International Journal of Software Engineering and Its Applications
Vol. 2, No. 3, July, 2008

Analysis of Traffic Splitting Mechanisms for 2D Mesh Sensor Networks[1]

Huimin She
[1]*Dept. of ECS, Royal Institute of Technology, Sweden*
[2]*ASIC & System State Key Lab., Dept. of Microelectronics, Fudan University, China*
huimin@kth.se

Zhonghai Lu, Axel Jantsch, Li-Rong Zheng
[1]*Dept. of ECS, Royal Institute of Technology, Sweden*
{zhonghai, axel, lirong}@kth.se

Dian Zhou
[2]*ASIC & System State Key Lab., Dept. of Microelectronics, Fudan University, China*
[3]*E.E. Department, the University of Texas at Dallas, USA*
zhoud@fudan.edu.cn

Abstract

For many applications of sensor networks, it is essential to ensure that messages are transmitted to their destinations within delay bounds and the buffer size of each sensor node is as small as possible. In this paper, we firstly introduce the system model of a mesh sensor network. Based on this system model, the expressions for deriving the delay bound and buffer requirement bound are presented using network calculus theory. In order to balance traffic load and improve resource utilization, three traffic splitting mechanisms are proposed. And the two bounds are derived in these traffic splitting mechanisms. To show how our method applies to real applications, we conduct a case study on a fresh food tracking application, which monitors the food freshness status in real-time during transportation. The numerical results show that the delay bound and buffer requirement bound are reduced while applying traffic splitting mechanisms. Thus the performance of the whole sensor network is improved with less cost.

1. Introduction

Recently, wireless sensor network (WSN) has become a popular technology with a wide range of applications, such as health care, environment monitoring, process tracking, traffic management and military [1]. A sensor network may contain a huge number of sensor nodes that are densely deployed at some inspected sites. In these scenarios, the sensor network is likely to form a mesh structure which has significant potential for use in commercial applications [2]. Wireless mesh sensor network is attracting more and more research attentions because of its advantages. Firstly, mesh networking enables better overall connectivity than other topologies, such as star or cluster-tree topologies. Secondly, mesh sensor networks support multi-path routing, which is good for improving the reliability and

[1] This work was supported partly by VINN Excellence iPack Center at Royal Institute of Technology (KTH), Sweden, partly by the Natural Science Foundation of China under Grant No. 60673029, and partly by the US NSF research project (No. 0727751).

scalability. Unlike that in cluster-tree sensor networks [7], data from a source node can only be transmitted to the sink through one path. In this case, if one of the routers is broken, all of its children nodes can not send data to the destination. Thirdly, with path diversity, traffic load can be better balanced, which is important for decreasing overall transmission delay and mitigating congestion.

In sensor networks, especially for real-time applications, it is essential to ensure that messages are transmitted to the destinations before their deadlines. Moreover, it is important to ensure that messages which contain critical information are not dropped even in worst cases. However, it is hard, if not impossible, to model the worst-case behavior of real-world sensor networks. Therefore, an analytic method is needed. Recently, network calculus has been developed for worst-case analysis in packet switched networks [3]. With network calculus, some fundamental properties of packet switched networks, such as buffer dimensioning, delay dimensioning and scheduling, can be studied. In [4] [5] [6], Jens et al. extended the network calculus theory to sensor network calculus, which can be used as an effective tool for the worst-case performance analysis in sensor networks.

Traffic splitting mechanism plays an important role in traffic load balancing in packet-switched networks [13]. With traffic splitting, a traffic flow is divided into several sub-flows and each of them is sent to the destination through different routing paths. Therefore, the overall network efficiency and reliability can be enhanced. In [8], Andrew et al. proposed an algorithm to split traffic across an optimal number of disjoint paths. It is shown that the spare capacity can be reduced and thus the overall performance of the system is improved.

In this paper, a system model of mesh sensor networks is presented firstly. Based on this model, we propose three traffic splitting mechanisms, which are even traffic splitting (ETS), weighted traffic splitting (WTS), and probabilistic traffic splitting (PTS). Using network calculus, the delay bound and buffer requirement bound are derived in non-traffic-splitting and splitting mechanisms respectively. To apply the analysis method to real applications, a case study of sensor networks for fresh food tracking is conducted. From the numerical results, we can see that the delay bound and buffer requirement bound are reduced while applying those traffic splitting mechanisms in mesh sensor networks. Furthermore, in our mesh sensor network model, both the delay and buffer requirement bounds are lower than those in cluster-tree sensor networks.

The rest of this paper is organized as follows: Section 2 introduces the basic knowledge of network calculus theory. In section 3, the system model and traffic model of mesh sensor networks are presented. In section 4, the delay bound and buffer requirement bound are derived in different traffic splitting mechanisms. Section 5 presents a case study and the numerical results. Finally, the conclusions are drawn in section 6.

2. Network calculus theory

Network calculus is a theory of deterministic queuing systems for packet switched networks [3]. The foundation of network calculus is min-plus algebra (also called min-plus dioid). Using network calculus theory, some fundamental properties of packet switched networks, such as buffer dimensioning, and delay dimensioning can be studied. In the following paragraphs, the basic definitions and properties of network calculus theory are briefly introduced. Detailed results are available in [3].

