A QoS-aware Graded Erosion Queuing Model in Smart Grid

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Abstract. The Smart Grid (SG), which incorporates two-way communications and offers intelligent control and convenient interaction is in the booming developments. The implement of the Power Fiber to the Home (PFTTH) technology and systems makes the optical fiber core network in smart grid outstanding in both delay and reliability. However, the Quality-of-Service (QoS) of the peripheral networks becomes a major bottleneck in network performances. This paper takes the heterogeneous characteristics of the SG traffic into consideration and proposes a prioritization mechanism for the communication networks in SG, named as Graded Erosion Queuing Model (GEQM). The GEQM can ensures that the high-priority data can be serviced first, while the medium priority data would not be interfered too much. And the simulation analysis shows that the performance of high priority messages can get a reliable guarantee, and most of the lower priority levels of messages can get an acceptable performance.

Introduction

Smart grid is recognized as the new generation of power system, which employs various monitoring and actuating devices. It autonomously monitors, diagnoses, controls, and efficiently operates the power equipment used in power generation, distribution, and utilization \cite{1}. As the essential link of the intelligent in the SG, the two-way communication infrastructure is required to exchange the real-time information between utilities and consumers \cite{2}. And because of low cost of equipment and installation, quick deployment, widespread access and greater flexibility, wireless communication networks technologies play an extremely important role in the SG communication infrastructure \cite{3}, \cite{4}. The communication infrastructure of the SG is described in Fig.1. As showed in Fig.1, the Home Area Network (HAN) and the Neighbor Area Network (NAN) are the most suitable application scenarios for wireless communication networks, Wide Area Network (WAN), core network and even part of the NAN can be covered by the Power Fiber to the Home (PFTTH) systems. Smart grid use tremendous amount of sensors and actuators to collect data in the last mile, and all the data converge to DAU and consolidated, upload to the core network through the PFTTH and fiber backbone network. It means wireless communication network is mainly used in last mile of smart grid.

QoS brings the ability of providing different priorities to various users, applications, and data flows, frames or packets based on their requirements by controlling sharing resources, which is very necessary in the smart grid. A lot of researches have been conducted on the topic of QoS, among which numerous surveys have focused on the QoS problems for specific wireless networks, such as: Wireless Sensor Networks (WSNs), Wireless Mesh Networks (WMNs), and IEEE 802.11-based WLANs etc.

With the growing demand for information priority processing in SG, a channel allocation and traffic scheduling scheme is necessary to ensure the implement of QoS. In previous studies, lots of methods are used to improve the QoS performance, such as Differentiated Services (DiffServ), queue management and packet scheduling (First in first out (FIFO), preemption, multi-queue switch model,
etc.), network switches. The most suitable way of supporting QoS is DiffServ [5]. And many queuing models based on the DiffServ are presented. Andelman et al. [6] generalized the values of packets to any value between 1 and $\alpha$. Another generalization was to allow preemption, namely, one may drop a packet that was already stored in a queue, and results of the competitiveness on this model were given in [7]. The multi-queue switch model in [8] and [9] consisted of m FIFO queues. In this model, the task of an algorithm was to manage its buffers and to schedule packets. Azar et al. [8] considered the multi-queue switch model, which formulated the buffering problem of one input port of the switch. And the overall performance of several switches, such as shared-memory switches [10], CIOQ switches, and crossbar switches were extensively studied. From works above, we can conclude that, the priority in buffering or scheduling can be achieved by designing a suitable algorithm or a targeted queuing model.

However, the existing prioritization mechanisms can only provide a small amount of fixed priority partition, which are not suitable for smart grid environment, and the traditional channel allocation and traffic scheduling schemes are not designed for wireless communication environment in smart grid. In this paper, an innovation channel allocation and traffic scheduling scheme, which named as Graded Erosion Queuing Model (GEQM) is proposed. Formula derivation and performance simulation are accomplished to prove that the priority prioritization mechanism is suitable for smart grid environment and GEQM can ensure the QoS of high priority data with the fairness to other grade data.

