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A Smart Wireless Paging Sensor Network for Elderly Care Application using LoRaWAN

Guangxiang Yang 1,2*, Hua Liang1

***Abstract*—Long range wide area network (LoRaWAN) is increasingly gained much attention due to its advantages in wireless sensor networks (WSNs) application. The message delivery between participated nodes and gateway in the WSNs affects the quality of service (QoS) such as energy consumption and the successful delivery rate (SDR). In this paper, we present a novel packet transmission model for a smart wireless paging sensor network (WPSN) based on LoRaWAN, which supports a real-time elderly care application. The model is used to investigate the performance of star topology communication on elderly care via Markov discrete-time M/M/1 queuing system. The proposed traffic model enables the performance evaluation of WPSN for elderly care. Moreover, an optimal cluster allocation policy is proposed by which maximizing SDR are obtained and QoS constraint requirements are met in terms of energy consumption. We conduct analytic analysis and simulation to exploit the QoS of LoRa based WSNs for elderly care application. The proposed WPSN is experimental studied and validated in a real elder care scenario. The contributions presented in this work may be referenced in the design of LoRa based WPSN.**

***Index Terms*—Wireless Sensor Networks; Paging; Elderly Care; LoRaWAN; Traffic Model; Markov Queuing Model;**

I. INTRODUCTION

With the growing social population aging problem, the elderly care has entered a new stage of development. The aging of social population is a hot research topic both in natural science and social science. The aged adult population problem is now getting increased health services utilization[1] and better policy support. The health monitoring system and smart paging system is very significant for the elderly care in the community. A smart paging network is able to better organize the elderly as well as provide higher service quality for aged persons in a residential area.

The Internet of things (IoT) connects any items with the Internet for information exchange. IoT is implemented through radio frequency identification technology and infrared sensor, global positioning system, laser scanner and other information sensing equipment. IoT application aims to realize the positioning, tracking, monitoring and management, and finally realizing the intelligent network of automatic information interaction and processing between objects and objects, people and objects[2-4]. It has been widely investigated in industry, agriculture, military, chemistry and other fields[5-7]. IoT is a nationwide coverage plan in China[8]. Elderly care is the fulfillment of daily assistance and health care in nursing homes. IoT is a preferred technology for elderly care because of its convenient connection between persons and objects. One of the important solutions of intelligent elderly care is wireless paging sensor networks (WPSNs) in IoT. WPSNs employ sensors to make the daily life of aged persons in remote monitoring state, as well as connect the elderly and the medical personnels to provide them with the safe and health care service. The IoT application in elderly care services is benefit for reducing the health and care risk of elderly, as well as meeting the different service requirements of senior citizens.

As the rapidly growth of IoT market, Low power wide area network (LPWAN) is one of new technologies in IoT, such as long range (LoRa) and narrow band (NB)-IoT. Among them, LoRa is one of the most promising solutions. LoRaWAN[9] is an LPWAN technology presented by Semtech, which employs LoRa modulation and makes data propagation in sub-GHz unlicensed spectrum. LoRaWAN networks can cover large areas with low power and are increasingly exploited in various areas. LoRa based wireless networks provide long range connectivity at an adaptive data rate, which uses a star topology to transfer messages to multiple nodes by a gateway. In this star topology network, traffic access to the media from the multiple sensor nodes should be effectively arranged to avoid packet collisions, which have a dramatic impact on the lifetime of the WSNs[10]. On the other hand, for real time monitoring and servicing, the time delay and the successful data delivery rate (simplified with SDR) should be considered in elder care system in which the SDR is especially sensitive. Therefore, a traffic modeling strategy is necessary for analytical study of LoRa based WSNs and performance evaluation of the system especially in terms of energy consumption.

This paper introduces the LoRa based wireless data transmission technology applied in the smart elderly care system. An analytical traffic model is deployed based on a Markov discrete-time M/M/1 model for an uplink paging access media technique, which aims to find the optimal QoS based solution. The QoS performances of WPSN including

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packet latency, collision rate and SDR are evaluated. The proposed WPSN is experimentally studied and verified by both simulation and real elderly care engineering scenerio.