Definition 1. Wide-sense increasing: A function $R(t)$ is wide-sense increasing, if $R(t_1) \le R(t_2)$ for all $t_1 \le t_2$.

Definition 2. Min-plus convolution and deconvolution: Let *f(t)* and *g(t)* be wide-sense increasing, and *f(0)=g(0)=0*. Their convolution under min-plus algebra is defined as,

$$(f \otimes g)(t) = \inf_{0 \le s \le t} \{f(t-s) + g(s)\} \tag{1}$$

And their deconvolution is defined as,

$$(f \oslash g)(t) = \sup_{s \ge 0} \{f(t+s) - g(s)\} \tag{2}$$

Definition 3. Arrival curve: Let α be a wide-sense increasing function defined for $t \ge 0$, we say that a flow *R* is constrained by arrival curve α if and only if for all $t \ge s$,

$$R(t) - R(s) \le \alpha(t-s) \tag{3}$$

Definition 4. Service curve: Consider a system *S* and a flow through *S* with input and output function R and R^*, respectively. *S* offers a service curve β to the flow if and only if β is wide-sense increasing, $\beta(0) = 0$, and $R^* \ge R \otimes \beta$.

From the above definitions, the following theorems are then stated as follows. The proofs of these theorems are presented in [3].

Theorem 1 Delay bound: Assume a flow *R(t)*, constrained by arrival curve $\alpha(t)$, traverses a system *S* that offers a service curve $\beta(t)$. The delay bound *D(t)* satisfies,

$$D(t) \le h(\alpha, \beta) = \sup_{s \ge 0} \{\inf\{\tau \ge 0 : \alpha(s) \le \beta(s+\tau)\}\} \tag{4}$$

$h(\alpha, \beta)$ is also often called the horizontal deviation between $\alpha(t)$ and $\beta(t)$.

*Theorem 2. Backlog bound***:** Assume a flow *R(t)*, constrained by arrival curve $\alpha(t)$, traverses a system *S* that offers a service curve $\beta(t)$. The backlog bound *B(t)* satisfies,

$$B(t) \le v(\alpha, \beta) = \sup_{s \ge 0} \{\alpha(s) - \beta(s)\} \tag{5}$$

$v(\alpha, \beta)$ is also called the vertical deviation between $\alpha(t)$ and $\beta(t)$.

*Theorem 3. Output bound***:** Assume a flow *R(t)*, constrained by arrival curve $\alpha(t)$, traverses a system *S* that offers a service curve $\beta(t)$. Then the output function is constrained by the following arrival curve.

$$\alpha^*(t) = (\alpha \oslash \beta)(t) = \sup_{s \ge 0} \{\alpha(t+s) - \beta(s)\} \tag{6}$$

Theorem 4. Concatenation of systems: Assume that a flow *R(t)* traverses systems S_1 and S_2 in sequence, where S_1 offers service curve $\beta_1(t)$ and S_2 offers service curve $\beta_2(t)$. Then the resulting system *S*, defined by the concatenation of the two systems offers the following service curve to the flow,

$$\beta(t) = (\beta_1 \otimes \beta_2)(t) \tag{7}$$

Theorem 5. Aggregate multiplexing: Consider a lossless node serving two flows, 1 and 2, in FIFO order. Assume that flow 2 is constrained by an arrival curve $\alpha_2(t) = r_2 t + b_2$ and the FIFO node provides a guaranteed service curve $\beta_{R,T}(t) = R(t-T)^+$ to the aggregate of the two flows. Then, for any $\tau \ge 0$, flow 1 is guaranteed by a service curve,

$$\beta_\tau^1(t) = (R - r_2)[t - (\frac{b_2 + r_2(T-\tau)}{R - r_2} + T)]^+ 1_{\{t > \tau\}} \tag{8}$$

The expression $(x)^+$ equals to *x* when *x*>0, and 0 otherwise.

3. Mesh sensor networks

3.1. System model

Like in many other sensor networks, there are generally three kinds of sensors in mesh sensor networks. Their functions and properties are described as follows: 1) *Sink*: The sink is responsible for gathering data from all the other sensors and sending the data to a base station. In our model, we assume only one node acts as the sink. 2) *RN*: relay node. These nodes have the ability to sense the events as well as forward messages for other nodes. 3) *SN*: source node. These nodes only have the ability to sense the events.

The mesh sensor network is composed of $(m \times n-1)$ relay nodes and one single sink which is located at the center of the mesh (m and n represents the number of nodes in x and y dimension respectively). For simplicity, assuming m and n are odd integers. Similar analysis methods can be applied when they are even integers. Each relay node connects the same number of source nodes (assume the number is N). An example of mesh sensor network is illustrated in Fig. 1(a), where $m=5$, $n=3$, $N=2$, and the sink is located at the center.

