IEEE Ninth International Symposium on Wireless Communication Systems, August 2012, Paris, France

Delay Constraints for Multiple Applications in Wireless Sensor Networks

Zhiliang Chen, Alexander Kuehne and Anja Klein
Communications Engineering Lab, Technische Universität Darmstadt, Germany
Email: {z.chen,a.kuehne,a.klein}@nt.tu-darmstadt.de

***Abstract*—Sensors are capable of supporting multiple applications concurrently. Recent works reveal several possibilities of running multiple applications in a wireless sensor network. In this work, we introduce the compression factor to quantify the change of the message length due to the aggregations of application messages. Delay constraints are introduced for two communication paradigms in wireless sensor networks, 1) the routing-based paradigm where sinks are specified and the routing trees are built for the aggregation; 2) the random-gossiping paradigm where aggregations are done by sensor nodes randomly communicating with the neighbour sensor nodes without specifying the sinks. Optimization problems which minimize the total energy consumption in the network are proposed for the two communication paradigms with the corresponding delay constraints. An example of a wireless sensor network with three sensor nodes and two concurrently running applications is used to demonstrate the optimization problems. Simulation results shows how compression factors affect the energy consumption while the message length of the application is increasing.**

I. Introduction

Sensors nodes in wireless sensor networks (WSNs) are able to measure data from the physical world and generate messages of several applications, e.g. temperature, humidity, moving subjects, etc.. Diversities of solutions of supporting multiple applications in WSNs are proposed by recent researches such as [1], [2], [3], [4]. In [1], a cross-layer energy management and admission control policy on sensor node level is proposed. The queueing problem when WSNs run concurrent applications is discussed in [2] and algorithms are proposed to keep the WSN running efficiently while allowing multiple users (applications) to use the network. The work in [3] proposes a network layer protocol that forwards data packets of different applications one after another towards multiple gateways. In [4], a WSN is partitioned with a weighted balanced two-slice problem in order to support two applications running in a WSN concurrently. In our previous work [5], we proposed a method using two-way relaying to support bi-directional communications with multiple applications where the computation function of multiple applications and the power allocation are jointly considered.

The delay of the message transmission and aggregation is a commonly used parameter to specify the QoS required by the applications [6]. In this paper, we propose two delay constraints for two types of communication paradigms in WSNs. The first one is based on generating routing trees in the WSN where messages generated by sensor nodes are forwarded towards given sinks where delays are measured [7]. The second paradigm is based on random gossiping among sensor nodes without sinks being specified [8]. Delays in this paradigm can be measured by the sensor node who is the first to aggregate the messages of the entire network of a given application successfully.

This work was performed within the LOEWE Priority Program Cocoon (www.cocoon.tu-darmstadt.de), supported by the LOEWE research initiative of the state of Hesse/Germany.

In this paper, we provide two types of delay constraints and analyse the minimization of total energy consumption of all sensor nodes in the two communication paradigms. A simple three-nodes WSN is used for simulations. The remainder of the paper is organized as follows. Section II discusses the aggregation functions shortly and introduces the compression factors of applications. In Section III, the energy minimization problems in the two communication paradigms are given in general. Section IV analyses the minimization problem with an example of a WSN consisting three sensor nodes. Section V gives the simulation results and the conclusion of this paper is given in Section VI.

II. Aggregation Functions and Compression Factor

In this paper, we refer to the applications in WSNs by their aggregation functions whose input arguments are the messages of the applications generated by all sensor nodes from their measurements. The set of applications running in the WSN is denoted as $\mathcal{F}$, whose cardinality is $F = |\mathcal{F}|$. For any application $f_i \in \mathcal{F}$, it is assumed that *the initial messages* which are generated by each sensor node before performing aggregations are always of the same length. This length is denoted by symbol M^{f_i} as the *unit message length* of application f_i. Symbol $\mathcal{L}$ denotes the set of all sensor nodes in the WSN, and its cardinality is $L = |\mathcal{L}|$. The set of initial messages generated by sensor node $l \in \mathcal{L}$ for application f_i is denoted as $\mathcal{X}_l^{f_i}$, the cardinality $\eta_l^{f_i} = |\mathcal{X}_l^{f_i}|$ denotes the number of messages with unit message length that sensor node l generates for application f_i.

We use the symbol $\cup$ as the union operation of sets. Let the operator $\langle \mathcal{S} \rangle$ returns the elements of the set $\mathcal{S}$. The aggregations in WSN are to calculate the functions $f_i(\langle \cup_{l\in\mathcal{L}} \mathcal{X}_l^{f_i} \rangle)$ of all applications, which can only be done by communications among sensor nodes [7]. Each sensor node receives messages from other sensor nodes, performs the aggregation and transmits the aggregated messages to other sensor nodes. The aggregation functions supported in WSNs which are calculated in a distributed way are so-called *divisible functions* [9]. Examples of divisible functions are the mean function, the download function, the max/min function, histogram, etc..

