Stochastic QoS Performance Analysis of DiffServ-based Wireless Sensor Network

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***Abstract*—In wireless sensor network (WSN), real-time network applications require good quality-of-service (QoS) guarantees, such as low packet delay and small backlog. Differentiated services (DiffServ) mechanism is proposed to satisfy the QoS requirements in WSN. The stochastic characteristics need to be considered for the QoS performance analysis of DiffServ-based WSN. However, the existing works merely derive the average packet delay and backlog in steady states. In this paper, we use stochastic network calculus (SNC) to analyze the stochastic per-flow delay and backlog in DiffServ-based WSN. Firstly, the stochastic service curve for each data flow is derived under strict priority (SP) service scheduling discipline. Then, stochastic per-flow delay and backlog bounds are obtained. As a comparison, we also analyze the stochastic per-flow QoS performances without DiffServ mechanism. Finally, a numerical experiment is conducted with $(\rho(\epsilon), \sigma(\epsilon))$-constrained traffic process.**

I. Introduction

Wireless sensor network (WSN) significantly improves the way of gathering hard-to-obtain information and high fidelity information. Thus, WSN has been widely used in environment surveillance, patient care, battlefield monitoring, etc.

Various types of data flows can be gathered by sensor nodes in WSN. Traditionally, all data flows are aggregated into a single flow to reduce transmission loads and save energy [9]. In this case, WSN provides the same level of QoS guarantees to all data flows. In fact, different types of data flows require different levels of QoS guarantees. For example, the information about earthquake or tsunami should be transmitted with much lower latency and smaller backlog than information about rain or wind so that immediate defensive actions can be taken. Similarly, real-time traffics are much more sensitive to delay and packet loss than delay-tolerate traffics. To ensure more critic network traffics having better QoS performances, new QoS guarantee mechanisms are needed.

Differentiated services (DiffServ) mechanism [10] has been proposed to satisfy the QoS requirements in WSN. In DiffServ-based WSN, input data flows with higher priority receive more services under a priority-based service scheduling discipline. The QoS performance analysis of DiffServ-based WSN has been conducted in [11]-[14]. However, the authors mainly focus on the average packet delay and backlog in steady states. These results are obtained with deterministic input traffic processes and constant service rates. In fact, since the sensor field is changing all the time, the input traffics are always uncertain. Besides, the services received by a certain flow is affected by the stochastic characteristics of WSN. In this case, the existing QoS analysis methods lose their effectiveness.

The main objective of this paper is to propose a practical approach to analyze the stochastic delay and backlog performances in DiffServ-based WSN. Unlike the exsiting QoS analysis methods [8], network calculus (NC) [1][2] is based on the min-plus algebra. Schmitt et al. [6][7] innovatively use deterministic network calculus (DNC) [3] to evaluate the worst-case delay and backlog performances in WSN. Unfortunately, these works still neglect the inherently stochastic characteristics of WSN. As the probabilistic counterpart of DNC, stochastic network calculus (SNC) [4][5] considers the stochastic nature of wireless networks. Thus, SNC has been proved as an effective QoS analysis tool for wireless networks. Deng et al. [15] use SNC to calculate the stochastic delay bounds in WSN under different aggregation schemes. However, Diffserv mechanism is not be considered.

In this paper, we present a stochastic network calculus based QoS analysis method for DiffServ-based WSN. Different from traditional WSN, input data flows are classified first in our DiffServ-based WSN model. Data flows belonging to the same class have the same level of QoS guarantee requirements. Thus, these data flows are aggregated into a single flow to be served. After data aggregation, aggregated flow requires better QoS guarantees is given a higher priority. Under a specific priority-based service scheduling discipline, WSN can provide different QoS guarantees to aggregated flows with different priorities.

To evaluate the QoS performances, we first analyze the service competition within input data flows belonging to the same class. Then, stochastic service curve for each aggregated flow is obtained under strict priority (SP) scheduling discipline. As a comparison, we also drive the stochastic per-flow service curves without DiffServ mechanism. In this case, data flows receive service guarantees under first-in-first-out (FIFO) scheduling discipline. Given these stochastic service curves, stochastic per-flow delay and backlog bounds are obtained. Finally, a numerical experiment is conducted with $(\rho(\epsilon), \sigma(\epsilon))$-constrained traffic process. The numerical results show that our method is capable of deriving the stochastic QoS performance bounds in DiffServ-based WSN.

