Event- and Priority-Driven Coordination in Next-Generation Grid

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***Abstract*—The confluence of power and cyber networks is key to the evolution of smart grid (SG). The explosive growth of data in SG to support pervasive communication demands the exchange of essential information guided by need based events. The scaling of such asynchronous event-driven communication for practical utility in SG needs to evolve with information prioritization. Owing to the size of the power grid, it is often necessary to aggregate such event-driven data to reduce the multitasking overhead of higher-level controllers. As such, prioritization of the processing of these event-driven pieces of information is essential. In this paper, using the context of a neighborhood-area network, where communication is enabled between consumer loads and supervisor energy-management system (EMS) controller to achieve balance between demand and supply, a priority-based event-driven communication mechanism is outlined. For that purpose, load-demands are grouped into different classes based on their priorities. The demand processing policy based on dynamic-priorities is analyzed using delay and fairness performance parameters. An optimization problem is also formulated to achieve performance tradeoff between delays experienced by different classes of load-demands and the EMS processing cost. The performance evaluation results show the effectiveness of the proposed priority-based solution.**

***Index Terms*—Communication network, dynamic-priority, energy-management system (EMS), event, neighborhood-area network (NAN), smart grid (SG).**

I. Introduction

THE balance between demand and supply of electric energy will be enhanced with the emergence of smart grid (SG), which delivers higher flexibility and control to the operators as well as end consumers. This optimal demand–supply balance is dependent on effective communication between load energy-management system (EMS) and the loads, which is enabled by the installation of smart consumer devices (SCDs) at the loads, facilitating real-time data exchange [1]. One such scenario is depicted in Fig. 1, where different loads (e.g., homes) are connected to the load EMS (for aggregation) using an underlying neighborhood-area network (NAN) [2]. The communication between load EMS and substation EMS is enabled by wide-area network (WAN). In addition, Fig. 1 also depicts the integration of distributed energy resources (DERs), which is an integral part of a SG. From demand response perspective, different loads are grouped into multiple classes based on their priority. Typically, the loads suitable for demand response scheduling are termed as elastic loads and can be grouped into multiple classes based on their priority [3].

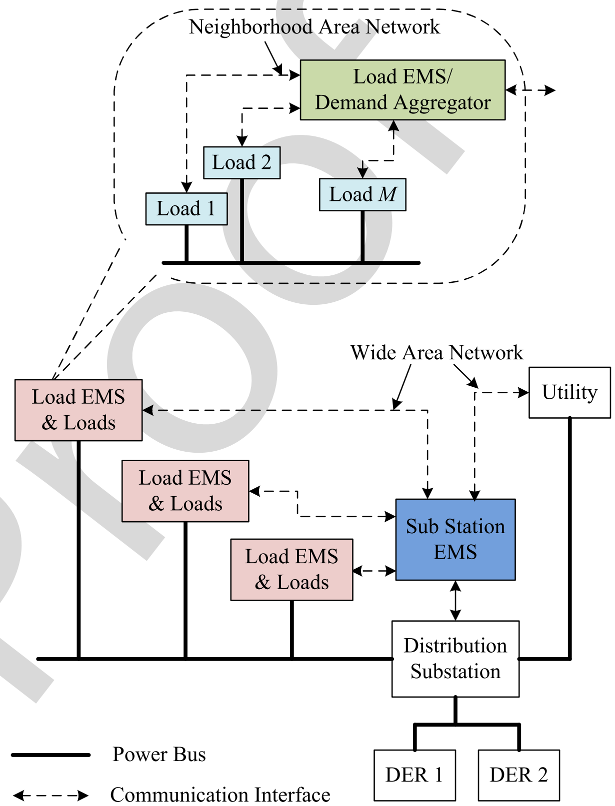

Fig. 1. Event-based energy-management system architecture.

Priority-based approach has also been employed for supervision of smart-grid assets as discussed in [4]. In another related work [5], priority-based scheduling and channel allocation for heterogeneous SG traffic is proposed. These solutions use static priority and if used for demand response management can lead to scenarios, where the waiting delay for low priority loads can be excessively large. This problem can be addressed partly by using time dependent, *dynamic priority* [6]. The linear time dependent priority has been used in wireless sensor

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networks [7] for fairness improvement of low-priority loads also utilized

In dynamic priority based demand response, the processing of an individual event is determined based on the number of demand events already in the system and their current priorities. Specifically, we consider time-dependent dynamic-priorities [6], [7], where the priority of an event is determined based on its initial priority assigned by the load EMS as well as the waiting time in the system.

The proposed dynamic-priority-based event-driven information communication solution is aimed at augmenting the advantages of SG data communication using time dependent dynamic-priority assignment to loads. Using dynamic-priority will provide a controllable fairness to the loads of different priorities, while implementing the demand response. The dynamic-priority based solution can be integrated with the existing SG application layer protocols, DNP3 [8] and IEC61850 [9], [10]. This is achieved by using the available flexibility in the middleware at the network interface between (DNP3 or IEC61850) and the underlaying lower layer protocols [11]. The dynamic-priority based solution approach, allows one to achieve a desired level of fairness in the processing delay experienced by the load-demands from different priority classes. In addition, an optimization problem has been formulated based on weighted cost function to exploit the tradeoff between substation EMS processing cost and the load-demand delay. For that purpose, a cost function is defined for the demand processing at substation EMS, which combined with the delay costs for different priority load-demands defines the weighted objective function of the optimization problem. The key contributions of the paper can be summarized as follows.

