Toward Intelligent Machine-to-Machine Communications in Smart Grid

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ABSTRACT

The advanced metering infrastructure of the smart grid presents the biggest growth potential in the machine-to-machine market today. Spurred by recent advances in M2M technologies, SG smart meters are expected not to require human intervention in characterizing power requirements and energy distribution. However, there are many challenges in the design of the SG communications network whereby the electrical appliances and smart meters are able to exchange information pertaining to varying power requirements. Furthermore, different types of M2M gateways are required at different points (e.g., at home, in the building, at the neighborhood, and so forth) of the SG communication network. This article surveys a number of existing communication technologies that can be adopted for M2M communication in SG. Among these, the most reliable technology to facilitate M2M communication in the SG home area network is pointed out, and its shortcoming is also noted. Furthermore, a possible solution to deal with this shortcoming to improve SG communications scalability is also presented.

INTRODUCTION

This decade is widely predicted to see the rise of machine-to-machine (M2M) communications over wired and wireless links. For instance, researchers predict that by 2014 there will be 1.5 billion wirelessly connected devices that are not mobile phones and do not require any human intervention. This will lead to an unprecendented increase in data traffic involving machines communicating with other machines without human interaction. Various applications of M2M have already started to emerge in various sectors such as healthcare, vehicular, smart home technologies, and so forth. The evolution of M2M has also begun in developing a smart power grid framework, referred to as the smart grid (SG). An electric grid having smart capability allows the power providers, distributors, and consumers to maintain near-real-time awareness of one another's operating requirements and capabilities. Through this awareness, SG is able to produce, distribute, and consume power in the most efficient and intelligent way. This type of communication takes place only among machines such as sensors, smart meters, and other equipment. Indeed, the M2M communication in SG must be private and secure since many of the autonomic functions that will run over it will be critical. SG will have numerous electrical appliances connected to one another in a complex manner so that they can report back on elements such as power consumption and other monitoring signals. This promises higher efficiency in the power distribution networks (i.e., greater availability of power to homes and factories at lower cost), and will allow distributed power generation such as local solar and wind generators. It will reach into home-based devices, which is why scalability and fast communication is crucial for practical deployment of SG.

To facilitate effective SG communication, existing networking technologies must be taken into account to deal with the multiple services and quality requirements of residential appliances. The need to differentiate high- and low-priority traffic will be just as important as being able to dynamically adapt the network to varying capacity requirements in real time. Therefore, it is essential that we consider appropriate technologies to implement the communication networks of SG, which may allow the flexible use of existing capacities without impacting the service quality of the SG.

Today's network infrastructure, largely based on synchronous optical network (SONET) and synchronous digital hierarchy (SDH) technologies, cannot physically or economically support the ever changing demands caused by the overwhelming increase in bandwidth, transport of IP traffic, and the need for more flexible connectivity, higher resiliency, and network automation. To address this concern and remain competitive, service providers have been investing heavily in building next-generation networks. Indeed, it is important to review how existing communication technologies such as IEEE802.11 (WiFi),

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IEEE802.15.4 (ZigBee), Bluetooth, and so on respond to the bandwidth and delay requirements of theM2M communication of SG. In this article, we provide a detailed M2M communication model for SG and verify the effectiveness of different adopted communication technologies. This article points out the shortcomings of the conventional networking technologies that may be adopted for SG M2M communications. We also investigate incorporating a level of intelligence in the smart meters so that we may be able to deal with such shortcomings and improve SG communications.

The remainder of this article is organized as follows. We discuss relevant research work. Next, we describe our considered M2M communication model for SG. We then describe SG communication requirements and compare some existing communication technologies to find the most reliable one for SG M2M communication. We highlight the limitations of this conventional communication technique and provide directions toward implementing intelligent smart meters to deal with this problem. Finally, we conclude the article with some future directions.

