} 1, & l \in \mathcal{O}(n) \text{ (link } l \text{ leaves node } n\text{)} \\ 0, & \text{otherwise} \end{cases} \tag{4}$$

3.2 Centralized Algorithms for Real-Time Data Routing in Sensor Networks

The first part of our work is focused on centralized algorithms for data flow routing through the multi-hop sensor network, where all data has to be delivered to the destinations in time. The objective is to optimize the energy consumption for the data transfer and we assume the following constraints: link capacities, node capacities and different deadlines for each value sensed. All data has to be delivered before their deadlines. We assume a TDMA (Time Division Multiple Access) protocol (e.g. GTS allocation in IEEE 802.15.4 [22, 23]) which ensures collision-free communication and causes communication delay. Due to the TDMA mechanism assumed, the worst-case delay from the source node to the sink node is the sum of the particular delays for each of the hops, assumed to be an integer (derived from the parameters like TDMA period, worst-case execution time of the communication stack...). In a particular setting, we may assume a unit hop delay (the same TDMA period, negligable influence of the transmission delay on the physical layer...). In this work we assume the unit hop delay (the deadlines are expressed as the number of communication hops between devices) which is very transparent for the reader and furthermore it can be generalized to integer delays that may differ for each hop [31].

The approach used to include the communication delay into the network flow model can be introduced in intuitive way as a network replication. The network is replicated into several layers, where each layer represents a different communication delay and the communication links are redirected into the upper layers. In this way, all flow routed through the network is routed both in the node space and in the delay space simultaneously. See Figure 2. We have converted the real-time constraint (i.e. the delay has to be shorter than the deadline) to the structural constraint. Only the flow, whose delay is shorter than the deadline, is represented. The flow, which does not meet the deadline, causes that the flow conservation law does not hold and then the network flow constraints are not satisfied, i.e. this solution is not feasible.

The final routing algorithm for the continuous data streams (flow), developed in this thesis, is described as Linear Programming problem:

$$\min_{\vec{x},\vec{s}} \quad \vec{c}^T\vec{t}$$

$$\begin{array}{rcll}
\multicolumn{4}{l}{\textbf{subject to:}} \\
A^-\vec{x}^{(m,w+1)} + \vec{s}_{out}^{(m,w)} & = & A^+\vec{x}^{(m,w)} + \vec{s}_{in}^{(m,w)} & \forall m \in \mathcal{M},\ 0 \le w \le d^{(m)} \\
\vec{s}_{out}^{(m)} & = & \sum_{w=0}^{d^{(m)}} \vec{s}_{out}^{(m,w)} & \forall m \in \mathcal{M} \\
\vec{t} & = & \sum_{m\in\mathcal{M}} \sum_{w=0}^{d^{(m)}} \vec{x}^{(m,w)} & \\
D\vec{t} & \le & \vec{\mu} & \\
\vec{x}^{(m,w)} \ge \vec{0};\quad \vec{s}_{in}^{(m,w)} & \ge & \vec{0};\quad \vec{s}_{out}^{(m,w)} \ge \vec{0} & \forall m \in \mathcal{M},\ 0 \le w \le d^{(m)} \\
\vec{x}^{(m,0)} = \vec{x}^{(m,d^{(m)}+1)} & = & \vec{0} & \forall m \in \mathcal{M}
\end{array} \tag{5}$$

Vector $\vec{x}^{(m,w)} \in \mathcal{R}^L$ denote the flow of communication demand m with integer communication delay w. The $d^{(m)}$ denotes the deadline of the communication demand m. Vector $\vec{s}_{out}^{(m,w)} \in \mathcal{R}^N$ stands for the flow of the demand m leaving the network with communication delay w and vector $\vec{s}_{in}^{(m,w)} \in \mathcal{R}^N$ denotes the flow of demand m coming into the network with initial delay w.

