Utility-based PMU data rate allocation under end-to-end delay constraints

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1. Introduction

Modern power transmission systems are networks of systems operated by independent operators. The proper operation of the power system requires that generation and demand be balanced continuously respecting the capacity constraints of the power transmission and distribution infrastructure. Maintaining the balance is ever more challenging due to the increasing penetration of solar and wind energy, which are highly intermittent. Economic operation requires that the system should operate close to its capacity limits, but large interconnected power systems under high stress can exhibit frequency and power oscillations that can grow over time and can lead to a disconnection of the power system into islands, with blackouts as a consequence.

To monitor the state of the power system, operators require accurate, frequent and time synchronized measurements of the state of the power system. Phasor Measurement Units (PMUs) are increasingly used to periodically measure the instantaneous state of the power system, such as voltage and current phasors (i.e., amplitude and phase angle). The frequency at which measurements can be taken is selectable, from 1/s up to twice the mains frequency of the power system (i.e., up to 100Hz or 120Hz). PMUs rely on the time information provided by the global positioning system (GPS) to attach time stamps with sub-millisecond precision to measured data [1][8]. The data collected by PMUs at the substations need to be delivered from the substations to one or more control centers or to distributed controllers.

The communication infrastructure of most modern power systems is based on Optical Ground Wire (OPGW) installations along the power transmission lines, and time division multiplexing (TDM) based on SDH/SONET is typically used for establishing channels between the substations and the control center. TDM provides predictable end-to-end delays if every flow has a dedicated channel at the price of low bandwidth use efficiency and little flexibility in terms of the connections that can be established. IP over switched Ethernet could provide flexibility and efficient use of the available bandwidth, but providing delay guarantees over IP networks with high utilization has proven to be challenging in general.

PMU measurement data can be used to implement a variety of power system applications. Wide-area frequency monitoring systems allow operators to analyze frequency trends, to draw conclusions on the future stability of the system and to implement feedback control systems for stabilizing the system [3]. PMU measurement data taken at the two ends of a transmission line can be used for dynamic thermal monitoring, which allows dynamic rating and thus, more efficient utilization of individual transmission lines [2]. PMU data can also be used to monitor power and frequency oscillations in large power systems with significant power flows over long distances [3][5], to prevent system separation. The frequency at which PMU measurements are needed, the location where the data should be delivered to, and the latency at which the data should be available for processing vary significantly depending on the particular application [2][3][4][5]. The measurement frequency might increase in the future if applications monitoring higher frequency harmonics become wide spread. Higher frequency measurement data might, however, not be needed all the time and thus dimensioning the communication infrastructure for peak bandwidth would be inefficient. Instead, the communication infrastructure could be dimensioned such that it can accommodate high frequency measurement data from a subset of the PMUs, and the rate between the PMUs would be allocated as a function of their importance.

In this paper, we formulate the problem of adaptive PMU rate allocation subject to end-to-end delay constraints as a utility maximization problem. We show that for a shape preserving scheduling principle the problem can be converted into a network utility maximization problem, and provide a solution to the problem. We use the IEEE 118 bus benchmark power system to obtain numerical results.

2. Adaptive Rate Allocation Problem

We model the communication infrastructure as a directed graph $G=(V,E)$, where every vertex is a switch and there is an edge e_{ij} between two vertices v_i and v_j if there is a link connecting v_i to v_j. We denote the bandwidth of edge e by c_e. We assume that the switches implement non-preemptive priority queuing, and PMU data are assigned highest priority.

We denote the set of PMUs by $S=\{1,\ldots,N_S\}$. We denote the vertex to which PMU s is attached by v_s. We denote by d_s the vertex that is the destination of the data generated by PMU s, and assume that there is a path $L(s)$ configured in the network. We denote by $r_s \geq 0$ the rate at which PMU s generates measurement data and by D_s the end-to-end delay budget of the data generated by PMU s. We assume that the rate is continuous and that the utility of the PMU data is a concave continuous function $U_s(r_s)$ of its rate. We denote by P_s the packet size used by PMU s, which is determined by the number of digital and analog values sent, and is typically constant. Furthermore, we denote by P_{max} the maximum packet size in the network.

Utility Maximal Rate Allocation

Given the above notation we can formulate the problem of utility maximal rate allocation in the framework of network utility maximization [7] as

$$\begin{aligned} &\max \sum_s U_s(r_s) \\ &s.t. \\ &\sum_{e\in L(s)} d_e(r_1,\ldots,r_S) \le D_s \quad \forall s\in S \end{aligned} \tag{1}$$

The worst case queuing delay d_e at edge e is a function of the rates and the arrival process of the messages belonging to the flows traversing the edge. Although the arrival process of the data from PMU s is deterministic (i.e., 1 message per sample) upon entering switch v_s, this is not necessarily the case upon arrival to the second switch on the path due to multiplexing with other PMU data and possibly with background traffic.