Related Research Work

Three task forces have been created for IEEE P2030 SG standards. These three task forces are dedicated to standardization of power engineering, information, and communications technologies, respectively [1]. The policies laid out by the communications technology work group are broad in nature and should be considered design directives for choosing a suitable communication protocol in SG M2M communications. Recently, a Verizon Wireless and Qualcomm joint venture has focused on smart services enabled by M2M capabilities. This project envisions SG technology enabling utilities to wirelessly connect to their grid assets, such as circuit breakers, transformers, and other substation equipment, allowing them to develop more interactive utility networks. Analysts predict that the M2M market will have more than 85 million connections globally by 2012 [2]. The work in [3] explored M2M communication applications and scenarios, which are growing and leading the way to new business cases. The work revealed the practical requirements and threats of M2M application scenarios, and pointed out two main aspects, the unpredictable connectivity to the core network, and the demand for high configurability and flexibility of M2M devices. While this work attempted to identify security threats against M2M communications, the exact technologies on which M2M communications are based were not taken into account. Ullo *et al.* [4] analyzed the main performances of IEEE 802.15.4-based wireless sensor networks (WSNs) in order to evaluate their applicability in supporting the functionalities of SG. Their research showed that WSN-based communications services exhibit reliable network services and may be of particular use in several SG applications. However, they did not investigate the exact SG applications that may benefit from the deployment of such WSNs in SG home area/automation networks. On the other hand, various challenges in the design of the home M2M network are presented in [5]. This work shows that home networks are expected to require effective M2M gateways to facilitate communication among the various M2M devices and provide a connection to a backhaul (e.g., the core communication network of SG). While the backhaul connection may be fiber, cable, digital subscriber line (DSL), Ethernet, or even cellular, the authors suggest that it is also important to choose appropriate network protocols to enable M2M devices to communicate inside a home environment. Among the available technologies to serve as the embodiment of the home area network, this work investigates IEEE 802.15.4 (ZigBee/6LoWPAN), IEEE 802.11 (WiFi), and Bluetooth protocols. However, the work did not take into account the impact of choosing these technologies in the specific case of SG M2M communications in the home area network. We base our article on investigating the appropriate M2M communications technology for the residential networks belonging to a typical SG.

Considered Architecture for SG Communications

Figure 1 shows our considered SG communication architecture. In this considered architecture, the SG power transmission and distribution system is separated from the communication system. For the sake of clarity, let us first briefly describe the power distribution network (DN). Power is delivered from the power plant to end users through two components, the transmission substation (TS) located near the power plant and a number of distribution substations (DSs). The TS delivers power from the power plant over high voltage transmission lines (generally over 230 kV) to DSs. DSs, on the other hand, are placed in different regions and are responsible for converting the electric power to medium voltage levels. DSs then distribute this medium-voltage-level power to building feeders. To make it usable by consumers, the building feeders have to convert the medium voltage level to a lower level.

For communications, however, the above consideration may not be applicable since communications links have different requirements than those of power lines. The TS and the control centers (CCs) of the DSs are connected to one another in a meshed network, which can be built over optical fiber technology. Next, the rest of the considered SG communication topology is divided into a number of networks that feature real-life setups of a city or metropolitan area. Broadly speaking, a city has many neighborhoods, each neighborhood has many buildings, and each building may have a number of apartments. We derive our SG communication architecture from this real-life planning of a metropolitan area, described next.

The communication architecture for the lower distribution network (i.e., from CCs onward) is divided into a number of hierarchical networks: the neighborhood area network (NAN), building area network (BAN), and home area network (HAN). For simplicity, each DS is considered to

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The BAN smart meter/GW is typically set up at the building's power feeder. The BAN GW can be used to monitor the power need and usage of the residents of the corresponding building. In order to facilitate BAN-HANs communication, 3G may be used to cover more areas.

