Adaptive Congestion Control in Information-Centric Networking for the IoT Sensor Network

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Abstract. In order to diminish the network congestion rate and enhance the network performance of ICN (Information-Centric Networking) architecture, especially in the IoT (Internet of Things) era, this research proposes an adaptive congestion control mechanism for the IoT sensor network. Particularly, the proposal can respond the content requests from the consumers by caching an appropriate number of content chunks at the ICN router according to the content popularity and priority levels. We also utilize both content popularity and priority-based ranking delay time for the data transmission from sensors to the data server. The evaluation results show that the proposal with the dynamic control/adaptive mechanism can provide higher network performance efficiency for the future Internet by achieving higher throughput with lower request (Interest) packet drop rate and higher cache hit rate as we increase the number of IoT sensors, then solving the network congestion issue in ICN.

Keywords: ICN (Information-Centric Networking), IoT (Internet of Things), Sensor Networking, FI (Future Internet), Congestion Control, Adaptive Congestion Control

1. Introduction

Nowadays, the IoT (Internet of Things) has become an important part of our lives since it enables efficient global communications. The reason is that the IoT devices can be connected to the Internet easily by exploiting the emerging technologies, including ubiquitous and pervasive computing, embedded devices and communicated technologies. Typically, the IoT allows different objects to communicate with each other, share information, and make decisions [1], especially for the FI (Future Internet) in the case of sensor network applications.

Recently, ICN (Information-Centric Networking) design [2] has been proposed as a potential Internet architecture for the global-scale FI paradigm. ICN becomes a promising networking system because it enables network higher performance than the IP-based Internet architecture such as lower latency and better mobility support. Generally, ICN realizes the
new concept of named data transmission, and implements extensive cache structure to distribute and deliver content at the same time, instead of using the host-name address to avoid disadvantages of the current Internet design. However, ICN still has many challenges including higher energy consumptions due to additional energy for caching capability [3,4,5] and higher congestion rate compared to IP-based Internet architecture [6,7].

There are two different kinds of network resource management to handle the network congestion problems: congestion avoidance and congestion control mechanisms. Congestion avoidance mechanisms aim to prevent the network from getting congested whereas congestion control’s objective is to recover the network from the congested state [8]. In this paper, we study the congestion control for the practical ICN implementation to solve the problems of content request flooding due to in-network caching mechanism of ICN [7]. In order to reduce the ICN architecture’s congestion problem and enhance the performance, we propose an adaptive congestion control mechanism for ICN-based sensor network in the context of IoT. Specifically, in our ICN-enabled sensor network scenario, the proposal can response the content requests from the consumers by caching only a portion of content data according to the content popularity, instead of whole data as existing ICN work. Typically, the system calculates the appropriate number of content chunks at router according to the popularity-based caching partition scheme for the efficient cache management. We also utilize content popularity and priority-based ranking as network metrics for defining delay time to transmit data from sensors to the server. In this way, the proposal is applicable for various practical IoT applications [7]. We also proved that ICN performs better than TCP/IP (Transmission Control Protocol/Internet Protocol) in terms of caching and naming in the context of sensor networking [6].

The rest of this study is arranged as follows: In Section 2, we state related work, and the proposed schemes together with the network topology are demonstrated in Section 3. We then analyze the evaluation results and discussion in Section 4. Finally, in Section 5, we present a summary of this study and conclude the paper with our potential directions for future work.

2. Related work

Currently, several ICN platform deployments for the FI have been implemented, thanks to the innovative operating mechanisms of ICN. The main ideas of ICN include: in-network caching, data naming, and multicasting [9]. Also, ICN architecture can optimize bandwidth usage by aggregating multiple content requests of the same content then forwarding them at the same time [10]. However, in the case of ICN sensor networking in the IoT era, as sensors are connected to the Internet to collect data for analysis, a huge number of content requests from users in the network during the high traffic periods can produce the high network congestion rate.

