Introduction of the proposed Simulink-based platform

The details of the Simulink-based platform are detailed here. The total framework is shown in Fig. 1.

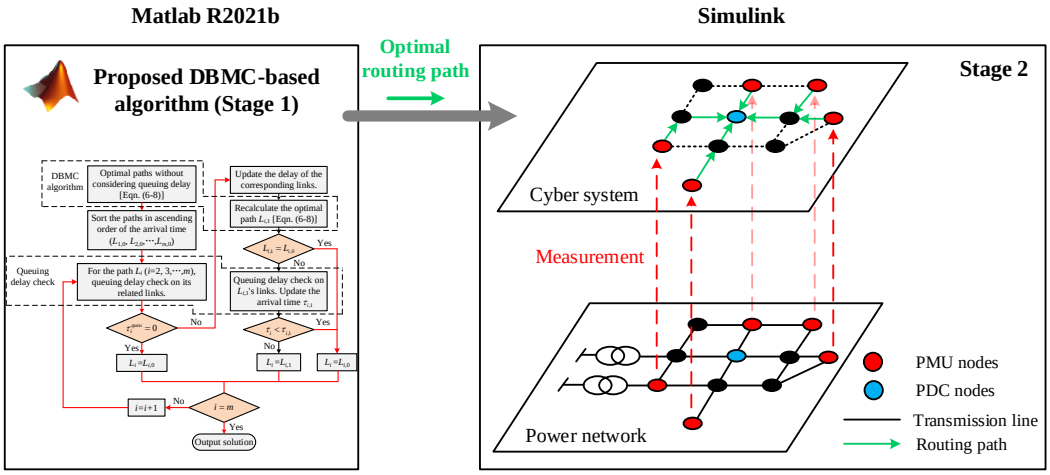


Fig. 1. The designed framework in the manuscript

In Fig. 1, the proposed DBMC-based algorithm is implemented in Matlab R2021b. The related process, including ***the PMU data sending***, ***the ETE delay suffered by the data of PMUs to the PDC***, and ***the data reception of PDC***, is emulated in the Simulink platform. The details of the simulation platform are as follows:

1. The PMU models (*The PMU data sending*)

The Entity Generator block is used to emulate the process of PMU sending data periodically by generating periodic signals. 1) Its generating rate is consistent with that of the PMU, which is set to 30 milliseconds in this paper. 2) The ETE delay (without the queuing delay) suffered on each link along the path is set in this block, which will be recognized by the link it transferred. The logo of ***the Entity Generator block*** is given in Fig. 2.

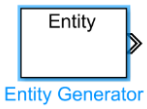


Fig. 2. The logo of the Entity Generator block

2. The PDC models (The data reception of PDC)

The Entity Terminator block is applied to emulate the data reception process the PDC. By selecting the option "Number of entities arrived, a" and add a ***Scope*** in this port, the arrival time of each PMU data can be recorded, that is, the ETE delay that they experienced. Then, the data arrival rate under a given PDC waiting time can be obtained. The logo of ***the Entity Terminator block*** is given in Fig. 3.

Fig. 3. The logo of the Entity Terminator block

3. The links models (The transmission and propagation delay suffered by the data of PMUs to the PDC)

The links of each path is modeled by ***the Entity Server block***. Each Entity Server block corresponds a specific link. As mentioned in ***the Entity Generator block***, the ETE delay (without the queueing delay) suffered on each link will be performed by ***the Entity Server blocks***. "1" refers to the capacity of the link, which means it cannot transfer multiple data at the same time. The logo of ***the Entity Server blocks*** is given in Fig. 4.

Fig. 4. The logo of the Entity Server block

4. The queueing models (The queuing delay suffered by the data of PMUs to the PDC)

In our manuscript, the queuing mechanism selects the First-in-First-out (FIFO). Therefore, ***the FIFO Entity Queue block*** in the Simulink is considered. By selecting the option "Number of entities in block, n" and add a ***Scope*** in this port, the arrival and leaving time in this block of each PMU data can be recorded. That is, the queuing time suffered on this link of each PMU data is obtained. The logo of ***the FIFO Entity Queue block*** is given in Fig. 5.

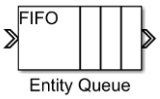
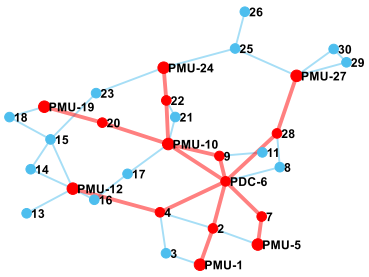
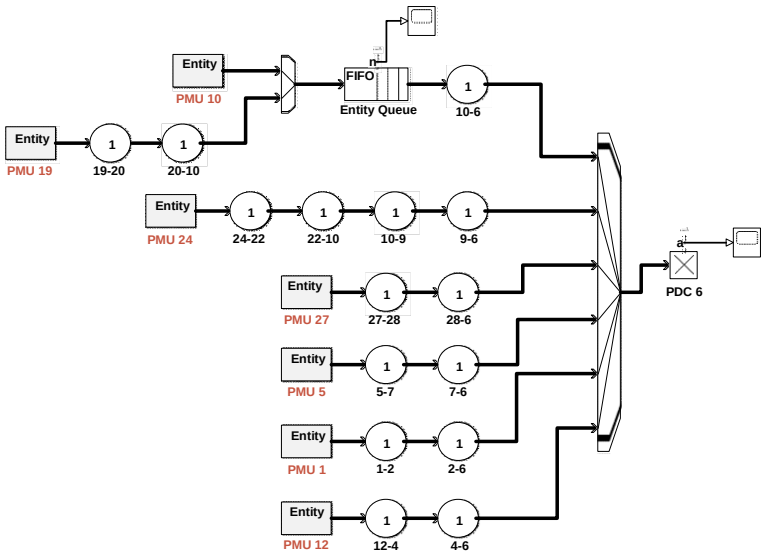


