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Proactive content caching in future generation communication networks: Energy and security considerations

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Proactive Content Caching in Future Generation Communication Networks: Energy and Security Considerations

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USE OF THESIS

Abstract

The proliferation of hand-held devices and Internet of Things (IoT) applications has heightened demand for popular content download. A high volume of content streaming/downloading services during peak hours can cause network congestion. Proactive content caching has emerged as a prospective solution to tackle this congestion problem. In proactive content caching, data storage units are used to store popular content in helper nodes at the network edge. This contributes to a reduction of peak traffic load and network congestion.

However, data storage units require additional energy, which offers a challenge to researchers that intend to reduce energy consumption up to 90% in next generation networks. This thesis presents proactive content caching techniques to reduce grid energy consumption by utilizing renewable energy sources to power-up data storage units in helper nodes. The integration of renewable energy sources with proactive caching is a significant challenge due to the intermittent nature of renewable energy sources and investment costs. In this thesis, this challenge is tackled by introducing strategies to determine the optimal time of the day for content caching and optimal scheduling of caching nodes. The proposed strategies consider not only the availability of renewable energy but also temporal changes in network traffic to reduce associated energy costs.

While proactive caching can facilitate the reduction of peak traffic load and the integration of renewable energy, cached content objects at helper nodes are often more vulnerable to malicious attacks due to less stringent security at edge nodes. Potential content leakage can lead to catastrophic consequences, particularly for cache-equipped Industrial Internet of Things (IIoT) applications. In this thesis, the concept of "trusted caching nodes (TCNs)" is introduced. TCNs cache popular content objects and provide security services to connected links. The proposed study optimally allocates TCNs and selects the most suitable content forwarding paths. Furthermore, a caching strategy is designed for mobile edge computing systems to support IoT task offloading. The strategy optimally assigns security resources to offloaded tasks while satisfying their

individual requirements. However, security measures often contribute to overheads in terms of both energy consumption and delay. Consequently, in this thesis, caching techniques have been designed to investigate the trade-off between energy consumption and probable security breaches.

Overall, this thesis contributes to the current literature by simultaneously investigating energy and security aspects of caching systems whilst introducing solutions to relevant research problems.

Keywords

Caching, communication networks, content delivery, energy consumption, IoT, renewable energy, security.

Declaration

I, Muhammad Ishtiaque Aziz Zahed, certify that this thesis titled, "Proactive Content Caching in Future Generation Communication Networks: Energy and Security Considerations" and the conducted research works in it are my own. I solemnly state that this thesis does not, to the best of my knowledge:

- Contain any research work without acknowledgement, which have been submitted for a degree or diploma to this University or any institution;
- Incorporate any material previously published or written by another person except where due acknowledgement and reference are provided;
- Comprise any defamatory material.

[redacted]

Signed: Muhammad Ishtiaque Aziz Zahed
Dated: 24.11.2020

This thesis is dedicated to my parents.

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List of Publications Arising From This Thesis

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- M. I. A. Zahed, I. Ahmad, D. Habibi, Q. V. Phung, and L. Zhang, "A Cooperative Green Content Caching Technique for Next Generation Communication Networks," *IEEE Trans. Netw. Serv. Manage.*, vol. 17, no. 1, pp. 375-388, Mar. 2020.
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- M. I. A. Zahed, I. Ahmad, D. Habibi, and Q. V. Phung, "Green and Secure Computation Offloading for Cache-Enabled IoT Networks," *IEEE Access* vol. 8, pp. 63840-63855, 2020.
- M. I. A. Zahed, I. Ahmad, D. Habibi, Q. V. Phung, L. Zhang, and A. Mathew, "Security Aware Content Caching for Next Generation Communication Networks," *in Proc. IEEE Int. Conf. Commun. (ICC)*, Shanghai, China, May 2019, pp. 1–6.