1) A dynamic-priority based demand event processing for multiple classes of loads.
2) An optimization problem formulation to achieve the performance tradeoff between multiple priority load-demands and the processing cost at the substation EMS.

The rest of the paper is organized as follows. In Section II, characteristics of basic system model are outlined. Event-driven demand-management policies and delay performance are discussed in Section III. An optimization problem that provides optimal performance tradeoff is formulated in IV. Numerical evaluation results are discussed in Section V, and we conclude our findings in Section VI.

II. System Model

We consider the scenario shown in Fig. 1, where load EMS communicates with the substation EMS (for ensuring balance of demand and supply) using WAN. Each load generates an aperiodic event based on a threshold value, which is transmitted to the respective load EMS. At the load EMS, each demand event is assigned an initial priority-based on the delay that can be tolerated by the respective load (generating the event) before its demand request is processed. The demands from disparate loads are divided into multiple classes based on the requested priority.

For the realization of the dynamic-priority policy, it is assumed that each home location labeled as load is equipped with an SCD that communicates with the load EMS, making it part of the NAN. The realization of the NAN can be based on either wireless (e.g., IEEE 802.11 or IEEE 802.15.4 [12]) or power-line (e.g., IEEE 1901.2-2013 [13]) communication. The user facility can be equipped with its own local energy optimization capability that takes into account user configurations as constraints [14], which in turn affect the priority of the demand requests generated by the user.

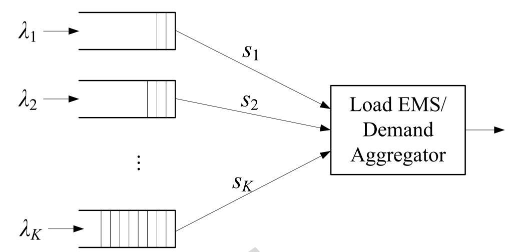


Fig. 2. Multiclass priority-based demand generations and their processing by the load EMS.

We model the load-demand events as Poisson arrivals. There are K different priority classes, and the mean interarrival time for the demands from class k is denoted by $(1/\lambda_k)$ for $k \in \{1, 2, \ldots, K\}$. A class with smaller index is assigned a higher priority. Furthermore, we assume that every class has multiple nodes and for each class k, node n_k initiates the demand events with rate λ_{k,n_k}. If the total number of nodes for class k is N_k then we have $\lambda_k = \sum_{n_k=1}^{N_k} \lambda_{k,n_k}$. The mean service time required to process class k demand is denoted by $(1/s_k)$. In addition, the service times can follow any arbitrary distribution. When the load-demands from the SCD are received by the load EMS, it is the responsibility of the latter to process the demands based on the dynamic-priorities and subsequently communicate with the substation EMS. A functional block diagram of the load EMS, illustrating arrivals of demands with multiple priorities and their processing, is shown in Fig. 2.

Large-scale integration of communication infrastructure in the SG also makes it vulnerable to cyber attacks. The attacks in SGs can be grouped in the following two major categories.

1) Denial of service (DoS) attacks target the system availability, by blocking, delaying, or even corrupting the communication link used by SG.
2) System integrity and confidentiality attacks target modification or disruption of data exchanges among different entities in the SG. In addition, the intruder intends to gain unauthorized access to SG data, putting the system confidentiality at stake.

The detection of and remedial measures against DoS attacks are primarily integrated at different layers of the communication network. For instance, rate limiting, reconfiguration, and filtering are among the more widely used approaches at network layer. Similarly, antijamming measures, including frequency hopping as well as spread spectrum, are used at the physical layer. The network level countermeasures against DoS attacks are least effective against the system integrity/confidentiality attacks. This is true because the

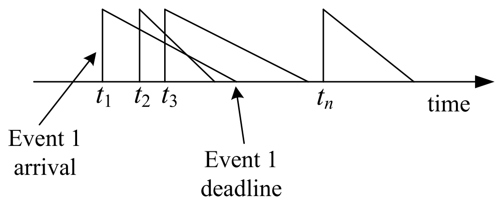


Fig. 3. Arrivals of events with their corresponding deadlines.

system integrity attacks try to gain access to the contents of communication and eventually modify the information. This type of malicious activity does not affect the data packet rates or packet size and as a result is not visible from statistical performance measures used to detect DoS attacks. Rather cryptographic approaches for securing data integrity become the main countermeasure tool against these types of attacks.

III. Dynamic-Priority-Based Event Processing

We consider a dynamic-priority policy based on nonpreemption for event processing, which is implemented by the load EMS. The advantages and disadvantages associated with no preemption of the low priority demands are discussed in [15]. The dynamic-priority policy allows one to trade off the fairness experienced by the lower-priority events with the delay incurred to the high-priority events.

Specifically, we introduce a time-dependent priority of the load-demands. In this case, when the processing of a demand from an arbitrary load is completed, the load EMS selects a new demand request with the current highest time-accumulated priority, which could allow a low-priority demand waiting for long enough to be selected in advance of a newly arrived higher-priority request. In time-dependent dynamic-priority, the load priority increases with the waiting time according to a specific rule. Let a load-demand of priority k arrives at time t_k. Then, we define the dynamic-priority, $k(t)$ of this demand request at time t as

$$k(t) = c_k(t - t_k)^{\frac{1}{\theta}} \tag{1}$$

where c_k is kth-priority scaling coefficient and the common parameter θ is the priority accumulation exponent for different priority classes. The coefficient c_k is determined by the initial priority assigned by the load EMS, which can choose c_k based on the event processing deadline. Fig. 3 illustrates pictorially the arrival of events along with their associated deadlines. Now if another load of higher priority l (i.e., $l < k$) and correspondingly $c_l > c_k$, arrives then its time accumulated priority $l(t)$ can become larger than $k(t)$ because $c_l > c_k$.