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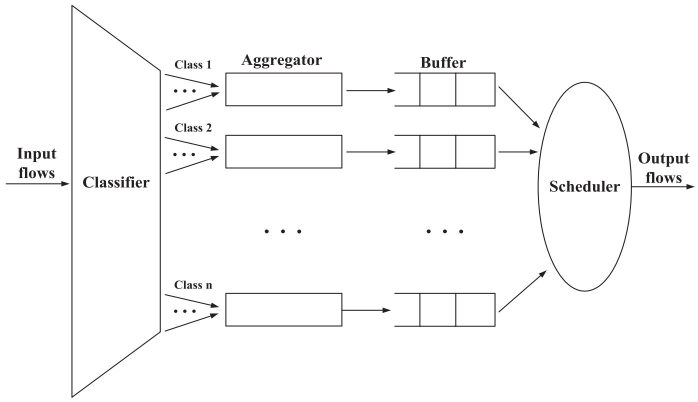


Fig. 1. DiffServ mechanism at a cluster-head node.

The rest of the paper is organized as follows. A DiffServ-based WSN model is presented in Section II. In Section III, we first derive the stochastic service curves provided to each data flow under FIFO and SP scheduling discipline. Then, stochastic per-flow delay and backlog bounds are obtained. In Section IV, numerical results are shown for $(\rho(\epsilon), \sigma(\epsilon))$-constrained traffic process. Finally, conclusions are drawn in Section V.

II. System Model

A. DiffServ-based WSN Model

In this paper, we consider a DiffServ-based WSN model based on cluster-tree architecture. In each cluster, sensor nodes monitor various types of data flows and forward them to the cluster-head (CH) node. These data flows are classified and aggregated at the CH node. Aggregated flows are transmitted to either upper level CH nodes or sink node. Finally, sink node collects all data flows and transmits them to the base station.

As shown in Fig.1, each CH node provides service guarantees to data flows based on a DiffServ mechanism. Since CH nodes perform the functions of both ingress nodes and core nodes, they determine the priority level and the per hop behavior (PHB) of each data flow. At each CH node, data flows are classified based on the level of QoS guarantee requirements. After classification, data flows belonging to the same class are aggregated into a single flow under a specific aggregation scheme. Each aggregated flow is assigned an unique priority and enters the specified buffer to wait for serving. The buffer sizes are assumed to be large enough. At scheduler, different aggregated flows receive services under a priority-based service scheduling discipline. CH nodes provide stochastic services, which will lead to stochastic service guarantees.

B. SP Scheduling Discipline

Without DiffServ mechanism, a CH node provide services to data flows under FIFO scheduling discipline. We assume data flows belonging to different classes are aggregated under FIFO aggregation scheme [15]. The data packet enters the buffer first will be served first no matter which class it belongs to. Clearly, the CH node ignores the priority of data flows.

On the contrary, DiffServ mechanism is always working with priority-based service scheduling disciplines. In this paper, SP scheduling discipline is taken into account. Under SP scheduling discipline, WSN gives each aggregated flow an unique priority. Aggregated flows with lower priorities will not be served if there exist workloads from aggregated flows with higher priorities waiting for serving. We assume the DiffServ-based WSN is work-conserving. When the services for aggregated flows with higher priorities are guaranteed, aggregated flows with lower priorities can receive the leftover services.

C. Stochastic Network Calculus Basics

In stochastic network calculus, $A(t)$, $A^*(t)$ and $S(t)$ denote the cumulative arrival process, the cumulative departure process and the cumulative service process respectively. For any $0 \le s \le t$, we have $A(s,t) = A(t) - A(s)$.

Stochastic arrival curve and stochastic service curve are two fundamental concepts in SNC. Stochastic arrival curve provides the probabilistic upper bound of an input data flow A, while stochastic service curve characterizes the probabilistic lower bound of stochastic service an input data flow receives.

