Maximizing Network Lifetime under QoS Constraints in Wireless Sensor Networks

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***Abstract*—In this paper, we study a randomized scheduling algorithm, and analyze the problem of maximizing network lifetime under Quality of Service constraints such as bounded values of detection delay, detection probability, and network coverage intensity in wireless sensor networks. We show that the optimal solutions exist and provide the conditions of the existence of the optimal solutions.**

Keywords- Wireless Sensor Network, Quality of Service, Network Life Time, Coverage

I. INTRODUCTION

Sensor nodes in wireless sensor networks (WSNs) have limited computational capability with a limited memory size, a limited range of wireless radio transmissions, and limited energy supply. Energy efficiency becomes an essential aspect in designing protocols in WSNs. One common way to save energy of sensor nodes is to turn off redundant sensor nodes. A sensor node is called a redundant sensor if its sensing range is fully covered by other sensor nodes.

Sensor networks have a wide variety of applications in both military and civil environment. However, since a sensor network is typically expected to last several months without recharging, minimizing network lifetime is an important design objective. In the meantime, how well a sensor network can collect sensory data depends on its sensing coverage and network connectivity. Therefore, maintaining sufficient sensing coverage and network connectivity are important for designing sensor networks.

To minimize energy consumption and extend network lifetime, some sensors are put in the sleep mode while the other sensor nodes are in the active mode for the sensing and communication tasks. When a sensor node is in the sleep mode, it is shut down except that a low-power timer is on to wake itself up at a later time, and therefore it consumes only a tiny fraction of the energy consumed in the active mode. There are many research efforts on coverage-preserving scheduling schemes to extend network lifetime for WSNs [1-8].

In this paper, we study a randomized scheduling algorithm, and analyze the problem of maximizing network lifetime under Quality of Service (QoS) constraints such as the bounded values of the detection delay, the detection probability, and the network coverage intensity. We show that the optimal solutions exist and provide the conditions of existence of the optimal solutions.

The rest of the paper is organized as follows. In Section II, we introduce the random coverage algorithm [9] and the problem definition. In section III, we analyze the problem of maximizing network lifetime under QoS constraints. Performance evaluation is presented in Section IV. Finally, we conclude the paper in Section V.

II. RANDOM COVERAGE ALGORITHM AND PROBLEM DEFINITION

One advantage of a random coverage algorithm (also called randomized scheduling algorithm) in [9] is that it does not assume location and directional information.

A. *Random Coverage Algorithm*

Let S denote the set including all the sensor nodes which are deployed in a wireless sensor network. Each sensor node is randomly assigned to one of k disjoint subsets (S_j, $j=0,1,2,\ldots,k$), which work alternatively. In other words, at any time, only one set of sensor nodes are working, and the rest of sensor nodes sleep.

B. *Problem Definition*

Network lifetime is the elapsed time during which the network functions well. In case that there is an intrusion such as an enemy tank invading a field covered with sensor nodes, detection delay is the average delay in terms of scheduling rounds to detect such an event. Detection probability is the probability of detecting the intrusion event. Network coverage intensity is the ratio of the time when a point in the field of the sensor network is covered by at least one active sensor node to the total time.

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Let T_{Nlife}, D, P_d, n, and C_n denote the network life time, the event detection delay, the detection probability, the number of sensor nodes, and the network coverage intensity, respectively. The problem which we will solve is an optimization problem with QoS constraints defined as follows.

Optimization Problem 1*: To maximize T_{Nlife} under the following conditions: 1) $D \le QoS_{DD}$, 2) $P_d \ge QoS_{DP}$, 3) $C_n \ge QoS_{C_n}$, and 4) $n = c$, where QoS_{DD}, QoS_{DP}, and QoS_{C_n} are pre-defined QoS constraints, and c is a constant value.*

Let r, a, and k denote the size of sensing area of each sensor, the size of the whole sensing field, and the number of disjointed subsets. Assume that an intrusion event happens randomly. Let L denote a duration when the event lasts. Let T denote the length of a scheduling round.