II. Related Works

LoRaWAN is a wireless communication protocol and has got more and more researches in recent years. Its application domains include smart agriculture, security city, river bank monitoring and street lighting control. However, LoRaWAN employs simple random access schemes that may suffer from important latency and low data delivery, which are key performance indicators in smart elderly care networks. Some researches focus on the features and performance of LoRaWAN. Rémi Bonnefoi, et al[11] present reinforcement learning algorithms to reduce the collision probability and the network latency. Jaehyu Kim, et al[12] propose a secure device-to-device link establishment scheme to guarantee security features in LoRaWAN and evaluated the performance by comparing the energy consumption. Ramon Sanchez-Iborra, et al[13] evaluate the performance of LoRaWAN on different real scenarios. Also the energy consumption is considered by some researchers. Analytical models of energy consumption and the performance of LoRaWAN are analyzed by Lluís Casals, et al[14]. The impact of LoRa transmission parameter selection on communication performance is presented by Bor, Martin; Roedig, Utz[15], a link probing regime to save energy consumption and improve communication reliability is also developed. Considering energy constraints of wireless sensor networks iin IoT, Fadi Al-Turjman, et al[16] propose a novel traffic model to investigate the effects of multi-hop communication of IoT. C. Tunc, et la[17] present a Markov fluid queue model for energy management to prolong the lifetime of IoT. For Markov model itself, a classical single server vacation model is generalized by Servi and Finn to consider a server in a WDM optical access network.[18]. Wang and Chang exploit the equilibrium joining strategies for customers in an M/M/1 queue with working vacations and vacation interruptions[19]. Kempa and Kobielnik consider a single-channel finite-buffer queuing model with a general independent input stream of customers [20]. Besides the characteristics of LoRaWAN network researches, the applications in industry and IoT are also attracted some researchers' attention. A solution is proposed in article[21] aims to integrate LoRaWAN with 4G/5G mobile networks, which will allow the current infrastructures of mobile network operators are reutilized. On the contrary, although LoRaWAN is rising with a promising future, Adelantado, et al[22] give an objective description of limitations of LoRaWAN in accordance with the development questions in research and application. Pedro Cruz, et al[23] address the IoT utilization of the public transportation system in smart city. The combined use of IoT with industrial sensors in structural health monitoring is given by Luis Alonso, et al[24]. Antonis Tzounis, et al[25] discuss the IoT solutions towards the modernization of agriculture and present a survey of IoT technologies in the agricultural sector. Yonghua Songa, et al[26] propose a IoT solution in energy management system based on the LPWAN technology. René Brandborg Sørensen, et al[27] have investigated the performance of LoRaWAN including delay, collision rate, and throughput. These articles have provided valuable works for the research in this paper.

According to the literature review, most of the works about LoRa has focused on the study of the network characteristics such as coverage, time delay, or energy consumption. As we know, the network performance and the availability such as collision rate and SDR are significant in elderly care solutions. Moreover, the data delivery policy among the nodes and the gateway in the star topology network is very important for avoiding packets collision and increasing SDR. But it has been carried out limited studies. Therefore, we mainly focus on the performance improvement and optimal cluster allocation policies for maximizing SDR in LoRaWAN. The network QoS factors, including average time delay, SDR and energy consumption, are analyzed. Based on this topic, a smart WPSN solution in elderly care system is implemented and evaluated experimentally.

III. Traffic Modeling Framework

The wireless paging sensor network in an elderly care system is a technical solution for message transmission and communication between the elderly and the workers. The aged people are distributed in the different rooms of a building. When the aged persons need help, they can press the pager in the room and ask workers for help. A gateway is located in the spatial middle floor of the building. In this way, the workers in the building can receive the paging messages of all aged persons in all rooms. Each worker is with a wrist watch in their hands which can display the detailed message such as room number, clock, etc. The pager and the wrist watch are actually a node in WPSN which employs the LoRa technique. The data transmitted between pager and wrist watch is delayed by a gateway in the WPSN. A LoRa modulation integrated microcontroller SX1278 is used as a radio frequency (RF) processor in the WPSN design. The SX1278 provides ultra long range while maintaining low current consumption, making it optimal for numerous applications. The devices cover the major ISM bands from 137 MHz to 1050 MHz. It offers separate high band and low band support for applications wanting to cover dual bands for world-wide operation, dual band support, or security against future band allocation changes[28]. A chip of STM32103 by STMicroelectronics is selected as the microcontroller of a node. The wireless paging sensor network architecture is depicted in Fig.1.