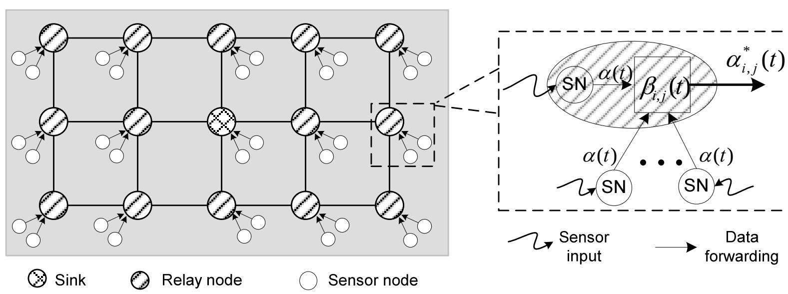


Fig. 1 a) A mesh sensor network b) A relay node

3.2. Traffic model

In sensor networks, there are typically two kinds of traffic flows: upstream traffic flows (from sensor nodes to the sink) and downstream traffic flows (from the sink to a sensor node). Since the methods used to analyze upstream traffic flows and downstream traffic flows are similar, we concentrate on the upstream traffic flows in this paper.

From previous descriptions, we know that relay nodes, source nodes and the sink have the ability to sense their environment. Assuming the maximum individual data flow that can be sent by the relay node or source node is constrained by arrival curve $\alpha(t) = rt + b$, where r is the average data rate, and b is the maximum burst size of the data flow. Each relay node *(i, j)* provides a guaranteed service constrained by service curve $\beta_{i,j}(t) = R_{i,j}(t - T_{i,j})^+$, where R_{ij} denotes the guaranteed service rate, and T_{ij} is the maximum latency caused by the relay node.

Let the input and output traffic of relay node *(i, j)* be constrained by arrival curve $\alpha_{i,j}(t)$ and $\alpha^*_{i,j}(t)$ respectively. The traffic model of a relay node is shown in Fig. 1(b). From the definitions and theorems of network calculus, the delay bound $D_{i,j}$ and buffer requirement bound $B_{i,j}$ of each node can be derived.

We assume $R_{i,j} \geq r_{i,j}$, which means that the available bandwidth should be bigger than the input data rate. Otherwise, the backlog will be increasing infinitely and thus the delay bound may become infinite. Obviously, this case is out of our interest.

From Fig. 1(b) and Theorem 1, 2, 3, we can get the following expressions,

$$\alpha_{i,j}(t) = (N+1) \cdot \alpha(t) = r_{i,j}t + b_{i,j} \tag{9}$$

$$\alpha^*_{i,j}(t) = (\alpha_{i,j} \oslash \beta_{i,j})(t) = \alpha_{i,j}(t) + r_{i,j} \cdot T_{i,j} \tag{10}$$

$$D_{i,j} = \frac{b_{i,j}}{R_{i,j}} + T_{i,j} \tag{11}$$

$$B_{i,j} = b_{i,j} + r_{i,j} T_{i,j} \tag{12}$$

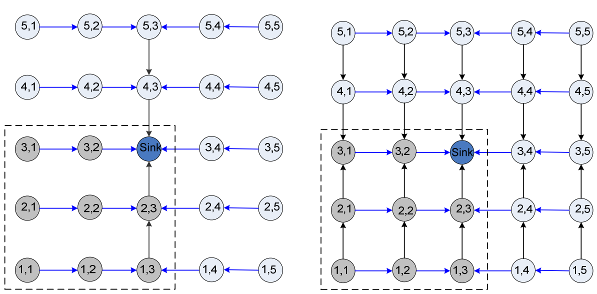
4. Analysis of traffic splitting mechanisms

In this section, the data transfer delay bound and buffer requirement bound of mesh sensor networks will be derived. The maximum data transfer delay refers to the worst-case time experienced by a data flow from the source to the destination. And the buffer requirement of a node refers to the minimum buffer size required to store the incoming bulk of data without buffer overflow.

Assuming the routing algorithm is minimum path routing, which is a practical and efficient routing policy for mesh sensor networks. In this routing policy, the $m \times n$ mesh network is symmetric (Fig. 2). Therefore, for a $m \times n$ mesh, we only need to analyze part of the nodes with index (i, j), where $1 \leq i \leq (m+1)/2$, $1 \leq j \leq (n+1)/2$. For example, in a 5×5 mesh network, only a 3×3 mesh is needed to be analyzed (Fig. 2, dashed frame). In the following, firstly we analyze the mesh sensor network without traffic splitting using network calculus theory. And then, the mesh sensor network is analyzed with traffic splitting mechanisms.

4.1. Non-traffic-splitting scenario

As we mentioned before, the mesh sensor network is symmetric. Therefore, we only need to analyze part of the whole mesh (As shown in Fig. 2, dashed frame). It is further assumed that data from each source node or relay node is sent to the sink through dimension order XY routing (That is to say, packets are routed in the *X* direction first, and then the *Y* direction). In this routing policy as shown in Fig. 2(a), the nodes in the same column (except the central column) have the same behavior, which means that the input traffic, delay bound, backlog bound[2], and output traffic of node $(1, j), (2, j), \ldots, (i, j), \ldots, ((m+1)/2, j)$ are the same, where $(1 \leq j < (n+1)/2)$. Since the traffic pattern of the central column is different from other columns, we will analyze the central column separately. And for the central column, node $(i, (n+1)/2)$ and node $(m+1-i, (n+1)/2)$ have the same behavior.