The aggregation function at a sensor node maps several input messages to one output message, i.e., the length of the message is changed. To quantify such difference of the message length, we introduce *the compression factor*. If a sensor node has an output messages aggregated from k initial messages of application f_i, the output message has the length of $k \cdot c^{f_i}(k)$ unit message length M^{f_i} where $c^{f_i}(k)$ is defined as the compression factor of application f_i. For example, if sensor node $l \in \mathcal{L}$ who has already generated $\eta_1^{f_1}$ initial messages of application f_1 receives a message aggregated from $\eta_2^{f_1}$ initial messages, the output messages of sensor node l is of length $(\eta_1^{f_1}+\eta_2^{f_1}) \cdot c^{f_1}(\eta_1^{f_1}+\eta_2^{f_1})$ times M^{f_1}. The following comments on the compression factor can be made.

- For aggregation functions such as averaging (consensus), the length of the output message is always the unit message length of the application. In this case, $c^{f_i}(k) = \frac{1}{k}$.
- For aggregation functions such as downloading, all the original messages will be preserved, i.e. $c^{f_i}(k) = 1$.
- In general, the compression factor is $c^{f_i}(k) \in [\frac{1}{k}, 1]$.

Denoting $\mathcal{A}$ as a subset of all sensor nodes $\mathcal{L}$, in this paper a sensor node having a "set of messages $\cup_{l \in \mathcal{A}} \mathcal{X}_l^{f_i}, \mathcal{A} \subseteq \mathcal{L}$ in aggregated form" indicates that the aggregation has been performed to messages $\cup_{l \in \mathcal{A}} \mathcal{X}_l^{f_i}, \mathcal{A} \subseteq \mathcal{L}$ and the length of the aggregation output is $\sum_{l \in \mathcal{A}} \eta_l^{f_i} \cdot c^{f_i}(\sum_{l \in \mathcal{A}} \eta_l^{f_i})$ times the unit message length M^{f_i}.

III. Energy Minimization with Delay Constraints

Energy consumption is a critical figure of merit in WSNs due to the fact that sensor nodes are normally equipped with limited battery capability. In this paper, minimization problems are proposed with the total energy consumption of the sensor nodes being the objective function. In WSNs, two sensor nodes are able to communicate with each other when they are within each other's communication range. We assume all sensor nodes have the same fixed communication range D_{C} in the WSN. The distance between sensor nodes m and n is $D_{m,n}$. The set $\mathcal{C} = \{(m,n) : \forall m,n \in \mathcal{L}; D_{m,n} < D_{\mathrm{C}}\}$ is denoted as the set of all partner nodes who are able to communicate with each other, with m as the transmitter and n as the receiver. Also, we define $\mathcal{C}^m = \{(m,l) : \forall l \in \mathcal{L}; (m,l) \in \mathcal{C}\}$ as the set of communication pairs with sensor node m as the transmitter and $\mathcal{C}_n = \{(l,n) : \forall l \in \mathcal{L}; (l,n) \in \mathcal{C}\}$ as the set of communication pairs with sensor node n as the receiver. The time duration $T_{\mathrm{T},(l,m)}^{f_i}$ gives the transmit time spent by sensor node l when transmitting to sensor node m of application f_i with $(l,m) \in \mathcal{C}$. $T_{\mathrm{R},l}^{f_i}$ denotes the total receive time duration of sensor node l when it receives messages from all its transmit partners during the aggregation time of application f_i. Correspondingly, we denote $P_{\mathrm{T},(l,m)}^{f_i}$ as the transmit power when sensor node l transmits and m receives, $P_{\mathrm{R},l}^{f_i}$ as the power spent by sensor node l for receiving. The transmitting, receiving and processing in WSNs are based on application messages, therefore, we measure the rate of sensor nodes transmitting and processing messages by defining the *message rate*. We define the transmit message rate $r_{\mathrm{T},(l,m)}^{f_i}$, with $(l,m) \in \mathcal{C}$ as the number of initial messages in aggregated form of application f_i that sensor node l transmits to sensor node m per second. $r_{\mathrm{T},(l,m)}^{f_i}$ has the unit *message per second*. The corresponding bit rate $R_{\mathrm{T},(l,m)}^{f_i}$ is then $R_{\mathrm{T},(l,m)}^{f_i} = M^{f_i} r_{\mathrm{T},(l,m)}^{f_i}$.

We assume sensor nodes process the messages with a certain rate in bit-per-second. For application f_i at node l, the processing rate is $R_{\mathrm{Ps},l}^{f_i}$ and the corresponding message rate for processing is then $r_{\mathrm{Ps},l}^{f_i} = R_{\mathrm{Ps},l}^{f_i} / M^{f_i}$. Denoting $\tilde{\eta}_l^{f_i}$ as the total number of messages to be aggregated by sensor node l, the processing time is then given by $T_{\mathrm{Ps},l}^{f_i} = \tilde{\eta}_l^{f_i} / r_{\mathrm{Ps},l}^{f_i}$.