Fig. 5. The logo of the FIFO Entity Queue block

By now, all the elements related with the cyber system are listed in the Simulink. Take the IEEE-30 bus system in our case study as an example. The node 6 is selected as the optimal PDC placement. The corresponding paths connecting PMUs and the PDC is given as:



(a) The paths connecting each PMU and the PDC 6 in IEEE-30 bus system



(b) The establishment of the paths connecting PMUs and the PDC in Simulink

Fig. 6. The optimal paths planning in IEEE-30 bus system

In Fig. 6 (a), the established paths topology in Simulink is consistent with that in Fig. 6 (b). **Note that the path construction process in Simulink is automatically formulated by the procedure coding in Matlab 2021b.** Meanwhile, the oscilloscope added at the FIFO and PDC are to read the information on the number of data waiting in the FIFO and the number of data arriving at the PDC.

In the Simulink platform, the simulation duration is set to 30 milliseconds, that is, one data sending cycles. The arrival time of PMU data (i.e., the ETE delay suffered by each PMU data) received by the PDC obtained in Simulink and our algorithm are shown in Figure 7 and Table I.

TABLE A-I

THE DATA ARRIVAL TIME OF EACH PMU DATA TO THE PDC

PMU	Data arrival time (*ms*)	PMU	Data arrival time (*ms*)
10	3.91	1	7.29
27	6.87	19	10.44
5	7.20	24	13.51
12	7.26		

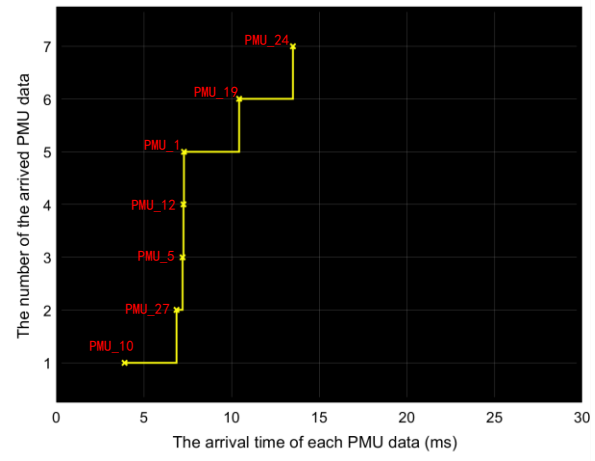


Fig. 7. The data arrival time of each PMU data obtained in Simulink

In Fig 7, it can be found that the data arrival time obtained from the proposed method is consistent with the results generated by the Simulink, which verifies the effectiveness of the proposed method.

Also, by checking *the number of entities in block* of the FIFO module, the queuing delay experienced by the PMU data on links can be determined. In this case, the data of PMU 10 and 19 experience the same link (10, 6). The number of entities in block of the FIFO module corresponding to this link is exported in Fig. 8.

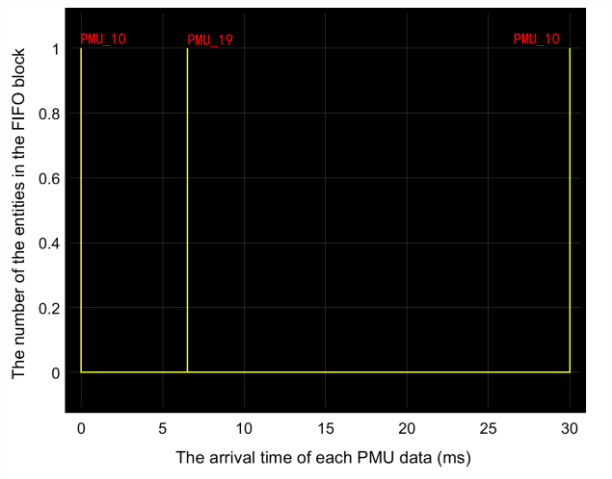


Fig. 8. The number of the entities in the FIFO blocks

In the first period, it can be seen that the data of PMU 10 arrives first, then it leaves immediately. After about 6.5 *ms*, the data of PMU 19 arrives. Since the first arrived data has already passed through the link (10, 6) at this time, the data also does not experience queuing delay.