The delay $D_k^{(d)}$ for the kth-priority demands following dynamic-priority policy has two components, processing delay $(1/s_k)$ and the waiting $(W_k^{(d)})$ delay [6] and is defined as:

$$D_k^{(d)} = W_k^{(d)} + \frac{1}{s_k}. \tag{2}$$

The waiting delay in (2) comprises the mean residual time (R) required to complete the processing of currently being processed event, the delay due to new demand arrivals of higher-priority $(W_{k,1}^{(d)})$, and the delay due to processing of the demands that were already in the system denoted by $W_{k,2}^{(d)}$. Thus, delay $W_k^{(d)}$ is given by

$$W_k^{(d)} = R + W_{k,1}^{(d)} + W_{k,2}^{(d)} \tag{3}$$

where the mean residual time R and is given by [16]

$$R = \frac{1}{2}\sum_{i=1}^{K} \lambda_i E\left[Y_i^2\right] \tag{4}$$

where Y_i is the random variable representing the demand processing delay and correspondingly, $E[Y_i] = (1/s_i)$. The expressions for waiting times $W_{k,1}^{(d)}$ and $W_{k,2}^{(d)}$ are given in (7) and (8), respectively, and next we detail their derivation.

Assuming that a demand with kth-priority is already queued in the load EMS and a new higher-priority demand with priority l is received. If the time of occurrence of the kth-priority demand is $t = 0$ and that of the lth-priority demand is $t = \tau_l$. Then using (1), the accumulated priority of kth event after waiting for $W_k^{(d)}$ time is given by $c_k(W_k^{(d)})^{1/\theta}$ and that of lth event is $c_l(W_k^{(d)} - \tau_l)^{1/\theta}$. It is straightforward to realize that, when the equality given by

$$c_k\left(W_k^{(d)}\right)^{\frac{1}{\theta}} = c_l\left(W_k^{(d)} - \tau_l\right)^{\frac{1}{\theta}} \tag{5}$$

holds, then the lth-priority event will be served ahead of the kth-priority event, if the lth-priority event occurs in the time interval $(0, \tau_l)$. This critical time instant τ_l can be obtained from the equality in (5) and is given by

$$\tau_l = \left(1 - \left(\frac{c_k}{c_l}\right)^{\theta}\right) W_k^{(d)}. \tag{6}$$

The waiting time due to these new higher-priority events, which arrive after the kth-priority event and are processed before the kth-priority event, is denoted by $W_{k,1}^{(d)}$, and is given by

$$\begin{aligned} W_{k,1}^{(d)} &= \sum_{l=1}^{k-1} \frac{\lambda_l}{s_l}\tau_l \\ &= \sum_{l=1}^{k-1} \frac{\lambda_l}{s_l}\left(1 - \left(\frac{c_k}{c_l}\right)^{\theta}\right) W_k^{(d)}. \end{aligned} \tag{7}$$

In addition, the waiting time experienced by the kth-priority event, due to the events that were already received by the load EMS before its arrival, is obtained as

$$W_{k,2}^{(d)} = \sum_{m=1}^{k} \frac{\lambda_m}{s_m} W_m^{(d)} + \sum_{q=k+1}^{K} \frac{\lambda_q}{s_q} T_q. \tag{8}$$

In (8), the first term represents the set of events, which are of either higher or same priority as that of kth-priority event and will be processed prior to the kth-priority event. The second term represents the fraction of the low-priority events, which have already been in the load EMS for long enough time to get processed earlier than the kth-priority event due to their higher dynamic-priority (as result of time accumulation). Next, we concentrate on these lower-priority events and evaluate the waiting delay incurred due to these low-priority events to the kth-priority event.

Consider now a scenario where the kth-priority event arrives at $t = 0$, while a lower-priority qth event arrived at time $t = -t_q$ (earlier than the kth-priority event). Now, the qth-priority event will be processed before the kth event, if at some arbitrary time $t = t_k$, the accumulated priority of the qth-priority event is higher than that of the kth-priority event, as stated by the following condition:

$$c_k(t_k)^{\frac{1}{\theta}} \le c_q(t_q + t_k)^{\frac{1}{\theta}} \tag{9}$$

which can be rewritten as

$$t_k \le t_q\left(\frac{c_q^{\theta}}{c_k^{\theta} - c_q^{\theta}}\right). \tag{10}$$

Now the delay term T_q in (8) can be computed as

$$T_q = \int_0^{\infty} P\big(t_q < \tilde{W}_q^{(d)} \le (t_k + t_q)\big)dt_q. \tag{11}$$

In (11), $\tilde{W}_q^{(d)}$ represents the instantaneous delay experienced by the qth-priority event. Substituting t_k from (10) in (11), we get

$$T_q = \int_0^{\infty} P\left(t_q < \tilde{W}_q^{(d)} \le t_q\left(\frac{c_k^{\theta}}{c_k^{\theta} - c_q^{\theta}}\right)\right)dt_q \tag{12}$$

which can be decomposed using the probability of intersection of intervals as

$$T_q = \int_0^{\infty} P\left(\tilde{W}_q^{(d)} \le t_q\left(\frac{c_k^{\theta}}{c_k^{\theta} - c_q^{\theta}}\right)\right)dt_q - \int_0^{\infty} P\big(\tilde{W}_q^{(d)} \le t_q\big)dt_q. \tag{13}$$