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Abbreviations

5G	Fifth generation
BC	Betweenness centrality
BS	Base station
CC	Closeness centrality
CCN	Content-centric network
CDN	Content delivery network
CMEC	Cooperative mobile edge computing
CPU	Central processing unit
C-RAN	Cloud radio access network
CS	Content store
D2D	Device-to-device
DC	Degree centrality
DNS	Domain name system
DRL	Deep reinforcement learning
E2E	End-to-end
EC	Eigenvector centrality
FIB	Forwarding information base
FIFO	First in first out
F-RAN	Fog radio access network
HetNet	Heterogeneous network
ICN	Information-centric networking
IIoT	Industrial Internet of Things
ILP	Integer linear program
IoT	Internet of Things
IP	Internet protocol
LFRU	Least frequent recently used
LFU	Least frequently used
LP	Linear programming

LRU	Least recently used
MBS	Macro base station
MEC	Mobile edge computing
MILP	Mixed integer linear program
NAP	Network attachment point
NLP	Non-linear program
PDGC	Proposed deterministic green caching
PIT	Pending interest table
PPGC	Proposed probabilistic green caching
PUC	Packet update caching
QoE	Quality of experience
QoS	Quality of service
RAN	Radio access network
RL	Reinforcement learning
RRH	Remote radio head
SBS	Small-cell base station
SDN	Software defined networking
SGC	Secure green caching
SNM	Shot noise model
STO	Secure task offloading
TCN	Trusted caching node
TCO	Task caching and offloading
TLRU	Time-aware least recently used
UAV	Unmanned aerial vehicle
UDN	Ultra dense network
UE	User equipment
VoD	On-demand video
WA	Western Australia

Chapter 1

Introduction

1.1 Overview

Advancements in on-demand streaming services, smart hand-held devices, Internet of Things (IoT) applications, wireless networks as well as unprecedented increases in Internet subscribers have resulted in significant growth of global Internet traffic [1–4]. In recent years, the role of communication networks has evolved from pair-wise telephony conversations towards content distribution [5, 6]. By 2030, the number of communication devices served by diverse networking paradigms is expected to reach 100 billion with mobile data traffic approximately 10,000 times higher than 2010 [7]. To fulfill this growing demand, operators are continually deploying networking resources, where capital expenditure is increasing dramatically [8, 9].

The phenomenal growth of Internet traffic is mainly fueled by two major data sources [10]. The first source is on-demand video (VoD) streaming (e,g., Netflix, Hulu) and content-sharing services (e,g., YouTube). According to a report by Cisco [11], video streaming services are envisioned to make up more than 80% of Internet traffic by 2021. 4k streaming services are becoming increasingly popular and 8k services will soon become available. The second source is the IoT data generated from thousands of sensors, actuators, and applications in IoT networks [12]. These devices, which are connected to different network nodes, can share, exchange, and analyze data about their surroundings as well as individuals' activities [13]. It is expected that more than 75 billion IoT devices will be connected to the Internet by 2025 [14]. IoT services include, but are not limited to, intelligent emergency services, e-health, smart traffic management, environmental monitoring, and industrial automation [15]. These VoD services and IoT applications will create enormous traffic volume and result in network congestion, spectrum scarcity, and degraded quality of experience (QoE).

Popular video content and IoT data items are frequently downloaded and require high data rates [10, 12, 16]. However, such content is not suitable for broadcasting, as user requests are generated in an asynchronous manner. This is because broadcasting can cause significant delay to earlier requests and degrade user experiences. Traditional networking solutions are not efficient in combating the associated technical challenges of this bandwidth-greedy network traffic [17, 18]. Therefore, there is a need to redesign existing networks and introduce innovative content delivery techniques.

1.1.1 Content caching: A paradigm shifting technology

To cope with increasing traffic demand, caching popular data items at network nodes has emerged as a prospective solution [19, 20]. Conventional host-based networks serve subscribers from content providers' remote servers, which causes redundant content transfers [21]. Caching frequently requested content at the network edge can reduce this redundancy in content distribution and boost spectral efficiency [22]. The deployment of content storage devices at edge nodes, commonly known as helper nodes, ensures faster distribution of content and cuts down delivery distance [23, 24]. Fig. 1.1 presents the concept of caching, which enables users to receive requested content from an edge node without creating redundant backhaul transmission.