III. Analysis on Optimality

In this section, we study an optimization problem, i.e., to maximize network lifetime under QoS constraints such as bounded values of detection delay, detection probability, and network coverage intensity.

Let T_{Slife} denote the average lifetime of a typical sensor. We provide the following definition (denoted as T_{Nlife}) for the network lifetime as follows.

$$T_{Nlife} = kT_{Slife} \quad (1)$$

The optimization problem is defined in Section II. Since we have $T_{Nlife} = kT_{Slife}$, to maximize T_{Nlife} is to search the maximum k value to satisfy the QoS constraints. When k is very large, the detection delay must be large so that a very large k value is not the best solution. In other words, there is an upper bound on k values with a relative small detection delay. Since $C_n \ge QoS_{C_n} > 0$ can be re-written $1 \le k \le \dfrac{r}{a\left(1-\left(1-QoS_{C_n}\right)^{1/n}\right)}$ [10], the optimal problem can be re-written as follows.

Optimization Problem 2*: To find the maximum k value under the following conditions: 1) $D \le QoS_{DD}$, 2) $P_d \ge QoS_{DP}$, 3) $1 \le k \le \dfrac{r}{a\left(1-\left(1-QoS_{C_n}\right)^{1/n}\right)}$, and 4) $n = c$, where QoS_{DD}, QoS_{DP}, and QoS_{C_n} are pre-defined QoS constraints, and c is a constant value.*

We can prove the following Theorem, while the proof is omitted due to space limit. Details can be found in the journal version of this paper in the near future.

Theorem 1*: The above optimal problem has an optimal solution, if* $QoS_{DD} < \dfrac{\frac{L}{T}\left(\left\lceil \frac{L}{T}\right\rceil^2 - \left\lceil \frac{L}{T}\right\rceil + \frac{L}{T}\right)}{2\left\lceil \frac{L}{T}\right\rceil\left(\left\lceil \frac{L}{T}\right\rceil+1\right)}\left[1-\left(1-\frac{r}{a}\right)^c\right]$, $\dfrac{r}{a\left(1-\left(1-QoS_{C_n}\right)^{1/c}\right)} \ge 1$, $1-\left(1-\frac{r}{a}\right)^c \ge QoS_{DP} > 0$ *and* $1 > QoS_{C_n} > 0$, *where c is a constant. In other words, The following set S' is non-empty, and is bounded, where*

$$S' = \left\{ k \;\middle|\; D \le QoS_{DD} < \frac{\frac{L}{T}\left(\left\lceil \frac{L}{T}\right\rceil^2 - \left\lceil \frac{L}{T}\right\rceil + \frac{L}{T}\right)}{2\left\lceil \frac{L}{T}\right\rceil\left(\left\lceil \frac{L}{T}\right\rceil+1\right)}\left[1-\left(1-\frac{r}{a}\right)^n\right],\; P_d \ge 1-\left(1-\frac{r}{a}\right)^c \ge QoS_{DP} > 0,\; 1 \le k \le \frac{r}{a\left(1-\left(1-QoS_{C_n}\right)^{1/n}\right)},\; 1 > QoS_{C_n} > 0,\; n = c \right\}.$$

IV. Performance Evaluation

In this section, we provide a performance evaluation. Simulations are conducted with discrete event simulation using C++.

Fig. 1 shows the maximum k value vs. QoS_{C_n}, i.e., QoS constraints of C_n, with fixed QoS constraints of detection probability and detection delay, where *n =10000*, *a=10000*, *r=30*, *T=1*, *L=1*, $QoS_{DD} = 0.15$, and $QoS_{DP} = 0.6$. As illustrated in the figure, the maximum k value remains flat when QoS_{C_n} is small, but when QoS_{C_n} is large enough, it decreases sharply as QoS_{C_n} increases.