In the following, we provide the delay constraints for two communication paradigms, the Node-Specific-Delay (NSD) constraint for the communication paradigm with routing trees being built and Node-Non-Specific-Delay (NNSD) constraint for the paradigm with random gossiping.

A. Node-Specific-Delay Constraint

For applications such as gateways acquiring measurement data from all sensor nodes, sinks are specified. In this paradigm, aggregation is performed along a routing tree branched off from the sinks to every sensor nodes. The aggregation delays are measured at sinks, i.e., NSD constraint is applied. There are three kind of sensor nodes when the aggregation tree of application f_i are built, the sink node w^{f_i}, the set of branch nodes $\mathcal{Z}^{f_i}$ and the set of leaf nodes $\mathcal{B}^{f_i}$. The sink node w^{f_i} is the root of the aggregation tree. The branch nodes receive messages from their children nodes and forwards the aggregated messages to their father nodes. Each leaf node only has a father node. We have $\{w^{f_i}\} \cup \mathcal{Z}^{f_i} \cup \mathcal{B}^{f_i} = \mathcal{L}$. For node l, we define the set of its children nodes as $\mathcal{K}_l^{f_i}$, where $\forall v \in \mathcal{K}_l^{f_i}$ and $(v,l) \in \mathcal{C}_l$. The father node of sensor node $l \in \mathcal{L}/w^{f_i}$ is $\mathcal{V}(l)$.

If for application f_i, there is only one node active for transmission at a time, i.e., deploying a time-division transmission mode, the receive time of node l is the sum of all the transmission time durations of the nodes in $\mathcal{K}_l^{f_i}$, i.e.,

$$T_{\mathrm{R},l}^{f_i} = \sum_{v \in \mathcal{K}_l^{f_i}} T_{\mathrm{T},(v,l)}^{f_i} \ . \tag{1}$$

The total time for the WSN to finish the aggregation of application f_i is

$$\begin{aligned} T^{f_i} \;=\; & \sum_{b \in \mathcal{B}} \left(T_{\mathrm{Ps},b}^{f_i} + T_{\mathrm{T},(b,\mathcal{V}(b))}^{f_i} \right) \\ & + \sum_{z \in \mathcal{Z}} (T_{\mathrm{Ps},z}^{f_i} + T_{\mathrm{T},(z,\mathcal{V}(z))}^{f_i}) + T_{\mathrm{Ps},w^{f_i}}^{f_i} \ . \end{aligned} \tag{2}$$

When time-division is also applied for different applications, the NSD constraint in the WSN is

$$\sum_{f_i \in \mathcal{F}} T^{f_i} \leq T^c, \tag{3}$$

where T^c is the maximum allowed aggregation delay in the WSN.

The transmit message rate depends on the transmit power of the sensor node. If sensor node l receives from all its children nodes the messages of application f_i that are aggregated from η initial messages, the minimum transmit messages rate $r_{\mathrm{Tx},l}^{f_i,\min}$ that node l requires for application f_i is given by

$$r_{\mathrm{T},(l,\mathcal{V}(l))}^{f_i,\min} = (\eta + \eta_l^{f_i}) \cdot c^{f_i}(\eta + \eta_l^{f_i}) / T_{\mathrm{T},(l,\mathcal{V}(l))}^{f_i} \,. \tag{4}$$

The total energy consumption of application f_i is

$$\begin{aligned} E^{f_i} = & \sum_{b \in \mathcal{B}} \left(P_{\mathrm{Ps},b}^{f_i} T_{\mathrm{Ps},b}^{f_i} + P_{\mathrm{T},(b,\mathcal{V}(b))}^{f_i} T_{\mathrm{T},(b,\mathcal{V}(b))}^{f_i} \right) \\ & + \sum_{z \in \mathcal{Z}} (P_{\mathrm{Ps},z}^{f_i} T_{\mathrm{Ps},z}^{f_i} + P_{\mathrm{T},(z,\mathcal{V}(z))}^{f_i} T_{\mathrm{T},(z,\mathcal{V}(z))}^{f_i} + P_{\mathrm{R},z}^{f_i} T_{\mathrm{R},z}^{f_i}) \\ & + P_{\mathrm{Ps},w^{f_i}}^{f_i} T_{\mathrm{Ps},w^{f_i}}^{f_i} + P_{\mathrm{R},w^{f_i}}^{f_i} T_{\mathrm{R},w^{f_i}}^{f_i} \,. \end{aligned} \tag{5}$$