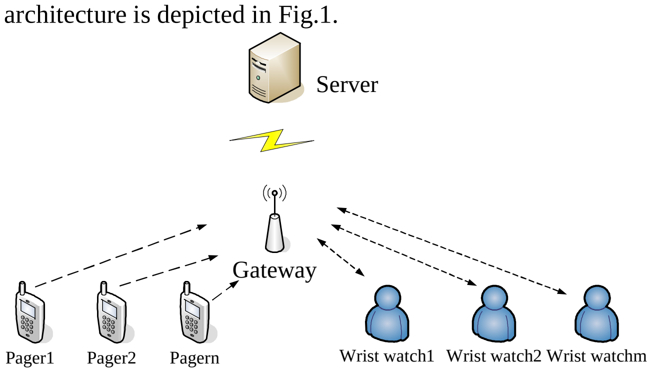

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Fig.1. The wireless paging sensor network architecture.

The smart wireless paging sensor network consists of one gateway and multiple pager nodes and wrist watch nodes. The gateway in the paging network is powered by an external AC. The pager nodes are equipped in the rooms in the elderly care building and they are powered by a DC battery. The aged persons initiate a service request by transmitting a packet from a pager node to a gateway. As soon as the gateway received the packet, it will relay the packet to the relevant wrist watch node which is wore in the worker's hands. When there are collisions in the transmission, the pager will retransmit the packet twice. The retransmission scheme is illustrated in Fig.2.

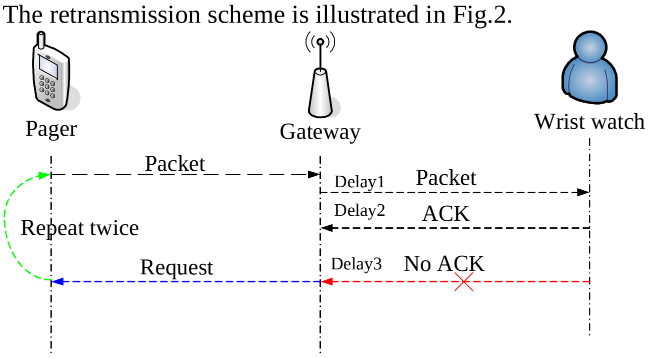

Fig.2. The retransmission scheme of WPSN.

In order to estimate the performance of the wireless paging sensor network in elderly care application, we propose a traffic model based on Markov discrete-time stochastic process M/M/1 queuing model. The data packets of the pager nodes for duty cycling are controlled by the random access mechanism because of the specific scenario of elderly care application. In the proposed model, the arrival and departure of data packets is operated under the assumption that there exist a finite queue size, which is similar to [25]. In addition, we assume that the pager nodes and the wrist watch nodes are making use of the multichannel random access to the media. As a consequence a retransmissions scheme is employed when the collisions occurred. It is shown that we can model the data packets transmission of each node in the network using discrete-time M/M/1 Markov queue. The Markov queuing model is with the general independent arrival process with Poisson distribution of the interarrival times, negative exponential service times and finite capacity N. In the normal mode, the gateway offers the service with the rate μ. Table 1 lists all the notations used in the model.

TABLE 1. NOTATIONS OF THE TRAFFIC MODEL.

Symbol	Definition
x(t)	The total number of packets arrival in the queue at time t
λ	Packets arrival rate
μ	Average service rate
ρ	Service capacity
β	The independent probability of transmitting data packet
t1	The time of packets arrival
t2	Service time
t3	Waiting time
t4	The time of packets leave
N	The number of packets in the queue
N	The capacity of queue for data packets

It is assumed that the arrival of the data packets is mutual independent and the arrival of data packets obeys the Poisson distribution. There is only one service desk (gateway). The length of the queue is N (that is, the maximum N packets in the system are allowed to queue up). It is the first in and first service in the queue. The service time of each packet is independent, which has an exponential distribution. The average service rate isμand the average arrival rate isλ. Therefore the average arrival time interval is 1/λ and the average service time is 1/μ.