(a) (b)

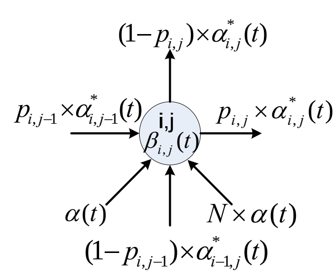


Fig. 2 A mesh sensor network a) Non-traffic-splitting; b) Traffic splitting;

Fig. 3 Input and output of node (i,j)

---

[2] In this paper, *backlog bound* and *buffer requirement bound* are equivalent.

According to the traffic model described in section 3.2, the input and output traffic flows are constrained by the following arrival curves,

$$\alpha_{1,1}(t) = \alpha(t) + N \cdot \alpha(t) = (N+1)(rt+b) \tag{13}$$

$$\alpha_{i,j}(t) = \begin{cases} (N+1)\cdot\alpha(t) + \alpha^*_{i,j-1}(t), & when \quad (1 \le i \le \frac{m+1}{2}, 1 \le j < \frac{n+1}{2}), \\ (N+1)\cdot\alpha(t) + \alpha^*_{i-1,j}(t) + 2\cdot\alpha^*_{i,j-1}(t), & when \quad (1 \le i \le \frac{m+1}{2}, j = \frac{n+1}{2}), \\ (N+1)\cdot\alpha(t) + 2\cdot[\alpha^*_{i-1,j}(t) + \alpha^*_{i,j-1}(t)], & when \quad (i = \frac{m+1}{2}, j = \frac{n+1}{2}) \end{cases} \tag{14}$$

According to Theorem 3, output traffic of node *(i, j)* is constrained by,

$$\alpha^*_{i,j}(t) = (\alpha_{i,j} \oslash \beta_{i,j})(t) = \alpha_{i,j}(t) + r_{i,j} \cdot T_{i,j} \tag{15}$$

With Eq. (13), (14), (15), the input and output arrival curves at each node can be recursively calculated, then we obtain data rate $r_{i,j}$ and burst size $b_{i,j}$ of node *(i, j).* Then the delay bound and buffer requirement bound of each node can be calculated according to Eq. (11) and (12) respectively. After getting the maximum transfer delay at each node, the delay bound of the whole mesh network can be calculated easily. The details will be introduced in section 4.3.

4.2. Traffic splitting mechanisms

In non-traffic-splitting scenarios, a traffic flow is sent to the sink through a single routing path. This may result in traffic imbalance problem, since the links along the routing path are always occupied while others are vacant. For example, in Fig. 2(a), the link between node (1,1) and (1,2) is occupied, and the link between (1,1) and (1,2) is not used. In order to balance the traffic load and efficiently make use of the resources of sensor networks, three traffic splitting mechanisms are proposed for mesh sensor networks. They are *Even Traffic Splitting* mechanism (*ETS*), *Weighted Traffic Splitting* mechanism (*WTS*), and *Probabilistic Traffic Splitting* mechanism (*PTS*). Along all routing paths between the source node and the sink, traffic flow is split at each relay node (Fig. 2(b)). As mentioned in the previous sections, the routing policy is minimum path routing. Therefore, part of the packets forward to the downstream node in X direction, and the other part in Y direction.

The traffic model is the same as that described in section 3.2. Assuming that traffic outputted at node *(i, j)* will be routed along X direction with probability $p_{i,j}$, and Y direction with probability $(1- p_{i,j})$, where $(0 \le p_{i,j} \le 1)$. The input and output traffic flow at node *(i, j)* is shown in Fig. 3. From Eq. (13), (15), (16), (17), (18), (19), the input and output arrival curve of each node can be recursively calculated.

$$\alpha_{i,j}(t) = (N+1)\cdot\alpha(t) + p_{i,j-1}\cdot\alpha^*_{i,j-1}(t) + (1-p_{i-1,j})\cdot\alpha^*_{i-1,j}(t), \quad when\ (1 \le i < \frac{m+1}{2}, 1 \le j < \frac{n+1}{2}) \tag{16}$$

$$\alpha_{i,j}(t) = (N+1)\cdot\alpha(t) + 2p_{i,j-1}\cdot\alpha^*_{i,j-1}(t) + \alpha^*_{i-1,j}(t), \quad when\ (1 \le i < \frac{m+1}{2}, j = \frac{n+1}{2}) \tag{17}$$

$$\alpha_{i,j}(t) = (N+1)\cdot\alpha(t) + \alpha^*_{i,j-1}(t) + 2(1-p_{i-1,j})\cdot\alpha^*_{i-1,j}(t), \quad when (i = \frac{m+1}{2}, 1 \le j < \frac{n+1}{2}) \tag{18}$$

$$\alpha_{i,j}(t) = (N+1)\cdot\alpha(t) + 2\cdot\alpha^*_{i,j-1}(t) + 2\cdot\alpha^*_{i-1,j}(t), \quad when\ (i = \frac{m+1}{2}, j = \frac{n+1}{2}) \tag{19}$$

After obtaining the expression of input arrival curves at each node, we obtain data rate $r_{i,j}$

and burst size $b_{i,j}$. The maximum delay $D_{i,j}$, and backlog bound $B_{i,j}$ can be calculated according to Eq. (11) and (12) respectively. Then the delay bound of the whole sensor network can be calculated according to the method describe in section 4.3.

