Performance Comparison of IP and CCN as a Communication Infrastructure for Smart Grid

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***Abstract*—The infrastructure for smart grid is classified into three categories: infrastructure for electric power generation, delivery, and consumption, infrastructure for information measurement, surveillance, and management, and infrastructure for information communication. In this paper, we derive the total amount of traffic in the network, average end-to-end communication delay, and availability when using IP and CCN (Content-Centric Networking) as the communication infrastructure for a smart grid, respectively. Through several numerical examples, we clarify under what conditions either IP or CCN is suitable for the communication infrastructure of a smart grid. We found that, in terms of the total amount of traffic and the average end-to-end communication delay, CCN is effective compared with IP except when cache hit rates in RGCC (Remote Grid Control Center) and LGCC (Local Grid Control Center) are very low. We also found that, in terms of availability, the performance advantage of CCN over IP is marginal.**

I. INTRODUCTION

Smart grid is an electric power network that utilizes the communication and control functions of smart meters and enables to achieve a diversity of electricity contract or cost reduction, in addition to the electric outrage prevention and the electric transmission conditioning [1]. A smart meter is a device that is installed as a replacement of a conventional electric meter and transfers the information of consumed power at home or in a company to the electricity company in real-time. One of the purposes for smart grid is to reduce the wasteful electric generation. By generating electric power equivalent to the current electric demand based on the real-time information from smart meters, the reduction of wasteful electric generation is expected.

The infrastructure for smart grid is classified into three types as the one for generating electricity, delivery and consumption, the next for the measurement of the information, monitoring and management, and the infrastructure for the information and telecommunication [1].

In the past, communication technologies for control systems and switching systems such as PLC (Power-Line Communication) and DSL (Digital Subscriber Line) were widely used for the communications infrastructure for smart grid [2]. Recent years, the hardware and software with sophistication, high functionality and lower price raise expectations that communication technologies for information systems represented by the Internet, Ethernet and wireless LAN will be used for the communication infrastructure for smart grid.

The network architecture is categorized into two types as the host-centric type like IP (Internet Protocol) [3] and the data-centric type like CCN (Content-Centric Networking) [4]. IP is the communication protocol for the Internet and one of the network architectures based on hosts that perform communication. IP provides the virtual communication link between end hosts. On the contrary, CCN is one of the network architectures based on data that are transferred in the network. CCN employs a request-and-response communication model. CCN doesn't provide the virtual communication link between end hosts, but it searches the contents requested by an end host in the network and returns the relevant contents to the end host.

The basic requirements and the realization methods of the infrastructure for smart grid have been actively discussed [1], [2], [5]–[9]. In [1], as the requirements of the communication infrastructure for smart grid, provision of QoS (Quality of Service), high reliability, high availability and guarantees for the security and privacy were listed. In [5], as the requirements of the communication infrastructure for smart grid, QoS for delay and bandwidth, connectivity among different smart grid systems, scalability for the the number of devices and services, and security were listed. In [7], the required bandwidth for the communication infrastructure was estimated by examining several smart grid applications. In [6], it was pointed out that wireless sensor networks had promise as the communication infrastructure for smart grid, but there were issues about the selection and deployment of appropriate technologies from many available communication technologies, and about realization of reliability, latency requirement, and interconnection. Realization of the communication infrastructure for smart grid was discussed in [2], [8], [9], but those studies were limited to discussion on layers 1 and 2 in the OSI reference model.

Furthermore, most of these studies assumed to use the host-centric network architecture like IP, but didn't assumed to use the data-centric network architecture like CCN [1]. Unlike IP, a router in the network caches relayed contents in CCN. Due to this, high availability is expected because of the same contents' copies being maintained by multiple repositories, as well as the traffic volume can be reduced. For example, for smart grid, if the application that regularly collects the data of many smart meters is assumed, it has a possibility to work effectively in reducing the traffic volume and improving availability by the introduction of CCN. In the future, it is expected that smart grid will have a larger scale and be highly developed, the appropriate selection of the architecture for the communication infrastructure is required depending on the scale of smart grid and applications that are realized on it.

