Effective Capacity Analysis of Smart Grid Communication Networks

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Abstract—Smart grid represents a significant new technology of improving the efficiency, reliability and economics of the production, transmission and distribution of electricity that helps reduce carbon emissions. Communication networks become a key to achieving smart grid benefits due to their capability of delivering data and control signals. However, there does not exist a unified approach to quantify how well a communication network supports smart grid applications. In this paper, effective capacity is exploited as a good candidate to quantitatively measure how well the communication network supports smart grid applications, regardless of specific network technologies. Case studies using the effective capacity are given and analyzed by simulations in different smart grid application scenarios.

Index Terms—Smart grid, communication networks, effective capacity, case studies.

I. Introduction

Smart grid has been a hot research area in recent years. Although its definition and architecture may vary, it has been widely agreed that the effective, reliable and secure communication network is the most critical component of smart grid [1]. The communication network shall be able to provide bidirectional link anywhere within the smart grid to support a variety of smart grid applications via Information and Communication Technologies (ICTs). The wireless communication network is a powerful alternative method to the wired network and it can provide a more flexible connection link for the information flows between intelligent components.

The interconnection between smart grid components is very critical, because most of the applications in smart gird are real-time applications. Moreover, for delay-sensitive applications, not only the delay in quantities matters, but also the reliability is usually very crucial [2]. For example, if a control command violates a delay allowance, it might result in an unstable power system or even a disaster. There are already several smart grid standards addressing the communication requirement, such as IEC 61850 for substation automation and protection, HomePlug for Home Area Network device communication and information model and IEC 60870 for inter-control center

communications [3]. However, much unlike the wired communication network, the wireless communication network has a complex delay performance. What is more, sever environment may result in unreliability in the communication link. Hence, as smart grid technology may be applied in many scenarios, it is very important to perform the system analysis considering the delay performance over various channel conditions. However, the conventional Shannon's ergodic capacity cannot account for the delay aspect.

The delay might come from any component along the end-to-end link path [4], [5]. But for the wireless communications, the temporal fading character of the communication medium may contribute most to the unreliability of the delay performance. There are channel models in the residential and office building scenarios can be directly exploited in the performance analysis in smart grid systems, but only a few efforts have been made to the industrial environment, especially models for temporal fading effects [6], [7]. In the remaining part of this paper, it will be shown that the temporal fading channel statistical characteristics may affect the system performance significantly.

Channel model parameters are directly related to the physical layer (PHY), but Quality of Service (QoS) metrics like delay and delay violation probability used in higher layers are hard to be extracted. So when the channel statistical characteristics are available, how to map these parameters into QoS metrics and then to use them in the network control mechanisms is of great importance and challenging. In this paper, the effective capacity theory [8] is exploited, which has been used as the base of cross layer optimization in mobile networks [9] and cognitive radio networks [10]. But according to the authors' best knowledge, no articles have used the effective capacity theory as a general analysis method in the context of smart grid. In this paper, situations and examples as well as simulations in typical smart grid scenarios' channels including industrial, residential and office building are considered to illustrate how effective capacity can be used for the admission control, resource allocation and trade-offs between information quality and delay performance.

In the remainder of this paper, we will briefly introduce the effective capacity concept in Section II. Section III will then provide a simple way to estimate parameters involved in the effective capacity concept. Case studies and simulations are

presented in Section IV where different smart grid application scenarios are considered. Conclusions are drawn in Section V.

II. EFFECTIVE CAPACITY THEORY

As a dual concept of effective bandwidth, which has been widely used in wired communication systems, effective capacity shows a cross layer way to analyze the relation between the link layer queueing behaviour and the physical channel conditions.

Let $c(t)$ be the instantaneous channel capacity at time t. Assume the asymptotic log-moment generation function of $c(t)$ defined as [11]

$$\Lambda(-x) = \lim_{t \to \infty} \frac{1}{t} log_e \mathbb{E}[e^{-x \int_0^t c(\tau)d\tau}], \quad (1)$$

exists for all $x \geq 0$. Then the effective capacity function $E_C(x)$ of $c(t)$ is defined as [8]

$$E_C(x) = -\frac{\Lambda(-x)}{x} = -\lim_{t \to \infty} \frac{1}{xt} log_e \mathbb{E}[e^{-x \int_0^t c(\tau)d\tau}]. \quad (2)$$