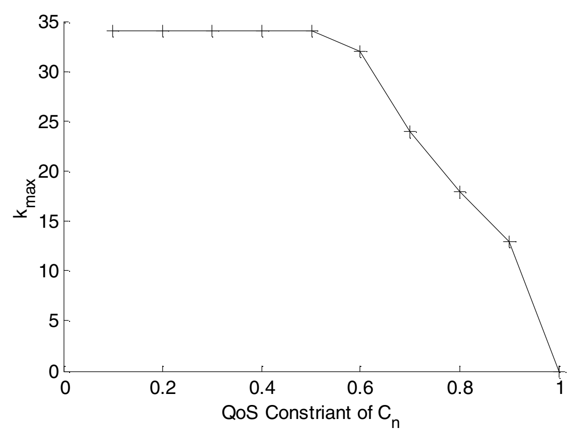

Fig. 1 Maximum k vs. QoS_{C_n}

Figs. 2-5 compare network coverage intensity, detection delay, detection probability, and network lifetime with the maximum k values obtained from Fig.1 with those not at the maximum k values under the same parameters as Fig.1. Although Fig. 3 shows that all three cases have detection probabilities higher than the required $QoS_{DP} = 0.6$, Fig. 2

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shows that when QoS_{C_n} is large, the case of $k_{max}+5$ has a network coverage intensity smaller than the required QoS_{C_n} and Fig. 4 shows that when QoS_{C_n} is small, the case of $k_{max}+5$ has a detection delay larger than the required $QoS_{DD} = 0.15$. In other words, the case of $k_{max}+5$ does not satisfy all QoS requirements. Furthermore, Fig. 5 shows that the case of $k_{max}-5$ has a network lifetime smaller than the case of k_{max}. In other words, the optimal one is the best among three cases.