In this paper, we therefore investigate whether IP or CCN is appropriate as the communication infrastructure for smart grid through mathematical analysis. We focus on a usage scenario that the data of smart meters installed at home, in companies and factories are consolidated in the multiple remote grid control centers. In case that IP and CCN are used as the communication infrastructure for smart grid, the total communication volume, average communication delay and availability are derived.

The organization of this paper is as follows. In Section II, we will explain the analytic model used in this paper. In Section III, the total communication volume in the entire network, the average communication delay and the availability, in case that either IP or CCN is used as the communication infrastructure for smart grid, are derived. In Section IV, with several numerical examples, it is quantitatively shown whether IP or CCN is appropriate as a communication infrastructure for smart grid under what type of conditions. Finally, in Section V, the conclusion and future issues are summarized.

II. ANALYTIC MODEL

We focus on a layered network that consists of multiple remote grid control centers (RGCC (Remote Grid Control Center)), local grid control centers (LGCC (Local Grid Control Center)), and concentrators and meters (Fig. 1).

In this paper, AMI (Advanced Metering Infrastructure) is assumed as the application for smart grid, and the case that multiple RGCCs collects the data regularly derived from all meters is considered. AMI is an infrastructure to connect devices at home, like air conditioners and security devices, and electric meters (smart meters), to perceive the operating status of devices, and for the electric company to manage the data from meters.

N_R RGCCs and N_L LGCCs exist, and N_C concentrators are connected under each LGCC. Each concentrator connects to N_M meters. Each RGCC directly connects to entities that collect the data of meters. In this analytic model, RGCC, LGCC and concentrators correspond to routers (switching nodes), and entities and meters correspond to end hosts (clients, servers and repositories, etc.). Full-duplex links connect between entities–RGCC, RGCC–RGCC, RGCC–LGCC, LGCC–concentrators, and concentrators–meters. Each link has the enough bandwidth to transfer messages generated by meters.

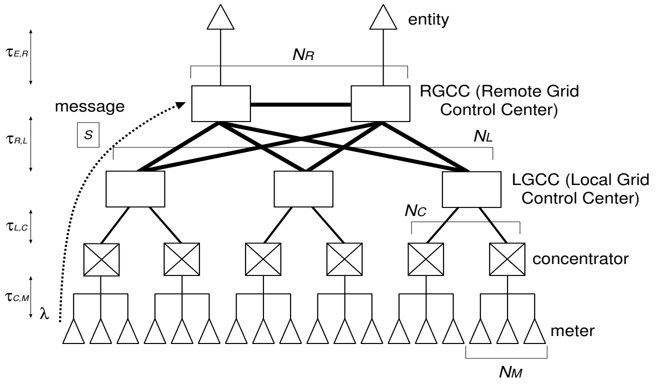

Figure 1. Analytic model

The communication delay between entities–RGCC is denoted as $\tau_{E,R}$, the communication delay between RGCCs as $\tau_{R,R}$, the communication delay between RGCC–LGCC as $\tau_{R,L}$, the communication delay between LGCC–concentrators as $\tau_{L,C}$, the communication delay between concentrators–meters as $\tau_{C,M}$. Processing delay in entities, RGCC, LGCC, concentrators and meters is assumed to be negligibly small.

For full-duplex links, failures of links are assumed to occur independently in both upstream and downstream, and the failure rate for each link is equally denoted as η.

Each entity is assumed to collect the data regularly generated in all meters through the connected RGCC, LGCC or concentrators under RGCC. The message generation rate in each meter is denoted as λ, and the size of each message is denoted as S.