Definition 1: (Stochastic Arrival Curve [5]) An input data flow A is said to have a virtual-backlog-centric (v.b.c) stochastic arrival curve $\alpha(t) \in F^1$ with bounding function $f(x) \in \overline{F}^2$, denoted by $A(t) \sim_{vb} \langle f(x), \alpha(t)\rangle$, if for all $t \ge 0$ and $x \ge 0$ there holds

$$P\left\{\sup_{0\le s\le t}\{A(s,t) - \alpha(t-s)\} > x\right\} \le f(x). \tag{1}$$

Definition 2: (Stochastic Service Curve [5]) A system S is said to provided a stochastic service curve $\beta(t) \in F$ with bounding function $g(x) \in \overline{F}$, denoted by $S \sim_{sc} \langle g(x), \beta(t)\rangle$, to input process $A(t)$ with corresponding departure process $A^*(t)$, if for all $t \ge 0$ and $x \ge 0$ there holds

$$P\left\{\sup_{0\le s\le t}\{A \otimes \beta(s) - A^*(s)\} > x\right\} \le g(x), \tag{2}$$

where $\otimes$ is the min-plus convolution and we have $a \otimes b(x) = \inf_{0\le y\le x}[a(y) + b(x-y)]$.

Given the two curves, the per-flow delay and backlog bounds can be obtained as follow.

Theorem 1: (Per-flow Performance Bounds [5]) An input flow A has a v.b.c stochastic arrival curve $A(t) \sim_{vb} \langle f(x), \alpha(t)\rangle$ and enters a server. If the server provides the flow with service $S \sim_{sc} \langle g(x), \beta(t)\rangle$, for all $t \ge 0$ and $x \ge 0$, the delay $D(t)$ and backlog $B(t)$ of the flow at time t are bounded by

$$P\{D(t) > h(\alpha + x, \beta)\} \le f \otimes g(x), \tag{3}$$

$$P\{B(t) > x\} \le f \otimes g(x - v(\alpha, \beta)). \tag{4}$$

Here, $h(\alpha, \beta) = \sup_{s\ge 0}\{\inf\{\tau \ge 0 : \alpha(s) \le \beta(s+\tau)\}\}$ denotes the maximum horizontal distance between $\alpha(t)$ and $\beta(t)$. $v(\alpha, \beta) = \alpha \oslash \beta(0) = \sup_{s\ge 0}\{\alpha(s) - \beta(s)\}$ denotes the maximum vertical distance between $\alpha(t)$ and $\beta(t)$.

[1] F is the non-negative wide-sense increasing function.
[2] $\overline{F}$ is the non-negative wide-sense decreasing function.

III. Stochastic Performance Analysis

At a CH node, data flows are classified as follow: real-time data flows (high priority) belonging to class 1, non-real-time data flows (medium priority) belonging to class 2 and delay-tolerant data flows (low priority) belonging to class 3. $k_i \in N^+$ denotes the number of data flows belonging to class i, $i = 1, 2, 3$. Each data flow belonging to class i has a v.b.c stochastic arrival curve, denoted by $A_{i,j}(t) \sim_{vb} \langle f_{i,j}(x), \alpha_{i,j}(t)\rangle$, $j = 1, 2, ..., k_i$. Furthermore, the CH node provides to these flows a stochastic service curve, denoted by $S \sim_{sc} \langle g(x), \beta(t)\rangle$. We assume that the arrival curves of these input data flows should fulfill $\sum_{i=1}^{3}\sum_{j=1}^{k_i} \alpha_{i,j}(t) \le \beta(t)$. According to Theorem 1, QoS guarantees can be provided under all circumstances.

A. The Service Competition within Data Flows belonging to Class i

In this subsection, the service competition within input data flows belonging to the same class will be analyzed. Data flows belonging to class i, $i = 1, 2, 3$, are aggregated into a single flow A_i. The aggregated flow A_i also has a v.b.c stochastic arrival curve, denoted by $A_i(t) \sim_{vb} \langle f_i(x), \alpha_i(t)\rangle$. Because of data correlations and information redundances, $A_i(t)$ lies between $\max_{1\le j\le k_i}(A_{i,j}(t))$ and $\sum_{j=1}^{k_i} A_{i,j}(t)$, where the former one denotes the maximum correlations within input data flows and the latter one represents no correlation. The actual A_i is determined by a specific aggregation scheme [15]. Without loss of generality, we use an abstract model to obtain a broadly applicable result.