Proactive content caching is an attractive option that capitalizes on skewed disparities in content popularity [25, 26]. This technique identifies frequently requested content objects and caches them at the helper nodes before the arrival of delivery requests [27]. Hence, a cache-equipped network edge can significantly alleviate backhaul bottlenecks by

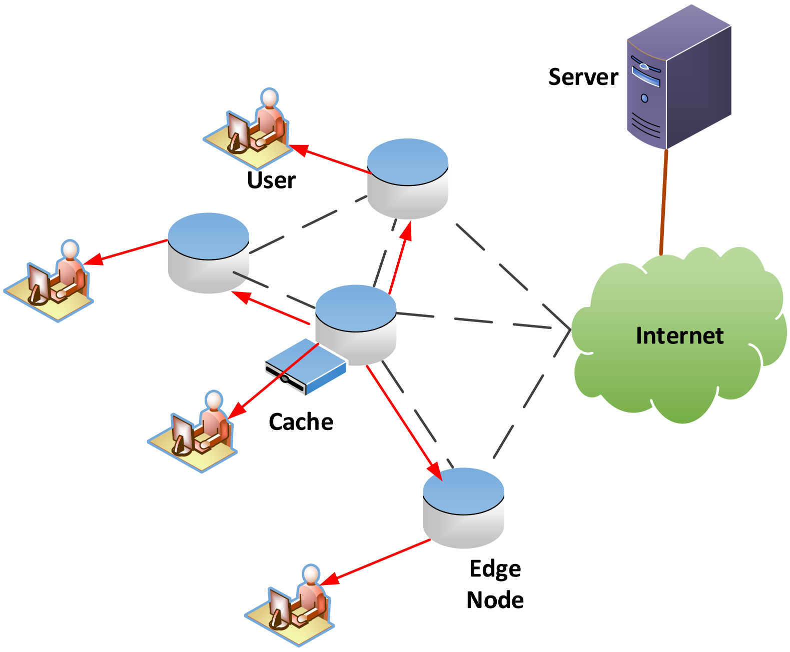

Fig. 1.1: The concept of caching.

serving user requests locally. Consequently, caching helps in reducing bandwidth requirement, user-perceived latency, and transmission energy consumption [28–30]. Caching also improves spectrum efficiency and network throughput [31].

Caching nodes are also frequently updated because of the changing popularity of cached content objects [18, 23]. Therefore, content replacement techniques require accurate identification of less popular items to accommodate currently popular contents. In addition to content popularity, an efficient caching strategy considers content size, delivery path, and transmission time [10, 32, 33].

1.1.2 Energy aspects of caching

The deployment of network resources to facilitate Internet services is also leading to a rise in energy consumption [27, 34]. Every single content object of the Internet traffic requires efficient processing, transmission, and dissemination resulting in massive energy consumption and an increased carbon footprint. Consequently, energy-efficient network planning and resource management are regarded as the key features of future networking systems. Network operators, vendors, infrastructure manufacturers, and researchers from academia are investigating environmentally friendly, cost-efficient, and high performing green communication solutions [7, 35].

Although caching has been proposed to achieve faster content delivery [36], it has also shown remarkable potential in reducing energy demand [1, 37]. This is because shortening content delivery distance reduces both content transmission energy and network resource utilization. On the other hand, edge servers with computing and caching resources consume a considerable amount of energy [30, 38]. Moreover, cached data items and associated applications are diverse in terms of content popularity, input data sizes, and execution process [39, 40]. This additional computational complexity at edge nodes raises concerns regarding operational expenditure and energy budget. Caching can reduce energy bills as long as the energy savings in content delivery are higher than the energy utilized by data storage units [34]. Therefore, a fundamental consideration of green caching networks is to minimize the difference between utilized and offered caching resources. To address this, a number of studies [34, 41–43] have investigated and proposed diverse optimal caching resource allocation, network management, and green energy utilization techniques to support latency-critical and bandwidth-greedy applications.

Energy-aware cache node selection and optimal network planning improve energy savings substantially [19, 41]. In this process, the nodes serve a maximum number of user requests by deploying a minimum number of caching units in a network. According to existing studies [34, 42], smart selection of content delivery path and activation of caching nodes based on network traffic demand achieves considerable improvements in energy efficiency. Furthermore, the utilization of green energy in operating caching nodes reduces not only the dependence on grid energy but also carbon emissions [44]. In addition, the joint utilization of these techniques exhibits remarkable potential in limiting peak-to-average disparity of energy load and improves network load adaptation [45, 46]. However, exploitation of green approaches in cache-equipped networks may impact network throughput and transmission delay [47, 48]. The inclusion of security protection services at the caching nodes also increases energy consumption [49, 50]. Therefore, smart allocation and management of caching resources is crucial for achieving energy savings and simultaneously fulfilling QoE requirements.