The remainder of the paper is organized as follows: In Section 2, we descript the whole idea of GEQM. Pseudo code and flowcharts are used to clarify the specific steps of GEQM. In Section 3, simulations based on MATLAB are presented to show the performance improvement by GEQM. Finally, we demonstrate concluding remarks in Section 4.

**Graded Erosion Queuing Model (GEQM)**

**Model description and analysis**

The innovative model GEQM in our paper is based on the QoS level of numerous communication messages in smart grid, which can be determined by the prioritization mechanism in the previous chapter. In order to balance the priority and fairness, GEQM attempts to process multi levels of information according to its priority, supplying superior service for messages with high priority, at the same time, ensuring a certain fairness for messages of low priority. The GEQM can be described as follows:

Supposing that there are a total of $n$ QoS levels, each QoS level has its corresponding channel resource, and the channel resource can be divided. With the increase of serial number, the priority of the QoS level get lower. The arrival rates of each level are mutually independent, and all of the $n$ levels messages follow Poisson process with mean arrival rates $\{\lambda_1, \lambda_2, \lambda_3, \ldots, \lambda_n\}$. All the messages are
served following the discipline of first come first serve (FCFS), and all of the \( n \) levels of messages are served according to exponential distribution with service rates \( \{ \mu_1, \mu_2, \mu_3, \ldots, \mu_n \} \). We suppose that different level of messages should be served at the same rate even in diverse channels. For all the \( n \) QoS levels of messages there are \( n \) channels associated with them, and there are \( (j-1) \) queues in the \( j \)th channel for all the potential higher QoS levels data (one-to-one mapping) and one queue for its own data (i.e. level \( j \) messages), which means that the \( j \)th channel can be regarded as a multi-server finite queuing model with \( j \) levels of messages. In each channel, as the channel resources are divided, the higher priority messages and the messages with lower priority can be served at the same time by the resources allocated to them.

When there is no higher priority message in the \( i \)th cache, the level \( i \) messages can use the full resources of channel \( i \), and the service rate of it is \( \mu_i \) as previously mentioned. However, if there are some higher priority message try to erosion the channel resource of level \( i \), the service rate of level \( i \) messages will change to \( \mu'_i \), which is related to the degree of erosion by higher level messages in channel \( i \), i.e. \( Er_{(1,2,\ldots,i-1),i} \), as \( Er_{(1,2,\ldots,i-1),i} \) rise \( \mu'_i \) decreased. So we can have

\[
\mu'_i = f \left( Er_{(1,2,\ldots,i-1),i} \right) \cdot \mu_i. \tag{2.1}
\]

And the service rate of higher level messages in channel \( i \) also related to the degree of erosion, we can denote it as

\[
\mu_{j,i} = g \left( Er_{j,i} \right) \cdot \mu_j \left( j < i \right). \tag{2.2}
\]

The queue length of different level of messages in diverse channels can be adjusted according to the demand by users. The number of level \( i \) messages in the \( j \)th channel restricted to a finite number \( L_{j,i} \) \((1 \leq j \leq n, 1 \leq i \leq j)\), by setting the length of \( L_{j,i} \) in different channels, the performance of the queuing system will change. \( P_{oi}(i=1, 2, 3, \ldots, n-I) \) shows the probability that the queue of level \( i \) messages in its corresponding channel \( i \) is congested, the level \( i \) messages come after will overflow and take the channel resources from the lower QoS levels. As the queues length in the nth channel are setting to infinite, there will be no overflow message from the level \( n \) queue. \( \tau_{ij} \) \((1 \leq i \leq n-I, 1 \leq j \leq n) \) demonstrates the probability that next overflow message of level \( i \) preempt channel resource of level \( j \) (one of the lower channel). While the value of \( \tau_{ij} \) can be determined by (2.1), from which we can infer that \( \tau_{ij} \) is related to three key elements: the priority of level \( j \) (with the increase of \( j \) the QoS level gets lower, and the corresponding channel can be more suitable to be preemption, which reflected as the increase of \( \tau_{ij} \)), the arrival rate of level \( j \) (if \( \lambda_j \) gets larger, the channel should be busier and should not be preemption too frequently, which reflected as the decrease of \( \tau_{ij} \)) and the queue length of level \( i \) message in channel \( j \) (if \( L_{j,i} \) gets larger, the ability of channel \( j \) to carry level \( i \) data become stronger, which reflected as the increase of \( \tau_{ij} \)), if \( L_{j,i} \) is infinite, we set \( L_{j,i} = 2 \cdot \max[L_{j,i}, j \in (i, n-1)] \), and we have constraint condition for the formula \( \alpha_1-\alpha_2=1 \) and \( \sum_{\mu=1}^{n} \tau_{ij} = 1 \) \((i=1,2,3,\ldots n-1) \). A very important assumption in the model is that if one message is overflowed from a channel with level lower than its own QoS level, the delay of this message can be regarded as beyond the tolerance limit, which means that the message can be discarded directly, while packet loss rate (PLR) can be calculated from this train of thought.