Now using the fact that $W_q^{(d)} = E[\tilde{W}_q^{(d)}]$, the expression in (13) simplifies to

$$T_q = W_q^{(d)}\left(\frac{c_q}{c_k}\right)^{\theta}. \tag{14}$$

Now, substituting the value of T_q in (8) and then $W_{k,1}^{(d)}$ and $W_{k,2}^{(d)}$ in (3) for dynamic-priority waiting delay, we obtain the following expression:

$$W_k^{(d)} = \frac{\frac{\frac{1}{2}\sum_{i=1}^{K}\lambda_i E[Y_i^2]}{1-\sum_{i=1}^{k-1}\frac{\lambda_i}{s_i}} - \sum_{i=k+1}^{K}\frac{\lambda_i}{s_i}W_i^{(d)}\big(1 - \big(\frac{c_i}{c_k}\big)^{\theta}\big)}{1 - \sum_{i=1}^{k-1}\frac{\lambda_i}{s_i}\big(1 - \big(\frac{c_k}{c_i}\big)^{\theta}\big)}. \tag{15}$$

From (15), we observe that $W_k^{(d)}$ can be evaluated recursively and requires to fix the value of maximum number of priority classes, K. Finally, the mean delay $D_k^{(d)}$ for dynamic-priority-based event handling is obtained using (2). It is important to mention here that for $\theta \to \infty$, (15) reduces to the weighting delay for nonpreemptive priority policy, which is a special case of dynamic-priority policy and is given by

$$W_k^{(n)} = \frac{\frac{\frac{1}{2}\sum_{i=1}^{K}\lambda_i E[Y_i^2]}{1-\sum_{i=1}^{k-1}\frac{\lambda_i}{s_i}} - \sum_{i=k+1}^{K}\frac{\lambda_i}{s_i}W_i^{(n)}}{1 - \sum_{i=1}^{k-1}\frac{\lambda_i}{s_i}}. \tag{16}$$

In (16), the superscript n in the weighting delay expression, $W_k^{(n)}$, represents the nonpreemptive priority policy.

IV. Stability Constrained Optimization

To evaluate delay experienced by the kth-priority demand, we have to characterize parameter, Y_k, as required in (4). Let the total processing delay, which includes communication delay between load and substation EMS, follow exponential distribution. As a result, we have $E[Y_k^2] = (2/s_k^2)$. In addition, to simplify the analysis with out loss of generality, two priority levels are considered; however, it is straightforward to include more priority classes. Using these parametric values, we obtain the delay expressions for the high ($k = 1$) and low ($k = 2$) priority events by solving (15). Specifically, for two priority case (i.e., $K = 2$), the delay expression for low-priority events is obtained by substituting $k = 2$ in (15) along with (2) and is given by

$$\begin{aligned} D_2^{(d)} &= \frac{1}{s_2} + W_2^{(d)} \\ &= \frac{1}{s_2} + \frac{A}{s_1 s_2 B}\left[\frac{s_1}{\big(s_1 - \lambda_1\big(1 - \big(\frac{c_2}{c_1}\big)^{\theta}\big)\big)}\right] \end{aligned} \tag{17}$$

where $A = (\lambda_1\ s_2^2 + \lambda_2\ s_1^2)$ and $B = (s_1\ s_2 - \lambda_1\ s_2 - \lambda_2\ s_1)$. Similarly for the high-priority events, using $k = 1$ in (15) and (2) leads to the following delay expression:

$$D_1^{(d)} = \frac{1}{s_1} + \frac{A}{s_1 s_2 B} - W_2^{(d)}\left[\frac{\lambda_2}{s_2}\left(1 - \left(\frac{c_2}{c_1}\right)^{\theta}\right)\right] \tag{18}$$

which after substituting the expression for $W_2^{(d)}$ from (17) becomes

$$D_1^{(d)} = \frac{1}{s_1} + \frac{A}{s_1 s_2 B}\left[1 - \frac{s_1\lambda_2\big(1 - \big(\frac{c_2}{c_1}\big)^{\theta}\big)}{s_2\big(s_1 - \lambda_1\big(1 - \big(\frac{c_2}{c_1}\big)^{\theta}\big)\big)}\right]. \tag{19}$$

To reduce the total delay experienced by a load-demand, an increase in event processing rates s_1 or s_2 is required. Based on this fact, one can expect that the delay experienced by the load-demands will be reduced, but at the expense of increased demand requests to be processed by the substation EMS.

We assign processing costs, at the substation EMS and to the high as well as low-priority demands based on their delay requirements. Specifically, let $\sigma s_1^{\alpha_1}$ and $\sigma s_2^{\alpha_2}$ represent the processing costs for the high- and low-priority loads, where σ is the per event cost scaling factor, while α_1 and α_2 represent the cost exponents corresponding to high and low-priority load-demands, respectively. Obviously, we require $\alpha_1 > \alpha_2$. The underlying tradeoff between substation EMS processing cost and the load-demand delay can be achieved optimally based on a measure of weighted total cost. Now an optimization problem based on weighted total cost using dynamic-priority policy, while satisfying the system stability constraint can be formulated as

$$\begin{aligned} \text{minimize}\ f(s_1, s_2) &= \beta\big(\sigma s_1^{\alpha_1} + D_1^{(d)}\big) \\ &\quad + (1 - \beta)\big(\sigma s_2^{\alpha_2} + D_2^{(d)}\big) \\ \text{s.t.}\ \frac{\lambda_1}{s_1} + \frac{\lambda_2}{s_2} &\le 1. \end{aligned} \tag{20}$$