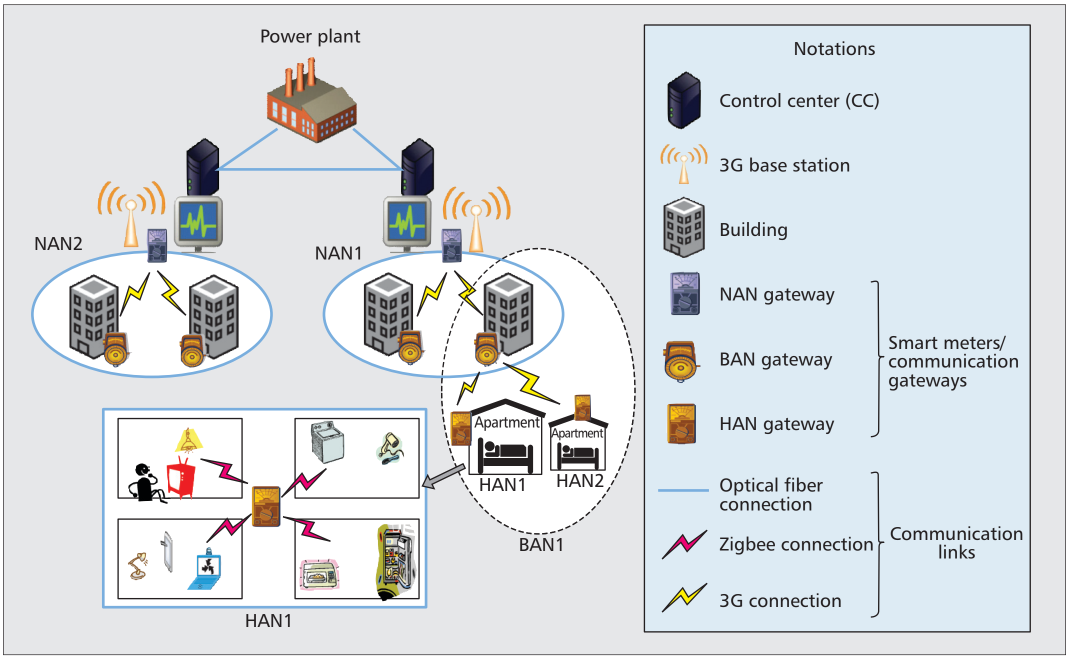

Figure 1. *Considered SG communications architecture.*

cover only one neighborhood zone. Each NAN can be considered to be composed of a number of BANs. On the other hand, every BAN contains a number of apartments. In Fig. 1 the apartments are shown to have their respective LANs, each of which is referred to as a HAN. In addition, there are advanced meters called smart meters deployed in the SG architecture that represent advanced metering infrastructure (AMI) for enabling automated two-way communication between the utility meter and the utility provider. Smart meters are equipped with two interfaces: the power reading and communication gateway (GW) interfaces. The smart meters used in NANs, BANs, and HANs are referred to as NAN GWs, BAN GWs, and HAN GWs, respectively. In addition, it is also worth mentioning that based on the existing standards of SG, IP-based communications networking is preferred, which permits virtually effortless interconnections with HANs, BANs, and NANs. Below, we describe the SG communication networks.

Neighborhood Area Network

A NAN is a localized or regional network of the considered SG communication topology. A NAN comprises one or more third-generation (3G) base stations and a number of BANs. It is worth noting that the 3G framework used for SG communications should be separated from the existing ones used for providing other services such as the Internet. This should be done in order to prevent network congestion. Also, this way it is possible to avoid security threats arising from the Internet that may have an impact on delay-sensitive SG communications. It should also be noted that other modes of communications apart from 3G may be alternative solutions for this purpose. The NAN GW can monitor how much power is being distributed to a particular neighborhood by the corresponding CC at the DS.

Building Area Network

Every building connected to the smart power grid maintains its own BAN. A BAN consists of a number of apartments having HANs. The BAN smart meter/GW is typically set up at the building's power feeder. The BAN GW can be used to monitor the power need and usage of the residents of the corresponding building. In order to facilitate BAN-HANs communication, 3G may be used to cover more areas.

Home Area Network

A HAN is a subsystem within the SG dedicated to effectively manage the on-demand power requirements of the end-users. For example, *HAN1* in Fig. 1 connects the equipments (e.g., television, washing machine, oven, and so forth) in the end user's apartment to a HAN GW, which, in turn, communicates with *BAN1*. Indeed, the HAN GWs are the ones that facilitate M2M communications in the SG framework. In other words, the HAN GW of a residence communicates with the electrical appliances of that residence that features as M2M communication. In the next section, we investigate the existing SG M2M network protocols and compare their performances.

Toward Effective SG Communication

In the beginning of this section, we investigate the communication requirements for SG. Then, we survey a number of available network technologies that can facilitate M2M communication by fulfilling these requirements. We then present the best possible technology to be adopted for SG M2M communication, and also propose a simple enhancement to the existing technology to increase the effectiveness of the communication system.