By assigning different values to $p_{i,j}$, three traffic splitting mechanisms for mesh sensor networks are proposed. They are introduced as follows:

1) Even Traffic Splitting mechanism (ETS): As shown in Fig. 2(b), in even traffic splitting mechanism, traffic is evenly split at each node. That is to say, 50% of packets flow to downstream node in X direction and 50% of packets flow to downstream node in Y direction. In this case, splitting coefficient $p_{i,j}$ equals to 0.5 for every node. Therefore, the arrival curve of input and output traffic, the delay bound and buffer requirement bound can be derived accordingly.

2) Weighted Traffic Splitting mechanism (WTS): In weighted traffic splitting mechanism, traffic is split at each node not evenly. The packets outputted at each node will be routed along X dimension with probability p, and Y dimension with probability $1-p$, where $(0 \le p \le 1)$. In this case, splitting coefficient $p_{i,j}$ of every node is the same but not fixed. Its value can be adjusted according to different requirements in practical applications. By setting p, we can derive the expressions of input and output arrival curve recursively, then the delay bound and the buffer requirement bound can be derived accordingly. In fact, *ETS* can be regarded as a special case of *WTS* when $p=0.5$.

3) Probabilistic Traffic Splitting mechanism (PTS): When a node receives a packet to be routed to downstream nodes, it has to determine which downstream node the packet should be forwarded to. In probabilistic traffic splitting mechanism, the relay node (i,j) firstly generates a random number $p_{i,j}$ $(0 \le p_{i,j} \le 1)$. Then the packet is forwarded to the downstream nodes with probability $p_{i,j}$ and $1-p_{i,j}$ in X direction and Y direction respectively.

4.3. End-to-end delay bounds

After obtaining the per-router delay bound, the end-to-end delay bound of the whole mesh network can be calculated by two ways. The first way is to calculate the end-to-end delay bound by summing up the single delay together. For example, in Fig. 2, the maximum delay may happen between node $(1,1)$ and the sink, so the maximum delay can be calculated by $D = D_{1,1} + D_{1,2} + D_{1,3} + D_{2,3} + D_{3,3}$. However, the delay bound derived by this approach is pessimistic. The other way is to derive an equivalent service curve for each traffic flow based on the concatenation theory and the aggregate multiplexing theory (see theorem 4 and 5). And then the end-to-end delay bound can be calculated using the equivalent service curve (theorem 1). This algorithm is proposed by Lenzini et al. [10] for deriving end-to-end delay bound in sink-tree networks. It can also be applied in our mesh sensor networks. For the detailed descriptions of this method, refer to [7] and [10].

5. A case study and numerical results

To illustrate how the traffic splitting mechanisms apply to real applications, we conduct a case study of sensor networks for fresh food tracking. Then, we gave numerical results and compared the results with those of cluster-tree sensor networks.

5.1 A case study

In European market, approximately 10% of the whole cargo of fruits and vegetables coming from different parts of world is deteriorated during the transportation process, which leads to a loss of billions of dollars per year [12]. The loss can be mitigated by deploying a sensor network to track the food during its transportation process. In this section, we conduct a detailed case study for the application of sensor networks on fresh food tracking.

For the scenario of fresh food tracking, sensors are deployed in the boxes filled with fruits or vegetable in a truck carriage (as shown in Fig. 4). During food transportation process, the possible causes of food deterioration might be microbiological infestation and improper environmental condition. Therefore, three kinds of sensors are used in our applications, which are humidity sensor, temperature sensor, and O_2 sensor. These sensors are in charge of collecting the information of food. All the data collected by sensors are sent to a base station, which is located on the top of the truck. The base station then transmits the data to a remote server through GSM networks and Internet. The experts at the remote server side receive and analyze the data, and then send instructions to the base station to protect the food from becoming deteriorate if something wrong happens. In addition, there is a wired connection between the base station and the driver monitor. So the driver can also read the information collected by the sensor network and take proper measures to prevent the food from getting bad.

To illustrate the effectiveness of the proposed traffic splitting mechanisms, we performed several numerical experiments based on the case study. Assume the size of the truck carriage is 2m×3m×5m. A mesh sensor network was generated by scattering three sensors in every food box with size 0.6m×0.6m×1m (Fig. 4). As shown in Fig. 5, the whole mesh consists of three layers of 2D meshes. In each 2D mesh network, there are one sink, 24 relay nodes and 50 source nodes.