Denote $D(t)$ the end-to-end delay experienced by a source packet arriving at time t. For a data source of constant data rate μ, if $c(t)$ is a stationary Markov-fading process, then the probability of $D(t)$ exceeding a delay bound D_{max} satisfies [11]

$$\sup_t Pr\{D(t) > D_{max}\} \approx \gamma(\mu)e^{-\theta(\mu)\{D_{max}-D_{const}\}}, \quad (3)$$

where the QoS exponent $\theta(\mu)$ is defined as the solution of $E_C(\theta) = \mu$. $\gamma(\mu)$ is the probability that the buffer is non-empty at a random chosen time t. D_{const} includes the constant delay components such as the propagation delay (when transceivers are static) and the processing delay. From the discussion above, we can see that the QoS metrics for an application in the effective capacity are the maximum data rate μ, delay bound D_{max} and the delay violation probability $Pr\{D(t) > D_{max}\}$. $c(t)$ is influenced by both the system's design and channel conditions. For a source data rate of μ, the QoS exponent $\theta(\mu)$ is decided by the instantaneous channel capacity $c(t)$. The queueing status is reflected by the parameter $\gamma(\mu)$. Hence the pair $\{\gamma(\mu), \theta(\mu)\}$ models the whole system. All the parameters are connected by (3).

III. PARAMETER ESTIMATION

The pair $\{\gamma(\mu), \theta(\mu)\}$ can reflect the queueing behaviour under the time-varying service rate. The service rate may change with time due to several reasons, such as the contention due to Media Access Control (MAC) mechanism and the fluctuation of the instantaneous channel capacity due to temporal fading. In this paper, we focus on a unified analysis method and an understanding of the system performance regardless of specific MAC and PHY layers. The temporal fading situation is mainly considered.

A great advantage of effective capacity theory is that the parameters $\{\gamma(\mu), \theta(\mu)\}$ can be estimated through measurement and simple calculation. A simple estimation algorithm is [12]

$$\frac{\gamma(\mu)}{\theta(\mu)} = \mathbb{E}[D(t)] = \tau_s(\mu) + \frac{\mathbb{E}[Q(t)]}{\mu}, \quad (4)$$

and

$$\gamma(\mu) = Pr\{D(t) > 0\}, \quad (5)$$

where $\tau_s(\mu)$ is the average remaining service time, and $\mathbb{E}[Q(t)]$ is the average queue length. Hence $\theta(\mu)$ can be calculated by

$$\theta(\mu) = \frac{\gamma(\mu) \times \mu}{\mu \times \tau_s(\mu) + \mathbb{E}[Q(t)]}. \quad (6)$$

Thus $\{\gamma(\mu), \theta(\mu)\}$ can be derived from $Pr\{D(t) > 0\}$, $\tau_s(\mu)$ and $\mathbb{E}[Q(t)]$. In practical systems, these parameters can be estimated by taking the average over N times

$$\hat{\gamma} = \frac{1}{N} \sum_{n=1}^{N} S_n, \quad (7)$$

$$\hat{q} = \frac{1}{N} \sum_{n=1}^{N} Q_n, \quad (8)$$

and

$$\hat{\tau}_s = \frac{1}{N} \sum_{n=1}^{N} T_n, \quad (9)$$

where $S_n \in \{0, 1\}$ is the queue busy indicator, Q_n is the number of bits in the queue, and T_n is the remaining service time if the service is occupied. Then the estimated $\hat{\theta}$ can be obtained by

$$\hat{\theta} = \frac{\hat{\gamma} \times \mu}{\mu \times \hat{\tau}_s + \hat{q}}. \quad (10)$$

It has been verified that τ_s can be approximated by $\tau_s = 1/(2\mu)$ [12], [13]. So a simple approximation of $\hat{\theta}$ considering the effect of MAC layer can be obtained by

$$\hat{\theta} = \frac{\hat{\gamma} \times \mu}{0.5 + \hat{q}}. \quad (11)$$

By using (7)-(11), the delay violation probability (3) can be approximated by

$$Pr\{D(t) > D_{max}\} \approx \hat{\gamma}e^{-\hat{\theta}(D_{max}-D_{const})}. \quad (12)$$

IV. CASE STUDIES

The typical smart grid application scenarios involve industrial, residential and office environment. In this paper, we consider smart grid applications in these environments. The considered system model is shown in Fig. 1, where the data from several intelligent electronic devices (IEDs) (or sensors) are aggregated at the gateway and transmitted using wireless technologies. In the case of industrial environment, a typical application is the raw data collection from IEDs, where the data consist of continuous streams of synchronized samples