In the optimization problem formulation in (20), s_1 and s_2 are the optimization variables that can be controlled by the load EMS for minimizing the weighted objective cost and the parameter β is the weighting coefficient, which further provides the relative significance between low- and high-priority loads. The constraint in (20) ensures the system stable operation in the sense that demand processing rate is higher than the demand arrival rate. An important feature of the optimization problem formulation is that it provides an optimal delay-performance tradeoff between load-demands of different priority classes. Let $c' = (1-(c_2/c_1))^{\theta})$. Now using the delay expressions for $D_1^{(d)}$ and $D_2^{(d)}$ from (19) and (17), respectively, and introducing the slack variables u_1 and u_2, the problem in (20) is rewritten in the revised form as

$$\text{minimize } \beta\left(\sigma s_1^{\alpha_1} + u_1\right) + (1-\beta)\left(\sigma s_2^{\alpha_2} + u_2\right) \quad (21)$$

$$\text{s.t. } \frac{\lambda_1}{s_1} + \frac{\lambda_2}{s_2} \le 1 \quad (22)$$

$$\frac{(s_1-\lambda_1 c')s_2^2 B + (s_1 s_2 - s_2\lambda_1 c' - s_1\lambda_2 c')A}{\left(s_1^2 s_2^2 - s_1 s_2^2 \lambda_1 c'\right)B} \le u_1 \quad (23)$$

$$\frac{\left(s_1^2 - s_1\lambda_1 c'\right)B + s_1 A}{\left(s_1^2 s_2 - s_1 s_2 \lambda_1 c'\right)B} \le u_2. \quad (24)$$

The optimization problem in (21)–(24) is transformed to the generalized geometric program by using auxiliary variables u_3, u_4, u_5, u_6 and rewriting the constraints in (23) and (24) as

$$\text{minimize } \beta\left(\sigma s_1^{\alpha_1} + u_1\right) + (1-\beta)\left(\sigma s_2^{\alpha_2} + u_2\right) \quad (25)$$

$$\text{s.t. } \frac{\lambda_1}{s_1} + \frac{\lambda_2}{s_2} \le 1 \quad (26)$$

$$u_1^{-1} u_3 u_4^{-1} \le 1 \quad (27)$$

$$(s_1 s_2 - s_2\lambda_1 c' - s_1\lambda_2 c')A t_3^{-1} + \left(s_1 s_2^2 - s_2^2\lambda_1 c'\right)B u_3^{-1} \le 1 \quad (28)$$

$$\left(s_1^2 s_2^2 - s_1 s_2^2 \lambda_1 c'\right)B u_4^{-1} \le 1 \quad (29)$$

$$u_2^{-1} u_5 u_6^{-1} \le 1 \quad (30)$$

$$u_5^{-1}\left(\left(s_1^2 - s_1\lambda_1 c'\right)B + s_1 A\right) \le 1 \quad (31)$$

$$u_6^{-1}\left(s_1^2 s_2 - s_1 s_2 \lambda_1 c'\right)B \le 1. \quad (32)$$

Specifically, the above optimization problem falls in the category of *signomial* optimization due to the presence of negative coefficients in the constraint polynomials. The signomial optimization problems are nonconvex and different approaches are proposed for solving these problems [17]. One possible solution approach, without any loss of generality, is based on problem relaxation at optimal solution point, but is applicable to special scenarios involving signomial programming [17]. The problem in (25) falls in that category and to utilize this relaxation approach, let us consider the signomial constraint in (32). By introducing an auxiliary variable x, we can rewrite this constraint as

$$t_6^{-1}\left(x + s_1 s_2^2 \lambda_1^2 c' + s_1^2 s_2 \lambda_1 \lambda_2 c'\right) \le 1$$
$$s_1^{-3} s_2^{-2}\left(s_1^2 s_2^2 \lambda_1 c' + s_1^2 s_2^2 \lambda_1 + s_1^3 s_2 \lambda_2 c' + x\right) = 1. \quad (33)$$

The posynomial equality constraint in (33) is the main limitation, which otherwise is equivalent to geometric optimization that can be transformed to a convex problem. Based on the relaxation approach, this constraint is relaxed to an inequality constraint and the resulting problem is a geometric optimization problem and can be solved efficiently. The effectiveness of the above-mentioned approximation is achieved by constructing a trust region as discussed in [17].

TABLE I
PARAMETER VALUES SELECTED FOR PERFORMANCE EVALUATION RESULTS

Parameter	Value
Number of priority classes (K)	2
Number of nodes per class, N_1, N_2	10
Cost scaling factor per event (σ)	0.2
High-priority event cost exponent (α_1)	2
Low-priority event cost exponent (α_2)	1