In case of using IP as the communication infrastructure for smart grid, each entity sends the request message to every meter via unicast (Fig. 2). The meter that received the request message returns the corresponding message via unicast to the requesting entity. Both requesting and responding messages are assumed to be routed along the shortest path between the entity and the meter. The size of request messages is assumed to be equal and denoted as S_R.

In case of using CCN as the communication infrastructure for smart grid, each entity sends an Interest packet that requests the data of a meter to the nearest RGCC (Fig. 3). RGCC and LGCC have caches called *Contents Store*, but a concentrator is assumed to be a simple switching router

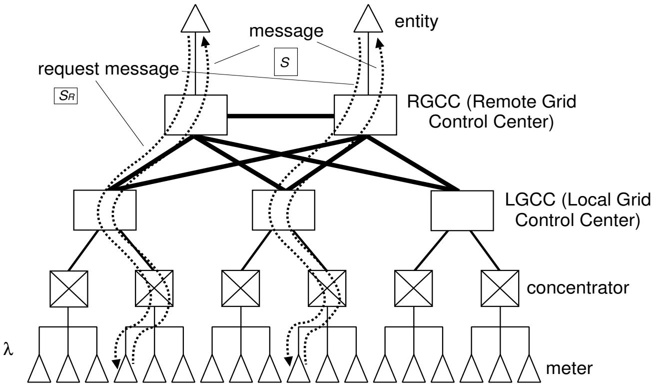

Figure 2. Requesting message and message flow in case of using IP as the communication infrastructure for smart grid

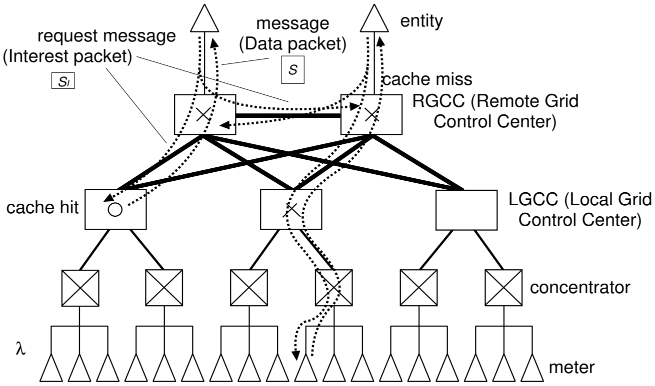

Figure 3. Requesting message and message flow in case of using CCN as the communication infrastructure for smart grid

and not to have a cache. If the content (i.e., the message) is cached in RGCC or LGCC, the relevant router returns the message as the Data packet. If both RGCC and LGCC do not cache the message, the Interest packet is transferred to the meter and the meter returns a message as the Data packet. The size of Interest packet is assumed to be equal and denoted as S_I.

The Interest packet sent from an entity gets routed in the network according to FIB (Forwarding Information Base) of each router. It is assumed that all FIBs of RGCCs are properly configured; i.e., FIB has appropriate entries for neighbor RGCCs and neighbor LGCCs reachable to all meters. Additionally, it is assumed that FIBs of LGCCs are properly configured to forward Interest packets to a concentrator reachable to the meter holding the relevant messages.

III. ANALYSIS

A. Derivation of total communication volume

To compare the communication efficiency of IP and CCN, the total communication volume (i.e., the total of communication volume that transferred over all links in the network per unit time) is to be derived in each case that IP or CCN is used as the communication infrastructure for smart grid. For instance, if there are 10 links in the network and each link transfers 1 [Mbit/s], the total communication volume in the network is 10 [Mbit/s]. The communication volume that transferred over all links is the total volume of the UDP traffic for requesting and responding messages in case of IP, and the total volume of Interest and Data packets in case of CCN. In what follows, the case that the failures of links don't occur (i.e., $\eta = 0$) is considered.

First, we consider the case that IP is used as the communication infrastructure for smart grid.