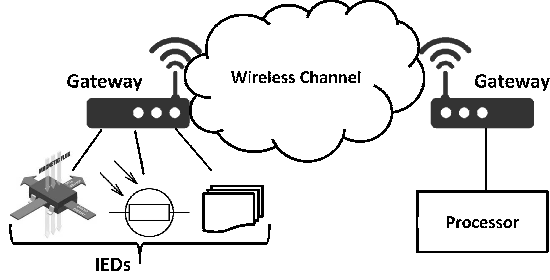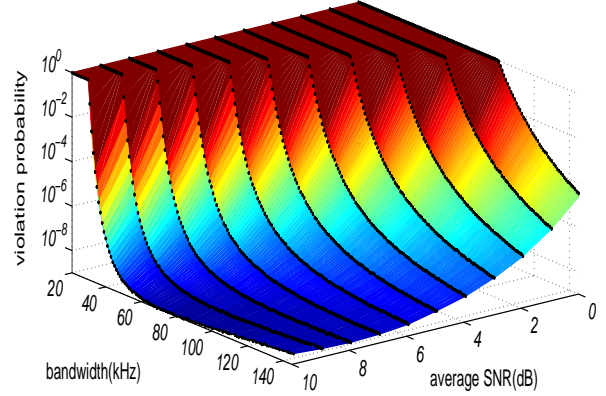| Channel Environment	Typical application	Channel Parameters	Communication requirements
Industrial building	Raw data collection from IEDs	Rician K=5.1dB	Source Rate 60∼100kbps, D_{max}=10ms, Delay violation probability $10^{-2} \sim 10^{-5}$
Residential building	Non-intrusive load monitoring	Rayleigh	
Office	Non-intrusive load monitoring	Rician K=-6.8dB	

Fig. 1. The Wireless Communication System Model

Fig. 2. Delay violation probability under different bandwidths and temporal fading channels, average SNR=0dB
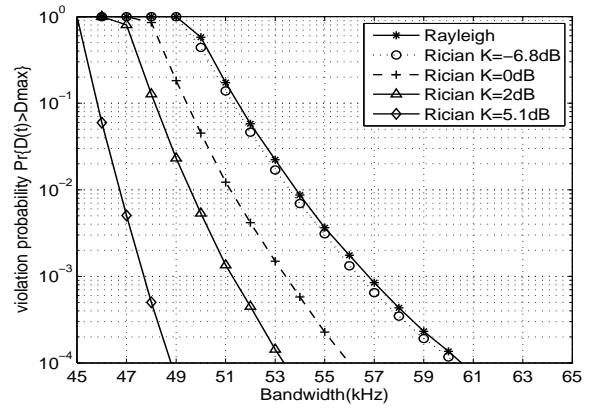

Fig. 3. Delay violation probability under different bandwidths and temporal fading channels, average SNR=5dB
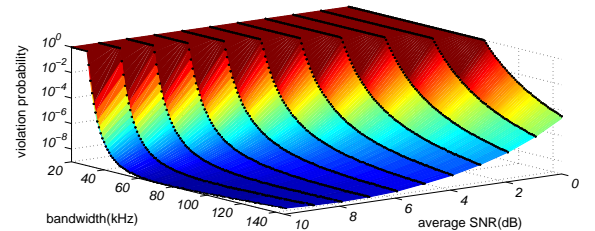

Fig. 4. Delay violation probability under different bandwidths with average SNR from 0dB to 10dB in Rayleigh fading channel

from each IED, and interleaved with data from other IEDs. The delay requirement for this type of application is 10ms, and the delay violation probability may range from 10^{-2} to 10^{-5} depending on the specific functions [14]. The channel can be modelled by Rician model with the estimate of mean random/specular power ratio (K) of 5.1dB [7]. This is a typical situation where light-of-sight (LOS) is expected due to the open architecture and significant reflection in industrial environment. As for the residential and office environment, the application of non-intrusive load monitoring is considered. A delay of 10ms with a delay violation probability ranging from 10^{-2} to 10^{-5} is considered. Rayleigh channel model is used for residential environment, where there is usually no LOS path between the transceivers. For an office building environment, a Rician model is applied while the typical K parameter is chosen as -6.8dB [15]. For the convenience of discussion, a data rate ranging from 60 to 100 kbps is considered. The parameters used are summarized in Table I. Also we assume that the queueing delay is dominant, where other delay components such as propagation delay is negligible. Moreover, Doppler effect is not considered since the transceivers in the smart grid are fixed to a position. An assumption is made that Shannon's capacity can be approached by the throughput of the system, in order to perform an analysis in a general way that might work with different MAC and PHY layers.