There are lots of ICN-based research work which aim to optimize the functions of data naming, and content caching by establishing the data flows between content locations and content consumers for the goal of matching the desired content from the user, such as study in [11]. However, one of the main concern on ICN is that multiple content requests and data exchange can result in considerable high delays, collisions, and packet loss rate. To address this issue, the authors in [12] proposed an adaptive forwarding strategy as an efficient congestion control mechanism in NDN (Named Data Networking), a commonly used ICN platform. Also, several congestion control mechanisms have been proposed for ICN such as
data-aggregation techniques in sensor network surveyed in [13], and Receiver-driven TCP-Reno congestion control and Multi-thread congestion protocol proposed in [14].

In fact, most of the ongoing ICN researches in wireless environment aim to deal with content consumer and publisher mobility to verify the benefit of ICN over IP regarding mobility support. In [15], an intelligent content prefix classification framework utilizing reinforcement learning is proposed to optimize Quality of Service (QoS) in ICN. Also, as ICN employs in-network caching, caching strategies can be utilized to improve the overall ICN performance efficiently. For instance, the integrated caching and routing solution is defined for efficient cache utilization [16].

Regarding the method for reducing the congestion rate of network systems, cache management is one potential primary policy for the ICN system. Specifically, many cache management schemes have been proposed, e.g., in [17], a cache-aware traffic shaping policy based on content popularity is designed to assign the appropriate video bit rate for data transmission. Authors in [18] studied congestion-aware cache policy to determine which content should be cached or evicted. Also, [19] presented the utility-driven cache partitioning for allocating cache resources for different contents.

Along this line, in our previous work [6], we proposed a dynamic congestion control mechanism. The proposed network system transmits the content with content popularity-based delay time, together with adaptive content lifetime, and cache management strategy to evaluate high performance and low congestion rate in ICN. We also investigated that the proposed model can provide higher network performance efficiency for the future Internet when we increase the number of IoT sensors in ICN. However, in that study, we only considered content popularity of content produced by sensors for identifying the content transmission delay time to reduce the network congestion rate.

To further prove that ICN outperforms IP-based system by utilizing less network resources and achieving lower Interest packet drop rate, in this study, we utilize both content popularity and content priority for the identification of the appropriate delay transmission time. Also, we introduce the content ranking-based delay transmission time and cache management scheme through the cache partitioning policies based on the content popularity. The evaluation results show that our adaptive congestion control algorithm is the efficient solution to diminish the high congestion rate in ICN architecture. The proposal is then feasible and applicable for a wide domain of different practical applications e.g., Healthcare, V2X (Vehicle to Everything) where sensors are utilized to sense and process the interactive data. The proposal details are stated and clarified in the next section (Section 3).

3. Proposed congestion control mechanism

The congestion rate of a network system is a critical factor for the network performance, especially in the context of the ICN-based sensor network. In this section, we propose an adaptive congestion control mechanism to transmit the Data packet from sensors for IoT era. The proposed congestion control mechanism's goal is to gain higher network performance and reduce the congestion rate via diminished data traffic at the same time.

In this paper, we propose an adaptive congestion control mechanism for ICN-based sensor network by utilizing both content popularity and priority-based ranking delay time to provide higher network performance efficiency and solve the network congestion issue in ICN at the same time.
3.1. Network Topology and Basic Assumptions

For practical implementation, we deploy our network scenario with a hierarchical network topology, given that ICN Sensor Network is the interconnection between the server (Data Center), content routers, and IoT sensors in ICN design. The proposed ICN system topology is shown in Fig. 1. Also, we assume that users send content requests to the servers/data center then the server forwards the request with the corresponding content popularity and priority level based on the content request traffic to all IoT sensors via the ICN content routers. Accordingly, the congestion may happen during the high traffic period with a huge number of content requests from consumers asked for data from the producers (IoT sensors). Typically, the ICN sensor network initiates high traffic by consuming high network resources utilization for data dissemination from sensors as the content sources [6].

![Figure 1: The proposed ICN based sensor network topology.](image)

3.2. Data transmission process in the proposal system

In ICN, there are two types of packet: Interest packet (content request) and Data packet which returns matched data according to the content name LPM (longest prefix match). A content is split into a number of chunks, which specify data transmission unit for forwarding and content delivery process. The content routers in ICN have three fundamental structures: FIB (Forwarding Information Base), CS (Content Store), and PIT (Pending Interest Table) as defined in NDN framework [14]. From now on, we refer and select NDN design as the conventional ICN model because it is designed for the goal of network scalability, security, robustness, and efficiency by utilizing in-network caching, content-based security, and content naming scheme.