3. Solution under Rate-controlled Priority Queuing

In the following we consider that every switch implements rate-controlled priority queuing. This makes it possible to bound the worst case per-hop delay. Under the rate-controlled priority queuing (RCPQ) discipline [6] every switch restores the message inter-arrival time of a flow of messages to the inter-arrival time at the origin of the flow. While such a queuing discipline can be impractical for Internet traffic, in the case of PMU data delivery the inter-arrival time of messages is known from the sampling frequency. Furthermore, every message carries a timestamp with sub-millisecond accuracy, which facilitates the implementation of this queuing discipline. Under RCPQ, the worst-case per hop delay of a message on link e is bounded by the smallest d_e that satisfies

$$\sum_{s:e\in L(s)} \left\lceil \frac{d_e}{t_s} \right\rceil \frac{P_s}{c_e} + \frac{P_{\max}}{c_e} \le d_e \tag{2}$$

If d_e is small enough so that for all flows the message inter-arrival time $t_s > d_e$ then (2) is only a function of the number of flows traversing the link, but not that of the rate of the individual flows. This allows us to simplify (2) and get a bound of the worst case delay at link e

$$\sum_{s:e\in L(s)} \frac{P_s}{c_e} + \frac{P_{\max}}{c_e} \le d_e \tag{3}$$

We can substitute the delay bound in (3) into the original optimization problem in (1) to obtain the following optimization problem

$$\begin{aligned} &\max \sum_s U_s(r_s) && && (4)\\ &s.t. && && \\ &\sum_{s:e\in L(s)} r_s \le c_e && \forall e\in E && (5)\\ &c_e d_e \ge \sum_{s:e\in L(s)} P_s + P_{\max} && \forall e\in E && (6)\\ &\sum_{e\in L(s)} d_e \le D_s && \forall s\in S && (7) \end{aligned}$$

(4)

The above problem can be solved in two steps. First, find the smallest possible link delays d_e for every link using (6). If there is a feasible allocation of per link delays d_e that satisfies the end-to-end delay constraints D_s in (7), then the rates rs that maximize (4) can be found by observing that $r_s=P_s/t_s$, and by assumption $t_s > \max_{e\in L(s)} d_e$. Rate allocation is not necessary in this case, but dynamic routing could be used to minimize t_s. Let us consider now the opposite, that is, when the message inter-arrival times $t_s \ll d_e$. In this case we can bound the left hand side of (2) by

$$\sum_{s:e\in L(s)} \left\lceil \frac{d_e}{t_s} \right\rceil \frac{P_s}{c_e} + \frac{P_{\max}}{c_e} \le \sum_{s:e\in L(s)} \left(\frac{d_e}{t_s} + 1 \right) \frac{P_s}{c_e} + \frac{P_{\max}}{c_e},$$

and by substituting $t_s=P_s/r_s$, and solving for d_e we obtain the lower bound

$$\frac{\sum_{s:e\in L(s)} P_s + P_{\max}}{c_e - \sum_{s:e\in L(s)} r_s} \le d_e$$

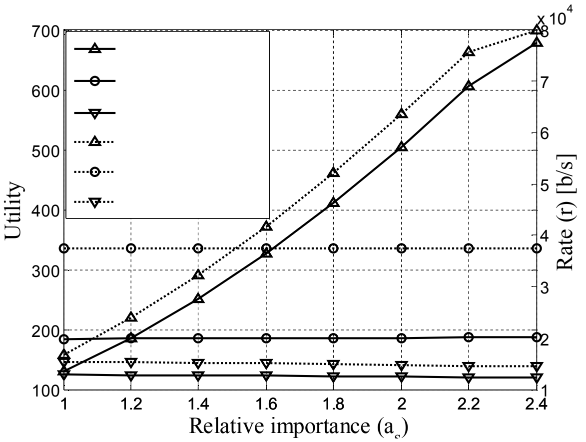
for the per hop delay d_e. We can use this lower bound to formulate the following optimization problem

$$\begin{aligned} &\max \sum_s U_s(r_s) && && (8)\\ &s.t. && && \\ &\sum_{s:e\in L(s)} r_s \le c_e - \frac{\sum_{s:e\in L(s)} P_s + P_{\max}}{d_e} && \forall e\in E && (9)\\ &\sum_{e\in L(s)} d_e \le D_s && \forall s\in S && (10) \end{aligned}$$

The objective function in (8) is strictly concave and the domain of the optimization is convex and compact, thus there is a global optimum and it is attained if there is a feasible solution to (9) and (10). The standard dual decomposition of the problem as described in [7] cannot be applied directly because the rate constraints in (9) are coupled through (10). We can nevertheless use the projected subgradient method to find the global optimum.

4. Numerical Results

We use the IEEE 118 bus system to illustrate the proposed adaptive rate allocation algorithm. We



consider that a PMU is installed at every substation, the number of phasors per message and thus the message size is given by the connectivity of the substation. All PMU data are delivered to the control center located at the bus with highest degree via a shortest path in the network topology which resembles the topology of the power system. All communication links have a capacity of 1Mbps, except for the link that connects the control center to the substation with highest degree, which has tenfold capacity. The end-to-end delay constraint D_s was set to 1s for all PMUs. We use $a_s\sqrt{r_s}$ as the utility function of PMU *s,* and use a_s to set the relative importance of the individual PMUs.

Figure 1 shows the change of the rate and that of the utility as the relative importance a_s is increased for a single PMU to prioritize its data. The results show that through adapting a_s the rate and the utility of PMU *s* increases monotonically, while the rate and utility of the other PMUs decreases slowly.

Conclusion

In this work we considered the problem of adapting the rate phasor measurement units subject to link capacity and end-to-end delay constraints. We formulated a network utility optimization problem and discussed the solution to two special cases of the problem. We illustrated the solutions on the IEEE 118 bus benchmark power system. The feasibility of the proposed approach for PMU rate adaptation depends on if it is possible to map end user requirements into utility functions, and whether a solution can be obtained for discrete sets of possible rates. Addressing these questions will be subject of our future work.

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