The total energy can be minimized by adjusting $T_{\mathrm{T},(l,\mathcal{V}(l))}^{f_i}$ and $P_{\mathrm{T},(l,\mathcal{V}(l))}^{f_i}$, therefore, the energy minimization problem is given by

$$\begin{aligned} \min_{T_{\mathrm{T},(l,\mathcal{V}(l))}^{f_i}, P_{\mathrm{T},(l,\mathcal{V}(l))}^{f_i}} \quad & \sum_{f_i \in \mathcal{F}} E^{f_i} \\ \text{st.} \quad & \sum_{f_i \in \mathcal{F}} T^{f_i} \leq T^c \\ & r_{\mathrm{T},(l,\mathcal{V}(l))}^{f_i} \geq r_{\mathrm{T},(l,\mathcal{V}(l))}^{f_i,\min} \\ & \forall l \in \mathcal{L}, \forall f_i \in \mathcal{F} \,. \end{aligned} \tag{6}$$

B. Node-Non-Specific-Delay Constraint

In the communication paradigm based on random gossiping, normally no sinks are specified. The aggregations are performed in such a way that two sensor nodes repeatedly activate the communication between them and share their aggregated messages [8]. We denote $\mathcal{N}_l$ as the set of neighbour sensor nodes of sensor node l where $\forall n \in \mathcal{N}_l, (l,n) \in \mathcal{C}^l, (n,l) \in \mathcal{C}_l$. We define an *active time set* $\tau_{l,n}^{f_i}$ that contains the time durations that sensor node l transmits its messages of application f_i to one of its neighbour sensor nodes n where $n \in \mathcal{N}_l$, receives messages from sensor node n, and both sensor nodes l and n process the messages for aggregation.

After the γ-th active time set $\tau_{l,n}^{f_i}(\gamma)$, the aggregated messages of application f_i at sensor nodes l and n are $\mathcal{X}_l^{f_i}(\gamma)$ and $\mathcal{X}_n^{f_i}(\gamma)$, respectively. Note that we have $\mathcal{X}_l^{f_i}(\gamma = 0) = \mathcal{X}_l^{f_i}$ and $\mathcal{X}_n^{f_i}(\gamma = 0) = \mathcal{X}_n^{f_i}$. After the $(\gamma+1)$-th active time set $\tau_{l,n}^{f_i}$, sensor nodes l and n both have all messages of the set $\mathcal{X}_l^{f_i}(\gamma) \cup \mathcal{X}_n^{f_i}(\gamma)$ in aggregated form, i.e. $\mathcal{X}_l^{f_i}(\gamma+1) = \mathcal{X}_n^{f_i}(\gamma+1) = \mathcal{X}_l^{f_i}(\gamma) \cup \mathcal{X}_n^{f_i}(\gamma)$. When there are at least two sensor nodes having the aggregated messages of all sensor nodes of application f_i, i.e., $\cup_{l \in \mathcal{L}} \mathcal{X}_l^{f_i}$, the aggregation of application f_i is finished. T^{f_i} is then defined as the aggregation delay of application f_i. The total number of active time set $\tau_{l,n}^{f_i}$ in the time duration T^{f_i} is denoted as $\Gamma_{l,n}^{f_i}$.

In this paper, we assume that only one pair of sensor nodes is active for communication at a time. The total energy spent in the WSN for application f_i is then

$$\begin{aligned} E^{f_i} = \sum_{l \in \mathcal{L}} \Bigg[\Bigg(& \sum_{n \in \mathcal{N}_l} \sum_{\gamma=1}^{\Gamma_{l,n}^{f_i}} P_{\mathrm{T},(l,n)}^{f_i}(\gamma) T_{\mathrm{T},(l,n)}^{f_i}(\gamma) \Bigg) \\ & + P_{\mathrm{R},l}^{f_i} T_{\mathrm{R},l}^{f_i} + P_{\mathrm{Ps},l}^{f_i} T_{\mathrm{Ps},l}^{f_i} \Bigg] \,. \end{aligned} \tag{7}$$

In the γ-th active time set $\tau_{l,n}^{f_i}$, the minimum transmit message rate of sensor node l required by application f_i is given by

$$r_{\mathrm{T},(l,n)}^{f_i,\min}(\gamma) = |\mathcal{X}_l^{f_i}(\gamma)| \cdot c^{f_i}(|\mathcal{X}_l^{f_i}(\gamma)|) / T_{\mathrm{T},(l,n)}^{f_i}(\gamma) \,. \tag{8}$$

The energy minimization problem is given by

$$\begin{aligned} \min_{T_{\mathrm{T},(l,n)}^{f_i}, P_{\mathrm{T},(l,n)}^{f_i}} \quad & \sum_{f_i} E^{f_i} \\ \text{s.t.} \quad & \sum_{f_i \in \mathcal{F}} T^{f_i} \leq T^c \\ & r_{\mathrm{T},(l,n)}^{f_i}(\gamma) \geq r_{\mathrm{T},(l,n)}^{f_i,\min}(\gamma) \\ & \forall l \in \mathcal{L}, n \in \mathcal{N}_l, \forall f_i \in \mathcal{F}, \forall \gamma = 1, \ldots \Gamma_{l,n}^{f_i} \,. \end{aligned} \tag{9}$$