SG Communication Requirements

SG communication depends on two important requirements [6], communication latency and large volume of messages. If the CC misses any input from a HAN GW, this may affect the decision made by the CC that may be important. If congestion occurs at the BAN GW, the packet may be delayed to be sent to the NAN GW and CC. Furthermore, it may also be dropped if the memory of the HAN GW becomes full due to multiple messages arriving from different M2M devices at the same time and limited processing capability of the HAN GWs. If this is the case, the HAN GW may request the M2M device to retransmit the required packets. This also contributes to increased communication latency. While the overall SG communication latency in the order of a few miliseconds as depicted in the work in [6, 7] may not be practically achievable in large-scale SGs, focus should be given towards reducing the communication latency as much as possible starting from the HAN level.

Hauser et al. [6] also suggests that the SG communication network should be able to accommodate more messages simultaneously without any major impact on communication latency. The large volume of messages in SG communication will affect the bandwidth required. Therefore, it is important to take into account if it is possible to reduce the number of messages received from many M2M devices at each HAN GW so that the total number of messages generated in the whole building does not overwhelm the BAN GW.

M2M Network Technologies for HAN

To meet the above requirements of SG communications, several short and medium range wireless technologies emerged in the recent past. The electric appliances found in a HAN represent the M2M devices. In order to choose an appropriate M2M network protocol in SG HANs, we need to take into account the features of M2M devices in terms of low power consumption. A number of low-power and low-cost technologies have evolved to present themselves as enablers of SG M2M communications. Among these, the prominent technologies include Bluetooth, IEEE 802.11 (WiFi), ultra wideband (UWB), IEEE 802.15.4 ZigBee, 6LoWPAN, and so forth. The major network technologies that can be adopted for HAN communications are presented below.

IEEE 802.15.3a — UWB communications evolved for a number of applications that belong to two major types. The first type of application is for high-data-rate communications (typically over 1 Mb/s) such as high definition television transmission. The other type of application is for data rates below 1 Mb/s (e.g., sensor networks), which can also employ UWB technology for communications. The M2M devices in a HAN that can be considered as sensors may use UWB technology. However, the shortcoming of this technology lies in its high power requirements. Also, after several years of deadlock, the IEEE 802.15.3a task group was dissolved in 2006. Therefore, further support for UWB may not be possible in the future if UWB is selected as the communication technology in the SG HAN.

IEEE 802.11 — The IEEE 802.11 protocol, commonly referred to as WiFi, is suited for higher-data-rate applications over larger areas. WiFi is by far the most accepted protocol for wireless in-home communications. WiFi enjoys an enormous infrastructure for residences and support for IPv6 addressing. The main shortcoming of this technology is similar to that of UWB: the high power requirement of devices using WiFi. As a consequence, WiFi is considered impractical for SG M2M communications.

IEEE 802.15.1 — The Bluetooth protocol has become popular for wireless connections for voice, data, and audio applications over short range. The Bluetooth protocol stack supports IP addressing and therefore can be adopted in SG HAN communication. The Bluetooth protocol is well suited for low-power/low-data-rate applications. However, Bluetooth works well in peer-to-peer communications over a short distance. Furthermore, Bluetooth networks or "piconets" support up to only eight devices communicating simultaneously. To provide scalability among M2M devices using Bluetooth, a HAN therefore will require a number of piconets (each consisting of eight M2M devices). Each piconet has a master M2M device, and the piconets are able to communicate with one another via their master devices. This, however, leads to increased communication latency. Another shortcoming of Bluetooth is its periodical waking up and synchronization with the master device of the piconet. A Bluetooth device may consume approximately 3 s to wake up prior to synchronization.

IEEE 802.15.4 — ZigBee is a protocol is employed in many home networking solutions including HANs. ZigBee was developed particularly for wireless devices, ensuring low power and long life time. The ZigBee network layer allows for a cluster tree, self-healing mesh network, or star topology, whereby the HAN GW and M2M devices can be configured flexibly. Furthermore, ZigBee devices may take only milliseconds to exit their sleep states compared to Bluetooth or WiFi devices. In addition, a ZigBee device using carrier sense multiple access with collision avoidance (CSMA/CA) does not require scheduling special wake-up events in order to communicate and maintain synchronization with the HAN GW. Thus, ZigBee presents itself as a much better candidate (for SG M2M communication in the HAN) than UWB, WiFi, and Bluetooth.