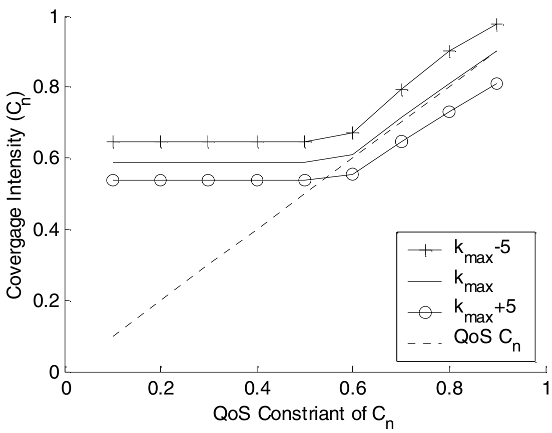

Fig.2 Coverage Intensity for QoS_{C_n}

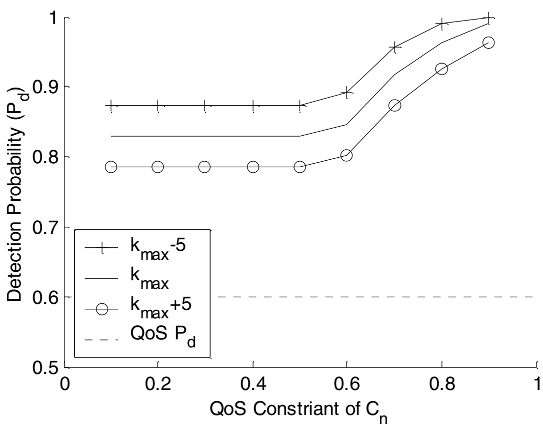

Fig.3 Detection Probability for QoS_{C_n}

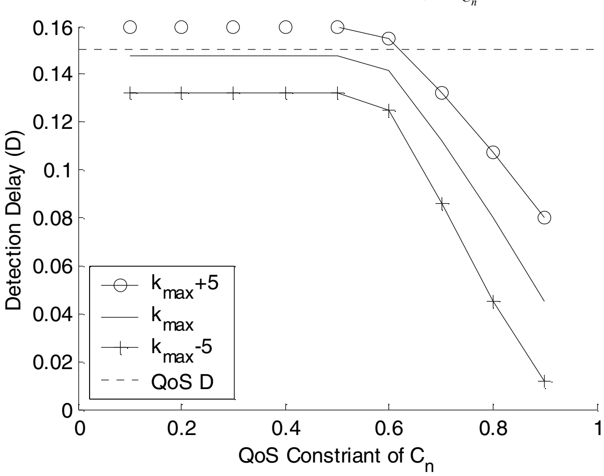

Fig.4 Detection Delay for QoS_{C_n}

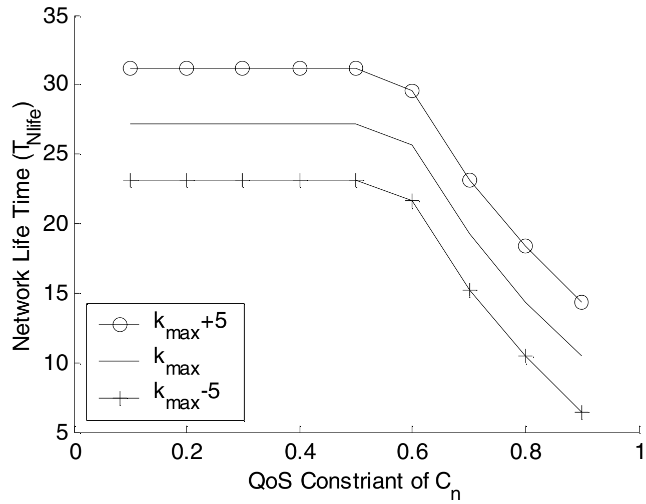

Fig. 5 Network Lifetime for QoS_{C_n}

Fig. 6 shows the maximum k value vs. QoS_{DP} , i.e., QoS constraints of P_d , with fixed QoS constraints of network coverage intensity and detection delay, where n =10000, a=10000, r=30, T=1, L=1, $QoS_{DD} = 0.15$, and $QoS_{C_n} = 0.6$. As illustrated in the figure, the maximum k value remains flat when QoS_{DP} is small, but when QoS_{DP} is large enough, it decreases sharply as QoS_{DP} increases.

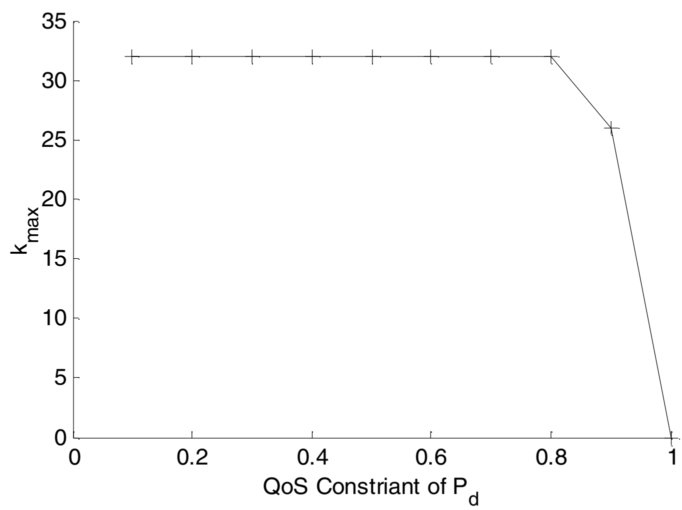

Fig. 6 Maximum k vs. QoS_{PD}

Figs. 7-10 compare network coverage intensity, detection delay, detection probability, and network lifetime with the maximum k values obtained from Fig.6 with those not at the maximum k values under the same parameters as Fig.6. Fig. 7 shows that when QoS_{DP} is small, the case of $k_{max}+5$ has a network coverage intensity smaller than the required $QoS_{C_n} = 0.6$. Fig. 8 shows that when QoS_{DP} is large, the case of $k_{max}+5$ has a detection probability smaller than the required QoS_{DP} and Fig. 9 shows that when QoS_{DP} is small, the case of $k_{max}+5$ has a detection delay larger than the required $QoS_{DD} = 0.15$. In other words, the case of $k_{max}+5$ does not satisfy all QoS requirements. Furthermore, Fig. 10 shows that

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the case of k_{max}-5 has a network lifetime smaller than the case of k_{max}. In other words, the optimal one is the best among three cases.

