Implementation of Communication Network Components for Transient Simulations in PSCAD/EMTDC

Saranga Menike, Pradeepa Yahampath, Athula Rajapakse

***Abstract*—A comprehensive analysis of a power system with communication-based protection and control can only be carried out by co-simulation of the power system and the data communication network. This paper presents the development of a basic set of communication components for PSCAD/ EMTDC power system simulation software which enables the co-simulation of a power system and a communication system. In particular, these components can be used to simulate the important performance measures such as communication delay and packet loss probability of a communication network which can negatively impact the protection and control system operations. The accuracy of the communication components is verified by comparing the simulation results with the results taken by using an analytical method based on queuing theory.**

***Keywords*: Communication delay, Packet loss probability, Phasor measurement units, Wide area monitoring, protection and control**

I. Introduction

High-speed data communication is becoming an integral part of the modern power grid, particularly in monitoring and control applications. When used in real time control applications, a data communication network forms a critical link in a real-time feedback-loop by transmitting measurements acquired at various points in the power system to the decision making devices. However, relying on data communication in power system monitoring and control presents a unique set of challenges in terms of ensuring the reliable and timely exchange of information between measurement units and computers.

The performance of a modern packet-based data communication network is determined by its bandwidth (supported data rate), architecture (topology) and the communication protocols employed. In particular, a system designer must be able to determine the impact of a given communication network infrastructure on critical power system applications that rely on it and identify the potential bottlenecks. The ability to co-simulate the communication network and the power system is a key requirement for Monte-Carlo simulation studies commonly used for the performance analysis of control and monitoring applications. However, at present, widely used power system simulation software does not have tools to implement communication networks. Even though software such as OPNET, OMNET++, NS2 currently exists for simulation of data networks they cannot be readily integrated into power system simulation platforms such as PSCAD [1], [2].

In order to address this issue a set of communication network simulation tools is developed in this paper. These tools are intended to be used for co-simulation of a data communication network and the associated power system in PSCAD simulation environment. The emphasis has been placed on modeling those characteristics, which are critical to protection and control applications in power systems. As most of the stability control and protection applications in power systems require response time of less than few hundred milliseconds after a disturbance such as fault, the communication delays typical in a packet-data network can be very significant. Also the loss of data packets can negatively impact the timely operation of the protection and control devices. Therefore, the goal of this paper is to accurately model the delay characteristics and reliability measures like packet loss probability of a given data network.

Previous work on the performance evaluation of communication networks in wide area power systems, by using a stand alone network simulation software appears in [1]–[5]. In this work they have investigated the possibility of improving wide area power system applications based on the simulation results obtained using stand alone network simulation software. There are two methods exist to link the simulation results of power system and communication system. They are ADEVS approach [6] and EPOCHS [7] approach. Typically, most widely used network simulation software in power system studies is the OPNET [1], [4]. Other examples include OMNET++ [2] and NS2 [8]. Authors in [2] present performance of the IP network infrastructure when utilized for transmission of both continuous PMU data streams and critical intelligent electronic device (IED)/remote terminal unit (RTU) data. They have used OMNET++ to simulate the communication network and have examined the end-to-end(ETE) delay between PMUs and phasor data concentrator(PDC) in a wide area power system. Specially, [1] and [4] present the results of simulations performed using OPNET Modeler in order to determine the characteristics of

This work has been supported by Manitoba Hydro and MITACS.
Saranga Menike is with Department of Electrical and Computer Engineering, University of Manitoba, Canada (email:umediris@cc.umanitoba.ca).
Pradeepa Yahampath is with Department of Electrical and Computer Engineering, University of Manitoba, Canada (email:pradeepa@ee.umanitoba.ca).
Athula Rajapakse is with Department of Electrical and Computer Engineering, University of Manitoba, Canada (email:athula@ee.umanitoba.ca).

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communication delays in wide area monitoring and control systems (WAMCS) which use multiple PMUs distributed over a large geographic area. Such systems normally include one or several PDCs that collect and sort the data from the PMUs. Furthermore, [5] addresses the analysis of PMU systems and two communication architectures, i.e., dedicated and shared communication network scenarios. The OPNET Modeler has been used to implement and analyze the ETE delay between PMUs and PDC connected by those two communication architectures. That work specifically focus on the transmission of phasor data to the PDC and control signals from the WAMCS back to substations devices. However, as most of the stability control and protection techniques require operation of the relays within less than 0.05 ms of an event, including the delay in the communication network, off-line simulations can be incorrect, due to the fact that the integration of the results of two stand alone simulations can lead to errors in synchronization of the results [8].