1.1.3 Security aspects of caching

While content caching at the network edge can potentially reduce energy demands, the privacy and security of the cached content objects at the network edge are major concerns for cache-equipped networks [51–54]. Caching servers, located at the network edge, are in close proximity to attackers and are vulnerable to hostile attacks [51]. In addition, the authentication and access control mechanism at edge nodes are less resilient than core nodes [55]. Whenever security breaches occur, service providers are held responsible by subscribers. Thus, content-leakage not only affects client privacy, but also damages the reputation of an organization. As a result, efficient access control at these nodes is essential for cache-equipped networks.

The distinctive features of IoT applications make the situation even worse [56, 57]. This is because IoT applications deal with different types of confidential information, including human movement, healthcare data, financial records, and industrial process control [57–59]. Potential security breaches can lead to system failures and have life threatening consequences for subscribers [55, 60].

Industries are constantly looking for innovative and cost-effective solutions to provide ubiquitous connectivity and reduce computation overhead [15]. As a promising solution to these requirements, the IoT is anticipated to be widely utilized in industrial communications, leading to the concept of the industrial IoT (IIoT) [61, 62]. In IIoT systems, any kind of unauthorized access, data tempering, or confidential content leakage may result in substantial financial damage or disruption of operations [63, 64]. Inevitably, IIoT content requires robust supervisory control as well as monitoring for smooth, efficient, and secured data transmission. The security requirements of different applications are also diverse in terms of authentication, confidentiality, and integrity processes [57, 65]. This requires an optimal caching system designed for secure content storage and delivery.

1.2 Research significance and motivation

From an energy consumption perspective, excessive energy demand resulting from the explosive growth of Internet traffic and data centers has two significant impacts [66–68]. First, energy expenses related to the communication sector will increase significantly. Energy cost makes up about 30% of the operational costs of a network operator [7]. Cellular operators' annual energy bills have already surpassed the $10 billion [69] threshold. Second, excessive energy usage creates negative environmental consequences. The information and communication industry is anticipated to produce 1.4 billion tons of carbon dioxide towards global emission totals in 2020 [70]. These factors not only adversely affect human health and environment [7, 44], but also escalate operational expenditure [71]. To deal with this massive demand and skyrocketing energy cost, a green communication network is being envisioned as a new paradigm for future communication networks [27, 72].

Content caching has emerged as a prospective solution to improve the energy efficiency of cache-equipped networks [34, 47]. This is because edge nodes serve user requests locally and consume less transmission energy. However, these nodes require additional energy in operation and maintenance procedures. The use of renewable energy to power up communication networks is considered as an emerging solution to excessive energy consumption and environmental concerns [46, 71]. Among these energy sources, solar has drawn significant attention in recent times [73] because of its declining upfront cost and comparatively easy installation process. However, solar energy supply drops in the evening, when network traffic rises rapidly and reaches its peak [46]. Therefore, it is important to introduce alternative and complementary techniques to make the best use of solar energy in powering cache-equipped networks. As a result, next generation communication networks require optimal allocation of caching resources and innovative traffic-aware management solutions to achieve further energy savings.

At the same time, storing content at the network edge introduces additional security threat [52, 74–76]. Among cacheable content objects, IoT data items are more sensitive to malicious attacks since IoT systems deal with confidential information [56]. In

2016, major websites, including Netflix, Airbnb, and Soundcloud, experienced an unprecedented attack originating from an IoT system [57]. Moreover, the value of the IoT market is expected to bypass $8.9 trillion by 2020 [57]. Hence, an incident related to a security breach can cause significant financial damage.

In recent years, industries have witnessed several cyberattacks. These incidents are predicted to be more frequent with drastic outcomes in the near future [63]. Unauthorized access to IIoT control information may lead to a catastrophic consequence [64]. Consequently, IoT content requires robust authentication process and surveillance systems. A number of preventive measures have been introduced to achieve stringent security. However, preventive services for security threats inevitably increase computational overheads and lead to additional computing delay and energy consumption [51, 77]. These overheads lead to degraded system performances and disruption of services [78]. Therefore, in IoT task caching, simultaneously addressing these conflicting issues is a major research challenge.