The communication volume in case that a message is sent from a meter to an entity is $4\,\lambda\,(S_R + S)$ because of going through four links (Fig. 2). The number of meters in the network, N, is given by

$$N = N_L\, N_C\, N_M. \tag{1}$$

Since each entity collects messages from all meters, the total communication volume in the entire network T_IP is simply given by

$$T_{IP} = 4\, N_R\, \lambda\, (S_R + S)\, N. \tag{2}$$

Next, we consider the case that CCN is used as the communication infrastructure for smart grid.

In CCN, caching of Data packets is performed in RGCCs and LGCCs. In case that a RGCC receives an Interest packet but doesn't have a cache of the relevant content, the Interest packet is forwarded to all neighbor RGCCs and the LGCC that is located above the meter holding the relevant message (Fig. 3).

The hit rate of cache in RGCC is denoted as p_R, and the hit rate of cache in LGCC as p_L. We denote, for an Interest packet sent by an entity, the probability of cache hit at one of N_R RGCCs as q_R, the probability of cache hit at LGCC as q_L, and the probability of cache miss at RGCCs and LGCC as q_{miss}. q_R, q_L and q_{miss} are given by

$$\begin{aligned} q_R &= 1 - (1 - p_R)^{N_R} && (3) \\ q_L &= (1 - q_R)\, p_L && (4) \\ q_{miss} &= 1 - (q_R + q_L) && (5) \end{aligned}$$

In case that an Interest packet hits at RGCC, it hits at RGCC that directly connects to the entity with probability $1/N_R$ and hits at RGCC that doesn't directly connect to the entity with probability $1 - 1/N_R$. Therefore, in this case, total communication volumes T_R^I and T_R^D of Interest and Data packets, respectively, are given as follows.

$$\begin{aligned} T_R^I &= \left(1 + \frac{(N_R - 1)^2}{N_R}\right) N_R\, \lambda\, S_I\, N && (6) \\ T_R^D &= \left(1 + \frac{(N_R - 1)^2}{N_R}\right) N_R\, \lambda\, S\, N && (7) \end{aligned}$$

In case that an Interest packet hits at LGCC, the Interest packet is forwarded to all neighbor RGCCs and the relevant LGCC based on FIB of the RGCC. The Data packet is then transferred from the LGCC to the entity in the opposite way of the route that the Interest packet passed through. Therefore, in this case, total communication volumes T_L^I and T_L^D of Interest and Data packets, respectively, are given as follows.

$$T_L^I = (N_R + 1)\, N_R\, \lambda\, S_I\, N \tag{8}$$

$$T_L^D = 2\, N_R\, \lambda\, S\, N \tag{9}$$

In case that an Interest packet doesn't hit at RGCCs and LGCC, the Interest packet is forwarded to RGCCs, LGCC, a concentrator, and a meter in order based on FIB, and finally the meter that receives the Interest packet returns the Data packet to the entity. Therefore, total communication volumes T_{miss}^I and T_{miss}^D of Interest and Data packets, respectively, are given as follows.

$$T_{miss}^I = (N_R + 3)\, N_R\, \lambda\, S_I\, N \tag{10}$$

$$T_{miss}^D = 4\, N_R\, \lambda\, S\, N \tag{11}$$

Hence, the total communication volume of the entire network T_{CCN} is given by

$$\begin{aligned} T_{CCN} &= q_R(T_R^I + T_R^D) + q_L(T_L^I + T_L^D) \\ &\quad + q_{miss}(T_{miss}^I + T_{miss}^D). \end{aligned} \tag{12}$$

B. Derivation of average communication delay

Next, the average communication delay is derived in each case of using IP and CCN as the communication infrastructure for smart grid. The average communication delay is defined as the expected duration from the time when an entity requests a message to the time when the message is returned to the entity. In what follows, we consider the case that the failures of links do not occur (i.e., $\eta = 0$).