The work in [9] presents an equation to calculate the communication delay between a PMU and the PDC. This equation can also be used to approximately evaluate the ETE delay between PMUs and the PDC in a particular wide area power system. The results can be subsequently imported into a power system simulation software platform such as PSCAD/EMTDC, but this calculation may not be very accurate since the aforementioned equation does not capture the randomness of the communication network.

The main effects caused by the data network on the operation of power system applications can be in the form of packet delays and packet losses. Although, it is possible to simulate pre-defined constant delays in PSCAD by using the delay component, the delays associated with the data communication network are not constant and depend on various factors in the communication network such as congestion, distance between the communication devices, the type of communication media (copper cables, fiber optic, satellite, microwave), etc. Therefore, it is important to simulate the random communication delays according to the network properties. Furthermore packet losses can occur due to traffic congestion and switch buffer overflows.

II. Overview of Simulation Tools

We have implemented a basic set of PSCAD/EMTDC blocks which enables the simulation of a TCP/IP based communication network.

A. The PSCAD Data Link Model

The PSCAD model developed in this study for the data link is shown in Fig. 1. A user can specify the cable length, the supporting data rate, the desired protocol to be used over the network (either TCP/IP or UDP/IP), the type of data link (either Ethernet or fiber optic) and the bit error rate of the link. This PSCAD model is capable of simulating the effect of the packet delay due to factors such as the cable length and the time it takes to insert all the bits in an Ethernet frame to the data link. The packet delay (T) in data link can be defined as [9]

$$T = \text{propagation delay} + \frac{L}{R}, \qquad (1)$$

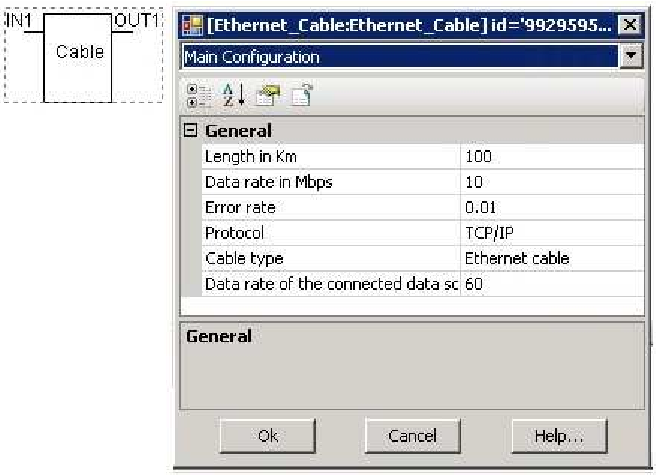

Fig. 1. PSCAD data link model.

where L is the number of bits in the frame and R is data rate. The propagation delay is defined as the delay of bits propagating between the transmitter and the receiver [10]. The propagation delay will be calculated according the distance that user specifies. The value of L can be calculated as

$$L = N_{data} + N_{TCP/IP} + N_{IP} + N_L, \qquad (2)$$

where N_{data} is the number of data message bits in a packet, $N_{TCP/IP}$ is the TCP/IP or UDP/IP header size, N_{IP} is the IP header size, and N_L is the size of the data link layer header and the trailer. This model is also capable of simulating random bit errors according to the user specified bit error rate. Fig. 2 presents details of the data link implementation in PSCAD/EMTDC.

B. The PSCAD Ethernet Switch Model

We have implemented a network switch equipped with multiple input ports and an output port. The packet delay or latency due to a switch in a communications network is defined as the time it takes for a packet to be forwarded through the switch. Switched networks have two sources of latency: 1) switch fabric processing time, 2) frame queuing [11]. While the switch fabric latency is deterministic, the queuing latency is random. Switches typically use queues to buffer the in coming packets as shown in Fig. 3, in conjunction with a store and forward mechanism to eliminate the problem of frame collisions that used to exist in broadcast Ethernet networks [12]. Queuing introduces a non-deterministic factor to the packet delay, since it can often be very difficult to predict the exact traffic patterns on a network. The data packets are stored in a buffer inside the switch. If a buffer is full, the next data packet the switch receives will be discarded, leading to a packet loss.

