Traffic Splitting with Network Calculus for Mesh Sensor Networks

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Abstract

In many applications of sensor networks, it is essential to ensure that messages are transmitted to their destinations as early as possible and the buffer size of each sensor node is as small as possible. In this paper, we firstly propose a mesh sensor network system model. Based on this system model, the expressions for deriving the delay bound and buffer requirement bound are presented using network calculus. In order to balance traffic load and improve resource utilization, three traffic splitting mechanisms are proposed. The numerical results show that the delay bound and buffer requirement bound are lowered while applying those traffic splitting mechanisms. And thus the performance of the whole sensor network is improved.

1. Introduction

As advances in wireless communication and sensor technologies, sensor networks have a wide range of applications [1]. A sensor network may contain a huge number of simple sensors that are densely deployed at some inspected site. In these scenarios, the sensor network is more likely to form a mesh structure which has significant potential for use in commercial applications [2]. There are several advantages of mesh networking. Firstly, mesh networking enables better overall connectivity than other topologies, like star or cluster-tree topologies. Secondly, multi-path routing is supported in mesh sensor networks. Unlike 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 work properly as well. Thirdly, with path diversity, traffic load can be balanced well, which is also important for decreasing overall transmission delay and congestion probability.

In sensor networks, especially for real-time applications, it is crucial to ensure that messages are transmitted to the destinations before their deadlines. Moreover, it is also important to ensure that messages which contain critical information are not dropped even in worst cases. However, it is hard or even impossible to model the worst-case behavior of real-world sensor networks. Therefore, an analytic method is needed. Recently, network calculus is 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 literatures [4-6], the network calculus theory is used to analyze sensor networks.

Traffic splitting mechanism plays an important role in traffic load balancing in data networks. With traffic splitting, data is divided into several flows and each of them is sent to the destination through different routing paths. Thus, the overall network efficiency and reliability can be enhanced. In [8], Andrew proposes 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, firstly, a system model for mesh sensor networks is presented. Based on this model, we propose three traffic splitting mechanisms: 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. From the numerical results, we can see that the delay bound and buffer requirement bound are lowered while applying those traffic splitting mechanisms in mesh sensor networks. Further more, 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: In section II, the basic knowledge of network calculus is introduced. Section III presents the system model and traffic model of mesh sensor networks are. In section IV, the delay bound and buffer requirement bound are derived in different traffic splitting mechanisms. The numerical results are presented in section V. And the conclusions are finally made in section VI.

2. Network calculus background

Network calculus is a theory of deterministic queuing systems for packet switched networks [3]. The foundation of network calculus is min-plus algebra. Using network calculus, some fundamental properties of packet switched networks, such as buffer dimensioning, and delay dimensioning can be studied. In the following paragraphs, some basic definitions and properties of network calculus are briefly summarized. 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 is 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^*. 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].

Theorem1 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 $\beta(t)$.

Theorem2. 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 $\beta(t)$.

Theorem3. 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.

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

Theorem4. Concatenation of systems: Assume that a flow *R(t)* traverses systems *S1* and *S2* in sequence, where *S1* offers service curve $\beta_1(t)$ and *S2* 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,

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

Theorem5. 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,

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

3. Mesh sensor network system model

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 in charge of 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*: routing node. These nodes have the ability to sense the events as well as forward messages from one of their neighbors to another. **3)** *SN*: ordinary sensor node. These nodes only have the ability to sense the events.

The mesh sensor network is composed of (n^2-1) routers and one sink which is located at the center of the mesh (*n* represents the number of nodes in *x* and *y* dimension). For simplicity, assuming the mesh size *n* is an odd integer. Similar analysis methods can be applied when the mesh size *n* is an even integer. Each router connects the same number of ordinary sensor nodes (assume the number is N). An example of mesh sensor network is illustrated in Fig. 1, n=5, N=2, and the position of the sink is (3, 3).

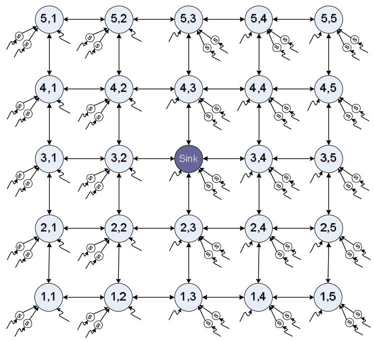


Fig. 1 An example of the mesh sensor network system model

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). The methods used to analyze upstream traffic flows and downstream traffic flows are similar, so only upstream traffic flows are taken into account in this paper.

From previous descriptions, we know that both routers and ordinary sensor nodes have the ability to sense their environments. Assuming the maximum individual data flow that can be sent by each router or sensor is constrained by arrival curve $\alpha(t) = rt + b$, where r is the average data rate, and b describes the maximum burst size of the data flow. Each router *(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 router. The expression $(x)^+$ equals to x when x>0 and 0 otherwise.