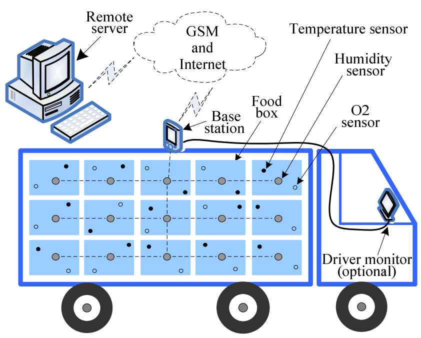


Fig. 4 Fresh food tracking

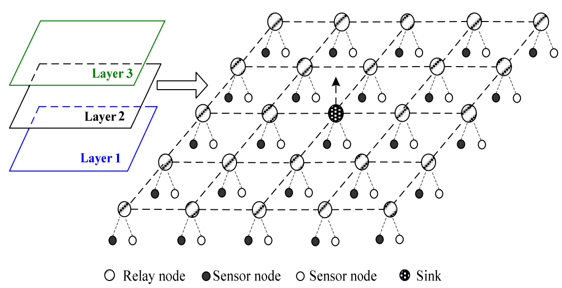


Fig. 5 Topology of the sensor network

5.2 The cluster-tree sensor network

In order to show the effectiveness of mesh sensor networks and the splitting mechanisms, we compared our results with those of cluster-tree sensor networks [7]. An example of a cluster-tree sensor network is shown in Fig. 6. In our numerical results, the depth of the cluster tree is 5. And the number of child sensor nodes and child routers are N_{child} = 2, and N_{router} = 2, respectively.

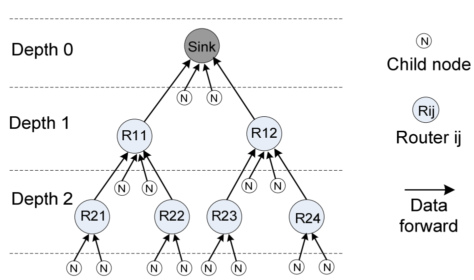


Fig. 6 A cluster-tree sensor network

5.3 Numerical results

Based on the case study and the cluster-tree sensor network, we conduct several numerical experiments. The parameters used in simulation are listed as follows. The maximum sensing rate *r* is assumed to be 15.36 bits/s which roughly correspond to sending a packet every five minutes. Assuming the burst size *b* = 40 bits. The Mica-2 motes [11] are assumed to be the sensor nodes, with maximum data forwarding rate 19.2 kbps. If the sensors are operated with duty cycle 11.5%, the maximum data forwarding rate *f* is 2488 *bits/s*, and latency *l* is 96 ms. Therefore, each relay node provides a rate-latency service curve $\beta(t) = R(t-T)^+$, where R = 2488 bits/s, T = 0.096 s. To study the delay bound and backlog bound of the mesh sensor networks, we choose a routing path with 5 hops from the source to the sink. In the figures of numerical results, *CTN* denotes *Cluster-Tree Networks*. Others represent different traffic splitting mechanisms in mesh sensor networks, where *NTS* denotes *Non-Traffic Splitting*, *ETS* denotes *Even Traffic Splitting*, *WTS* denotes *Weighted Traffic Splitting*, and *PTS* denotes *Probabilistic Traffic Splitting*.

The delay bounds and backlog bounds at each relay node along a 5-hop path are shown in Fig. 7 and Fig. 8 respectively. The figures show that the per-hop delay bound and backlog bound are becoming bigger if the relay node closer to the sink. This is mainly due to the fact that all the traffic is accumulated at the sink in sensor networks. From the figures, we can also see both bounds in mesh sensor networks are lower than that in cluster-tree sensor networks. And for mesh sensor network, the two bounds under traffic splitting mechanisms are lower than those without traffic splitting. Moreover, the two bounds of cluster-tree sensor networks are exponentially increasing as the tree depth increased.

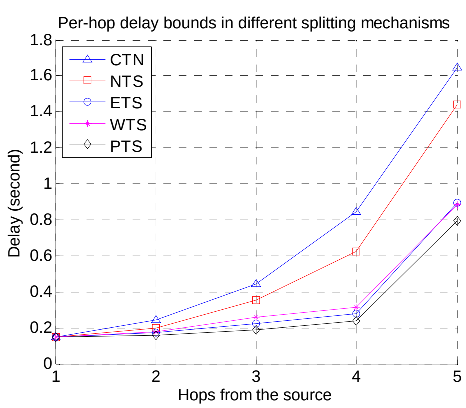


Fig. 7 Per-hop delay bounds

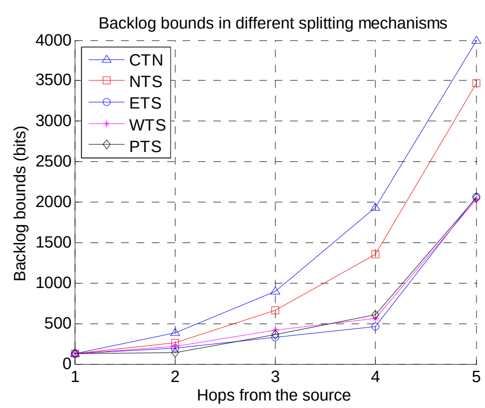


Fig. 8 Backlog bounds

Fig. 9 shows the maximum, average, and minimum per-hop delay bounds of the relay nodes. Compared with the maximum per-hop delay bound in CTN, the bound in ETS, WTS, and PTS are reduced by 45.3%, 45.9% and 51.9%, respectively. While compared with NTS, the maximum per-hop delay bound in ETS, WTS, and PTS, are reduced by 37.7%, 38.4%, and 45.2%, respectively. The minimum per-hope delay bounds are the same, which is 0.15 s. The average delay bound in the three traffic splitting mechanisms are reduced by 24.2% and 16.1% in average, compared with that in CTN and NTS, respectively. For the backlog bound, similar conclusions can be drawn from Fig. 10. In a word, the reduction of maximum delay bounds and maximum backlog bounds has significant effect on improving the performance of sensor networks.