First, we consider the case that IP is used as the communication infrastructure for smart grid. The entity sends a request messages to a mete via unicast, and the meter that receives the request message returns the corresponding message to the requesting entity. There are four links between an entity and a meter, and communication delays for those links are $\tau_{E,R}$, $\tau_{R,L}$, $\tau_{L,C}$, and $\tau_{C,M}$. Hence, the average communication delay D_{IP} is given by

$$D_{IP} = 2\,(\tau_{E,R} + \tau_{R,L} + \tau_{L,C} + \tau_{C,M}). \tag{13}$$

Next, we consider the case that CCN is used as the communication infrastructure for smart grid.

In case that an Interest packet hits at one of RGCCs, it hits at RGCC that directly connects to the entity with probability $1/N_R$, and it hits at RGCC that doesn't directly connect to the entity with probability $1 - 1/N_R$. Therefore, the average communication delays D_R^I and D_R^D of Interest and Data packets, respectively, are given by

$$D_R^I = D_R^D = \tau_{E,R} + \left(\frac{(N_R - 1)^2}{N_R}\right) \tau_{R,R}. \tag{14}$$

In case that an Interest packet hits at LGCC, the Interest packet passes through two links from the entity to the LGCC. The Data packet is returned from the LGCC to the entity in the opposite way of the route that the Interest packet passed through. Therefore, average communication delays D_L^I and D_L^D of Interest and Data packets, respectively, are given by

$$D_L^I = D_L^D = \tau_{E,R} + \tau_{R,L}. \tag{15}$$

In case that an Interest packet doesn't hit at RGCCs and LGCC, the Interest packet and the Data packet pass through four links between the entity and the meter. Therefore, average communication delays D_{miss}^I and D_{miss}^D of Interest and Data packets, respectively, are given by

$$D_{miss}^I = D_{miss}^D = \tau_{E,R} + \tau_{R,L} + \tau_{L,C} + \tau_{C,M}. \tag{16}$$

Hence, the average communication delay of the entire network D_{CCN} is given by

$$\begin{aligned} D_{CCN} &= q_R\,(D_R^I + D_R^D) + q_L\,(D_L^I + D_L^D) \\ &\quad + q_{miss}\,(D_{miss}^I + D_{miss}^D). \end{aligned} \tag{17}$$

C. Derivation of availability

Finally, the availability of messages is derived in each case of using IP and CCN as the communication infrastructure for smart grid. The availability of messages is defined as the probability that an entity can correctly obtain the message from a meter or a cache in RGCC or LGCC.

First, we consider the case that IP is used as the communication infrastructure for smart grid.

In case of IP, there are four links between an entity and a meter. Since the failure rate of all links in both upstream and downstream is equal to η, the availability A_{IP} is simply given by

$$A_{IP} = (1 - \eta)^8. \tag{18}$$

Next, we consider the case that CCN is used as the communication infrastructure for smart grid.

In case of CCN, the availability of messages is equal to the probability that an Interest packet arrives at any router caching the content or the meter holding the content, and that the message is correctly returned to the entity.

In case that an Interest packet hits at one of RGCCs, it hits at RGCC that directly connects to the entity with probability $1/N_R$, and it hits at RGCC that doesn't directly connect to the entity with probability $1 - 1/N_R$. Therefore, the availability A_R in this case is given by

$$A_R = \left((1 - \eta)^2 \frac{1}{N_R} + (1 - \eta)^4 \frac{N_R - 1}{N_R}\right). \tag{19}$$