For the case when the message transmission periods are much bigger than the one hop communication delay, we adjust the algorithm into more suitable form. We define for each communication demand the transmission period $p^{(m)} > 0$ and the transmission offset $o^{(m)} \ge 0$ (start time within the network period P). P denotes a network period defined as a least common multiple of periods $p^{(m)}$ of all communication demands $m \in \mathcal{M}$.

Variable $q \in \mathcal{N}$ denotes discrete time within the network period $1 \le q \le P$. We define a set $\mathcal{T}(q)$ of pairs (m, w). If pair (m, w) is in set $\mathcal{T}(q)$, the flow of demand $m \in \mathcal{M}$ with delay w is routed through the network in time q.

$$\begin{array}{rcl}
\mathcal{T}(q) & = & \Big\{(m,w) \mid m \in \mathcal{M};\ 1 \le w \le d^{(m)}; \\
& & q = \ (w + u \cdot p^{(m)} + o^{(m)}) \mod P; \\
& & 0 \le u < P/p^{(m)};\ u \in \mathcal{Z}_+^0\Big\}
\end{array} \tag{6}$$

In summary, the constraints of the real-time routing problem are:

$$\begin{array}{rcll} A^{-}\vec{x}^{(m,w)} + \vec{y}^{(m,w)} & = & A^{+}\vec{x}^{(m,w-1)} + \vec{y}^{(m,w-1)} & \\ & & & \forall m \in \mathcal{M},\ 2 \leq w \leq d^{(m)} \\ A^{-}\vec{x}^{(m,1)} + \vec{y}^{(m,1)} & = & \vec{s}_{in}^{(m)} & \forall m \in \mathcal{M} \\ A^{+}\vec{x}^{(m,d^{(m)})} + \vec{y}^{(m,d^{(m)})} & = & \vec{s}_{out}^{(m)} & \forall m \in \mathcal{M} \\ \sum\limits_{(m,w)\in\mathcal{T}(q)} \vec{x}^{(m,w)} & = & \vec{t}^{(q)} & \forall 1 \leq q \leq P \\ D\vec{t}^{(q)} & \leq & \vec{\mu} & \forall 1 \leq q \leq P \\ \vec{x}^{(m,w)} \geq \vec{0}; \quad \vec{y}^{(m,w)} & \geq & \vec{0} & \forall m \in \mathcal{M},\ 0 \leq w \leq d^{(m)} \end{array} \tag{7}$$

An advantage of the presented algorithms is, that the real-time routing is described as a multi-commodity network flow problem with side constraints. The side constraints of the problem are in form, which allow future problem distribution as an in-network algorithm.

3.3 Distributed Routing Algorithms

Without loss of generality, we rewrite the routing problem (1) into the equality form for a more transparent presentation.

$$\begin{array}{rcl} \min\limits_{\vec{x}} & & \vec{c}^{T}\vec{x} \\ & \textbf{subject to:} & \\ A\vec{x} & = & \vec{b} \\ \vec{x} & \geq & \vec{0} \end{array} \tag{8}$$

Based on the proximal-point method (see e.g. [3]) and on the dual decomposition we derive an in-network distributed routing algorithms called *Two Loops Distributed Routing Algorithm* (TLDRA), which consist of two nested loops:

```
LOOP 1
    LOOP 2
        $\vec{x} = \left[\vec{x}'' - \frac{1}{2\varepsilon}(\vec{c} + A^{T}\vec{\theta})\right]^{+}$
        $\vec{\theta} = \vec{\theta} + \alpha(A\vec{x} - \vec{b})$                (9)
    END 2
    $\vec{x}'' = \vec{x}'' + 2\alpha\varepsilon(\vec{x} - \vec{x}'')$
END 1
```

Where $\alpha > 0$ is a constant step size of gradient algorithm and $\varepsilon > 0$ is proximal-point constant.

The algorithm computes the energy optimal routing without the need of any central computational or data point. Each node knows only the cost (energy consumption per sent data unit c_i) of its outgoing communication links and the data which it is supposed to send and receive.

