Analytical Analysis of RFID Sensor Network Model

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Summary
Under RFID sensor network environment, there are many situations to accommodate a number of RFID sensors within a specific area. In this paper, we build an analytical model of RFID sensor network and develop the analysis by using queuing system with $M/M/1/N/\infty$. In order to study the application in RFID sensor network for the queue model, we give out long-run Time-average number of RFID sensor requests in system and steady-state probability in system. The optimized value can be deduced by optimization theory. In order to find RFID sensor requests' effect on the system, we give out the numerical simulation on number of possible requests per unit. Though the analysis, we provide the optimal number of RFID sensors within a specific area and relationship between serving capability and sensor requests.
Key words:
Server utilization, arrival rate, service rate, service time

1. Introduction

Under RFID sensor network environment, there are many situations to accommodate a number of RFID sensors within a specific area. In this paper, we build an analytical model of RFID sensor network and develop the analysis by using queuing system with $M/M/1/N/\infty$. Many classical queuing systems have been developed by researchers [1-7]. In the ubiquitous computing environment, a massive number of sensors are needed in any kinds of services and our daily common life.

Recently, the advent of technology has facilitated the development of extremely small and low power devices that combine programmable general purpose computing with multiple sensing, wireless communication capability, and RFID System which is for identifying, tracking and/or locating things. Composing these sensor nodes into sophisticated, ad hoc computational and communication infrastructures to form sensor networks will have significant impact on applications ranging from military situation awareness to factory process control and automation. For instance, several thousand sensors are thrown from an airplane and rapidly deployed in a disaster area. The sensors communicate and coordinate to form an ad hoc communication network automatically. Emergency response teams can emanate concurrent queries into the sensor network to collect environmental information in the disaster area. The queries are automatically routed to the most appropriate sensors, and replies are collected and fused en route to the designated reporting points. The disaster area can also be monitored to alert emergency response teams with changing situations in the physical environment. However, the sheer number of these sensors and the dynamics of their operating environments for instance, limited battery power and hostile physical environment pose unique challenges in the design of autonomous sensor networks and their services and applications.

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2. Analytical Model Environment

In this section, we build an analytical model by considering network state description and possible valuable issues in our model. Also, in order to apply queuing system to the RFID sensor network environment properly, we define the terms and queuing notation.

2.1 Network state description

There are two kinds of network state: dynamic and steady state. In order to describe network state, we have to consider a number of issues in RFID sensor network environment. Since some RFID sensors can create their network automatically by their environment, applying a queuing system to RFID sensor environment has the following considerations:

(i) How many Intelligent RFID Sensors will be scattered in a specified area?
(ii) When will the system reach the steady state?
- If the number of RFID sensors increases, that is, the number of customers increases in terms of queuing system, the waiting line would tend to grow in length at an average rate of $\lambda - \lambda_s$. The sensor server that processes requests will eventually get further and further behind.

- The system wants to reach steady state, the server utilization $\rho = \dfrac{\lambda}{\mu} < 1$.

(iii) In what condition, the system can reach the steady state and every server utilization can be optimization.
(iv) How many sensors in the steady state system?

2.2 Queuing notation

A general queuing system has the queuing notation format of A/B/c/N/K, where A: represents the inter-arrival-time distribution, B: the service-time distribution. [Common symbols for A & B include M(exponential), D (const. or deterministic), E_k (Erlang of order k), and G(arbitrary or general)]. c: represents the number of parallel servers, N: represents the system capacity, and K: represents the size of the Population. Thus, $M/M/1/\infty/\infty$ indicates a single-server system with unlimited queue capacity and an infinite population of potential arrivals. The inter-arrival times and service times are exponentially distributed. When N and K are infinite, they may be dropped from the notation. That's $M/M/1/\infty/\infty$ shorten to $M/M/1$. More details of transient and steady-state behavior of queuing model is shown in Table 1.

Table 1: Queuing Model Notation

Symbol	Meaning
P_n	Steady-state probability of having n customs in system
$P_n(t)$	Probability of n customers in system at time t
λ	Arrival rate
λ_e	Effective arrival rate
μ_e	Effective service rate of one server
μ	Service rate of one server
ρ	$\rho = \dfrac{\lambda}{\mu}$, Server utilization
A_n	Inter-arrival time between customers n-1 and n
S_n	Service time of the nth arriving customer
W_n	Total time spent in system by the nth arriving customer
W_n^Q	Total time spent in the waiting line by customer n
$L(t)$	The number of customers in system at time t
$L_Q(t)$	The number of customers in queue at time t
L	Long-run time-average number of customers in system
L_Q	Long-run time-average number of customers in queue
ϖ	Long-run average time spent in system per customer
ϖ_Q	Long-run average time spent in queue per customer