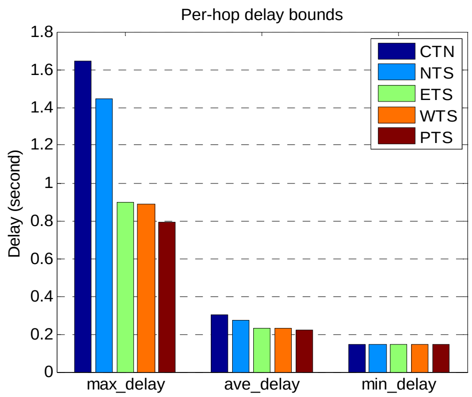


Fig. 9 Max, ave, min delay bound

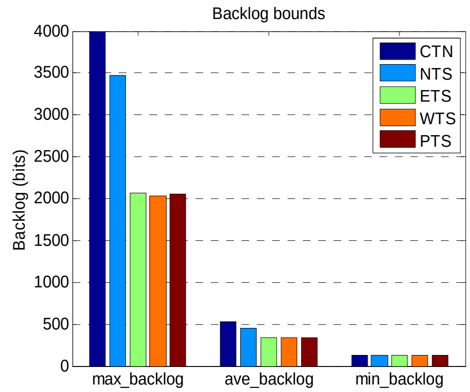


Fig. 10 Max, ave, min backlog bound

The end-to-end delay bounds from the source to sink are shown in Fig. 11, which also reveals that using traffic splitting mechanisms will reduce the end-to-end delay bound and thus improve the performance of the network. The end-to-end delay bounds scaling with network size are shown in Fig. 12 (The number of nodes in mesh sensor network are 16, 36, 64, and 144 respectively, and in cluster tree network are 15, 31, 63, and 127 respectively). This figure shows that adopting traffic splitting mechanisms will improve scaling properties. In conclusion, by splitting traffic among diverse routing paths in mesh sensor networks, the end-to-end delay can be decreased and the network resource utilization can be improved.

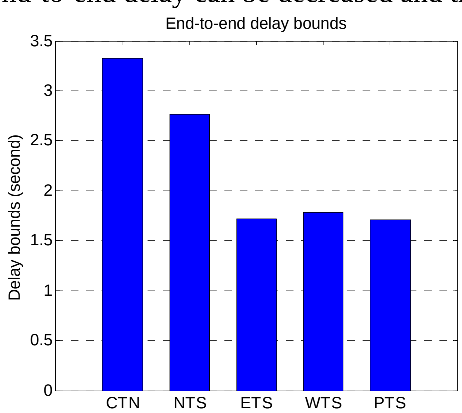


Fig. 11 End-to-end delay bounds

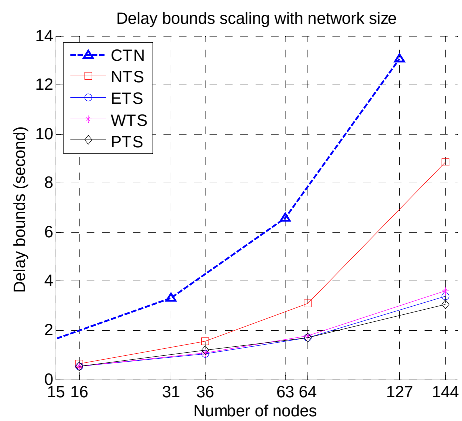


Fig. 12 Delay bounds VS. network size

6. Conclusions

In this paper, a system model and three traffic splitting mechanisms of mesh sensor networks are proposed. By using network calculus, the delay and buffer requirement bounds are derived. The numerical results show that the two bounds in mesh sensor networks are lower than those in cluster-tree sensor networks. Furthermore, by splitting traffic among all the minimum routing paths, both the delay and buffer size can be reduced. Therefore, the performance of the whole sensor network is improved and the total energy consumption may be reduced as well. However, there is only one sink in our proposed mesh sensor network. In this case, data of the whole sensor network is accumulated at the sink, so the traffic density is extremely high around the sink. To solve this problem, our future work may focus on networks with non-uniform link capacity.