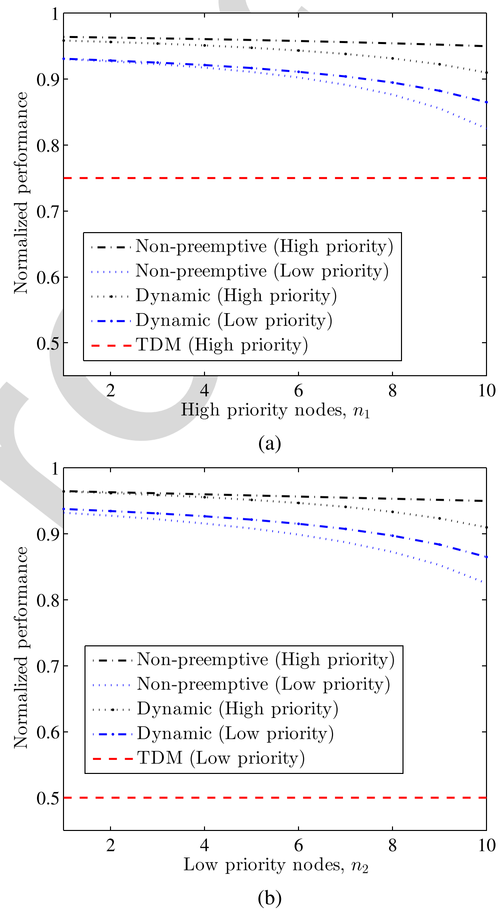
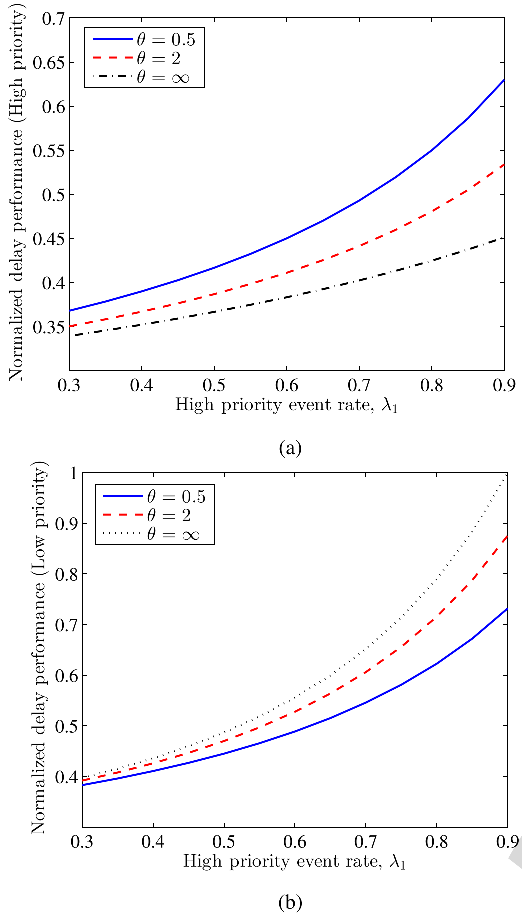


Fig. 4. Performance comparison of event-driven and time-driven approaches as a function of (a) high-priority nodes and (b) low-priority nodes. The parameters $\lambda_{1,n_1} = .08$, $\lambda_{2,n_2} = .04$, and $s_1 = 2$, $s_2 = 1$ are used for this case.

V. PERFORMANCE EVALUATION RESULTS

For the performance evaluation of dynamic-priority policy, we consider two priority classes of load-demand events, where high-priority events are marked by lower index. The selection of two priority classes is to keep the presentation simple, which otherwise is not restrictive. The mean event arrival rate λ_k, corresponding to priority class k is obtained as $\lambda_k = \sum_{n_k=1}^{N_k} \lambda_{k,n_k}$, for N_k nodes of priority k. The parameters chosen for performance evaluation are tabulated in Table I,



AQ:2 Fig. 5. Normalized delay-performance comparison for different values of parameter θ.

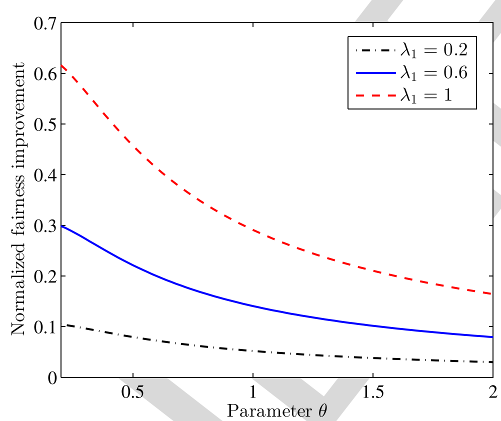


Fig. 6. Normalized fairness improvement as function of dynamic-priority parameter θ.

where we have assumed that each priority class has ten nodes. The choice of number of priority classes as well as the nodes in each priority class is a user-dependent attribute and may vary significantly. Based on this fact we have made a realistic selection of these parameters.

A. Dynamic-Priority Policy Performance

First, we compare the performance of dynamic-priority policy based load-demand event processing with that of