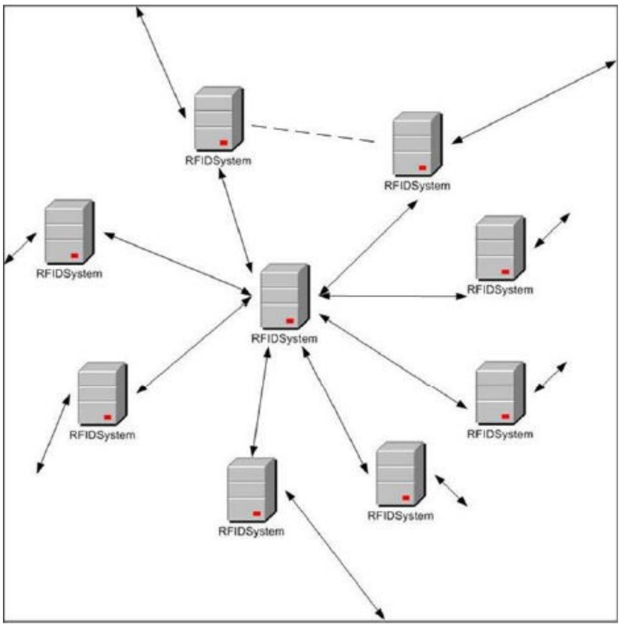

Fig. 1 Basic RFID System model.

3. Analytical Model of RFID Sensors System

As a basic RFID sensors system, we may consider a massive number of RFID sensors scattered in a system as shown in Figure 1. In order to form an ad hoc network, these RFID sensors connect to one other. A most simple case is a star topology that contains a server to process RFID sensor requests and a number RFID sensors, i.e., customers.

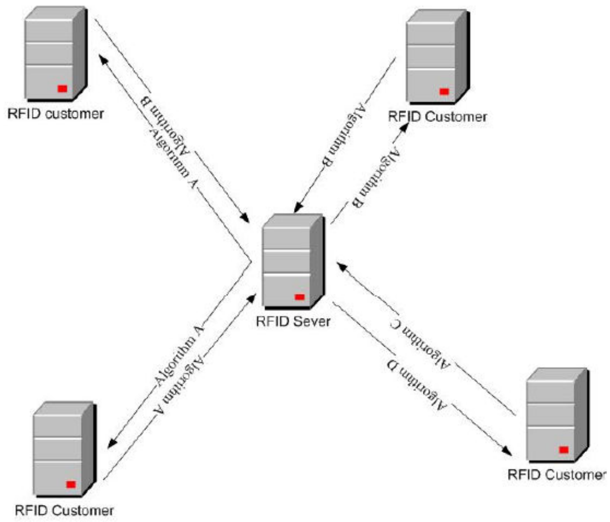

Fig. 2 single server $RFID$ System security algorithm model

This simple topology has a faster communication channel without complicated routing hops and is applicable in queuing system. In addition, we may consider that the RFID sensor communication between the server and customers uses the same algorithm, as shown in Figure 2.

Before developing the analytical model, we consider the characteristics of our model system. A RFID System contains a server and customers, and the server can be a customer in a larger domain of network. They form a network with the nearest RFID System automatically. The central RFID System acts as the server, and there is only one server in this system. Maybe there are several servers in a local steady-state system. They can form a local system dynamically. One RFID System can be in different local system as different environment.

4. Queuing model

For the infinite-population models, the arrival process is assumed to be a Poisson process with mean λ arrivals per time unit; that is, the inter-arrival times are assumed to be exponentially distributed with rate parameter λ. A Service time is assumed to be exponentially distributed with service rate μ. Because of the exponential distributed assumptions, these models are called Markovian models.

4.1 Steady-State Behavior of Infinite-Population Markovian Models

Suppose that service times are exponentially distributed at rate μ, there is a single server, and the total system capacity is N customers. If an arrival occurs when the system is full, that arrival is turned away and does not enter the system. As in the preceding section, suppose that arrivals occur randomly according to a Poisson process with rate λ arrivals per time unit. For any values of λ and μ, the $M/M/1/N/\infty$ queue has a statistical equilibrium with steady-state characteristics.

The effective arrival rate, λ_e, is defined as the mean of arrivals per time unit who enter and remain in the system.