First, the resource allocation is considered. Before each transmission, the amount of resource required to support the application's QoS requirement is calculated and reserved. In most algorithms, the resource allocation is static. Once an application is admitted, the total reserved resource would be hold for the whole transmission procedure. Therefore the amount of resource assigned and reserved for the application would be critical to guarantee the application's QoS require-

ment. We consider the bandwidth allocation cases, which is to provide the application with a source data rate of 85kbps and a maximum delay bound of 10ms under different channel conditions. It can be seen from Fig. 2-3 that the residential situation (Rayleigh fading), is the worst case which needs a wider bandwidth to support the same data rate transmission for the same delay performance. Office environment with weak LOS component, which is corresponding to the Rician model with K=-6.8dB, has almost the same performance with the Rayleigh fading. As the LOS component gets stronger, which is corresponding to the increase of K, the bandwidth needed to guarantee a desired violation probability (e.g. 0.01% for some delay-sensitive application) under specific average signal-to-noise ratio condition also decreases. A more detailed bandwidth required to support the application varying with the average SNR is shown in Fig.4. It indicates that in relatively low SNR situations (e.g. 0-10dB), the required bandwidth to support the same data rate for the delay performance increases significantly along with the drop of the average SNR. This makes sense since the Shannon capacity will decrease along with the drop of the average SNR under a fixed bandwidth. But a further calculation in Table II shows that the extra bandwidth needed to get the same delay performance along with the decrease of the average SNR also increases in an exponential way. If only assigned with the bandwidth using average SNR information, it will violate the delay bound in a probability of 100%. This gives a direct sense of the importance to consider channel fading statistical characteristics in resource allocation mechanisms.
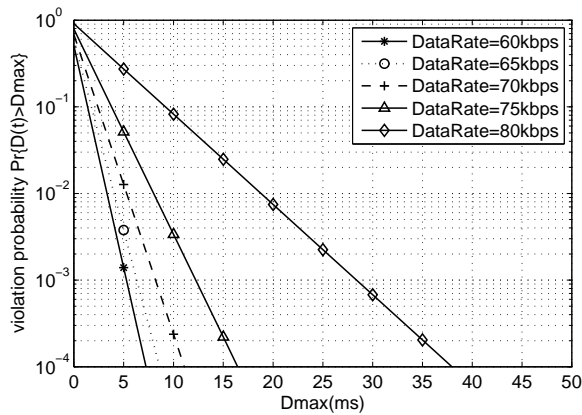

Fig. 5. Delay violation probability under different data rates and delay bounds, Rayleigh fading channel

Real channel capacity will vary randomly with time, which means that a guarantee of 100% that the transmission will not violate the upper delay bound is almost impossible. Indeed the increase of redundant bandwidth would certainly improve the delay bound violation performance. However, it can also be inferred from the Fig. 2-3 that the bandwidth increased exponentially while the delay-violation probability approaches zero, i.e. a 100% guarantee of transmission within the delay bound, which is unrealistic due to the limited bandwidth in practice. Hence the admission control and resource allocation

algorithms should assign resources, e.g. bandwidth, according to the delay bound and the reliability requirement of the application. A typical example is the system exploiting Orthogonal Frequency-Division Multiple Access (OFDMA), which is already used in many standards such as IEEE802.16 (WiMAX) and 3GPP LTE. The subsets of sub-carriers in OFDMA can be mapped to the bandwidth allocation problem.
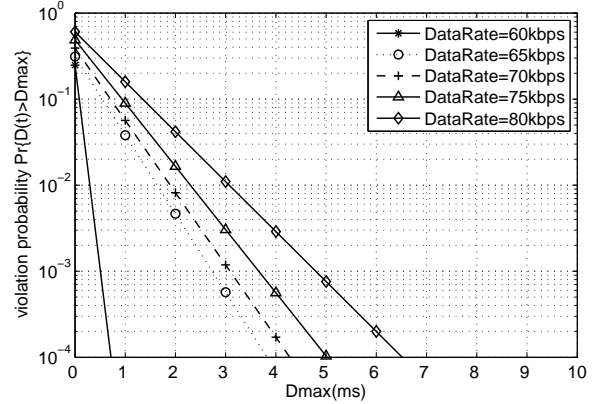

Fig. 6. Delay violation probability under different data rates and delay bounds, Rician fading channel K=5.1dB