Motivated by the above observations, this research explores smart utilization of solar energy for proactive caching. In particular, the investigation of optimal caching time and activation of caching units considering renewable energy supply are explored to achieve substantial energy savings. Furthermore, there is a requirement for simultaneous addressing of stringent security service allotment and energy consumption reduction in IoT systems. Hence, this research also introduces energy-aware caching policies for security service assignment in IoT networks.

1.3 Aims of the thesis

The general aim of this research is to design sustainable caching strategies and investigate trade-offs between security and energy consumption. The specific aims for this research are:

- To develop a proactive caching scheme that exploits intermittent renewable energy and finds optimal time of the day for caching. This technique limits energy cost and improves content availability at the network edge.

- To develop a cooperative content caching method that activates caching units based on traffic demand and solar energy availability. Eventually, the method would reduce on-grid energy demand and carbon dioxide emission.

- To design a strategy for optimal allocation of caching nodes with security features and route selection for IIoT content delivery. This strategy simultaneously reduces energy consumption and security damage cost.

- To introduce a collaborative approach that combines caching, mobile edge computing (MEC), and security service allocation for IoT applications. This technique investigates trade-offs between energy consumption and probable security breach costs, whilst maintaining delay conditions.

1.4 Research contributions

This thesis contributes to the development of caching strategies for future generation networks and optimizes not only energy savings but also secure content delivery. The prime contributions of this research are:

- First, this study demonstrates that proactive content caching using surplus renewable energy has the potential to reduce energy-related costs and create significant benefits for both energy and network service providers. The key idea is to determine the most suitable time of the day to commence caching while utilizing surplus solar energy for proactive caching. The optimal approach considers time as a management tool and designs two models for energy cost minimization. While one model considers self-sustained caching nodes, powered by only solar energy, the other model utilizes both solar and on-grid energy. Numerical analysis demonstrates that the proposed approach not only provides substantial economic benefits to service providers and households, but also reduces peak-to-average disparity of energy load and Internet traffic load.

- Second, the research introduces a caching strategy that stores content at the edge nodes in a cooperative manner considering intermittent renewable energy and variable content load for different hours of the day. The hypothesis is that the amount of renewable energy available to different nodes varies depending on node location and time of the day. The network load across caching nodes also varies with time. Accordingly, if these nodes work collectively, the aggregate non-renewable energy consumption for content caching can be further reduced. The optimization model is designed as a non-linear program (NLP) and converted into an integer linear program (ILP). A heuristic algorithm is also developed to reduce computational complexity. Extensive simulations prove that this strategy achieves a substantial reduction in non-renewable energy consumption without degrading end-to-end (E2E) delay.

- Third, the concept of a trusted caching node (TCN) is developed. TCNs not only cache popular IIoT content, but also provide surveillance and supervisory control to connected links. The proposed model finds the optimum locations for TCNs and selects secure routes for content distribution. A joint optimization problem is formulated to minimize costs related to probable content breach and energy consumption. A secure green caching (SGC) heuristic algorithm is also developed to solve this problem in an acceptable time span. Simulation results demonstrate that the proposed solution achieves significant performance gain and ensures secured IIoT content delivery.

- Fourth, a green and secure mobile edge computing technique is developed by combining caching, cooperative task offloading, and security service assignment for IoT networks. This proposed strategy not only investigates synergies between energy and security issues, but also offloads IoT tasks to edge servers without violating delay requirements. A resource-constrained NLP optimization model is formulated, which minimizes the overall cost combining energy consumption and probable security-breach cost. A two-stage heuristic algorithm is also designed to find an acceptable solution in polynomial time. Simulation results prove that the proposed technique achieves notable improvement over other existing strategies in terms of cumulative costs.

1.5 Thesis outline

This thesis has been organized in the following way.