3.3. Delay transmission time identification

We assume that IoT sensors are utilized for congestion control application. And, when the sensors receive the content requests, they then response the Data packet of the content corresponding to content popularity and priority. To characterize the content priority and content popularity levels, we take Zipf distribution-based model [20], and its formula can be defined as follows:
where \( r \) is a rank of the content, \( \alpha \) is the skewness factor characterizing the Zipf distribution, and \( C \) denotes the total number of content items (files). From the return value of \( Z \) as defined in (1), the system can identify the frequency of a specific content from the rank of content popularity and the priority level of the content.

Let \( K_{pri}, K_{pop} \) be the rank of content priority and content popularity, respectively. Next, the sensors compute the corresponding delay time of the Data packets based on both the priority and popularity of the content. Particularly, the system checks the value of both \( K_{pri} \) and \( K_{pop} \) to identify that whether a content belongs to the most important content class or not.

From our previous work \([6]\), we identified the content transmission delay time \((dtc)\) based on the content popularity. Then, in this study, we extend that idea by also considering the inclusion of content priority for content importance’s identification. If the content is a highly important or popular content, the system will respond content data to the user without any transmission delay time (i.e., its \( dtc = 0 \)). Otherwise, the transmission delay time value of the content \((dtc)\) can be modeled by using the following exponential function:

\[
dtc = \Delta \cdot e^{\frac{K_{pop} + K_{pri}}{c \cdot N}},
\]

where \( \Delta \) is the base value of delay time, and \( e \) denotes the mathematical constant (Euler number). Let \( c \) be the constant value which reflects the exponential growth rate of network based on the value of \( N \), which identifies the number of sensors in one domain.

Figure 2: The proposed IoT Sensor working algorithm’s flowchart.
Finally, the IoT sensors send Data packets to the server with \( dtc \) according to content priority and content popularity level as defined by (2). The detailed algorithm is depicted in Fig. 2.

### 3.4. Popularity-based cache management scheme

When the system transmits content through the intermediate routers (from the IoT sensors as the content sources), each content is assigned an appropriate caching ratio for storing the content at the router’s content store. For this objective, all routers in the proposed ICN have implemented a popularity-based cache management strategy through the cache partitioning scheme.

For simplicity, we assume that all the content objects share the same caching size of 1 MB because they are produced by sensors which have relatively constrained capacity. We simulate with a chunk payload size of 1 KB to avoid fragmentation. Specifically, the interest request frequency is empirically set as 10 interest packets/s so that the conventional ICN has sufficient but not too high congestion rate. The simulation link capacity/bandwidth is 100 Mb/s and 1 Mb/s for wired and wireless connections, respectively to guarantee sufficient link data transmission rate. The key simulation parameters are presented in Table 1. In this research, we focus on evaluating the congestion rate of the proposal compared to other relevant network systems during the high traffic period. Thus, we use a large number of sensors ranged from 1980 to 2700 to evaluate different network architectures including our proposal and other network systems.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Content size</td>
<td>1 MB</td>
</tr>
<tr>
<td>Interest request frequency/sensor</td>
<td>10 Interest packets/s</td>
</tr>
<tr>
<td>Payload size (chunk size)</td>
<td>1,024 Byte</td>
</tr>
<tr>
<td>Link capacity</td>
<td>100 Mbps</td>
</tr>
<tr>
<td>Sensor max data rate</td>
<td>1 Mbps</td>
</tr>
</tbody>
</table>

For this goal, each content is assigned to a cache partition of content store based on its \( K_{\text{pop}} \) value. Particularly, each cache partition employs a chunk-based caching ratio from a range of \( K_{\text{pop}} \) value. Then, based on the allocated caching partition with a particular popularity-based caching ratio, an adaptive chunk-level caching policy will be applied for each arriving content to the router. Let \( C_{\text{ratio}} \) be the caching-ratio of the content item (start from foremost chunk) and \( C_{\text{all}} \) be the total number of chunks for each content. Then, the caching policy for the arriving content can be identified by the following formula:

\[
C_{\text{ratio}} = \left[ \frac{K_{\text{low}}}{K_{\text{pop}}} \right] C_{\text{all}},
\]

where \( K_{\text{low}} \) indicates the rank of lowest content among the most popular content class. The detailed algorithm is shown in Fig. 3.
Figure 3: The flow chart of the proposed ICN Router’s popularity-based cache management scheme.