We further assume the input and output traffic of router *(i, j)* are constrained by arrival curve $\alpha_{i,j}(t)$ and $\alpha^*_{i,j}(t)$ respectively. The traffic model of a router node is shown in Fig. 2. 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.

Assuming $R_{i,j} \geq r_{i,j}$, 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. In this case, there is meaningless to derive the delay bound and buffer requirement bound.

From Fig. 2 and theorem 1, 2, 3, we can get the following expressions,

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

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

$$D_{i,j} = \frac{b_{i,j}}{R_{i,j}} + T_{i,j} \quad (11)$$

$$B_{i,j} = b_{i,j} + r_{i,j} T_{i,j} \quad (12)$$

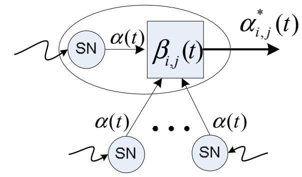


Fig. 2 Input and output traffic of a router

4. Analysis of mesh sensor networks

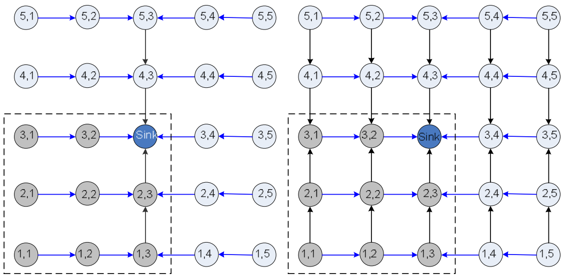
In this section, the data transfer delay bound and buffer requirement bound of mesh sensor networks will be analyzed. The maximum data transfer delay refers to the time experienced by a data flow of a node to reach the sink, and buffer requirement refers to the maximum buffer size to store the bulk of data.

Assuming the routing policy is minimum path routing, which is practical and efficient for mesh sensor networks. Then the $n*n$ mesh network is symmetric (Fig. 3). Therefore, for $n*n$ mesh, we only need to analyze part of the nodes with index *(i, j)*, where $1 \leq i \leq (n+1)/2$, $1 \leq j \leq (n+1)/2$. For example, in a 5*5 mesh network, only a 3*3 mesh is needed to be analyzed.

In the following sections, firstly we analyze the mesh sensor network without traffic splitting using network calculus theory. And then, the mesh sensor network is analyzed in 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. 3, dashed frame). It is further assumed that data from each sensor node or router is sent to the sink through dimension routing (That is to say, packets route in X direction first, and then Y direction). In this routing policy as shown in Fig. 3 (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, and output traffic of node $(1,j)$, $(2,j)$, …, (i,j), …, $((n+1)/2,j)$ 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 $(n+1-i,(n+1)/2)$ have the same behaviors.



(a) (b)

Fig. 3 Traffic model of a 5*5 mesh sensor network a) Non-traffic-splitting; b) Traffic splitting

According to the traffic model described in section 3.2, the expressions of input and output arrival curves are as follows,

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

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

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

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

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 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. Along all routing paths between the source node and the sink, traffic flow is split at each router node (Fig. 3(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.

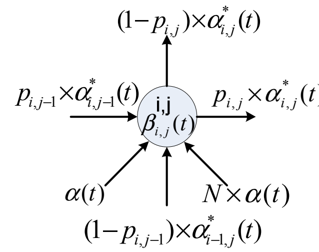


Fig. 4 Input and output traffic of node *(i, j)*

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. 4. From Eq. (13), (15), (16), (17), (18), (19), the input and output arrival curve of each node can be recursively calculated.

When $(1 \le i < \frac{n+1}{2}, 1 \le j < \frac{n+1}{2})$,

$$\alpha_{i,j}(t) = (N+1)\cdot\alpha(t) + p_{i,j-1}\cdot\alpha^*_{i,j-1}(t) + (1-p_{i-1,j})\cdot\alpha^*_{i-1,j}(t) \quad (16)$$

When $(1 \le i < \frac{n+1}{2}, j = \frac{n+1}{2})$,

$$\alpha_{i,j}(t) = (N+1)\cdot\alpha(t) + 2p_{i,j-1}\cdot\alpha^*_{i,j-1}(t) + \alpha^*_{i-1,j}(t) \quad (17)$$

When $(i = \frac{n+1}{2}, 1 \le j < \frac{n+1}{2})$,

$$\alpha_{i,j}(t) = (N+1)\cdot\alpha(t) + \alpha^*_{i,j-1}(t) + 2(1-p_{i-1,j})\cdot\alpha^*_{i-1,j}(t) \quad (18)$$

When $(i = \frac{n+1}{2}, j = \frac{n+1}{2})$,

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

After getting 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. And 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 even traffic splitting mechanism (ETS), weighted traffic splitting mechanism (WTS), and probabilistic traffic splitting mechanism (PTS).

1) Even traffic splitting mechanism (ETS): As shown in Fig. 3(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.