7. References

[1] D. Culler, D. Estrin, and M. Srivastava, "Guest Editors' Introduction: Overview of Sensor Networks," Computer, vol. 37, no. 8, pp. 41-49, August 2004

[2] N. Baker, "Real world wireless mesh sensor network solutions", the IEE Seminar on Industrial Networking and Wireless Communications for Control, Feb. 2006

[3] J. –Y. Le Boudec, and P. Thiran, "Network Calculus A Theory of Deterministic Queuing Systems for the Internet", Springer, LNCS 2050, May 2004

[4] Jens B. Schmitt, and Utz Roedig, "Sensor network calculus – A framework for worst case analysis", in Proc. of the IEEE/ACM Int. conference on Distributed Computing in Sensor Systems (DCOSS 05), USA, 2005

[5] Jens B. Schmitt, F. A. Zdarsky, and Utz Roedig, "Sensor network calculus with multiple sinks", in Proceedings of IFIP networking workshop on performance control in wireless sensor networks, Portugal, 2006

[6] Jens B. Schmitt and Utz Roedig, "Worst case dimensioning of wireless sensor networks under uncertain topologies", in Proceedings of the 3rd IEEE Int. Symposium on Modeling and Optimization in Mobile, Ad Hoc, and Wireless Networks, Workshop on Resource Allocation in Wireless Networks, Italy, 2005

[7] Anis Koubaa, M. Alves, and E. Tovar, "Modeling and worst-case dimensioning of cluster-tree wireless sensor networks", In Proceedings of the 27th IEEE International Real-time Systems Symposium (RTSS 06), Brazil, 2006

[8] Andrew Zalesky, Hai Le Vu, and Moshe Zukerman, "Reducing spare capacity through traffic splitting", IEEE Communications Letters, Vol. 8, No. 9, September 2004

[9] William Dally, and Brian Towles, Principles and practices of Interconnection networks: chapter 9. Morgan Kauffman, December 2003

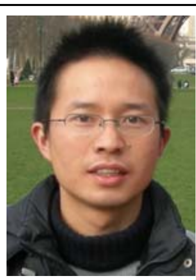
[10] L. Lenzini, L. Martorini, E. Mingozzi, and G. Stea, "Tight end-to-end per-flow delay bounds in FIFO multiplexing sink-tree networks", Performance Evaluation Journal(Elsevier), Vol. 63, pp 956-987, 2006

[11] Crossbow Technology Inc. http://www.xbow.com/

[12] Billerud AB, "The Billerud book of maths", http://www.billerud.com/

[13] S.-J. Lee, M. Gerla, "Split multipath routing with maximally disjoint paths in ad hoc networks", IEEE International Conference on Communications (ICC'01), 2001

Authors



Huimin She was born in Hunan province, China, in 1982. He received the B.S. degree in Electronic Information Engineering from Tongji University, Shanghai, China, in 2004. He is currently a joint Ph.D student in department of Electronic, Computer and Software Systems at Royal Institute of Technology (KTH), Stockholm, Sweden, and department of Microelectronics at Fudan University, Shanghai, China.

His research interests include traffic characterization and performance analysis in sensor networks.

Zhonghai Lu received his B.Sc. from Beijing Normal University, China in 1989. Since then he had worked for several computer and embedded systems companies as a system engineer and project manager for eleven years. He entered the Royal Institute of Technology (KTH), Sweden in 2000. From KTH, he received M.Sc. and Ph.D. in 2002 and 2007, respectively. He is currently a researcher at KTH, supervising a number of M.Sc. students and co-supervising several Ph.D. students.

Dr. Lu has published over 25 peer-reviewed technical papers in journals, book chapters and international conferences in the areas of networks/systems on chip, embedded systems, and communication networks. He is a reviewer for a number of journals and conferences. His research interests include computing and communication systems, architectures for interconnection and sensor networks, design methodologies and automation.

Axel Jantsch received a Dipl.Ing. (1988) and a Dr. Tech. (1992) degree from the Technical University Vienna. Between 1993 and 1995 he received the Alfred Schrödinger scholarship from the Austrian Science Foundation as a guest researcher at the Royal Institute of Technology (KTH). From 1995 through 1997 he was with Siemens Austria in Vienna as a system validation engineer. Since 1997 he is Associate Professor at KTH, since December 2002 he is full professor in Electronic System Design.

A. Jantsch has published over 160 papers in international conferences and journals and one book in the areas of VLSI design and synthesis, system level specification, modeling and validation, HW/ SW codesign and cosynthesis, reconfigurable computing and networks on chip. He has served on a number of technical program committees of international conferences such as FDL, DATE, CODES+ISSS, SOC, and NOCS and others. He has been TPC chair of SSDL/FDL 2000, TPC cochair of CODES+ISSS 2004 and general chair of CODES+ISSS 2005. Since December 2002 he is Subject Area Editor for the Journal of System Architecture. A. Jantsch is heading a number of research projects involving a total number of 10 Ph.D. students, in two main areas: System Modeling and Networks on Chip.

Dr. Li-Rong Zheng received his Tech. Dr. degree in electronic system design from the Royal Institute of Technology (KTH), Stockholm, Sweden in 2001. Since then, he was with KTH as a research fellow and project leader in Laboratory of Electronics and Computer Systems. He became an associate professor in electronics system design at KTH in 2003 and a full professor in media electronics in 2006.

His research experience and interest includes electronic circuits and systems for ubiquitous intelligence and media applications, radio and mixed-signal integrated circuits, wireless system-in-package, and signal integrity issues in electronic systems. He has authored and co-authored over 160 international reviewed publications, covering areas from electronic devices and thin film technologies, VLSI circuit and system design, to electronics system integration and system-in-package.

Dr. Dian Zhou is a professor at E.E. Department, the University of Texas at Dallas, USA and Changjiang Honor Professor at Fudan University, China.

His research interest includes VLSI Design, algorithms, and CAD tools.