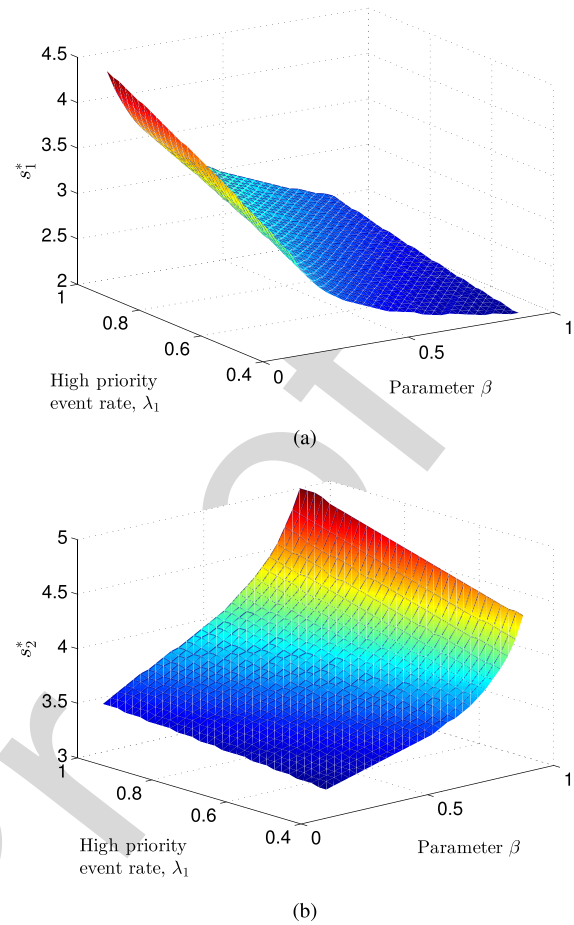
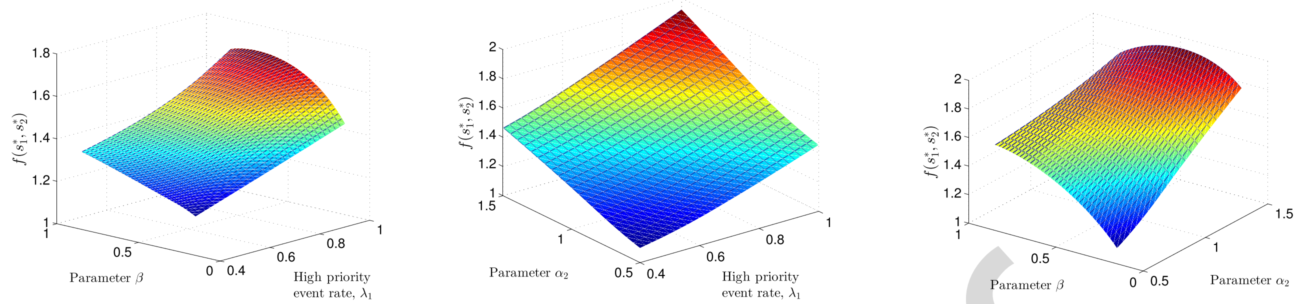


Fig. 7. Optimal event processing rate for (a) high-priority events and (b) low-priority events.

time division multiplexed (TDM) policy with equal priorities. For an arbitrary policy followed, we define the *normalized performance* as $1 - (D^{(i)}/N_t)$, where superscript i marks the policy followed and can be one of the dynamic, nonpreemptive or TDM based and $N_t = N_1 + N_2$. For the TDM based equal priority policy, the mean delay is defined as $D_1^{(\mathrm{TDM})} = (N_1/s_1)$ and $D_2^{(\mathrm{TDM})} = (N_2/s_2)$ for low- and high-priority classes of load-demand events, respectively.

The normalized performance comparison results are shown in Fig. 4. From the result in Fig. 4, it can be seen that both dynamic-priority and nonpreemptive policies perform better compared to TDM approach. In addition, we observe that the normalized performance for dynamic-priority policy is superior compared to nonpreemptive policy, for low-priority nodes, while opposite is the case for high-priority nodes. This is due to the fairness improvement capability of the dynamic-priority policy. We also observe that an increase in high-priority nodes, affects the performance of low-priority nodes more in the case of a nonpreemptive policy compared with a dynamic-priority policy, as can be observed from Fig. 4(a).

Next, we compare the normalized delay-performance of dynamic-priority policy for three different values of parameter θ. The normalization is done with the maximum delay of



(a) (b) (c)

Fig. 8. Optimal objective function variations as a function of (a) high-priority event rate λ_1 and weighting parameter β, (b) event rate λ_1 and cost exponent parameter α_2 and (c) parameters β and α_2.

TABLE II
PERFORMANCE COMPARISON SUMMARY FOR DIFFERENT EVENT PROCESSING POLICIES

Policy	Fairness	Priority
TDM	Highly fair	Fixed equal priority
Non-preemptive	Highly unfair	Fixed unequal priority
Dynamic priority	Moderately fair	Programmable

the low-priority nodes. It should be recalled that for parameter $\theta = \infty$ represents the nonpreemptive policy. The results are shown in Fig. 5. From these results, we can observe that the delay for high-priority events is minimum, while it is maximum for low-priority events when using nonpreemptive policy. While for the two other values of parameter θ, the delay reduces for low-priority events at the expense of an increased delay for high-priority events when compared with the nonpreemptive policy. This delay-performance tradeoff between high- and low-priority events is adjustable to the desired level by tuning the value of parameter θ.

For the dynamic-priority policy, the effect of tuning parameter θ on fairness experienced by the low-priority nodes is shown in Fig. 6. For that purpose, we define the normalized fairness improvement as $(D_2^{(d)} - D_1^{(d)}/D_2^{(d)})$. From the result in Fig. 6, it can be seen that by reducing the value of θ, a higher fairness improvement can be achieved at the expense of larger delays for high-priority events, when parameter λ_1 assume large values. This is based on the fact that the accumulated margin from a larger number of high-priority events is large and leads to higher fairness improvement when the value of parameter θ is reduced. The event processing fairness and priority based comparison for different policies is summarized in Table II.