In Fig. 2 [8], the power consumption for each of the aforementioned protocols to be adopted for communication in an SG HAN is shown. As evident from this graph, the Bluetooth and ZigBee protocols consume less power (for both transmission and reception) than WiFi and UWB technologies. Furthermore, from our earlier explanation, ZigBee is a superior technology for HAN communication ito BlueTooth. Therefore, we adopt Smart Energy Profile (SEP) Version 1.5 as the communication protocol in HANs that employ ZigBee radio communications. We

A number of low power and low cost technologies have evolved to present themselves as enablers of SG M2M communications. Among these, the prominent technologies include Bluetooth, IEEE 802.11 (WiFi), UltraWideBand (UWB), IEEE802.15.4 ZigBee, 6LoWPAN, and so forth.

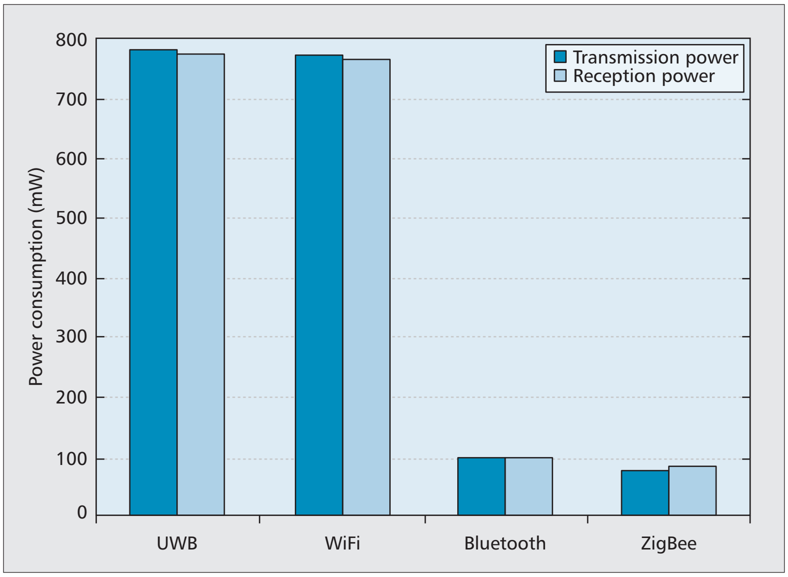

Figure 2. *Comparison of power consumption in case of different existing communication technologies adopted in SG home area network.*

choose IEEE 802.15.4 ZigBee instead of other wireless solutions due to its low power requirements, and simple network configuration and management. Indeed, ZigBee provides a decent communication range of 10–100 m while maintaining significantly low power (1–100 mW) and thereby lower cost.

ENVISIONED IMPROVEMENT TO HAN COMMUNICATIONS BASED ON ZIGBEE

As the HAN technology matures, the HAN GW should be able to intelligently manage the power concerns of the entire home network. In a conventional HAN, if the M2M devices always attempt to send their periodic messages to the HAN GW, the HAN GW is expected to receive a relatively high number of messages. Given the limited processing capability and low memory of the HAN GW, it is better if the M2M devices are designed to transmit their power requirements in a more efficient manner. Towards this end, we propose a simple yet effective solution. Let us assume that an M2M device denoted M_i transmits its power requirement messages to its HAN GW every δ time interval in the conventional way. Now, let us assume that the power requirements of M_i remain the same in δ_t and δ_{t+1}. In this situation, we propose that M_i does not require to transmit its power requirement message to the HAN GW at δ_{t+1}. In other words, M_i remains in silent mode unless its power requirement changes. Meanwhile, as the HAN GW is not receiving any periodic request from M_i, it initiates a substantially long timer, T_i, within which the HAN GW assumes M_i to be in silent mode. During T_i, the HAN GW will expect the same power requirement from M_i. Upon expiration of T_i, the HAN GW will send a beacon to M_i to be notified about its power requirements. Indeed, we expect that all the M2M devices in a HAN will not change their power requirements frequently and/or abruptly. Thus, by incorporating this type of granular-level intelligence about the status of M2M devices, the HAN GW is not overwhelmed much by incoming requests from many M2M devices at the same time.