Next in this part we present two approaches to adjust the two-looped algorithm in to one-looped algorithms. If we join the nested loops into one iteration loop, we get an algorithm, which consists of equations:

$$\begin{aligned}
\vec{x}_k &= \left[\vec{x}''_k - \tfrac{1}{2\varepsilon}\left(\vec{c} + A^T\vec{\theta}_k\right)\right]^+ \\
\vec{\theta}_{k+1} &= \vec{\theta}_k + \alpha(A\vec{x}_k - \vec{b}) \\
\vec{x}''_{k+1} &= \vec{x}''_k + 2\alpha\varepsilon(\vec{x}_k - \vec{x}''_k)
\end{aligned} \tag{10}$$

where variable k denotes the iteration number. The proof of the algorithm convergence is not a trivial problem and it is presented in the thesis. A necessary condition for the algorithm convergence assumed in the proof is $\alpha < 1/2\varepsilon$. To prove the algorithm convergence, we define a merit function P_k such that $P_k \geq 0$ and $P_k = 0$ for the optimal solution. We show that P_k is non-increasing during the algorithm computation. Next, we assume the merit function P_k to be non-decreasing for all $k \geq k_0$ and show, for feasible problems, that for some $k_1 \geq k_0$ we get the optimal solution.

As mentioned in Introduction, the other works from the area of network utility maximization (NUM) concentrate only on the strictly convex optimization problems, or they approximate the linear problems as strictly convex. They fail in the case of linear objective functions. According to our knowledge, this is the first work, which addresses and solves the problem of the dual decomposition of NUMs for problems with linear objective functions.

Considering the fact, that the algorithms are based on Linear programming formulation, we believe that the principle of the algorithms and the approaches used to their derivation can be used to solve many different problems in the sensor networks area, like resource sharing, network localization, object tracking, etc.

3.4 Distributed Algorithms for Real-Time Routing

The final result of the thesis is an in-network distributed algorithms for real-time routing. It is based on the modified multi-commodity network flow model for real-time routing which is defined as network flow problem with side constraints. The side constraints are in form, which allows the problem distribution as an in-network algorithm according to the previously derived approach.

The final algorithms is presented in Table 1.

4 Conclusion

In this thesis we have focused on the in-network distributed and real-time routing problems in the multi-hop sensor networks. The work is divided into three parts. The first part

1. Initialize variables $\vec{x}_0^{\prime\prime(m,w)}$, $\vec{s}_0^{\prime\prime(m,w)}$, $\vec{z}_0^{\prime\prime(m,w)}$, $\vec{\theta}_0^{(m,w)}$, $\vec{\lambda}_0$, $\vec{\gamma}_0^{(m)}$.
2. Compute primal variables $\vec{x}_k$, $\vec{z}_k$, $\vec{s}_k$ according to:

$$\begin{aligned}
\vec{x}_k^{(m,w)} &= \left[\vec{x}_k^{\prime\prime(m,w)} - \tfrac{1}{2\varepsilon}(A^{-^T}\vec{\theta}_k^{(m,w-1)} - A^{+^T}\vec{\theta}_k^{(m,w)} + D^T\vec{\lambda}_k + \vec{c})\right]^+ \\
\vec{z}_k &= \left[\vec{z}_k^{\prime\prime} - \tfrac{1}{2\varepsilon}\vec{\lambda}_k\right]^+ \\
\vec{s}_k^{(m,w)} &= \left[\vec{s}_k^{\prime\prime(m,w)} - \tfrac{1}{2\varepsilon}\vec{\gamma}_k^{(m)}\right]^+ \\
\vec{x}_k^{(m,0)} &= \vec{x}_k^{(m,d^{(m)}+1)} = \vec{0}
\end{aligned}$$