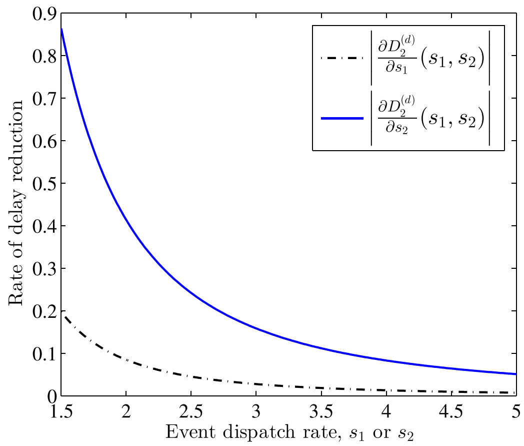
B. Optimal Performance Tradeoff

Based on the optimization problem formulation, we can analyze the performance tradeoff between the processing load on the substation EMS and the delay experienced by the load-demands. The differentiation for substation EMS processing cost is realized by assigning larger value to cost exponent parameter α_1 corresponding to high-priority events. The values used for parameters α_1 and α_2 are given in Table I. The optimization problem in (25) is solved using the relaxation method discussed in [17]. In the problem formulation in (25) the parameter β is the weighting coefficient that defines the relative importance of the two-priority classes. A higher value assigned to parameter β gives more weight to the high-priority load-demands.

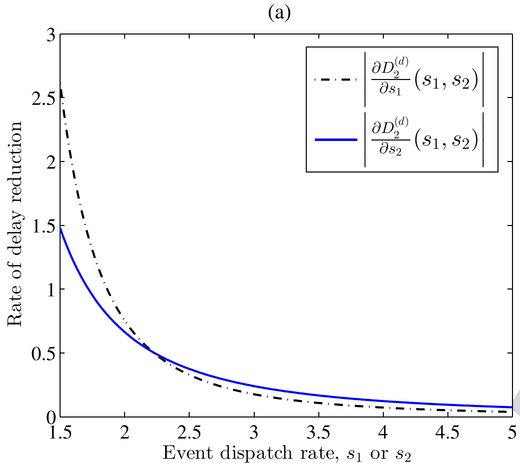
The variations in the optimal values for event-processing rates at the substation EMS, s_1^* and s_2^*, are shown in Fig. 7. We can observe that an increase in parameter β simultaneously reduces s_1^* and increases s_2^*. Since the objective is to minimize the weighted substation EMS processing cost and the load-demand delays, the dominance of cost component compared with the delay results in decreasing s_1^*, while the opposite is true for s_2^*.

The optimal sum cost variations for different parameters are shown in Fig. 8. The optimal cost, $f(s_1^*, s_2^*)$ as a function of high-priority event rate, λ_1 and weighting parameter β, is shown in Fig. 8(a). From this result, we observe an interesting aspect, for large values of λ_1, where the optimal value of cost first increases and then decreases with an increase in parameter β. This is attributed to the dominance of high-priority events, which results in an increase in optimal cost for lower values of parameter β. For larger values of β, the low-priority events are given more weight and result in decreasing the optimal cost. The effect of varying cost exponent α_2 (of lower priority events) and parameter β is shown in Fig. 8(c). We observe a similar behavior due to weighting coefficient β, as observed in Fig. 8(a), for larger values of cost exponent α_2. This type of response is based on the fact that both parameters, λ_1 and α_2, have a similar effect on the optimal cost. This can be verified from Fig. 8(b), where we observe an increase in the cost due to an increase in λ_1 as well as α_2.

Finally consider the scenario, where the substation EMS is required to reduce the delay of low-priority events. Since increasing event processing rates s_1 as well as s_2 can reduce the delay of low-priority events, we need to know which of the two options would perform better. One measure that can be used to make the choice is based on the magnitude of delay reduction per unit increment in s_1 or s_2 and can be quantified by evaluating the low-priority event delay partial derivative. For instance, if s_2 is used for delay reduction, then this measure is quantified as $|(\partial D_2^{(d)}/\partial s_2)(s_1, s_2)|$. Using this



(a)



(b)

Fig. 9. Delay reduction rate in response to increasing event-processing rate. The x-axis parameter s_2 corresponds to $|(\partial D_2^{(d)}/\partial s_2)(s_1, s_2)|$ and s_1 corresponds to $|(\partial D_2^{(d)}/\partial s_1)(s_1, s_2)|$. (a) For high-priority event arrival rate $\lambda_1 = 0.15$ and (b) $\lambda_1 = 0.6$. The low-priority event arrival rate $\lambda_2 = 0.3$ is selected for both the cases.

measure, the selection between s_1 or s_2 can be made as

$$s_i = \begin{cases} s_1, & \left|\frac{\partial D_2^{(d)}}{\partial s_2}(s_1, s_2)\right| \leq \left|\frac{\partial D_2^{(d)}}{\partial s_1}(s_1, s_2)\right| \\ s_2, & \text{otherwise.} \end{cases} \quad (34)$$

This fact is illustrated in Fig. 9. From the result in Fig. 9(b), we can conclude that for smaller values of λ_1 we select s_2, while s_1 is selected for larger values of λ_1 and the crossover point in (34) determines the switching point between s_1 and s_2.

VI. Conclusion

SG is evolving as a result of integration of the power and cyber networks. The large data volumes in SG demand for necessary information communication using a prioritization metric and are key to the scaling of such an event-driven based communication infrastructure. A priority-based event-driven communication mechanism is proposed to achieve balance between demand and supply. Load-demands are categorized into multiple priority classes, and demand processing based on dynamic-priorities is analyzed. Evaluation results based on delay and fairness parameters show performance improvement of priority based solution compared with TDM-based equal priority mechanism. The performance trade-off between EMS processing cost and the delays experienced by different priority classes of load-demands is achieved by using generalized geometric optimization. The priority-based load demand processing, while accounting for the substation EMS loading, provides multidimensional flexibility to achieve demand–supply balance. In the future, we plan to analyze the communication network performance scaling of substation EMS, when multiple load-demand aggregators are connected to it.

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