1. For all systems, $\lambda_e \le \lambda$.
2. For the unlimited capacity systems, $\lambda_e = \lambda$.
3. But for systems such as the present one which turn customers away when full, $\lambda_e < \lambda$.
4. Effective arrival rate: $\lambda_e = \lambda(1-P_N)$
5. $1-P_N$ is is the probability that a customer, upon arrival, will find space and be able to enter the system.
6. For $\lambda \ne \mu$, full system probability: $P_N = \dfrac{(1-\alpha)\alpha^N}{1-\alpha^{N+1}}$, where $\alpha = \dfrac{\lambda}{\mu}$. Empty system probability: $P_0 = \dfrac{1-\alpha}{1-\alpha^{N+1}}$. $\alpha = 0$, or $\lambda = \mu \Rightarrow P_0 = P_N = \dfrac{1}{N+1}$

Some conclusions on the $M/M/1/N/\infty$ queue model are shown in table 2.

Table 2. Steady-State Parameters for the $M/M/1/N$ queue

(N=System Capacity, $\alpha = \dfrac{\lambda}{\mu}$)

Symbol	Meaning
L	$\begin{cases} \dfrac{\alpha[1-(N+1)\alpha^N + N\alpha^{N+1}]}{(1-\alpha^{N+1})(1-\alpha)}, & \lambda \ne \mu \\ \dfrac{N}{2} & \lambda = \mu \end{cases}$
$1-P_N$	$\begin{cases} \dfrac{1-\alpha^N}{1-\alpha^{N+1}} & \lambda \ne \mu \\ \dfrac{N}{N+1} & \lambda = \mu \end{cases}$
λ_e	$\lambda(1-P_N) = \mu(1-P_0) = \mu_e$

ρ	$\dfrac{\lambda_e}{\mu}=1-P_0$
ϖ	$\dfrac{L}{\lambda_e}$
ϖ_Q	$\varpi-\dfrac{1}{\mu}$
L_Q	$\lambda_e W_Q = L-(1-P_0)$
P_n	$\begin{cases}\dfrac{(1-\alpha)\alpha^n}{1-\alpha^{N+1}} & \lambda\neq\mu \\ \dfrac{1}{N+1} & \lambda=\mu\end{cases} \quad n=0,1,2,...,N$

4.2 Optimized Solution to $M/M/1/N$ Queueing System

In order to obtain the best value of λ, μ, and N, we'll use no-linear optimization to get the optimized value.

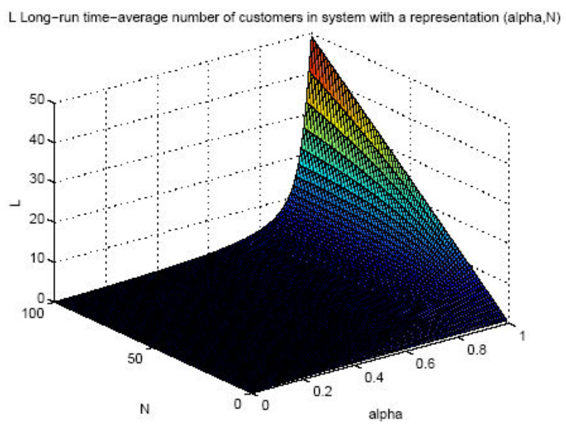

Fig. 3 Relationship between Stationary Queue length and $(\alpha, N=100)$

(i) If $\lambda=\mu$, then $W_Q=\varpi-\dfrac{1}{\mu}=\dfrac{N-1}{2\lambda}\geq 0.$ So we get $N\geq 1$.

(ii) $\lambda\neq\mu$, then

(a). $\alpha=\dfrac{\lambda}{\mu}<1$

(b). $\rho<1$

(c). $L=\dfrac{\alpha[1-(N+1)\alpha^N+N\alpha^{N+1}]}{(1-\alpha^{N+1})(1-\alpha)}$ will reach the maximum, $0<L<=N$. $L=L(\alpha,N)$ is the function of α and N.

(d). $P_N=P(\alpha,n)=\dfrac{(1-\alpha)\alpha^n}{1-\alpha^{N+1}}$ will reach the extremum.

(e) $\varpi=\dfrac{L}{\lambda_e}=\dfrac{L}{\lambda(1-P_N)}$ will reach the extremum.