Assuming service capacity is:

$$\rho = \frac{\lambda}{\mu} \tag{1}$$

Let the state probabilities is Pn(t), we have the steady state probabilities Pn is given by:

$$\lim P_n(t) = P_n \tag{2}$$

It can be concluded that:

$$P_0 = 1 - \rho \tag{3}$$

The stationary probability can be given by:

$$P_n = \frac{\lambda^n}{\mu^n} P_0 \tag{4}$$

$$P_n = \rho^n (1 - \rho) \tag{5}$$

When 0<ρ<1, M/M/1 model has the stationary probability; on the other hand, ifρ>1, there is not steady state for the queuing model.

According to Little formula, we have the equation of average packets in the queue:

$$L_s = \frac{\rho}{1-\rho} = \frac{\lambda}{\mu - \lambda} \tag{6}$$

The average waiting packets in the queue is given by:

$$L_q = \sum_{n=1}^{\infty} (n-1) P_n = \sum_{n=1}^{\infty} n P_n - \sum_{n=1}^{\infty} P_n = \frac{\lambda^2}{\mu(\mu - \lambda)} \tag{7}$$

The staying time of packet is:

$$W_s = \frac{1}{\mu - \lambda} \tag{8}$$

The waiting time of packet in the queue is depicted by:

$$W_q = W_s - \frac{1}{\mu} = \frac{\lambda}{\mu(\mu - \lambda)} \tag{9}$$

In the case of a finite-sized system, which means that the capacity of queue is N, the stationary probability can be given by:

$$P_n = \begin{cases} \rho^n P_0, n < N \\ 0, n > N \end{cases} \tag{10}$$

It means that the packet loss probability is P_N. In which,

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$$P_0 = \begin{cases} \dfrac{1-\rho}{1-\rho^{N+1}}, \rho \neq 1 \\ \dfrac{1}{N+1}, \rho = 1 \end{cases} \quad (11)$$

The average packets in the queue equation:

$$L_s = E(N) = \sum_{n=0}^{\infty} nP_n = \sum_{n=1}^{N} n\rho^n P_0 = \frac{\rho}{1-\rho} - \frac{(N+1)\rho^{N+1}}{1-\rho^{N+1}} \quad (12)$$

Consequently, the average waiting packets in the queue is given by:

$$L_q = L_s - (1 - P_0) \quad (13)$$

We have the actual average packet arrival rate

$$\lambda_e = \lambda(1 - P_N) \quad (14)$$

The total time delay of packet can be given by:

$$T = \frac{L_s}{\lambda_e} = \frac{\dfrac{\rho}{1-\rho} - \dfrac{(N+1)\rho^{N+1}}{1-\rho^{N+1}}}{\lambda(1-P_N)} \quad (15)$$

According to Fadi Al-Turjman[16], assuming that the Markov model with a finite queue transition states for each node is defined in space S = 0, 1, …, M and transitional probabilities $\pi_m(t)$ in matrix P of being in state m. The stationary distribution A = (π_0, π_1, …π_{N+1},). The stationary equation can be given by:

$$\lambda \pi_{n-1}(t) = n\mu \pi_n(t) \quad (16)$$

The steady state equations can be described as follows:

$$\pi_n(t) = \pi_{n-1}(t) * \beta * \delta + \pi_{n-1}(t) * (1 - \lambda\delta - \beta\delta) + \pi_{n+1}(t) * \beta * \delta + o(\lambda), \forall n! = 0 \quad (17)$$

As is mentioned by Fadi, et al that the packet arrival information λ and the probability of SDR β for a pager node in single-hop communication is also be considered to be variables of stationary probability.