4. Results and Evaluation

To evaluate and analyze the proposal, we simulate our ICN network scenario with ndnSIM [21], which is an ns-3 framework based NDN simulator. The network topology can be depicted as shown in Fig. 1.

We simulate five scenarios with various numbers of IoT sensors ranged from 1980 to 2700 for both of traditional ICN (NDN design) and our ICN design under the same network environment. Table 1 summarizes all key parameters for the simulation including the value of content size, interest request frequency for each sensor, payload size (chunk size), link capacity, and sensor max data rate. For simplicity, we utilize Zipf distribution [20] with the alpha value of one ($\alpha = 1$) for the content popularity and content priority distribution model. Also, we assign delta value ($\Delta$) and constant $c$ as 1 and 0.1, respectively for the evaluation.

Figure 4 illustrates the Interest packet drop rate of different ICN systems (including our proposal and traditional ICN design) in accordance with various numbers of sensors. The result shows that our adaptive congestion control ICN design can provide less Interest packet drop rate of content requests than the original ICN. Specifically, our proposed ICN can get much higher performance in terms of low packet drop rate when we increase the number of sensors. This is because the proposal transmits content according to its $dtc$ value based on both of popularity and priority ranking value as well as using the proposed chunk-level popularity-based cache partitioning scheme implementations as defined in Section 3.
Figure 4: Interest packet drop rate corresponding to different numbers of sensors.

Figure 5 depicts the cache hit rate according to various numbers of sensors between the proposed ICN design and the original ICN system. The evaluation result shows that our proposed congestion control ICN mechanism can get higher cache hit rate than the traditional ICN. The reason is that all routers at different levels of the adaptive congestion control ICN model are implemented with the cache management scheme via popularity-based cache partitioning strategy.

Figure 5: Cache hit rate versus different numbers of sensors.
Next, Fig. 6 shows the cache hit rate of the adaptive congestion control ICN model and the traditional ICN with the highest numbers of sensors for evaluation (2700 sensors). The results show that our proposal can gain a higher cache hit rate than original ICN, especially at the first level of network topology. Thus, consumers can get the content at nearest content routers at the edge side which are close to the server. Then, our proposal can provide higher network performance by responding to user requests with lower latency and hop-count, compared to the original ICN design.

![Graph showing cache hit rate comparison between Original ICN and Adaptive Congestion Control ICN across different network levels.

Figure 6: Cache hit rate according to different network levels with the highest numbers of sensors (2700 sensors).

![Graph showing network throughput corresponding to different numbers of sensors.

Figure 7: Network throughput corresponding to different numbers of sensors.
Finally, Fig. 7 presents the average network throughput of the proposal and the original ICN corresponding to various numbers of sensors. The evaluation results show that the adaptive congestion control ICN system can provide higher network throughput than the traditional ICN model. This confirms that our proposal system is an efficient solution to diminish the network congestion rate, with higher network performance, especially in the context of IoT sensor network in ICN design.

5. Conclusion and future work

In this article, we propose an adaptive congestion control mechanism based on transmission content delay time corresponding to both content popularity and priority level to reduce the network congestion rate in the hierarchical ICN-based model. Moreover, we implement a chunk-by-chunk popularity-based cache partitioning scheme as the network management policy to further improve the network performance in ICN. We evaluate and analyze the proposal by simulating our IoT sensor network scenario using ndnSIM. The evaluation results show that our adaptive congestion control ICN model can provide higher network performance compared to the conventional ICN design by achieving higher throughput with lower Interest packet drop rate and higher cache hit rate. These results demonstrate that our proposed ICN is a feasible and potential solution to solve the network congestion issues in the ICN-based sensor network, especially in the context of IoT and Big Data era.

As a scope of future work, we have a plan to employ the proposal with several content popularity models to improve the overall network efficiency under various network topologies. Also, we will implement our work as a practical approach to the Future Green sensor networking scenario, which aims to get low congestion as well as high network performance and power saving in ICN simultaneously.

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