In case that an Interest packet hits at LGCC, both the Interest packet and the Data packet pass through two links between the entity and the LGCC. Since the failure rate of all links in both upstream and downstream is equal to η, the availability A_L in this case is given by

$$A_L = (1-\eta)^4. \quad (20)$$

In case that an Interest packet doesn't hit at both RGCCs and LGCC, the Interest packet and the Data packet pass through four links between the entity and the meter. Therefore, the availability A_{miss} in this case is given by

$$A_{miss} = (1-\eta)^8. \quad (21)$$

Hence, the availability of the entire network A_{CCN} is given by

$$A_{CCN} = q_R\, A_R + q_L\, A_L + q_{miss}\, A_{miss}. \quad (22)$$

IV. NUMERICAL EXAMPLE

A. Parameter settings

In this section, by showing several numerical examples, we investigate whether IP or CCN is appropriate under what condition as the communication infrastructure for smart grid. In all numerical examples, the following parameters are used unless otherwise stated. The number N_R of RGCCs is 2, the number N_L of LGCCs is 5, the number N_C of concentrators connected to each LGCC is 10, the number N_M of meters connected to each concentrator is 20, the message generation rate λ is 0.1 [message/s], the size S of messages is 512 [byte], the size S_R and S_I of request packets for IP and Interest packets for CCN, respectively, is 64 [byte], communication delays, $\tau_{E,R}$, $\tau_{R,R}$, $\tau_{R,L}$, $\tau_{L,C}$, $\tau_{C,M}$, are 1 [ms], and the failure rate of each link η is 0.

B. Total communication volume

First, the total communication volume in case of using IP and CCN as the communication infrastructure for smart grid is shown in Fig. 4. In this figure, cache hit rates (p_R and p_L) at RGCCs and LGCCs are changed in case of CCN. The total communication volume of IP remains the same despite of the cache hit rates, but the total communication volume of CCN changes by cache hit rates.

From this figure, it is found that the total communication volume of the entire network for CCN is smaller than that for IP, except for the case that cache hit rates at RGCCs and LGCCs are very small. In case of CCN, as cache hit rates at RGCCs and LGCCs increase, the traffic reduction effect by cache becomes large, and the total communication volume of the entire network is reduced. However, in case that the cache hit rates at RGCCs and LGCCs are very small, since Interest packets that RGCC received from entities are also forwarded to neighbor RGCCs, the total communication volume of the entire network increases instead. In reality, cache hit rates at RGCCs and LGCCs change due to message request pattern from entities to meters or the size of the Contents Store at RGCCs and LGCCs.

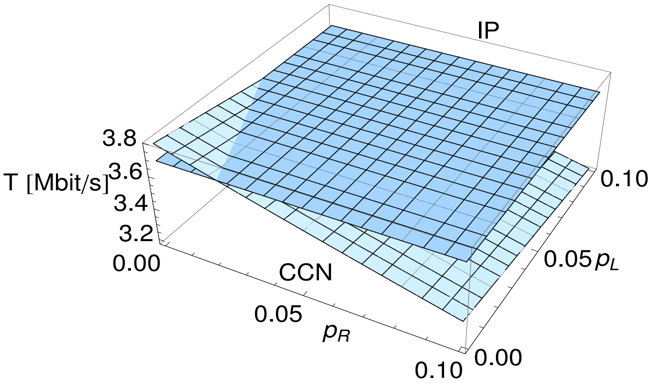

Figure 4. Relation between cache hit rates of RGCCs and LGCCs (p_R and p_L) and total communication volume

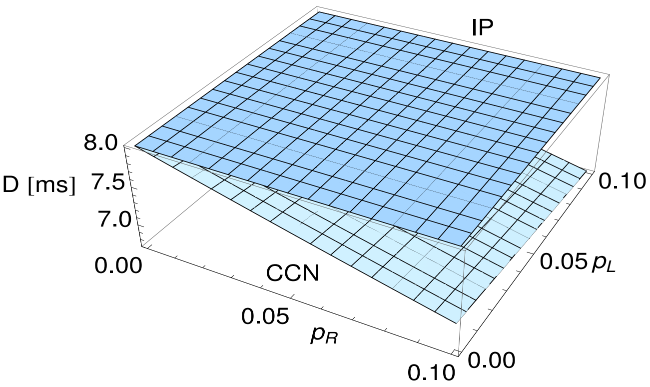

Figure 5. Relation between cache hit rates at RGCCs and LGCCs (p_R and p_L) and the average communication delay

From these observations, except for environments that cache hit rates at RGCCs and LGCCs are very small (for example, cases that RGCCs and LGCCs cannot be provided with a large Contents Store), it can be said that the introduction of CCN is preferable from the viewpoint of the total communication volume of the entire network.