3. Send/Receive the primal variables $\vec{x}_k$, $\vec{z}_k$, $\vec{s}_k$ to/from neighboring nodes.
4. Compute dual variables $\vec{\theta}_{k+1}$, $\vec{\lambda}_{k+1}$, $\vec{\gamma}_{k+1}$

$$\begin{aligned}
\vec{\theta}_{k+1}^{(m,w)} &= \vec{\theta}_k^{(m,w)} + \alpha(A^-\vec{x}_k^{(m,w+1)} - A^+\vec{x}_k^{(m,w)} + \vec{s}_k^{(m,w)} - \vec{s}_{in}^{(m,w)}) \\
\vec{\lambda}_{k+1} &= \vec{\lambda}_k + \alpha(D\sum_{m\in\mathcal{M}}\sum_{w=1}^{d^{(m)}}\vec{x}_k^{(m,w)} + \vec{z}_k - \vec{\mu}) \\
\vec{\gamma}_{k+1}^{(m)} &= \vec{\gamma}_k^{(m)} + \alpha(\sum_{w=0}^{d^{(m)}}\vec{s}_k^{(m,w)} - \vec{s}_{out}^{(m)})
\end{aligned}$$

5. Compute proximal-point variables $\vec{x}_{k+1}^{\prime\prime}$, $\vec{s}_{k+1}^{\prime\prime}$, $\vec{z}_{k+1}^{\prime\prime}$

$$\begin{aligned}
\vec{x}_{k+1}^{\prime\prime(m,w)} &= \vec{x}_k^{\prime\prime(m,w)} + \alpha(-2\varepsilon(\vec{x}_k^{(m,w)} - \vec{x}_k^{\prime\prime(m,w)})) \\
\vec{z}_{k+1}^{\prime\prime} &= \vec{z}_k^{\prime\prime} + \alpha(-2\varepsilon(\vec{z}_k - \vec{z}_k^{\prime\prime})) \\
\vec{s}_{k+1}^{\prime\prime(m,w)} &= \vec{s}_k^{\prime\prime(m,w)} + \alpha(-2\varepsilon(\vec{s}_k^{(m,w)} - \vec{s}_k^{\prime\prime(m,w)}))
\end{aligned}$$

6. Send/Receive the dual variables $\vec{\theta}_{k+1}$, $\vec{\lambda}_{k+1}$, $\vec{\gamma}_{k+1}$ to/from the neighboring nodes.
7. Set $k = k + 1$ and start new iteration in step 2.

Table 1: Distributed, Real-Time Routing Algorithm

deals with a centralized algorithm for the real-time routing. The second part deals with a general distributed algorithm for the non-real-time routing problems described by multi-commodity network flow model. The third part joints the works from the previous two parts and introduces a distributed algorithm for real-time routing in the sensor networks.

In the first part of the thesis, we have introduced centralized algorithm for the real-time routing in the sensor networks. The algorithm is based on the minimum-cost multi-commodity network flow model described as a Linear Programming problem. We have used the network replication to model the constant communication delay in the network. The derived real-time model stays in the form of multi-commodity network flow problem with side constraints. The structure of the side constraints allow us to derive the distributed algorithm. Solved in centralized way by Linear Programming, it exhibits a very good performance, as was shown in our experiments. Surprisingly, the performance does not degrade even in the presence of an integral flow constraint, which makes the problem NP hard. It follows that the model is very powerful from the practical point of view and can be used in many applications where the response time is the subject of constraints.

In the second part of this thesis, we have developed three in-network distributed routing algorithms, which are based on the dual decomposition of minimum-cost multi-commodity network flow problem. The algorithms derivation use the Linear Programming model in node-link form, which leads to unique peer-to-peer distributed algorithms. Only the communication between the neighboring nodes is needed during the computation. Moreover, the algorithms compute the energy optimal routing for problems with linear objective functions. All other distributed routing algorithms based on the dual decomposition focus only on the problems with strictly convex objective functions and fail in the case of the linear objective functions. According the fact, that the presented algorithms are based on the general minimum-cost multi-commodity network flow problem, it can be easily adapted for many other problems in the sensor network area, like resource sharing, network localization, object tracking, etc.