IV. Cluster Allocation Policies

Wireless paging sensor network is a specific WSN application in an elderly care system. A pager will transmit the paging message with specified package to the gateway when there is any transporting request initiated by the aged in each room. When the gateway receives the package from the pager, it will emit a beeping alarm and show the room number on an LED screen to inform the worker. There are multiple pager nodes and multiple wrist watch nodes in the network. The aged persons are distributed into several groups and each group is belonged to one worker. It means that each worker is responsible for one group of aged persons. Consequently, the pager nodes are divided into groups. Each group is a network cluster which includes multiple nodes. In the cluster, we concern the SDR of WPSN. Each worker node could only receive the packets from the same cluster and then respond to the gateway. The packets from other cluster will be discarded. Therefore the extra packets responded to the gateway and then forward to the pager node such as ACK and REQUEST are effectively eliminated. In addition, this cluster allocation is also able to effectively decrease packets collision rate. The cluster allocation is depicted as Fig.3.

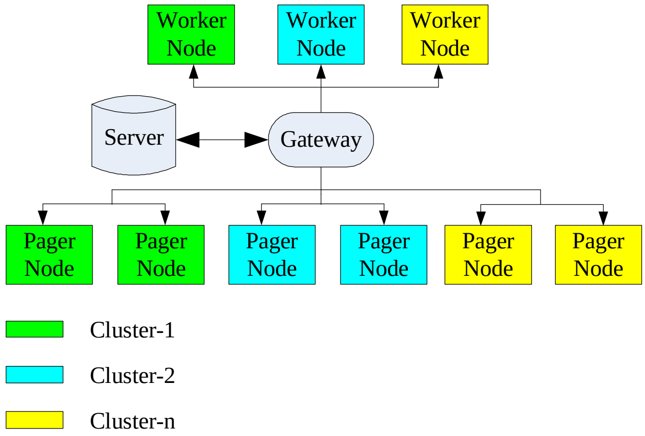

Fig.3. Hierarchical organization of network nodes in the WPSN.

Assuming that there are M pager nodes and N worker nodes in the WPSN, we have the total nodes in the network:

$$PN_i, i = 1,2,\ldots M; \quad WN_j, j = 1,2,\ldots N; \quad (18)$$

The nodes are allocated to different clusters as the following:

$$\begin{cases} PN_{i1}, WN_{j1}(i1 = 1,\ldots,x, i2 = 1,2,\ldots y) \in cluster_1 \\ \ldots \\ PN_{in}, WN_{jn}(in = x+1, x+2\ldots, M, in = y, y+1,\ldots N) \in cluster_n \end{cases} \quad (19)$$

When a node PN_i initiates a paging process by sending a packet to gateway, the cluster ID is attached in the packet. The gateway receives the packet and relay it to the worker nodes WN_j by unicast. If the packet from node PN_i is the same cluster with worker node WN_j, it will accept and decode the packet; else it will discard the packet. In other words, it is stated that the packets could only be delivered in the same cluster in the network. The cluster allocation policy in the gateway for the LoRaWAN is noted as follows.

1. Receive a packet x(i)
2. Get packet information such as cluster number, direction, function.
3. switch function of x(i)
4. case: paging
3. if x(i) belongs to cluster i
4. forwards packet to the destination node in the cluster i
3. retransmission Timer start
5. else discard packet x(i)
6. case:…
7. default:;
8. return

Accordingly, the packet transfer framework of cluster allocation policy is illustrated in Fig.4.

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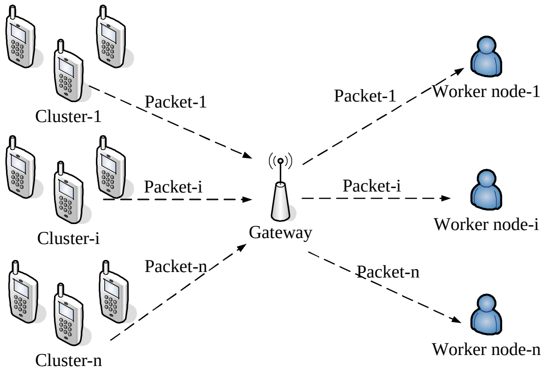

Fig.4. Packet transfer with cluster allocation policy.