4.3 Analysis of Stationary Queue Length and the Probability of Customers Served

Let $0<\alpha<1, N=100$, we get L from the simulation results. The $\max\{L\}$ is equal to 49.14971942669732 when α tends to 1, $N=100$, which connotes the

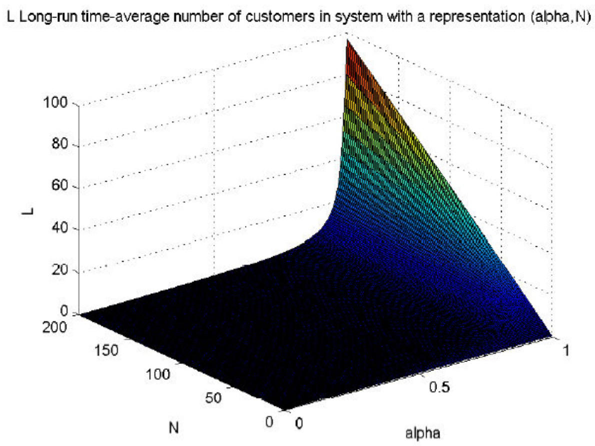

Fig. 4 Relationship between Stationary Queue length and $(\alpha, N=200)$

maximal point, $(100,0.998,49.15)$, $\max\{L\}$ just tends to 50 as shown in figure 3. If $\mathrm{N}=200$, when α tends to 1, $\mathrm{N}=200$, L reaches the maximum 96.6339 as shown in figure 4, which connotes the maximal point, $(200,0.998,96.634)$.

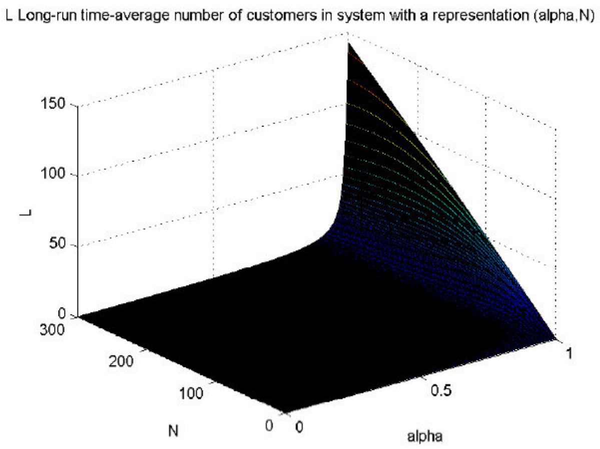

Fig. 4 Relationship between Stationary Queue length and $(\alpha, N = 300)$

If $\mathrm{N} = 300$, when α tends to 1, $\mathrm{N} = 300$, L reaches the maximum 142.4576 as shown in figure 5, which connotes the maximal point, $(300, 0.998, 142.458)$. No matter how to change α, N, $\max\{L\}$ just tends to $N/2$ which can be shown by figure 3-5. However $\max\{L\} \le N/2$, which connotes the $\max\{L\}$ just tends to $N/2$. However, if $\alpha = 1$, $\max\{L\} = N/2$. We conclude with that if $\lambda = \mu$, L reaches the maximal stationary queue length.

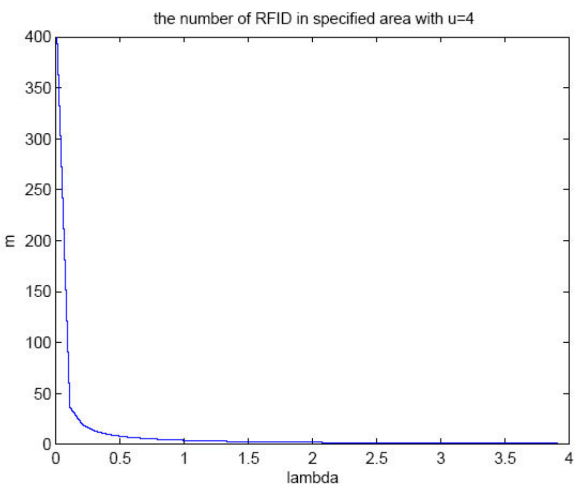

Fig. 6 the number of RFID sensor relates to λ_i

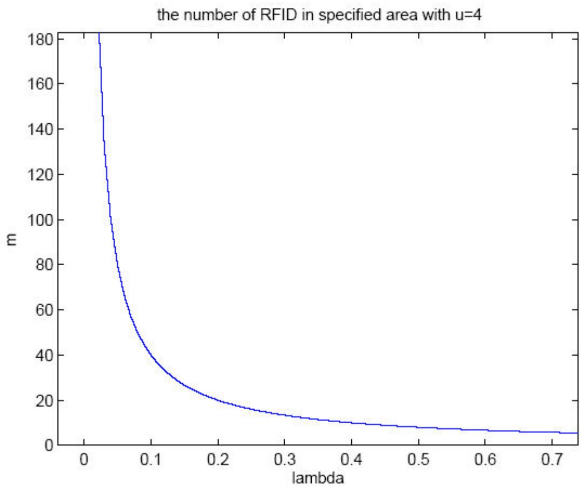

Fig. 7 magnified figure of the number of RFID sensor relates to λ_i

In order to compute the number of customers around the server, Let $\mu = 4$. Assuming that there are m customers in the populations' system and very customer has Poisson arrival with rate λ_i, $\mathrm{i} = 1,2,\ldots,\mathrm{m}$. If the system will reach the stationary system, we have