IV. Example with a simple Network Model

In this section, we use a simple network model of three sensor nodes shown in Figure 1 as an example to demonstrate the two optimization problems. Sensor nodes $\mathcal{L} =$

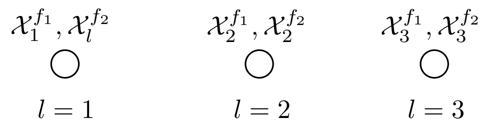


Fig. 1. Three sensor nodes and their data

$\{1,2,3\}$ are half duplex sensor nodes. Furthermore, $\mathcal{C} = \{(1,2),(2,1),(2,3),(3,2)\}$. The communication among sensor nodes are performed using bandwidth W. The reciprocal channels between sensor nodes $l = 1$ and $l = 2$, $l = 2$ and $l = 3$ are denoted by h_1 and h_3, respectively. The communication suffers from AGWN noise with the noise power P_N. There are two applications with $\mathcal{F} = \{f_1, f_2\}$ running in the three-nodes WSN where $c^{f_1}(k) = 1$, $c^{f_2}(k) = 1/k$. We assume that the three sensor nodes generate one initial messages of each of the two applications, i.e., $\eta_l^{f_i} = 1$, for $i = 1,2$ and $l = 1,2,3$.

A. Optimization with NSD constraint

In the communication paradigm that the aggregation messages are routed to sinks, we specify sensor node $l = 1$ as the sink of application f_1 and sensor node $l = 3$ as the sink of application f_2. Therefore, for application f_1, $w^{f_1} = \{1\}$, $\mathcal{Z}^{f_1} = \{2\}$ and $\mathcal{B}^{f_1} = \{3\}$. For application f_2, $w^{f_2} = \{3\}$, $\mathcal{Z}^{f_2} = \{2\}$ and $\mathcal{B}^{f_2} = \{1\}$. The energy consumptions of the three sensor nodes are

$$\begin{aligned} E^{f_1} &= P^{f_1}_{\mathrm{R},1}T^{f_1}_{\mathrm{R},1} + P^{f_1}_{\mathrm{Ps},1}T^{f_1}_{\mathrm{Ps},1} + P^{f_1}_{\mathrm{T},(2,1)}T^{f_1}_{\mathrm{T},(2,1)} \\ &\quad + P^{f_1}_{\mathrm{R},2}T^{f_1}_{\mathrm{R},2} + P^{f_1}_{\mathrm{Ps},2}T^{f_1}_{\mathrm{Ps},2} + P^{f_1}_{\mathrm{T},(3,2)}T^{f_1}_{\mathrm{T},(3,2)} \end{aligned} \quad (10)$$

$$\begin{aligned} E^{f_2} &= P^{f_2}_{\mathrm{T},(1,2)}T^{f_2}_{\mathrm{T},(1,2)} + P^{f_2}_{\mathrm{T},(2,3)}T^{f_2}_{\mathrm{T},(2,3)} + P^{f_2}_{\mathrm{R},2}T^{f_2}_{\mathrm{R},2} \\ &\quad + P^{f_2}_{\mathrm{Ps},2}T^{f_2}_{\mathrm{Ps},2} + P^{f_2}_{\mathrm{R},3}T^{f_2}_{\mathrm{R},3} + P^{f_2}_{\mathrm{Ps},3}T^{f_2}_{\mathrm{Ps},3} \,. \end{aligned} \quad (11)$$

We have $T^{f_1}_{\mathrm{R},1} = T^{f_1}_{\mathrm{Tx},(2,1)}$, $T^{f_1}_{\mathrm{R},2} = T^{f_1}_{\mathrm{T},(3,2)}$, $T^{f_2}_{\mathrm{R},2} = T^{f_2}_{\mathrm{T},(1,2)}$ and $T^{f_2}_{\mathrm{R},3} = T^{f_2}_{\mathrm{T},(2,3)}$ due to our system settings. The delay of application f_1 is $T^{f_1} = T^{f_1}_{\mathrm{T},(3,2)} + T^{f_1}_{\mathrm{Ps},2} + T^{f_1}_{\mathrm{T},(2,1)} + T^{f_1}_{\mathrm{Ps},1}$. Similarly, the delay of application f_2 is $T^{f_2} = T^{f_2}_{\mathrm{T},(1,2)} + T^{f_2}_{\mathrm{Ps},2} + T^{f_2}_{\mathrm{T},(2,3)} + T^{f_2}_{\mathrm{Ps},3}$. According to the initial messages at the three sensor nodes, the minimum transmit message rates are $r^{f_1,\min}_{\mathrm{T},(2,1)} = 2c^{f_1}(2)/T^{f_1}_{\mathrm{T},(2,1)}$, $r^{f_1,\min}_{\mathrm{T},(3,2)} = 1/T^{f_1}_{\mathrm{T},(3,2)}$, $r^{f_2,\min}_{\mathrm{T},(2,3)} = 2c^{f_2}(2)/T^{f_2}_{\mathrm{T},(2,3)}$, $r^{f_2,\min}_{\mathrm{T},(1,2)} = 1/T^{f_2}_{\mathrm{T},(1,2)}$. The actual transmit message rate from sensor node j to l of application f_i is determined by the capacity of the channel h_{jl}