There are different packets delivered between pager node and worker node in the WPSN. By these packets, it is able to implement retransmission scheme, cluster allocation policy and so on. Some important packets are listed in Table2.

TABLE2. PACKETS TYPE BETWEEN PAGER NODE AND WORKER NODE

Packet Function	Direction	Packet ID
Register	Worker node→ gateway	0xA0
Time synchronization	gateway → worker node	0xA2
Cluster allocation	gateway → worker node	0xA4
Paging	gateway → worker node	0xA7

V. EXPERIMENTS AND PERFORMANCE EVALUATIONS

In this section, we setup an experiment with real sensors and network topology application scenario to verify the proposed traffic model. On the other hand, the network characteristics and network QoS parameters are simulated under the LoRa based application. We estimate the traffic model and the cluster allocation policiy of WPSN in an elder care house in Chongqing, China. The experiment study aims to evaluate both the traffic load model and QoS parameters such as time delay, successful data delivery rate and energy consumption.

The elder care house we experimented is shown in Fig.5(a). There are totally 129 rooms in the elderly care building and each room is equipped with a pager node shown in Fig.5(b). There are totally 12 workers for the all aged persons' service. Each worker takes a wrist watch shown in Fig.5(c). A gateway in Fig.5(d) is located in the middle floor of the building so as to obtain maximum network coverage.

(a) an elderly care building

(b) a pager node

(c) a wrist watch

(d) a gateway

Fig.5 Scenario of wireless paging sensor network application

According to the cluster allocation policy, the proposed WPSN is divided into 12 clusters and each cluster includes 11 pager nodes and 1 wrist watch, as shown in Fig.6.

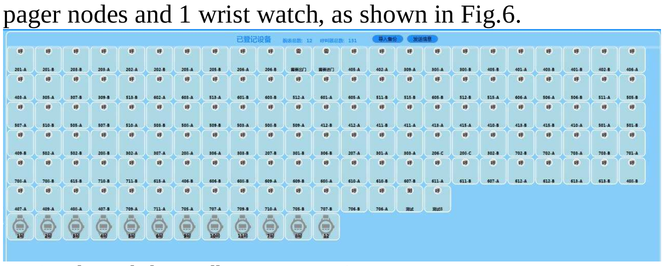

Fig.6 nodes and cluster allocation in WPSN

We analyze the QoS parameters obtained from the analysis of the random traffic effects on a unicast network and focus on realistic scenarios at different traffic load. Considering that the real time transmission and the packets loss may have a significant influence on the performance of WPSN, the factors such as average transmission packet delay, the energy consumption, and SDR are evaluated in terms of the impact of different packet arrival rates and service request. We use the discrete M/M/1 Markov queuing model in the simulation experiment, which matches the real elder care surrounding

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conditions within a sensor network. The simulation parameters are listed in table.3.

TABLE 3 THE SIMULATION EXPERIMENT PARAMETERS.

λpacket arrival rate (/min)	μ Average service rate (/min)	N The capacity of queue for data packets	Simulation time (min)
10	6	200	10
2,5,8,11,14	6	20	10

Fig. 7 depicts the arrival time and leaving time versus the packets arrived in the queue which will be transmitted from the pager node to the gateway. From the figure we can observe that the average time delay between arrival time and leaving time starts increasing as the arrival packet number increases. It means that when the packets arrived in the queue is increased, the gateway becomes busier and the needs to relay more packets to different cluster.

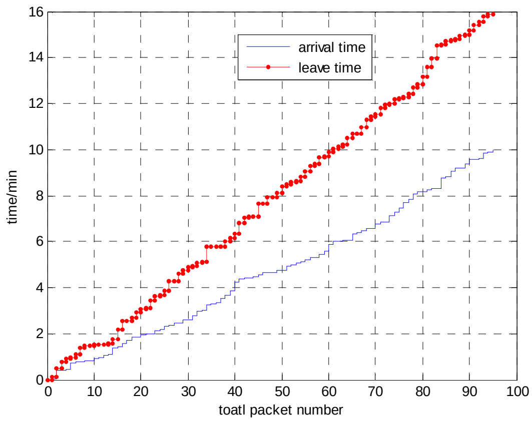

Fig.7 arrival time and leave time of packet

Similarly, the waiting time and total service time are shown in Fig.8. It is observed from the figure that general trend of both waiting time and service time is increasing with the packet number increases. But the gap between the two curves is very small which shows that the residence time of packet in the gateway is short.