In the third part of this thesis, we have used the results of the previous two parts and developed an in-network distributed real-time routing algorithm. As mentioned above the centralized real-time routing problem is described as minimum-cost multi-commodity network flow, which allow us to use the general distribution approach form second part of the thesis. The resulting algorithm finds the energy optimal routing with real-time constraints even for the problems with linear objective functions, using only the peer-to-peer communication between the neighboring nodes. In contrast to the other works, this algorithm uses constant communication delay independent on the routed flow volume. It allow using this algorithm e.g. in industrial networks with TDMA like mechanism. The other works in this area use the queuing delay, which is strictly convex function of the routed flow volume and it is not well suitable for problems with hard real-time constraints.

The main contributions of this work are:

1. Formulation of a real-time multi-commodity network flow problem and its solution by Linear Programming based on graph replication.
2. Discovery of a surprisingly good Integer Linear Programming performance for the above mentioned problem with an integral data flow constraint, which makes the problem NP hard.
3. Introduction of a new distributed algorithm based on dual decomposition of routing problem formulated in node-link form.
4. Presentation of novel approach to distribute the linear optimization problem by dual decomposition as an in-network distributed algorithm. (Other works using the dual decomposition on the routing problems are limited to strictly convex objective functions and fail in the linear case.)
5. Introduction of new mathematically derived, distributed algorithm for energy optimal real-time routing based on network replication and dual decomposition.
6. Performance evaluation of all presented algorithm on benchmarks for energy optimal routing in sensor networks.

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List of Candidate's Works

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List of Responses

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Distribuované a Real-Time Routování v Senzorových Sítích.

Jiří Trdlička
České Vysoké Učení Technické v Praze, 2011

Školitel: Doc. Dr. Ing. Zdeněk Hanzálek

Tato práce je zaměřena na distribuované a real-time routovací algoritmy pro senzorové sítě. Práce se soustředí na matematicky odvozené algoritmy, které jsou založeny na teorii konvexní optimalizace a jsou schopny nalézt optimální řešení ve smyslu spotřeby energie. Práce se skládá ze tří částí.

První část je věnována centralizovaným algoritmům pro real-time routování. V této části jsou odvozeny dva algoritmy. První algoritmus je určen pro souvislé datově toky s časovým omezením na komunikační zpoždění. Druhý algoritmus je pak určen pro periodicky zasílané zprávy s periodou vysílání výrazně vyšší, než doba jednoho komunikačního skoku. Oba algoritmy jsou založeny na teorii nejlevnějších multi-komoditních toků v síti. Algoritmy vykazují velmi dobrou časovou náročnost při řešení pomocí Lineárního Programování. Překvapivě, výkon algoritmů neklesá ani pro celočíselné problémy, které patří mezi NP-úplné problémy.

Druhá část práce je věnována distribuovaným ne-real-time routovacím algoritmům. V této části jsou odvozeny tři algoritmy: *Dvou-Smičkový Distribuovaný Algoritmus* (TLDRA), *Jedno-Smičkový Distribuovaný Algoritmus s Inkrementálním krokem* (OLDRAi) a *Jedno-Smičkový Distribuovaný Algoritmus s Optimálním krokem* (OLDRAo). Algoritmy jsou odvozeny za pomoci metody přibližného bodu a duální dekompozice pro konvexní problémy. Algoritmy naleznou optimální řešení bez potřeby centrálního výpočetního bodu a jednotlivá zařízení komunikují pouze se sousedy v komunikačním dosahu. Na rozdíl od ostatních prací v této oblasti, algoritmy prezentované v této disertační práci nejsou omezeny pouze na striktně konvexní problémy a dokáží řešit i lineární problémy. Důkaz konvergence je součástí odvození algoritmů.

Třetí část práce je zaměřena na distribuovaný real-time routovací algoritmus. Algoritmus je založen na OLDRAo algoritmu a na centralizovaném algoritmu pro real-time routování z předchozích dvou částí.

Chování všech prezentovaných algoritmů bylo otestováno a vyhodnoceno simulacemi v prostředí Matlab.