$$r^{f_i}_{\mathrm{T},(l,j)} = \frac{W}{M^{f_i}} \log_2 \left(1 + \frac{P^{f_i}_{\mathrm{T},(l,j)} |h_{jl}|^2}{P_N} \right) . \quad (12)$$

The energy minimization problem for the three-nodes WSN is therefore formulated as

$$\begin{aligned} \min_{\substack{T^{f_1}_{\mathrm{T},(2,1)}, T^{f_1}_{\mathrm{T},(3,2)}, T^{f_2}_{\mathrm{T},(1,2)}, T^{f_2}_{\mathrm{T},(2,3)} \\ P^{f_1}_{\mathrm{T},(2,1)}, P^{f_1}_{\mathrm{T},(3,2)}, P^{f_2}_{\mathrm{T},(1,2)}, P^{f_2}_{\mathrm{T},(2,3)}}} & \sum_{f_i \in \{f_1, f_2\}} E^{f_i} \\ \text{s.t.} \quad & T^{f_1} + T^{f_2} \le T^c \\ & r^{f_1}_{\mathrm{T},(2,1)} \ge r^{f_1,\min}_{\mathrm{T},(2,1)}, r^{f_1}_{\mathrm{T},(3,2)} \ge r^{f_1,\min}_{\mathrm{T},(3,2)} \\ & r^{f_2}_{\mathrm{T},(2,3)} \ge r^{f_2,\min}_{\mathrm{T},(2,3)}, r^{f_2}_{\mathrm{T},(1,2)} \ge r^{f_2,\min}_{\mathrm{T},(1,2)} \,. \end{aligned} \quad (13)$$

B. Optimization with NNSD constraints

In the communication paradigm where random gossiping is deployed, communications between two sensor nodes are randomly activated. In the system model shown in Figure 1 with two possible communication pairs, communications between sensor nodes $l = 1$ and $l = 2$, and between sensor nodes $l = 2$ and $l = 3$ are activated with equal probability of 1/2. With the given system settings, the neighbourhood sets are $\mathcal{N}_1 = \{2\}$, $\mathcal{N}_2 = \{1, 3\}$ and $\mathcal{N}_3 = \{2\}$. Without loss of generality, we assume sensor nodes $l = 1$ and $l = 2$ firstly exchange messages. The numbers of active time sets are $\Gamma_{1,2} = \Gamma_{2,3} = 1$ for each application. The total energy consumption of application $f_i \in \mathcal{F}$ is

$$\begin{aligned} E^{f_i} &= P^{f_i}_{\mathrm{T},(1,2)}T^{f_i}_{\mathrm{T},(1,2)} + P^{f_i}_{\mathrm{R},1}T^{f_i}_{\mathrm{R},1} + P^{f_i}_{\mathrm{Ps},1}T^{f_i}_{\mathrm{Ps},1} \\ &\quad + P^{f_i}_{\mathrm{T},(2,1)}T^{f_i}_{\mathrm{T},(2,1)} + P^{f_i}_{\mathrm{T},(2,3)}T^{f_i}_{\mathrm{T},(2,3)} + P^{f_i}_{\mathrm{R},2}T^{f_i}_{\mathrm{R},2} \\ &\quad + P^{f_i}_{\mathrm{Ps},2}T^{f_i}_{\mathrm{Ps},2} + P^{f_i}_{\mathrm{T},(3,2)}T^{f_i}_{\mathrm{T},(3,2)} + P^{f_i}_{\mathrm{R},3}T^{f_i}_{\mathrm{R},3} + P^{f_i}_{\mathrm{Ps},3}T^{f_i}_{\mathrm{Ps},3}, \end{aligned} \quad (14)$$

where $T^{f_i}_{\mathrm{R},1} = T^{f_i}_{\mathrm{T},(2,1)}$, $T^{f_i}_{\mathrm{R},2} = T^{f_i}_{\mathrm{T},(1,2)} + T^{f_i}_{\mathrm{T},(3,2)}$ and $T^{f_i}_{\mathrm{R},3} = T^{f_i}_{\mathrm{T},(2,3)}$. The aggregation delay of application f_i is

$$\begin{aligned} T^{f_i} &= T^{f_i}_{\mathrm{T},(1,2)} + T^{f_i}_{\mathrm{T},(2,1)} + T^{f_i}_{\mathrm{T},(3,2)} + T^{f_i}_{\mathrm{T},(2,3)} \\ &\quad + \max(T^{f_i}_{\mathrm{Ps},1}, T^{f_i}_{\mathrm{Ps},2}) + \max(T^{f_i}_{\mathrm{Ps},2}, T^{f_i}_{\mathrm{Ps},3}) \,. \end{aligned} \quad (15)$$