C. Average communication delay

Next, the average communication delay in case of using IP and CCN as the communication infrastructure for smart grid is shown in Fig. 5. As with the previous figure, cache hit rates (p_R and p_L) at RGCCs and LGCCs are changed in case of CCN.

This figure shows that, when certain level of cache hit rates at RGCCs and LGCCs are achieved, the average communication delay of CCN is much lower than that of IP. In CCN, when an Interest packet hits at RGCC or LGCC, the Data packet is returned from the relevant router to the entity, leading significant reduction in the delay needed for transferring messages. This figure also shows that the

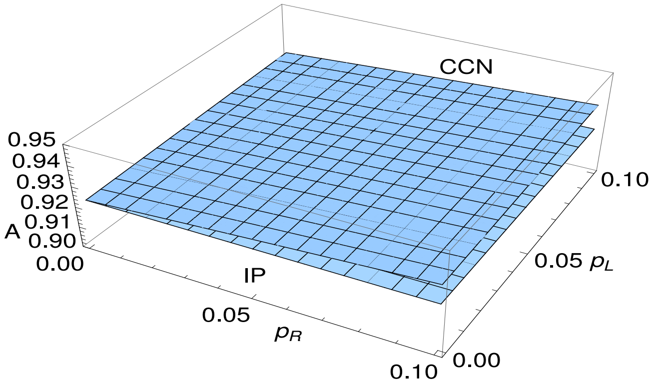

Figure 6. Relation between cache hit rates at RGCCs and LGCCs (p_R and p_L) and the availability (the failure rate of links $\eta = 0.01$)

increase in the cache hit rate p_R at RGCCs has the higher reduction effect of the average communication delay, instead of increasing the cache hit rate p_L at LGCCs. One reasons for this phenomenon is that, in addition to the difference in communication delay between entity–RGCC and entity–LGCC, LGCC can only cache messages of meters, which are connected to concentrators under the LGCC, though RGCC can cache messages of all meters in the network.

From these observations, it can be said that, under circumstances that can increase cache hit rates at RGCCs and LGCCs to some level, introduction of CCN is preferable from the viewpoint of the average communication delay.

D. Availability

Finally, the availability in case of using IP and CCN as the communication infrastructure for smart grid is shown in Fig. 6. In this figure, the failure rate of all links was set to $\eta = 0.01$.

One can find from this figure that CCN could achieve higher availability in the most of all areas than IP, regardless of cache hit rates at RGCCs and LGCCs. However, the difference between IP and CCN in terms of the availability is not significant even though differences in terms of the total communication volume and the average communication delay are significant. Even when cache hit rates at RGCCs and LGCCs are about 10%, the availability of CCN exceeds that of IP by a small fraction.

From these observations, it can be said that there are not much advantage to introduce CCN from the viewpoint of the availability.

V. CONCLUSION

In this paper, we investigated whether IP or CCN was appropriate as the communication infrastructure for smart grid under what type of conditions through mathematical analysis. We focused on a usage scenario that the data of smart meters installed at home, in companies and factories were consolidated in multiple RGCCs. We derived the total communication volume of the entire network, the average communication delay and the availability in case of using IP and CCN. Through several numerical examples, we showed that, except for the case that cache hit rates at RGCCs and LGCCs were very small, CCN was effective from the viewpoint of the total communication volume and the average communication delay but there was no significant difference between IP and CCN in terms of the availability.

Our future works include extension of our mathematical analysis to take account of unbalanced traffic sent from smart meters, other application scenarios than AMI, and a general network topology rather than the layered network.

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