\[
\tau_{ij} = \frac{\alpha_1 \cdot \lambda_j}{\sum_{\mu=1}^{n} \mu} \cdot \frac{\alpha_2}{\sum_{\mu=1}^{n} \lambda_{\mu}} + \alpha_3 \cdot \frac{L_{ij}}{\sum_{\mu=1}^{n} \mu_{\mu}}. \tag{2.3}
\]
Mathematical Formulation of Model

The GEQM can be regarded as a markovian. In order to obtain the solution of the system, we firstly develop a mathematical model for the system. For the sake of reducing the computational complexity, the mathematical model is structured in the scene of three priority architecture, i.e. \( n=3 \). The GEQM with \( n=3 \) can be described as Fig.2.

![Figure 2. A Schematic Diagram of the Preemptive Tidal Flow Queuing Model with n=3.](image)

(a) Channel 1 system

Level 1 messages in this model have the highest priority. Therefore, the channel 1 system can be simplified as an M/M/1/L\(_{1,1}\) single server finite waiting room queue system, in which the arrival and the departure rates are not constant. Messages arrive at rate \( \lambda_1 \). As long as there is less than \( L_{1,1} \) in the system, either in service or in the queue. The average number of messages in the system can be easily get as:

\[
\bar{Q}_{1,1} = \bar{Q}_v + \bar{Q}_r = \frac{\rho}{1-\rho} \left(1 + L_{1,1} \right) \frac{\rho^{h_{1,1}}}{1 - \rho^{h_{1,1}}} .
\]  

(2.4)

We can use Little’s formula to calculate average delay for level 1 messages in channel 1:

\[
\bar{D}_{1,1} = \frac{\bar{Q}_{1,1}}{\lambda_1} = \frac{1 - (L_{1,1} + 1) \rho^{h_{1,1}} + L_{1,1} \rho^{h_{1,1}+1}}{\mu_1 (1-\rho) (1-\rho^{h_{1,1}})} = \frac{1}{\mu_1 (1-\rho)} - \frac{L_{1,1} \rho^{h_{1,1}}}{\mu_1 (1-\rho^{h_{1,1}})} .
\]  

(2.5)

(b) Channel 2 system

Channel 2 can be considered as a single server finite queuing model with two types of messages, level 1 and level 2 messages with double orbits. The arrival of level 2 messages follows Poisson process with mean arrival rate \( \lambda_2 \), the arrival rate of level 1 messages can be given by

\[
\lambda_{1,2} = \lambda_2 \times P_{o1} \times \tau_{1,2} = \lambda_2 \times \frac{(1-\rho) \rho^{h_{1,1}}}{1 - \rho^{h_{1,1}+1}} \times \tau_{1,2} .
\]  

(2.6)