The PSCAD model developed in this paper for switch is shown in Fig. 4. A user can specify the buffer size and the processing time of the data packets in the buffer, i.e., switch fabric processing time. Note that this is capable of

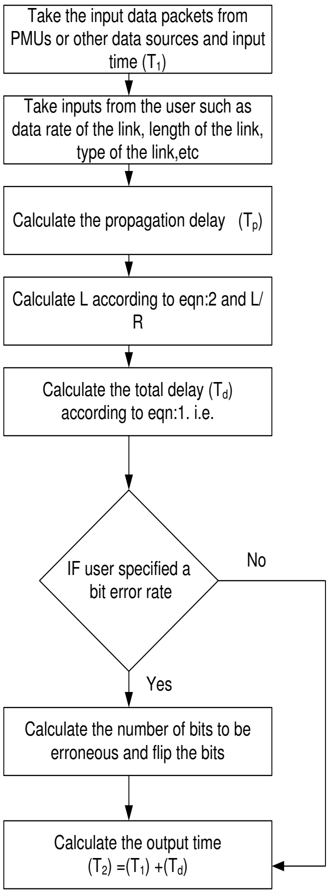

Fig. 2. PSCAD data link implementation.

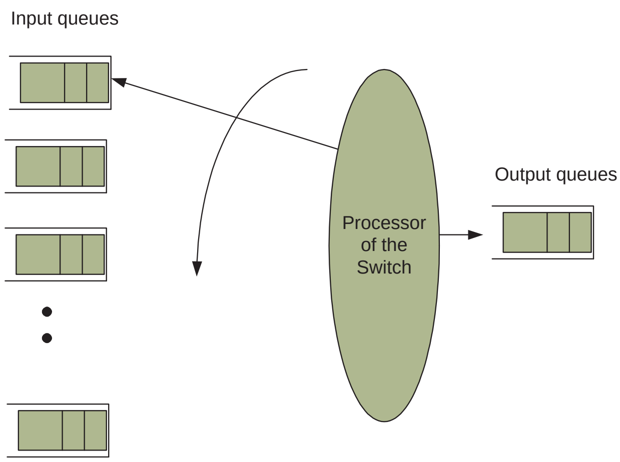

Fig. 3. Queuing model of a data switch.

simulating the delays due to the processing time, queuing in the buffer, and packet losses due to buffer overflows. Fig. 5 presents the algorithm used to implement the switch model in PSCAD/EMTDC.

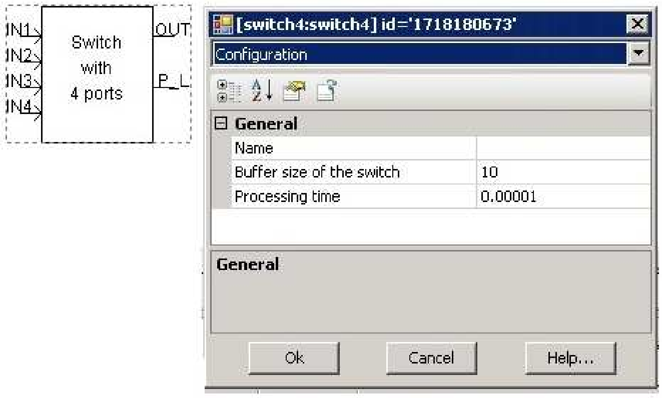

Fig. 4. PSCAD data switch model.

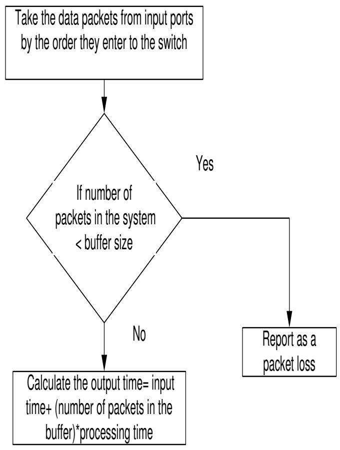

Fig. 5. PSCAD data switch implementation.