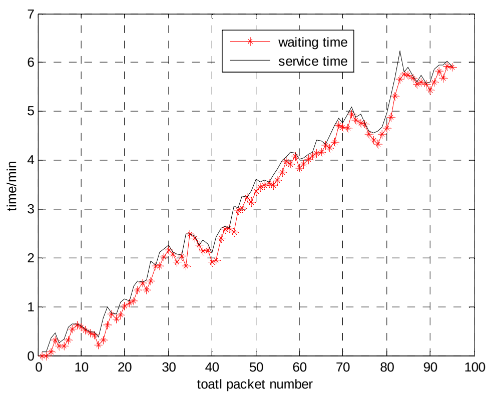

Fig.8 waiting time and service time of packet

Accordingly, the average time delay is computed by Equ.(15) and which is ploted in Fig.9. As discussed above, it is clear that the average time delay becomes larger with the packet number increasing. This figure shows that the higher packet arrival rates may determinate network congestion and cause the higher packet latency.

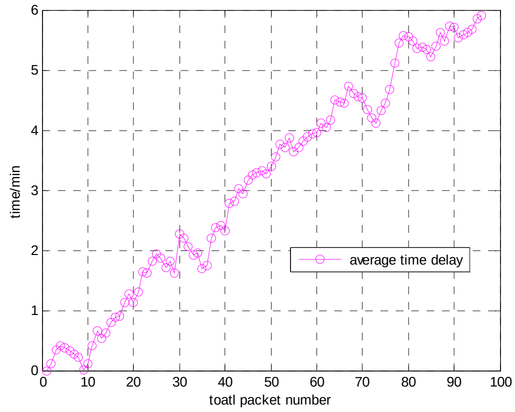

Fig.9 average time delay with different packet arrival

On the other hand, the average time delay is increased with the arrival packet increasing, which may result in higher packet loss or lower SDR. However we don't know exactly how the packet arrival rate will influence the SDR. In this case the average time delay and the packet loss are simulated based on the traffic model. The Fig.10 depicts the packet time delay among different packet arrival rates. It is observed that the average time delay becomes higher when the packet arrival rate increased from 2 to 14. Notice that the total packet number reaches its capacity under different arrival rates

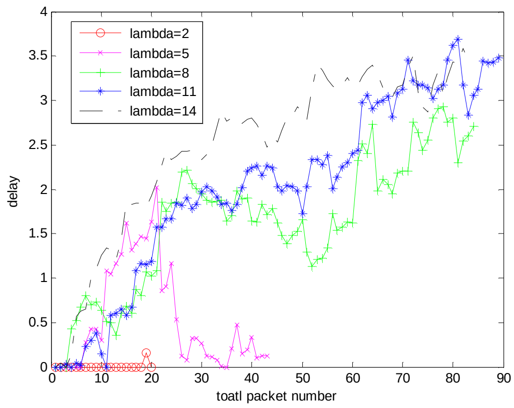

Fig.10 average time delay among different packet arrival rate

Additionally, the packet loss becomes worse with the higher packet arrival rate, which is denoted in Fig.11. We can observe that when the packet arrival rate is increased to 8 the packet loss number starts by hovering over zero. When the packet arrival rate is increased to 11 and 14, the total packet loss becomes about 27 and 67, respectively, which indicates that the SDR is sharply dropped to 27/90=30% and 67/90=7.8%. Since the load is spread more heavy over the channels at high arrival rate and we see a hover in collision rate by an increasing packet arrival rate, which makes the packets loss increased. It is clearly shown that the packet loss is higher in case of LoRaWAN than that of cluster allocation policy at the same packet arrival rate. The packet loss being reduced is probably because that more ACK and Request packets are eliminated by cluster allocation policy. The data collisions are decreased so as to lower the packet loss rate.