Here, we illustrate how our envisioned approach improves the performance of the ZigBee protocol dedicated for SG HAN through a simple scenario. In this scenario, a ZigBee network is considered for the sake of comparison between our approach using silent mode and the conventional approach. We consider 100 electrical appliances in a residence that are connected with a smart meter acting as the HAN GW over ZigBee. The packet delivery ratio in the HAN GW is considered as a performance metric. We consider the simulation environment described in [9] whereby the link bit error rate (BER) is varied from 10.6 to 10.5, and the statistical packet error rate (PER) is assumed to be 0.2 percent. Each M2M deviceis considered to have a transmission range of 9 m. ZigBee operates in the 2.4 GHz ISM band at a rate of 250 kb/s. We also consider that the devices have the same power requirements during an average time period of 1 s. Each M2M device is assumed to send periodic messages following a Poisson distribution. The message transmission rate and packet size are set to 10 packets/s and 90 bytes, respectively. As shown in Fig. 3, by varying the number of active appliances at the residence from 10 to 100, the proposed intelligent approach achieves a much better packet delivery ratio even with the increase in the number of devices inside the HAN. On the other hand, the packet delivery ratio in the conventional approach decreases quickly as more active devices are included in the system. For instance, when all 100 M2M devices are active, the packet delivery ratio for the intelligent system is 88 percent, while in the conventional one its value is approximately 55 percent. Figure 3 indicates that the incorporation of intelligence using the proposed technique improves the performance of ZigBee-based communication in the SG HAN.

CONCLUSION

While we expect smart power grids to continue to evolve in the next decade, it is necessary to consider the most robust and reliable technology to facilitate M2M communication in home area networks. In this article, we highlight the infrastructure of a smart grid and describe the major technologies available today for enabling smart grid home area communication. We stressed choosing ZigBee for the enabler of M2M communication in smart grid environments as it performs far better than other communication technologies such as UWB, WiFi, and Bluetooth. It should be stressed, however, that the described M2M communication in the smart grid takes place within the considered home area network, and the communications between the other entities (i.e., between home and building area networks, and between building and neighborhood area networks) are for data forwarding only. In other words, M2M communication is not occurring in the latter entities in the presented SG model. In addition, we present a technique to improve the performance of conventional ZigBee-based M2M communications in SG by incorporating intelligence in the smart meter and M2M devices of the HAN. In the future, the issue of the coexistence of different M2M communication technologies may require adequate attention.

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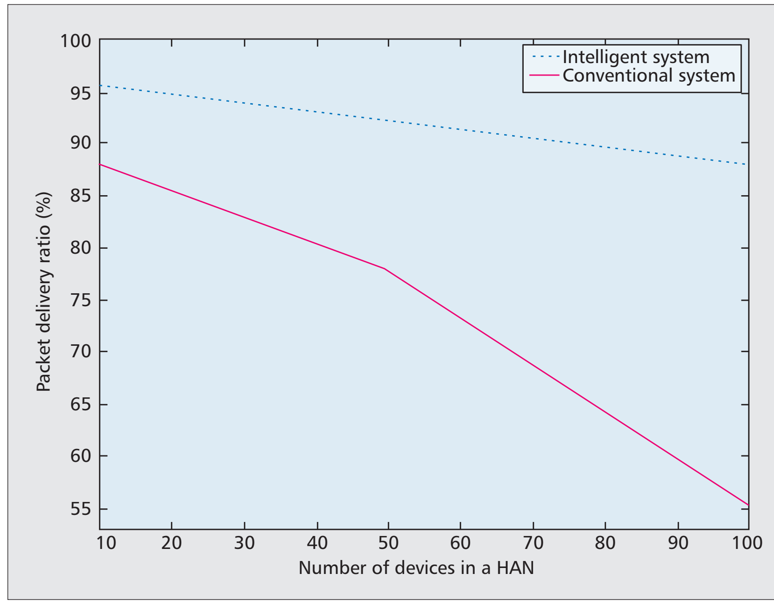

Figure 3. *Comparison of packet delivery ratio for the conventional and the improved (i.e., intelligent) systems based on ZigBee.*

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