Theorem 2: At a CH node, there are k_i input flows belonging to class i and each input flow has a v.b.c stochastic arrival curve, denoted by $A_{i,j}(t) \sim_{vb} \langle f_{i,j}(x), \alpha_{i,j}(t)\rangle$, where $j = 1, 2, ..., k_i$. After data aggregation, the aggregated flow A_i can be represented as $A_i(t) = \sum_{j=1}^{k_i} c_{i,j}A_{i,j}(t)$. Here, $c_{i,j} \in [0, 1]$ are the correlation parameters reflecting the data correlations within data flows belonging to class i. Specially, when $\max_{1\le j\le k_i}(A_{i,j}(t)) = A_{i,m}$, we have $c_{i,m} = 1$. In this case, aggregated flow A_i also has a v.b.c stochastic arrival curve, denoted by $A_i(t) \sim_{vb} \langle f_i(x), \alpha_i(t)\rangle$. We have

$$f_i(x) = \left[f'_{i,1} \otimes f'_{i,2} \otimes \cdots \otimes f'_{i,k_i}(x)\right]_1, \tag{5}$$

$$\alpha_i(t) = \sum_{j=1}^{k_i} c_{i,j}\alpha_{i,j}(t), \tag{6}$$

where $f'_{i,j}(x) = f_{i,j}(\frac{x}{c_{i,j}})$ and $[\cdot]_1$ denotes $\max[0, \min(1, \cdot)]$.

Proof: According to Definition 1, we can obtain

$$\begin{aligned}
&P\left\{\sup_{0\le s\le t}\{A_i(s,t) - \alpha_i(t-s)\} > x\right\} \\
\le& P\left\{\sum_{j=1}^{k_i}\left\{\sup_{0\le s\le t}\{c_{i,j}[A_{i,j}(s,t) - \alpha_{i,j}(t-s)]\}\right\} > x\right\} \\
\le& \left[f'_{i,1} \otimes f'_{i,2} \otimes \cdots \otimes f'_{i,k_i}(x)\right]_1,
\end{aligned} \tag{7}$$

where the last step is based on Lemma 1.5 in [5]. ∎

After data aggregation, the stochastic services provided to one of these data flow $A_{i,m}$, $m = 1, 2, ..., k_i$, is affected by other data flows. The following theorem presents the stochastic service curve received by $A_{i,m}$ after data aggregation.

Theorem 3: After data aggregation, a CH node provides to the aggregated flow $A_i(t) = \sum_{j=1}^{k_i} c_{i,j}A_{i,j}(t)$, $i = 1, 2, 3$, a stochastic service curve S_i, denoted by $S_i \sim_{sc} \langle g_i(x), \beta_i(t)\rangle$. Consider each input flow $A_{i,j}$ has a v.b.c stochastic arrival curve, denoted by $A_{i,j}(t) \sim_{vb} \langle f_{i,j}(x), \alpha_{i,j}(t)\rangle$. In this case, one of these input data flows $A_{i,m}$, $m = 1, 2, ..., k_i$, receives a stochastic service curve, denoted by $S_{i,m} \sim_{sc} \langle g_{i,m}(x), \beta_{i,m}(t)\rangle$. We have

$$g_{i,m}(x) = \left[\left(\bigotimes_{j=1, j\ne m}^{k_i} f''_{i,j}\right) \otimes g''_i(x)\right]_1, \tag{8}$$

$$\beta_{i,m}(t) = \beta_i(t) - \sum_{j=1, j\ne m}^{k_i} c_{i,j}\alpha_{i,j}(t), \tag{9}$$

where $f''_{i,j}(x) = f_{i,j}(\frac{c_{i,m}}{c_{i,j}}x)$ and $g''_i(x) = g_i(c_{i,m}x)$.