And the service rate of level 1 messages and level 2 messages are related to the degree of erosion of level 1 messages in channel 2 \( \text{Er}_{1,2} \), so we have \( \mu_{1,2} = g(\text{Er}_{1,2}) \times \mu_1 \) and \( \mu'_{1,2} = f(\text{Er}_{1,2}) \times \mu_1 \).
The Chapman–Kolmogorov equations for different states of the model (as shown in Fig. 3) are easily to constructed. By listing the state equations and representing them in a matrix, we can have:

\[
A(s)\tilde{\Pi}(s) = \Pi(0)
\]

where

\[
A(s) = \begin{pmatrix}
A_0 & C_0 & C_1 & \cdots & C_i & \cdots & C_{t_1} \\
B_0 & D & D & \cdots & D & \cdots & D \\
B_1 & F & D & \cdots & D & \cdots & D \\
\vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots \\
B_{t_1} & F & D & \cdots & D & \cdots & D \\
N & M & N & \cdots & N & \cdots & N \\
\end{pmatrix}, \quad M = \{L_{2,2} \times L_{2,2} + L_{2,1} + L_{2,2} + 1\}
\]

\[
\tilde{\Pi}(s) = \left[\tilde{\Pi}_1(s), \tilde{\Pi}_2(s), \tilde{\Pi}_3(s), \ldots, \tilde{\Pi}_{t_1 \times t_1 \times \cdots \times t_1 \times t_1}(s)\right]_{i=1, \ldots, t_1 \times \cdots \times t_1 \times t_1}
\]

From Eq. (2.5), we obtain (cf. Jain et al. [10]):

\[
\tilde{\pi}_i(s) = \frac{\text{det} \left[ A_i(s) \right]}{\text{det} \left[ A(s) \right]}, \quad (i = 1, 2, 3, \ldots, (L_{2,1} \times L_{2,2} + L_{2,3} + L_{2,4} + 1)),
\]

where \(\text{det}[A(s)]\) is the determinant of the matrix \(A(s)\) and \(\text{det}[A_i(s)]\) is the determinant of matrix which has been obtained by replacing the respective ith column vector of \(A(s)\) with initial vector \(\Pi(0)\). By solving the above equation we can have:

\[
\pi_i(t) = a_0 + \sum_{n=1}^{L_{2,1}} a_n e^{-\delta n t} + \sum_{n=1}^{L_{2,1}} \left[ b_n e^{-\nu n t} \cos(w_n t) + \frac{c_n-b_n}{w_n} e^{-\nu n t} \sin(w_n t) \right],
\]

\[
1 \leq i \leq (L_{2,1} \times L_{2,2} + L_{2,3} + L_{2,4} + 1),
\]

where \(a_0, a_n, b_n, c_n, w_n, v_n, w_n\) are real numbers. And

\[
\bar{Q}_{2,1} = \left(1 - \sum_{n=0}^{L_{2,1}} P_{0,n}(t)\right) + \sum_{i=1}^{L_{2,1}} \sum_{n=0}^{L_{2,1}} nP_{i,n}(t).
\]

The expected number of level 2 messages in channel 2 system at time t is
\[
\overline{Q}_{2,2} = \left(1 - P_{0,0}(t) - \sum_{m=1}^{l_{2,1}} \sum_{n=0}^{l_{2,2}} P_{n,m}(t)\right) + \sum_{m=1}^{l_{2,1}} \sum_{n=0}^{l_{2,2}} mP_{n,m}(t). \]  
\tag{2.12}
\]

We can use Little’s formula to calculate average delay for level 1 messages and level 2 messages, i.e. \(\overline{D}_{2,1}\) and \(\overline{D}_{2,2}\) respectively.

(c) Channel 3 system

All the three queues for different levels of messages in channel 3 are regarded as infinite length. The arrival of level 3 messages follow Poisson process with mean arrival rate \(\lambda_3\), the arrival rate of level 2 messages in channel 3 can be derived as

\[
\lambda_{2,3} = \lambda_{2,1} P_{2,1} \tau_{2,3} = \lambda_{2,1} \tau_{2,3} \sum_{n=0}^{l_{2,2}} P_{n,2}(t),
\]

and level 1 messages’ arrive rate at channel 3 is

\[
\lambda_{1,3} = \lambda_{1,1} P_{1,1} \tau_{1,3} = \frac{\lambda_{1,1} (1-\rho)}{(1-\rho_{1,1})} \tau_{1,3}.
\]

The service rate should be adjust as mentioned in Eq. (2.1) and (2.2).