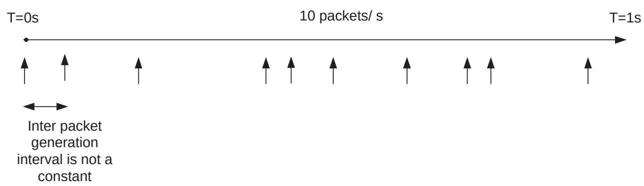

Fig. 6. Random packet generation example with $\lambda = 10$.

C. PSCAD Data Source Model

In order to be able to simulate a variety of data sources present in a power system data network we have developed a general data source. Usually, data sources other than PMUs appear in a power system application such as RTUs, video units, protective relays, and intelligent electronic devices (IED) [1]. The presence of such devices on a data network along side PMUs can have an impact on the operation of wide area power system applications. When modeling a general data source, the key parameters to be considered are the data rate of the source, length of the a data packet in bits, and a statistical model for packet generation. We have implemented both uniform and random data generation models.

1) Random Packet Generation Model: As the random packet generation model we have used the Poisson arrival process widely used in network traffic simulations. In this

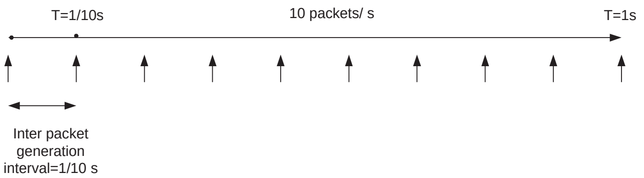

Fig. 7. Uniform packet generation. In this example data rate is 10 packets/s.

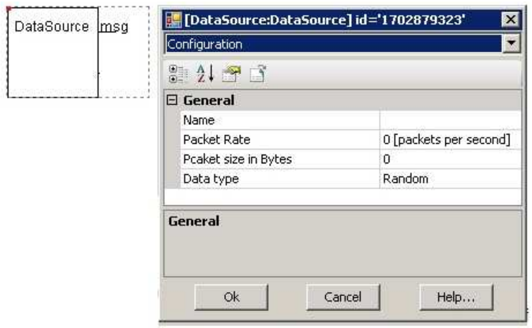

Fig. 8. PSCAD data source model.

model, the time interval between two consecutive packet follow an exponential distribution. Let $\lambda > 0$ be the rate parameter or the average rate of packets per unit of time (see Fig. 6). Then the probability density function of the inter-packet delay X, $f(x)$ is given by

$$f(x) = \lambda e^{-\lambda x}. \tag{3}$$

The cumulative density function $F(x)$ is given by

$$F(x) = 1 - e^{-\lambda x}, x \geq 0. \tag{4}$$

$$X = F^{-1}(u). \tag{5}$$

where, u is a uniform random variable between 0 and 1 [13]. Therefore, X can be written as

$$X = \frac{\text{-log u}}{\lambda}. \tag{6}$$

In our implementation, the time interval between two packets in random packet generation is thus simulated by, first generating a uniform random variable, and then applying (6).

2) Uniform Packet Generation Model: In this model the time interval between two consecutive packets is constant as shown in Fig. 7, where the user specifies the packet rate. In particular, this model is useful in simulating a PMU.

The PSCAD model for a general data source is shown in Fig. 8. In this model the user can specify the data rate, packet length, and the packet generation model (uniform or random).

In our PSCAD implementation of communication components, a critical issue that has been addressed is the synchronization of the bit-clock of the communication simulation with the time-step of the analog power system simulation. This issue arises as the data network simulation occurs at the bit level and the bit-rate in various links can be different. In order to resolve this issue we chose to implement the IEEE standard sychrophasor data packet format in [14] to simulate the data communication within PSCAD/EMTDC. Therefore the communication components developed in this

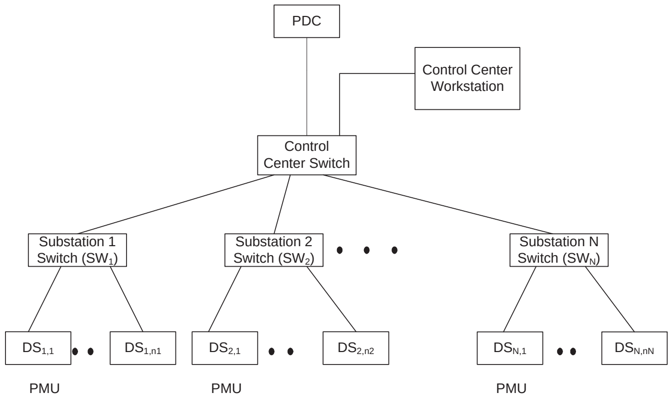

Fig. 9. Block diagram of the PMU-PDC communication system simulated in this paper.

paper accept and output data packets which confirm to this standard. We have also developed a PMU component for PSCAD/EMTDC, which is described in detail elsewhere in [15].