Proof: When A_i is aggregated by two data flow $A_{i,1}$ and $A_{i,2}$, i.e. $A_i(t) = c_{i,1}A_{i,1}(t) + c_{i,2}A_{i,2}(t)$, the corresponding output flow is $A^*_i(t) = c_{i,1}A^*_{i,1}(t)+c_{i,2}A^*_{i,2}(t)$. Furthermore, we have $A^*_i(t) \le A_i(t)$, $A^*_{i,1}(t) \le A_{i,1}(t)$ and $A^*_{i,2}(t) \le A_{i,2}(t)$. As to $A_{i,1}$, there holds

$$\begin{aligned}
&A_{i,1} \otimes (\beta_i - c_{i,2}\alpha_{i,2})(s) - A^*_{i,1}(s) \\
\le& \inf_{0\le u\le s}\left\{\frac{A_i(u)}{c_{i,1}} + \beta_i(s-u) - c_{i,2}\left[\alpha_{i,2}(s-u) + \frac{A_{i,2}(u)}{c_{i,1}}\right]\right\} \\
&- \frac{A^*_i(s) - c_{i,2}A^*_{i,2}(s)}{c_{i,1}} \\
\le& \inf_{0\le u\le s}\left\{\frac{A_i(u)}{c_{i,1}} + \frac{\beta_i(s-u)}{c_{i,1}} - c_{i,2}\left[\frac{\alpha_{i,2}(s-u)}{c_{i,1}} + \frac{A_{i,2}(u)}{c_{i,1}}\right]\right\} \\
&- \frac{A^*_i(s) - c_{i,2}A^*_{i,2}(s)}{c_{i,1}} \\
\le& \inf_{0\le u\le s}\left\{\frac{c_{i,2}}{c_{i,1}}[A_{i,2}(s) - A_{i,2}(u) - \alpha_{i,2}(s-u)]\right\} \\
&+ \frac{\inf_{0\le u\le s}\{A_i(u) + \beta_i(s-u)\} - A^*_i(s)}{c_{i,1}} \\
\le& \sup_{0\le u\le s}\left\{\frac{c_{i,2}}{c_{i,1}}[A_{i,2}(s) - A_{i,2}(u) - \alpha_{i,2}(s-u)]\right\} \\
&+ \frac{A_i \otimes \beta_i(s) - A^*_i(s)}{c_{i,1}}.
\end{aligned} \tag{10}$$

According to Definition 1, Definition 2, Lemma 1.5 in [5] and (10), we have

$$\begin{aligned}
&P\left\{\sup_{0\le s\le t}\{A_{i,1} \otimes (\beta_i - c_{i,2}\alpha_{i,2})(s) - A^*_{i,1}(s)\} > x\right\} \\
\le& \left[f''_{i,2} \otimes g''_i(x)\right]_1.
\end{aligned} \tag{11}$$

As to $A_{i,2}$, the similar result can be obtained. The proof can be easily extended to the condition in which A_i is aggregated by more than two input data flows. ∎

B. Stochastic Service Curves under FIFO Scheduling Discipline

Without DiffServ mechanism, data flows belonging to different classes receive services under FIFO service scheduling discipline. We assume data flows A_1, A_2 and A_3 are merged into a single flow $A_{fifo}(t) = A_1(t) + A_2(t) + A_3(t)$ under FIFO aggregation scheme. The service competition within A_1, A_2 and A_3 can be regarded as a special case of Theorem 3. In this case, there exists no data correlation within these aggregated flows. According to the leftover service characterization in [5], the CH node provides to A_1 a stochastic service curve, denoted by $S_1 \sim_{sc} \langle g_1(x), \beta_1(t)\rangle$, where $g_1(x) = [f_2 \otimes f_3 \otimes g(x)]_1$ and $\beta_1(t) = \beta(t) - \alpha_2(t) - \alpha_3(t)$. Here, $\beta_1(t)$ is the lower bound of stochastic services A_1 can receive under FIFO scheduling discipline. When $\sum_{i=1}^{3} \alpha_i(t) > \beta(t)$ or system is not work-conserving, the result is not correct.