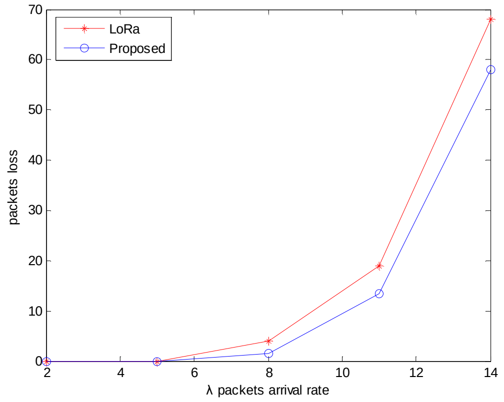

Fig.11 average packet loss in relation to packet arrival rate

The results shown are for the unicast in star topology network between nodes with the retransmission scheme. The model is useful for most real-time WPSN applications, particularly when the traffic load is randomly changed over time. The experimental study shows that the energy consumption is increased because the power module has to consume more energy to ensure a higher SDR by the retransmission scheme. The time delay for wrist watches in real elder care scenario is shown in Fig.12, in which the LED lighted when the packet is successfully delivered.

Fig.12 the packet arrive to wrist watch with time delay

Since the energy consumption is difficult to collection, a data table is written by adding the lifetime of wrist watch and pager nodes. The pager node uses a 12V/300mAH dry battery as a power supply while the wrist watch uses a lithium battery of 3.7V/200mAH. Generally a pager node can work for about 1 to 2 years at the paging frequency. While a wrist watch can only maintain about 10 days as its frequent work such as RF paging, displays, and vibration mode. Consequently, the energy consumption of wrist watch is more concerned in this work.

Given that the total work time of a wrist watch pager is about 10 hours per day. An average packets delivery D_L of 1860 for a wrist watch is estimated and obtained when using LoRa. While for a cluster allocation policy based wrist watch, average packets delivery D_C of 1512 is estimated according to data allocation policy. It is assumed that the time H for each data delivery process was 0.2s. Under the transmitting power of 20dBm, the transmitting current and the receiving current of a wrist watch is 120mA and 12mA, respectively. The rated voltage of battery is V. The electricity power consumed by LoRa is P_L and by cluster allocation policy is P_C, which are given by:

$$P_L = (D_L * H * 0.12 + D_L * H * 0.012) * V \quad (20)$$

$$P_C = (D_C * H * 0.12 + D_C * H * 0.012) * V \quad (21)$$

Consequently, the total electricity power consumed every day by a LoRa wrist watch is computed as follows:

$$P_L = 181.7J$$

The total electricity power consumed every day by a cluster allocation policy wrist watch is computed as follows:

$$P_C = 147.7J$$

We collected the average energy consumption data of 10 LoRa based wrist watches and 10 cluster allocation policy (CAP) based wrist watches which are shown in Table.4. The work time are collected on condition that each wrist watch receives 1500 paging packets from pagers and totally 10 pagers in the cluster randomly send packets to the wrist watches.

TABLE 4. ENERGY CONSUMPTION OF A WRIST WATCH.

nodes	Standby time (/hours)	Work time (/hours)
LoRa wrist watch	142	49
CAP wrist watch	146	62

This table depicts that the standby time of LoRa wrist watch is almost the same with CAP wrist watch because both of them consume the similar power in standby mode. But the work time of LoRa wrist watch is much less than that of a CAP wrist watch. It is probably that the CAP wrist watch may avoid more RF energy consumption by the retransmission scheme between the gateway and the wrist watch, which will consume more battery power from Equ.(20) and (21).

VI. CONCLUSION

A LoRa based smart wireless paging sensor network for elder care is proposed in this work. The SDR is a very sensitive QoS parameter in elder care service. Low SDR may cause server results when providing real time service for aged persons. A traffic model and cluster allocation policy are presented in this paper so as to improve the QoS parameters such as SDR, time delay and power consumption which aims to minimize the time delay and consumed energy, also increase SDR and balance the network load for nodes. The proposed WPSN is simulated and experimentally studied in terms of successful delivery rate, packet latency and traffic load in a real elder care scenario. The contributions proposed in this work may provide the reference for WPSN designs.

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