III. An Application Example

In this section, we present a typical application we have simulated using the PSCAD communication components described above. We have also derived analytically the network performance parameters for the purpose of comparing with simulation results. The model of the system we have considered is shown in Fig. 9. In this network model, the PMUs and other data sources such as RTUs and video units [2] are linked to a $switch$ in each substation. All substation switches are linked to the PDC and the control center workstation via a switch in the control center The control center switch routes the packets from the PMUs to the PDC while the packets from RTUs and video units are routed to the control center workstation.

All communication links within a substation are assumed to be the standard 10BASE5 Ethernet links, also known as the $thickEthernet$ with 0.1 Mbps data rate. On the other hand all the links from substation switches to the control center switch are assumed as fiber optic links with 1 Mbps data rate providing more bandwidth to the backbone communication. The number of PMUs and other data sources connected to each sub station switch is not necessarily a constant and can vary according to the application requirements. At least one PMU is connected to each substation switch. Let the number of substation switches in the network be N. Since the PMUs typically generate data at a constant rate [5], it is assumed that inter-arrival time of packets from a PMU is constant. On the other hand, the inter-arrival times of packets from other two data sources are assumed to be random. It is also assumed that all substation switches have an identical buffer size of B packets, i.e., a switch can keep a maximum of B data packets, including the one being served. In the following, we derive analytical expressions for the end-to-end packet loss probability and delay in the system shown in Fig. 9.

In [16], we have derived analytical expressions for the end-to-end packet loss probability and delay in the system shown

TABLE I

PSCAD/EMTDC SIMULATION RESULTS FOR SW_1. D=100 KM.

	Total Delay T (ms)		
	B=8	B=10	B=15
PMU	1.211	1.213	1.2169
RTU	6.028	6.0314	6.0423
Video Unit	9.2044	9.2049	9.2067

in Fig. 9. The PMU-PDC communication network has been modeled as a cyclic polling system and the associated Markov chain has been set up. Based on this model, it has been shown that the packet loss probability of the i^{th} substation switch in Fig. 9 can be given by

$$P_{L_i} = X_{i,B} \sum_{j=1}^{n_i} D_{i,j}, \quad (7)$$

and the queuing delay of the j^{th} data source connected to i^{th} substation switch is

$$W_{q_{(i,j)}} = \frac{\sum_{u=1}^{B} (u-1) X_{i,u}}{(1 - P_{L_i})(\lambda a_{i,j})}, \quad (8)$$

where, B is the buffer size of the switch, n_i is the number of data sources connected to i^{th} substation switch, $a_{i,j}$ is the packet arrival probability of the j^{th} data source connected to i^{th} substation switch, $D_{i,j}$ is the probability of arriving packets as batches with size of j for the i^{th} substation switch and $X_{i,u}$ is the u^{th} state of the transition matrix for the i^{th} substation switch [16].

IV. NUMERICAL RESULTS

In order to evaluate the PSCAD/EMTDC communication components developed in this paper numerically, we have used $N = 3$ (SW_1, SW_2, and SW_3), $n_1 = 3$ (1 PMU, 1 RTU and 1 video unit), $n_2 = 2$, (1 PMU and 1 RTU), $n_3 = 4$, (2 PMUs, 1 RTU and 1 video unit) and $B = 8, 10, 15$ as the system parameters to represent the PMU-PDC communication network. Ethernet frame size L for PMU, RTU and video unit is taken as 100 bytes, 700 bytes and 1100 bytes respectively [2]. In this paper, we assume a standard PMU data rate of 60 packets/s [14]. RTU data rate and video unit data rate are assumed as 30 packets/s and 200 packets/s respectively [2]. In this section, we present numerical results for packet loss probability, queuing delay T_q, and total communication delay T of each data source connected to three substation switches SW_1, SW_2, and SW_3. The total communication delay between each data source and control center is the delay due to the data link, queuing in the substation switch and the control center switch. On the other hand, using the analytical method presented in [16], we calculated the queuing delay and packet loss probability for the same network used to take the simulation results in PSCAD/EMTDC in order to verify the accuracy of the communication components. Table I, II and III presents the total communication delay for each data source connected to each substation switch for three buffer sizes.