Similarly, the stochastic service curves for A_2 and A_3 under FIFO scheduling discipline can be obtained. The stochastic service curves provided to different aggregated flows under FIFO scheduling discipline are summarized in Table I.

TABLE I
STOCHASTIC SERVICE CURVES UNDER FIFO SCHEDULING DISCIPLINE

Flow A_i	$g_i(x)$	$\beta_i(t)$
A_1	$[f_2 \otimes f_3 \otimes g(x)]_1$	$\beta(t) - \alpha_2(t) - \alpha_3(t)$
A_2	$[f_1 \otimes f_3 \otimes g(x)]_1$	$\beta(t) - \alpha_1(t) - \alpha_3(t)$
A_3	$[f_1 \otimes f_2 \otimes g(x)]_1$	$\beta(t) - \alpha_1(t) - \alpha_2(t)$

C. Stochastic Service Curves under SP Scheduling Discipline

With DiffServ mechanism, a CH node provides stochastic services to aggregated flows A_1, A_2 and A_3 under a specific priority-based service scheduling discipline. In this subsection, we analyze the stochastic service curve provided to each aggregated flow under SP scheduling discipline.

Analysis of aggregated flow A_1

Since A_1 has the highest priority, data packets from A_1 will be transmitted immediately when entering the buffer. In this case, A_1 receives the total available services at a CH node under SP scheduling discipline. Thus, the CH node provides to A_1 a stochastic service curve, denoted by $S_1 \sim_{sc} \langle g_1(x), \beta_1(t)\rangle$, where $g_1(x) = g(x)$ and $\beta_1(t) = \beta(t)$. Clearly, SP scheduling discipline is the most suitable service scheduling discipline for real-time data flows.

Analysis of aggregated flow A_2 and A_3

When the services for A_1 has been guaranteed, A_2 has a higher priority than A_3 to use the leftover service. It is equivalent that a single flow $A_{sp}(t) = A_1(t) + A_2(t)$ has the highest priority to receive the total available service. The CH node provides to A_2 a stochastic service curve, denoted by $S_2 \sim_{sc} \langle g_2(x), \beta_2(t)\rangle$, where $g_2(x) = [f_1 \otimes g(x)]_1$ and $\beta_2(t) = \beta(t) - \alpha_1(t)$. A_2 receives more services under SP scheduling discipline than under FIFO scheduling discipline.

When considering A_3, it is equivalent that a single flow $A_{sp}(t) = A_1(t) + A_2(t) + A_3(t)$ to receive the total available service. Thus, the CH node provides to A_3 a stochastic service curve, denoted by $S_3 \sim_{sc} \langle g_3(x), \beta_3(t)\rangle$, where $g_3(x) = [f_1 \otimes f_2 \otimes g(x)]_1$ and $\beta_3(t) = \beta(t) - \alpha_1(t) - \alpha_2(t)$. A_3 receives no more services under SP scheduling discipline than under FIFO scheduling discipline. The stochastic service curves provided to different aggregated flows under SP scheduling discipline are summarized in Table II.

TABLE II
STOCHASTIC SERVICE CURVES UNDER SP SCHEDULING DISCIPLINE

Flow A_i	$g_i(x)$	$\beta_i(t)$
A_1	$g(x)$	$\beta(t)$
A_2	$[f_1 \otimes g(x)]_1$	$\beta(t) - \alpha_1(t)$
A_3	$[f_1 \otimes f_2 \otimes g(x)]_1$	$\beta(t) - \alpha_1(t) - \alpha_2(t)$

D. Per-flow Performance Bounds

As discussed above, we derive the stochastic service curves $S_i \sim_{sc} \langle g_i(x), \beta_i(t)\rangle$ received by each aggregated flow A_i, $i = 1, 2, 3$, under FIFO and SP scheduling disciplines. According to Theorem 3, a CH node provides to data flow $A_{i,m}$, $m = 1, 2, ..., k_i$, a stochastic service curve, denoted by $S_{i,m} \sim_{sc} \langle g_{i,m}(x), \beta_{i,m}(t)\rangle$. With the stochastic service curves derived above, the stochastic delay $D_{i,m}(t)$ and backlog $B_{i,m}(t)$ bounds of $A_{i,m}$ at a CH node can be obtained. We have

$$P\{D_{i,m}(t) > h(\alpha_{i,m} + x, \beta_{i,m})\} \le [f_{i,m} \otimes g_{i,m}(x)]_1, \quad (12)$$

$$P\{B_{i,m}(t) > x\} \le [f_{i,m} \otimes g_{i,m}(x - \upsilon(\alpha_{i,m}, \beta_{i,m}))]_1. \quad (13)$$