Second, the admission control is considered. Whenever a new request of transmission is launched, the admission control algorithm would check the availability of the request. That means the available resources have to be evaluated and mapped to the required QoS metrics to see if or not the application can be admitted. As for delay-sensitive applications, not only the available throughput of the system is of matter, but also the estimated delay and the violation probability is essential. Take the video surveillance as an example, video frames would be useless and discarded if certain delay bound is exceeded. Moreover, for most control command, the delay performance is crucial, where a delay violation might even result in a disaster. Thus in the design of the admission control algorithm, delay and violation probability should be included in the QoS metrics to be estimated with the available resources. A scenario that the source data rate as well as the associated delay bound and reliability can be supported when a channel capacity of 100kbps is available under an average SNR of 5dB and different temporal fading channels is considered. The Rician model with K=5.1dB for industrial environment and Rayleigh model for residential scenario are presented in Fig. 5 and 6. It is worth noticing that D_{max} associated to a source data rate is the lower bound. For example, with an average SNR of 5dB and Rayleigh fading channel as shown in 5, it can be predicted that an application with a data rate of 80kbps and a delay bound requirement no less than 37ms would be guaranteed by 99.99%, which can be used as criteria for admissions.

Another situation is considered when variable source data rate is achievable. Communication under tough environment is involved in smart grid. Resources might be strictly confined and valued, yet the applications are still delay sensitive. Also in practice, even deployed within a close geographical location,
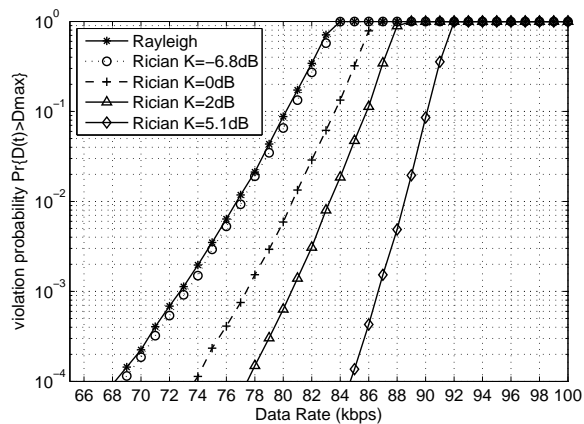
Fig. 7. Delay violation probability under different data rates and temporal fading channels

TABLE II
EXTRA BANDWIDTH UNDER DIFFERENT AVERAGE SNR

Average SNR(SNR_{avg})	0	2	4	6	8	10
bandwidth for SNR_{avg}(kHz)	85	62	47	37	30	25
bandwidth for pr=10^{-4}(kHz)	136	96	70	53	42	33
extra bandwidth(kHz)	51	34	23	16	12	8

the channel condition for different transceivers would still be heterogeneous. For example the channel between one pair of transceivers might be Rayleigh fading with an average SNR of 5dB yet the other is Rician fading with an average SNR of 0dB. The variable data rate can be achieved by many methods, for example a feedback control of a tunable Analog-to-Digital Converter (ADC) at the data source, or by an Adaptive Modulation and Coding (AMC) at the transmitter. An example of an application with a delay bound requirement of 10ms under different temporal fading models with an average SNR of 5dB is illustrated in Fig. 7. It can be indicated from Fig. 7 that the delay bound violation probability decays exponentially with the decrease of the source data rate, but for the same conditions other than temporal fading statistical characters, the maximum supported data rate is different. In such cases, if the source data rate can be adapted based on the prediction of delay bound violation under current and past channel condition of the transceivers along the path, a trade-off can be obtained between the information quality and the delay performance, or even enable some delay-sensitive applications which would not be admitted with a high data rate. For example, an application with a delay bound of 10ms, and delay violation probability of 0.1%, it might not be admitted (i.e. blocked) with a data rate of 78kbps, but it can expect a even lower delay violation probability of 0.01% with a drop (e.g. using AMC) of data rate to 74kbps as shown in Fig. 7.

V. CONCLUSION

Smart grid has a wide range of applications covering different scenarios, leading to different QoS requirements. Delay-sensitive applications often exist, hence the delay and the probability of delay bound violation should also be considered in the QoS metrics. This paper proposes to use effective capacity to evaluate the support level of communication networks to the smart grid applications. Examples as well as simulations with measured statistical channel model in common smart grid application scenarios including industrial, residential and office environment are used to verify the effective capacity concept. In the future, we will focus on integrating the effective capacity into the admission control and resource allocations algorithms for heterogeneous networks in smart grid systems.

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