The minimum transmit rate for application f_i is $r^{f_i,\min}_{\mathrm{T},(1,2)} = 1/T^{f_i}_{\mathrm{T},(1,2)}$, $r^{f_i,\min}_{\mathrm{T},(2,1)} = 1/T^{f_i}_{\mathrm{T},(2,1)}$, $r^{f_i,\min}_{\mathrm{T},(2,3)} = 2c^{f_i}(2)/T^{f_i}_{\mathrm{T},(2,3)}$ and $r^{f_i,\min}_{\mathrm{T},(3,2)} = 1/T^{f_i}_{\mathrm{T},(3,2)}$. Therefore, the optimization problem can be formulated as

$$\begin{aligned} \min_{\substack{T^{f_i}_{\mathrm{T},(2,1)}, T^{f_i}_{\mathrm{T},(3,2)}, T^{f_i}_{\mathrm{T},(1,2)}, T^{f_i}_{\mathrm{T},(2,3)} \\ P^{f_i}_{\mathrm{T},(2,1)}, P^{f_i}_{\mathrm{T},(3,2)}, P^{f_i}_{\mathrm{T},(1,2)}, P^{f_i}_{\mathrm{T},(2,3)}}} & \sum_{f_i \in \{f_1, f_2\}} E^{f_i} \\ \text{s.t.} \quad & T^{f_1} + T^{f_2} \le T^c \\ & r^{f_i}_{\mathrm{T},(2,1)} \ge r^{f_i,\min}_{\mathrm{T},(2,1)}, r^{f_i}_{\mathrm{T},(3,2)} \ge r^{f_i,\min}_{\mathrm{T},(3,2)} \\ & r^{f_i}_{\mathrm{T},(2,3)} \ge r^{f_i,\min}_{\mathrm{T},(2,3)}, r^{f_i}_{\mathrm{T},(1,2)} \ge r^{f_i,\min}_{\mathrm{T},(1,2)} \\ & \forall f_i \in \{f_1, f_2\} \,. \end{aligned} \quad (16)$$

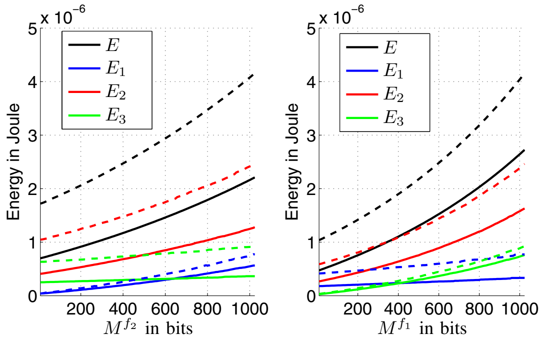
According to the assumption of the reciprocal channel and the compression factor of the two applications, we can reduce the number of time parameters in (16) by using $T^{f_1}_{\mathrm{T},(1,2)} = T^{f_1}_{\mathrm{T},(2,1)}$, $T^{f_2}_{\mathrm{T},(1,2)} = T^{f_2}_{\mathrm{T},(2,1)}$ and $T^{f_2}_{\mathrm{T},(2,3)} = T^{f_2}_{\mathrm{T},(3,2)}$.

Note that the power constraints can be transformed into time constraints with the given minimum transmit message rates using the relation shown in (12). To solve the optimization problems in (13) and (16), we discretize the total time T^c and then use an exhaustive search to numerically find the optimum solutions of each time parameter.