As all three queues are infinite, we can refer to [9] that in the case of \(r\) priority levels and exponential service distribution, and we can easily have:

\[
\overline{Q}_{3,1} = \frac{\rho_1}{1-\rho_1},
\]

\[
\overline{Q}_{3,2} = \frac{\rho_2 - \rho_3 \rho_2 + \rho \rho_2 (\mu_1/\mu_3)}{(1-\rho_1)(1-\rho_1 - \rho_2)},
\]

\[
\overline{Q}_{3,3} = \frac{\rho_3 - \rho_2 \rho_3 - \rho_3 \rho_2 + \rho \rho_3 (\mu_1'/\mu_3) + \rho_3 \rho_3 (\mu_1'/\mu_2)}{(1-\rho_1)(1-\rho_1 - \rho_2 - \rho_3)},
\]

where \(\rho_1 = \frac{\lambda_{1,1}}{\mu_1 + \mu_{1,2} + \mu_{1,3}}, \rho_2 = \frac{\lambda_{2,1}}{\mu_2 + \mu_{2,3}}, \rho_3 = \frac{\lambda_3}{\mu_3},\)

As the average queue length and arrival rate are given above, we can get the average delay for different level of messages in channel 3 system (i.e. \(\overline{D}_{3,1}, \overline{D}_{3,2}\) and \(\overline{D}_{3,3}\)) by multiple use of Little’s formula.

Performance Evaluation

In this section, we provide the numerical simulations and analog simulation of GEQM. A comparison between the GEQM, the non-preemptive queuing model (NP model) and the DiffServ model is presented to demonstrate the applicability and dependability of the GEQM for a WMSN in the smart grid communication environment.
Fig. 4 depicts the average delay for level 1 and level 2 messages as a function of the arrival rate of level 1 messages, $\lambda_1$. It is obvious that in the GEQM, level 1 messages have a lower average delay than in the NP model. And as $\lambda_1$ increases, the advantage of the GEQM becomes more significant; meanwhile, level 1 messages in the DiffServ model can have the lowest average delay because in this model, level 1 messages can monopolize all resources in the system. The average delays in all three models are minimal, and the slight increase in delay in the GEQM compared with the DiffServ model is offset by the former’s advantage in terms of the PLR, which has been shown in Fig. 5.

Fig. 6 shows that the trends of $\overline{D}_1$ for different values of $L_{1,1}$ are essentially the same, in all cases, the delay increases with increasing $\lambda_1$, and the increase in $\overline{D}_1$ become more gradual when $\lambda_1 > 0.55$. Importantly, in the curves for $L_{1,1}=7$ and 9, when $\lambda_1 > 0.65$, the average delay for level 1 messages actually declines to some degree as $\lambda_1$ increases. Which is because when $L_{1,1}$ is sufficiently large and the arrival of level 1 messages is sufficiently infrequent, level 1 messages are not constantly overflowing from channel 1.

Fig. 7 shows that the effect of $L_{1,1}$ on the PLR is not obvious; the PLR for level 1 messages remains at a low percentage for all considered values of $L_{1,1}$.

Summary

In this paper, we proposed the GEQM, a new QoS-aware and hybrid-priority-based queuing model for the challenging wireless communication environment of the WMSN in smart grid. The proposed model can process multiple levels of information in accordance with their priorities, supplying superior service for messages of high priority while ensuring a certain degree of fairness for messages of low priority. The results of formula derivations and extensive simulations showed that the GEQM outperforms the traditional NP model in providing high-priority data with superb service characterized by extremely low delays and high reliability, and in the comparison with a typical DiffServ model, GEQM can be dominant in reliability and the delays in the middle-low priorities. An
implementation of the GEQM in a MATLAB simulation showed that the performance requirements for a queuing model that is suitable for WMSN in the smart grid communication environment can easily be met and demonstrated the superior efficiency of our proposal over the traditional NP model and the typical DiffServ model.

In future work, by establishing buffer lanes in various channels, we will strive to further enhance the performance for high-priority data, by the mean time ensure the performance for low-priority data, thereby enhancing the fairness of the system without excessively impacting the performance for high-priority data.

References