Furthermore, the per-flow end-to-end delay from the source node to the sink node can be derived as the sum of delay at each CH node.

IV. NUMERICAL RESULTS

In this section, numerical results are obtained. When an input data flow has a certain stochastic arrival process, the stochastic arrival curve can be obtained. In our numerical experiment, we assume all input data flows are $(\rho(\epsilon), \sigma(\epsilon))$-constrained traffic flows. As shown in [5], a $(\rho(\epsilon), \sigma(\epsilon))$-constrained traffic flow has a stochastic arrival curve $\alpha(t) = \rho(\epsilon)t + \sigma(\epsilon)$ with bounding function $f(x) = a(\epsilon)e^{-b(\epsilon)x}$, where $\rho(\epsilon)$ is average arrival rate and $\sigma(\epsilon)$ is burstiness. After data flows classification, we assume each class has two data flows. Each data flow has a v.b.c stochastic arrival curve, denoted by $A_{i,j}(t) \sim_{vb} \langle a_{i,j}e^{-b_{i,j}x}, \rho_{i,j}t + \sigma\rangle$, where $i = 1, 2, 3$ and $j = 1, 2$. WSN provides to these data flows a stochastic service curve, denoted by $S \sim_{sc} \langle g(x), \beta(t)\rangle$, where $g(x) = e^{-2x}$ and $\beta(t) = Rt$.

Based on (10) and (11), the stochastic delay and backlog bounds of $A_{1,1}$ under FIFO scheduling discipline can be derived. We have

$$P\left\{D^F_{1,1}(t) > \frac{x + \sigma + \sigma^F_{1,1}}{R - c_{1,2}\rho_{1,2} - r}\right\} \le \left[f_{1,1} \otimes g^F_{1,1}(x)\right]_1, \quad (14)$$

$$P\left\{B^F_{1,1}(t) > x\right\} \le \left[f_{1,1} \otimes g^F_{1,1}(x - \sigma - \sigma^F_{1,1})\right]_1, \quad (15)$$

where $g^F_{1,1}(x) = f''_{1,2} \otimes \left(\left(\bigotimes_{i=2}^{3} \bigotimes_{j=1}^{2} f'_{i,j}\right) \otimes g(c_{1,1}x)\right)(x)$, $r = \sum_{i=2}^{3} \sum_{j=1}^{2} c_{i,j}\rho_{i,j}$ and $\sigma^F_{1,1} = c_{1,2}\sigma + \sum_{i=2}^{3} \sum_{j=1}^{2} c_{i,j}\sigma$.

Furthermore, we can obtain the stochastic delay and backlog bound of $A_{1,1}$ under SP scheduling discipline. We have

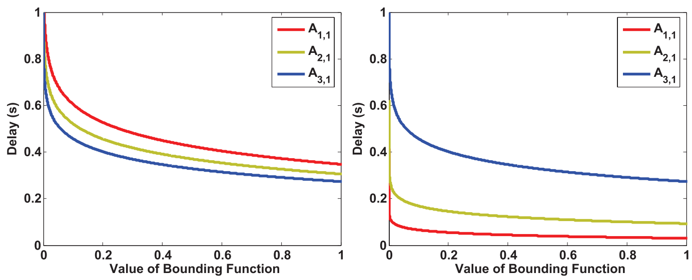
$$P\left\{D_{1,1}^{S}(t) > \frac{x+\sigma+\sigma_{1,1}^{S}}{R-c_{1,2}\rho_{1,2}}\right\} \leq \left[f_{1,1}\otimes g_{1,1}^{S}(x)\right]_{1}, \quad (16)$$

$$P\left\{B_{1,1}^{S}(t) > x\right\} \leq \left[f_{1,1}\otimes g_{1,1}^{S}(x-\sigma-\sigma_{1,1}^{S})\right]_{1}, \quad (17)$$

where $g_{1,1}^{S}(x) = f_{1,2}^{''}\otimes g^{''}(x)$ and $\sigma_{1,1}^{S} = c_{1,2}\sigma$.