V. Simulation Results

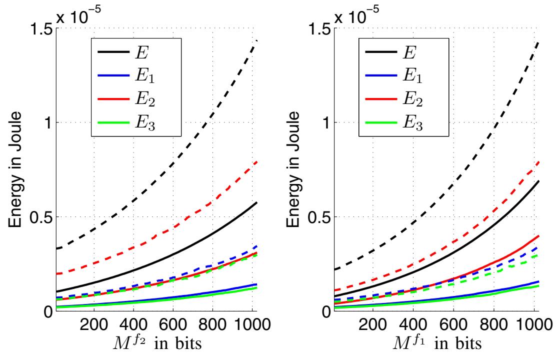
In the simulation, we deploy the system model with three sensor nodes as shown in the previous section. With the NSD constraint, the delay constraint is $T^c = 2$ms. The maximum delay with NNSD constraint is also $T^c = 2$ms. We assume the processing speed at each sensor node is extremely high (e.g. a 1MHz processing unit is able to finish an operation within 1μs), such that the delay caused by processing can be ignored due to $T^{f_i}_{\mathrm{Ps},l} \ll T^c, f_i \in \mathcal{F}, l \in \mathcal{L}$. We therefore further assume the energy consumption for processing of each sensor node is a negligible constant value. The communication among sensor nodes are using a bandwidth of 1MHz, the noise power is constantly $P_N = 1\mu W$, the distance between sensor nodes $l = 1$ and $l = 2$ as well as that between sensor nodes $l = 2$ and $l = 3$ are both 10 meters. The power consumption of a sensor node for receiving is assumed to be $P^{f_i}_{\mathrm{R},l} = 30\mu W$.

We denote E, E_1, E_2 and E_3 as the total energy consumption, the energy spent at $l = 1$, the energy spent at $l = 2$ and the energy spent at $l = 3$, respectively. Figure 2 and 3 give the total energy consumption as well as the energy consumption for each sensor node 1) as a function of M^{f_2} with fixed M^{f_1} and 2) as a function of M^{f_1} with fixed M^{f_2}. With fixed M^{f_2}, the energy consumption increases with larger steepness than with fixed M^{f_1}. This is because the compression factor of application f_1 does not compress the message length since $c^{f_1}(k) = 1$, while the compression factor $c^{f_2}(k) = 1/k$ keeps the message length the same of the output of all sensor nodes. It is also shown that with the same aggregation delay constraint, the communication paradigm with random gossiping and NNSD constraint consumes more energy than that with routing algorithm with specified sinks and NSD constraints. Figure 4 and 5 gives the time of each transmission between sensor nodes. One can see that the time used for transmission of application f_1 decreases when the message length of application f_2 increases. The same as for the energy consumption, the steepness is larger for fixed M^{f_2} than for fixed M^{f_1} due the compression factor.



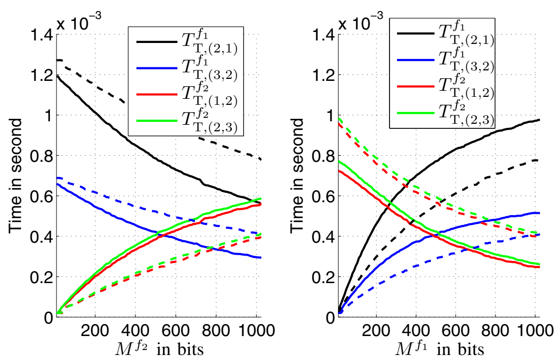
(a) solid line $M^{f_1} = 512$, dashed line $M^{f_1} = 1024$ (b) solid line $M^{f_2} = 512$, dashed line $M^{f_2} = 1024$

Fig. 2. Energy Consumption with NSD



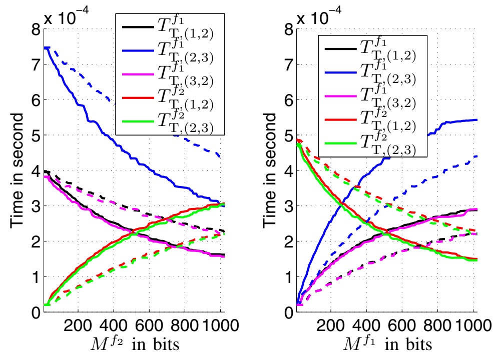
(a) solid line $M^{f_1} = 512$, dashed line $M^{f_1} = 1024$ (b) solid line $M^{f_2} = 512$, dashed line $M^{f_2} = 1024$

Fig. 3. Energy Consumption with NNSD



(a) solid line $M^{f_1} = 512$, dashed line $M^{f_1} = 1024$ (b) solid line $M^{f_2} = 512$, dashed line $M^{f_2} = 1024$

Fig. 4. Time Fractions with NSD



(a) solid line $M^{f_1} = 512$, dashed line $M^{f_1} = 1024$ (b) solid line $M^{f_2} = 512$, dashed line $M^{f_2} = 1024$

Fig. 5. Time Fractions with NNSD

VI. Conclusion

In this paper, we introduced the concept of the compression factor and the delay constraints NSD and NNSD for two communication paradigms where energy minimization problems are proposed for general sensor networks. With the example of a simple WSN of three sensor nodes, we solve the optimization problem numerically, and give the comparisons by simulations. It is shown that the compression factor will affect the steepness of the increasing of the energy consumption when the message length is increased and that with a given aggregation delay constraint, the communication paradigm with random gossiping consumes more energy than that with the routing algorithm.

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