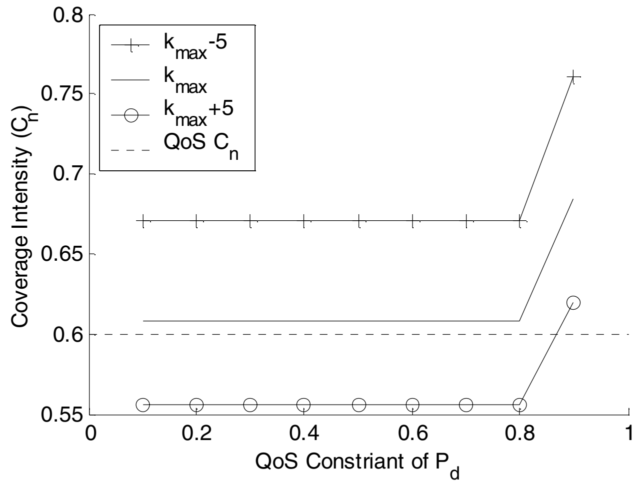

Fig.7 Coverage Intensity for QoS_{DP}

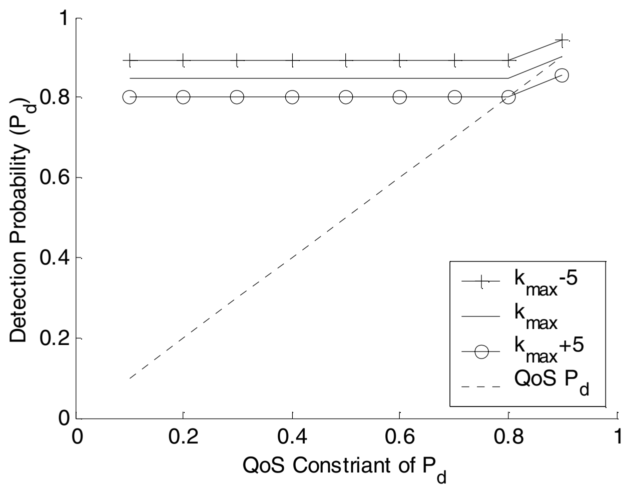

Fig.8 Detection Probability for QoS_{DP}

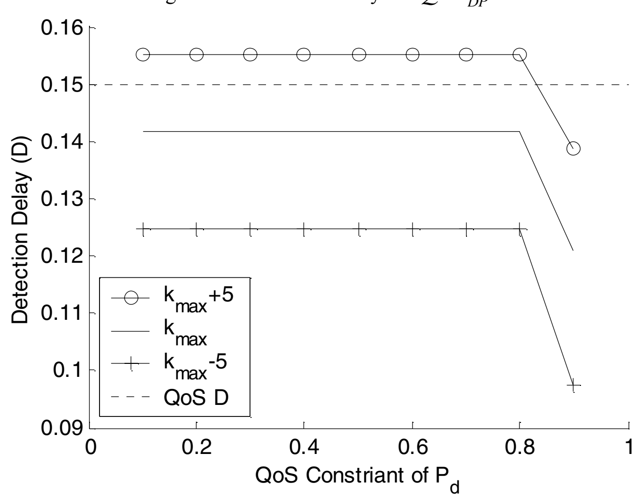

Fig.9 Detection Delay for QoS_{DP}

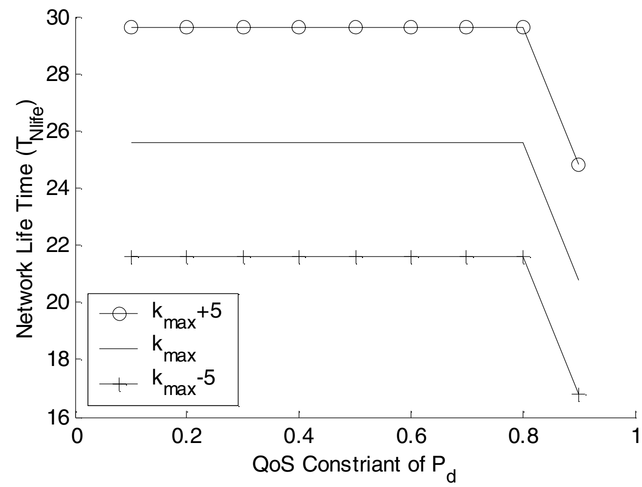

Fig.10 Network Lifetime for QoS_{DP}

Fig. 11 shows the maximum k value vs. QoS_{DD}, i.e., QoS constraints of D, with fixed QoS constraints of network coverage intensity and detection probability, where $n = 10000$, $a=10000$, $r=30$, $T=1$, $L=1$, $QoS_{C_n} = 0.6$, and $QoS_{DP} = 0.6$. As illustrated in the figure, the maximum k increases when QoS_{DD} is small, and it remains flat when QoS_{DD} is large.

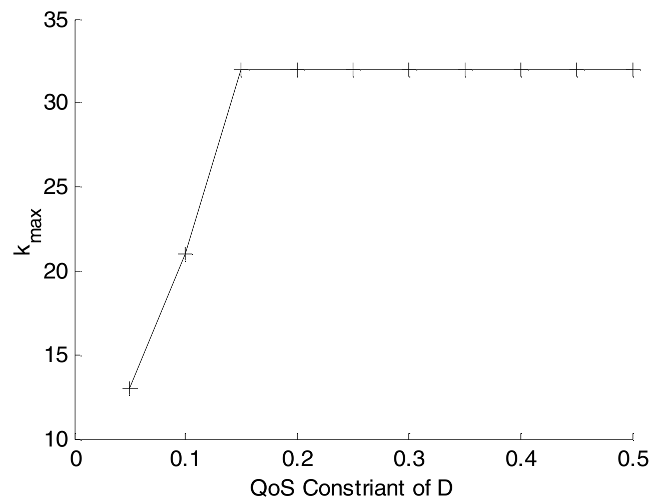

Fig. 11 Maximum k vs. QoS_{DD}

Figs. 12-15 compare network coverage intensity, detection delay, detection probability, and network lifetime with the maximum k values obtained from Fig.11 with those not at the maximum k values under the same parameters as Fig.11. Although Fig. 13 shows that all three cases have detection probabilities higher than the required $QoS_{DP} = 0.6$, Fig.12 shows that when QoS_{DD} is large, the case of k_{max}+5 has a network coverage intensity smaller than the required $QoS_{C_n} = 0.6$ and Fig. 14 shows that when QoS_{DD} is small, the case of k_{max}+5 has a detection delay larger than the required $QoS_{DD} = 0.15$. In other words, the case of k_{max}+5 does not satisfy all QoS requirements. Furthermore, Fig. 15 shows that the case of k_{max}-5 has a network lifetime smaller than the case of k_{max}. In other words, the optimal one is the best among three cases.

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V. CONCLUSION

We studied a randomized scheduling algorithm, and analyzed the problem of maximizing network lifetime under QoS constraints such as the bounded values of detection delay, detection probability, and network coverage intensity in wireless sensor networks. We presented a theorem to show that the optimal solutions exist and provided the conditions of the existence of the optimal solutions.