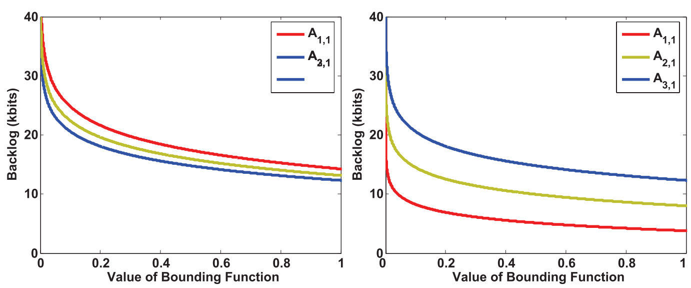
Similarly, the stochastic delay and backlog bounds for other input flows under FIFO and SP scheduling disciplines can also be obtained.

As to $(\rho(\epsilon),\sigma(\epsilon))$-constrained traffic flows, we assume $\rho_{1,1} = \rho_{2,1} = \rho_{3,1} = 20kbps$ and $\rho_{1,2} = \rho_{2,2} = \rho_{3,2} = 25kbps$. To ease the problem, all burstiness $\sigma_{i,j}$ is set to $1kbits$. Furthermore, $a_{i,j}$ and $b_{i,j}$ are set to 1 and 2 respectively for all bounding functions. Correlation parameters are set to $c_{1,2} = c_{2,2} = c_{3,2} = 1$, $c_{1,1} = 0.7$, $c_{2,1} = 0.8$ and $c_{3,1} = 0.9$. WSN provides a stochastic service curve $S \sim_{sc} \langle e^{-2x}, Rt\rangle$, where $R = 150kbps$.



(a) FIFO (b) SP

Fig. 2. Stochastic delay bounds under different scheduling disciplines.



(a) FIFO (b) SP

Fig. 3. Stochastic backlog bounds under different scheduling disciplines.

Fig.2 illustrates the stochastic delay bounds of input data flow $A_{1,1}$, $A_{2,1}$ and $A_{3,1}$ under FIFO and SP scheduling disciplines. As shown in Fig.2(a), the CH node fails to provide best delay guarantee to real-time data flow $A_{1,1}$ under FIFO scheduling discipline. Comparing Fig.2(a) with Fig.2(b), the results for $A_{1,1}$ and $A_{2,1}$ under SP scheduling discipline locate lower than results under FIFO scheduling discipline. It means the delay performances of $A_{1,1}$ and $A_{2,1}$ are improved with DiffServ mechanism. Furthermore, $A_{1,1}$ has a better delay guarantee than $A_{2,1}$. Meanwhile, the delay performance of $A_{3,1}$ is not be improved. It means that DiffSer-based WSN can provide better delay guarantees to data flows with higher priority under priority-based service scheduling disciplines.

As illustrated in Fig.3, similar results can be obtained for stochastic backlog performances. The numerical results show that our method is capable of deriving stochastic per-flow delay and backlog bounds in DiffServ-based WSN.

V. Conclusion

In this paper, we propose a stochastic network calculus based method to analyze the stochastic per-flow delay and backlog in DifferServ-based WSN. Stochastic service curves for input data flows are derived under strict priority (SP) scheduling discipline together with stochastic delay and backlog bounds. Comparing with the QoS performances without DiffServ mechanism, our results prove that DiffServ-based WSN can provide better delay and backlog guarantees to data flows with higher priority. The numerical results are shown for $(\rho(\epsilon),\sigma(\epsilon))$-constrained traffic process. In our future works, other QoS parameters (such as packet loss, delay jitter and throughput) in DiffServ-based WSN will be studied.

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