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, each router node 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. In mesh networks, there is a routing policy called Valiant's randomized routing algorithm which can balance the load of any traffic pattern well by sending each packet first to a random node [9].

4.3. End-to-end delay bounds

After getting the per-router delay bound, the total delay bound of the whole mesh network can be calculated by summing up the single delay together. For example, in Fig. 3, 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.

In [10], Lenzini presents an algorithm to derive tight end-to-end delay bound for sink-tree networks. The main idea of this algorithm is to derive an equivalent service curve for a given 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 approach can also be applied in our mesh sensor networks. For detailed descriptions of this method, refer to [7] and [10].

5. Numerical results

To illustrate the effectiveness of the proposed traffic splitting mechanisms, several numerical experiments are performed. Assuming the size of the mesh sensor network is 5*5, and the number of ordinary sensors that each router controls is $N=2$. Therefore, there are total 25 routers and 50 ordinary sensors. The maximum sensing rate r is assumed to be 15.36 *bits/s* which roughly corresponds to sending a packet every 5 minutes, which is the highest sensing rate for some of the scenarios. 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 router 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 buffer requirement bound of the mesh sensor networks, we choose a routing path with 5 hops from the source to the sink. In order to compare our results with cluster-tree sensor networks [7], assuming the depth of the cluster-tree is 5. The number of child sensor nodes and child routers are assumed to be N_{child} = 2, and N_{router} = 2 respectively.

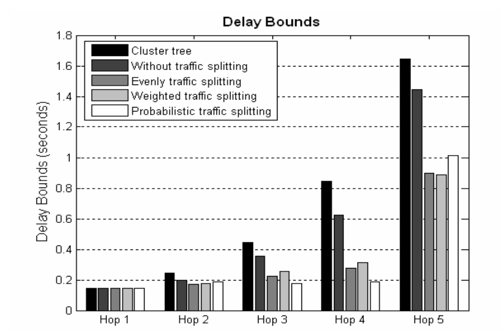


Fig. 5 Delay bounds at each router

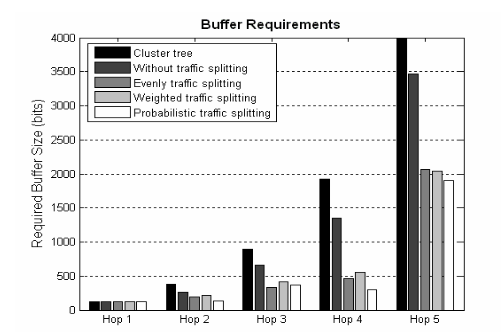


Fig. 6 Buffer requirement bounds at each router

The delay bound and buffer requirement bound at each router are shown in Fig. 5 and Fig. 6 respectively. We can see that the per-hop delay bound and buffer requirement bound of 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. Among three traffic splitting mechanisms, there is no big difference on the two bounds. Moreover, the two bounds of cluster-tree sensor networks are exponentially increasing as the tree depth increased.

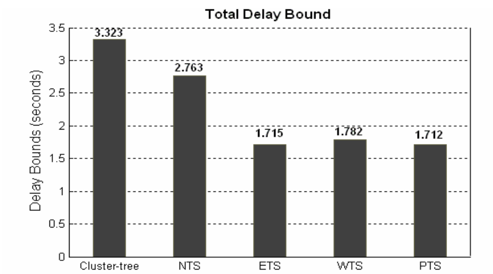


Fig. 7 Total delay bounds from the source to sink

The end-to-end delay bounds from the source to sink are shown in Fig. 7, which also reveals that using traffic splitting mechanisms will improve performance. The end-to-end delay bounds scaling with network size are shown in Fig. 8 (The number of nodes in mesh sensor network are 16, 36, 64, 144 respectively, and in cluster tree network are 15, 31, 63, 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 network resource utilization can be improved as well.

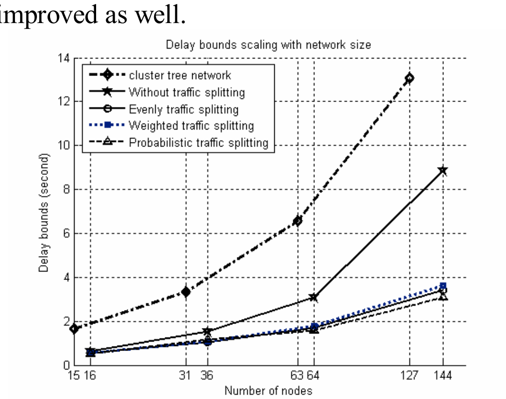


Fig. 8 Delay bounds scaling with size

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. Further more, by splitting traffic among all the minimum routing paths, both the delay and buffer size are 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, since data of the whole sensor network is accumulated at the sink, the traffic density is extremely high around the sink. Our future work may focus on multiple sinks cases of mesh sensor networks.

7. References

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