$$\sum_{i=1}^{m} \lambda_i \le \lambda = \mu, \quad when \quad \alpha = 1, L = \frac{N}{2}. \tag{1}$$

In order to simplify computation, suppose that each RFID's Poisson arrival rate is the same, and we have

$$\lambda_i = \frac{1}{24}, \quad i = 1,2,\ldots,m. \quad where \quad 0 < \lambda_i \le 4. \tag{2}$$

Therefore λ_i is equal to each other. Substituting equation 2 to equation 1, we have

$$m\lambda_i \le \mu, \tag{3}$$

From equation 3 we obtain

$$m \le \frac{\mu}{\lambda_i} = \frac{4}{1/24} = 96, \tag{4}$$

We get the curve relation between λ_i and m as figure 6, magnifying figure 6 of the number of RFID sensor relates to λ_i, and gets figure7. So we can conclude with that we should scatter 96 RFID sensor network in the specified area.

Table 3: Sample data from figure 6

λ_i	0.01	0.02	0.04	0.08	0.16	1	4
m	400	200	100	50	25	4	1

We give out sample data from figure 6 as follows table 3. Assuming that there are a number of different types of RFID sensors, they have different arrival rate λ_i such as company A's RFID sensors with $\lambda_1 = 0.01$, company B's RFID sensors with $\lambda_2 = 0.02$, company C's RFID sensors with $\lambda_3 = 0.04$, company D's RFID sensors with $\lambda_4 = 0.08$, company E's RFID sensors with $\lambda_5 = 0.16$, company F's RFID sensors with $\lambda_6 = 1$, and Company G's RFID sensors with $\lambda_7 = 4$. There are seven types of RFID sensors in our model. We get the average arrival rate of these 7 types of RFID sensors, and have

$$\bar{\lambda} = \frac{\sum_{i=1}^{7} \lambda_i}{7} = \frac{0.01+0.02+0.04+0.08+0.16+1+4}{7} = 0.7586. \quad (5)$$

Therefore, the total number of all types of RFID sensors is given by

$$m_1 + m_2 + ... + m_7 = m = \frac{\mu}{\lambda} = \frac{4}{0.7586} = 5.2729 \quad (6)$$

4.4 Station with areas RFID sensors example

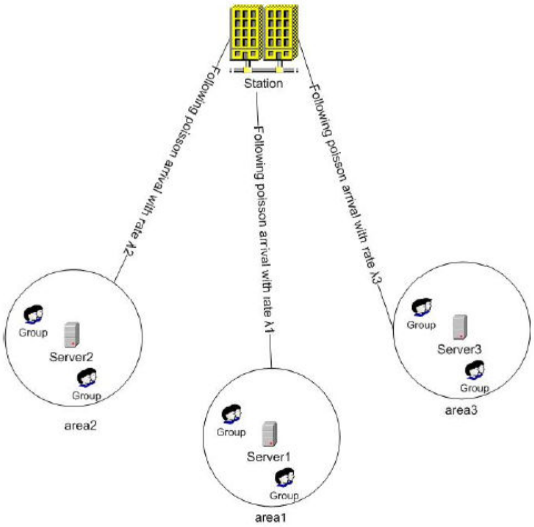

Fig. 8 Station with areas RFID sensors

In order to receive signal from all areas RFID sensors, we set a station shown as figure 8. In practical life we don't want to waste station because that it's every expensive to set a station. How many areas does one station can serve? It's also like that how many RFID sensors in one area that it can be optimized. From the above deducing process we can get the result, the number of areas is given by

$$sm = \frac{\mu}{\lambda} \quad (7)$$

5. Conclusion

We present a detail description on $M/M/1/N/\infty$ queue on RFID sensor network research. We give out the object function of queue length L, and get the maximum of L. When $\lambda = \mu$, the system can reach the maximal L. The server utilization $\rho = 1$ is the biggest value if the system wants to reach the steady state. The method is good to scatter RFID sensors in a specified area. The network can be used efficiently by using the simulation results.

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