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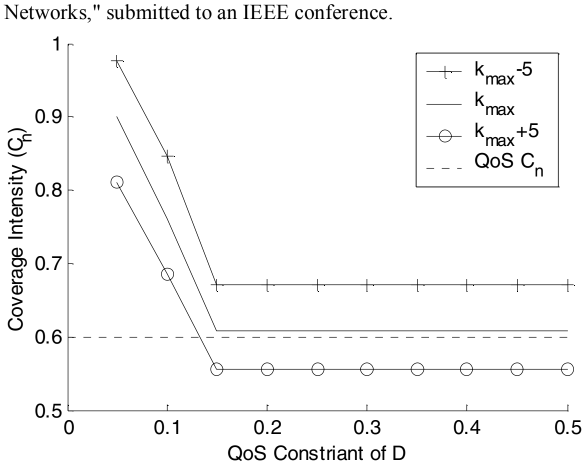

Fig. 12 Coverage Intensity for QoS_{DD}

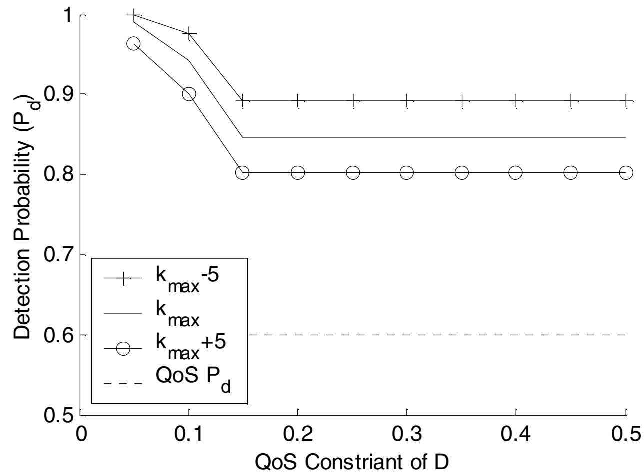

Fig. 13 Detection Probability for QoS_{DD}

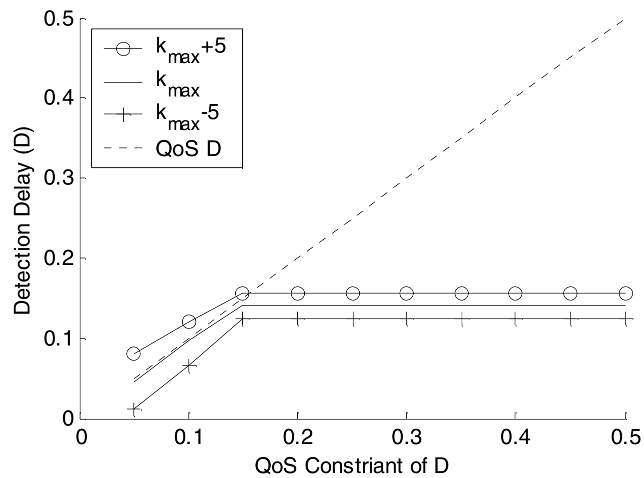

Fig. 14 Detection Delay s for QoS_{DD}

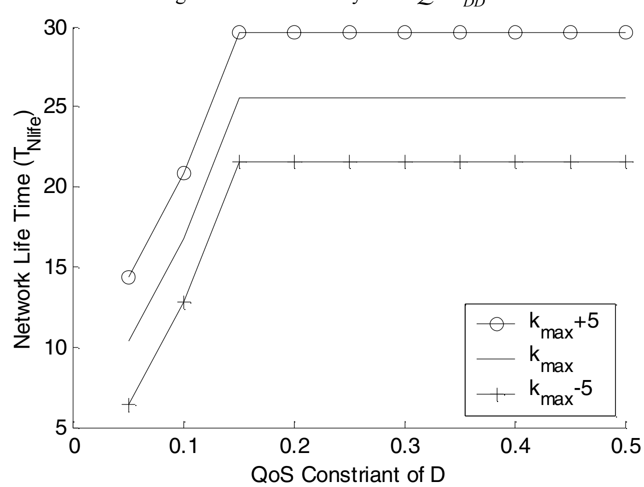

Fig. 15 Network Lifetime for QoS_{DD}

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