Table I presents the total delay corresponding to 3 data sources connected to the SW_1, for three buffer sizes, where D is the distance between the data sources and the control center. It is important to notice that video unit and RTU has a higher total delay compared to PMUs. The reason for this is that the Ethernet frame size for video unit and RTU are high compared to the PMU data frame size and therefore the frames with more bits take more time to travel through the communication network. Similarly, Table II and Table III present the total delay for data sources connected to SW_2 and SW_3 respectively.

TABLE II

PSCAD/EMTDC SIMULATION RESULTS FOR SW_2. D=200 KM.

	Total Delay T (ms)		
	B=8	B=10	B=15
PMU	1.6032	1.6043	1.6071
RTU	6.4065	6.4086	6.4144

TABLE III

PSCAD/EMTDC SIMULATION RESULTS FOR SW_3. D=325 KM.

	Total Delay T (ms)		
	B=8	B=10	B=15
PMU	2.1122	2.1160	2.1272
PMU	2.1122	2.1160	2.1272
RTU	6.926	6.9342	6.9579
Video Unit	10.1037	10.1049	10.1082

TABLE IV

COMPARISON OF SIMULATION RESULTS AND RESULTS TAKEN FROM ANALYTICAL METHOD FOR PACKET LOSS PROBABILITY.

	PSCAD Simulation			Analytical Method		
	B=8	B=10	B=15	B=8	B=10	B=15
SW_1	0.087	0.0771	0.063	0.0872	0.077	0.0629
SW_2	0.0851	0.0742	0.059	0.085	0.0741	0.059
SW_3	0.0897	0.0799	0.0675	0.0896	0.0798	0.067

In order to verify the accuracy of the PSCAD components developed in this paper, we next compare the network performance parameters calculated from our analytical model against those estimated by PSCAD simulations as shown in Table IV and V. According to Table IV, it is clear that if the number of PMUs connected to a substation is large, the packet loss probability increases. For example, SW_2 has only 2 data sources connected to it and therefore it has the lowest packet loss probability, while SW_3 with 4 data sources has the highest packet loss probability. Also, in order to present the effect of buffer size on the packet loss probability, we have also considered three buffer sizes in Table IV. For example, note that increasing the buffer size leads to a decrease in packet-loss probability. The comparison with analytically obtained values shows that the simulation models predict the impact of buffer size on the packet loss probability accurately.

As illustrated in Table V, queuing delay increases with the buffer size. When the buffer size is large, it gives more room for data packets and as a result, eventually the queuing delay increases. Also it is clearly noticeable that a small buffer size allows a smaller number of packets to be served, so that the queuing delay is less compared to higher buffer sizes, but packet losses will be higher.

V. CONCLUSIONS

We have presented an implementation of a basic set of flexible communication network components which can be used to realistically simulate WAMPaCS in PSCAD/EMTDC

TABLE V

COMPARISON OF SIMULATION RESULTS AND RESULTS TAKEN FROM ANALYTICAL METHOD FOR QUEUING DELAY IN μs.

	PSCAD Simulation			Analytical Method		
	B=8	B=10	B=15	B=8	B=10	B=15
PMU in SW_1	11.20	12.55	17.90	11.1519	12.5317	16.8433
PMU in SW_2	3.193	4.19	6.99	3.1417	4.1844	6.9781
PMU in SW_3	13.19	15.08	18.201	13.1998	15.0301	18.1934

simulation environment. We have also presented an application example which has been used to verify the accuracy of the communications network simulations based on our PSCAD components. It has been shown that the packet loss probabilities and communication delays predicted by the simulations closely agree with analytically calculated values. The PSCAD tools developed in this paper provide a starting point for further developing an extensive library of communication components which can be used to study the impact of the network architecture, the number of network traffic sources, and the link capacities on the the reliability of the WAMPaCS operation via the co-simulation of the power system and a communication network that overlays it.

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