- **Chapter 1** provides a detailed overview of energy and security related issues of caching. It also contains research significance, aims, contributions, and an outline of the thesis.
- **Chapter 2** presents an explicit review of state-of-the-art caching strategies. It presents a brief description regarding the role of caching in a communication network and identifies associated technical challenges. The green aspects and security related concerns of relevant content caching schemes are also discussed. Furthermore, this chapter scrutinizes research gaps and proposes the research questions to be explored in this thesis.
- **Chapter 3** designs a proactive caching model that exploits intermittent renewable energy and time-varying network traffic load. In this chapter, a practical case study on surplus solar energy supply is provided and the system model is proposed to determine the most suitable time for caching. The research problem is formulated to find optimal caching time and minimize energy-related costs. This technique investigates two different optimization models; one that considers self-sustained helper nodes for caching powered by only solar energy, while other utilizes hybrid energy supply. Finally, this chapter presents the performance analysis of the proposed technique. Compared to other existing techniques, the proposed model achieves significant reduction in energy-related costs and payback periods. This research has been published in the ***Future Generation Computer Systems, vol. 105, pp. 210-221, Apr. 2020.***
- **Chapter 4** develops a cooperative strategy that caches content collectively and schedules caching nodes based on renewable energy availability and Internet traffic demand. In the beginning, a system model is introduced that incorporates network configuration, content popularity, and traffic model. The proposed model also explores green energy supply and delay models for content delivery. After

this, an optimization program is formulated to minimize non-renewable energy consumption without degrading QoE. This chapter also presents a heuristic based on network centrality and solves the optimization problem within a reasonable time span. Finally, the obtained results are compared with a number of existing caching schemes in order to illustrate performance gain. This research has been published in the ***IEEE Transactions on Network and Service Management, vol. 17, no. 1, pp. 375-388, Mar. 2020.***

- **Chapter 5** introduces TCNs to provide caching and security services to the IIoT systems. In this chapter, an optimal policy allocates TCNs to the most suitable nodes and determines routes for energy-efficient and secure content delivery. A unified cost function is developed to combine probable security damage and energy consumption. The study also proposes an optimization model to minimize the unified cost and address the trade-off between energy and security issues of caching. Following this, a heuristic algorithm is developed to solve the problem in real-time. Finally, the chapter illustrates simulation outcomes and proves the effectiveness of the proposed model. This research has been published in the ***IEEE Internet of Things Journal , vol. 7, no. 1, pp. 491-504, Jan. 2020.***

- **Chapter 6** combines MEC and caching for IoT task offloading and designs a model to achieve energy savings as well as stringent security. This technique allocates caching and computing, as well as security resources to offloaded tasks at the network edge. Here, an optimization model jointly reduces energy requirements and probable security damage costs. Subsequently, the problem is decomposed into two sub-problems, where a two-stage heuristic algorithm is developed to solve the problem in polynomial time. Finally, the findings are compared with existing methods to present the performance gain of the proposed system. This research has been published in the ***IEEE Access, vol. 8, pp. 63840-63855, 2020.***.

- **Chapter 7** provides concluding remarks and presents the overall contribution of this research. Finally, areas for future research are identified and recommended.

Chapter 2

Background and Literature Review

Chapter 2 is not available in this version of the thesis.

Chapter 3

A Proactive Content Caching Technique Using Surplus Renewable Energy

3.1 Introduction

As discussed in Chapter 2, the synergy between intermittent solar energy and time-varying network traffic can be investigated to improve the system performance of a cache-equipped network. This chapter considers time as a management tool for the caching nodes and reduces the energy costs of a cache-equipped network with limited backhaul capacity. The proposed model finds optimum time for the utilization of surplus solar energy and caches popular content at the helper nodes. These helper nodes alleviate backhaul bottleneck and serve user requests when the traffic demand is high. Since the helper nodes shorten content delivery distance, both transmission delay and energy requirements drop significantly during peak-load hours.

Chapter 3 is not available in this version of the thesis.

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Chapter 4

A Cooperative Strategy for Green Content Caching

4.1 Introduction

According to Chapter 2, switching-off underutilized networking resources significantly reduces energy consumption. The approach presented in Chapter 3 determines the optimal time for content caching in a helper node to reduce energy costs. However, a collaborative approach combining content caching and the activation of multiple helper nodes can achieve further energy savings. In this chapter, a cooperative content caching strategy is introduced to minimize non-renewable energy consumption while maintaining a minimum end-to-end (E2E) delay in a cache-equipped network.

In the proposed model, network nodes cache popular content in a coordinated manner considering content popularity, hourly content demand, the intermittent supply of renewable energy, and associated E2E delay. If renewable energy supply is inadequate in meeting the energy demand of a helper node, the node utilizes on-grid energy. However, an increase in on-grid energy consumption introduces formidable challenges leading to increased operational expenses and carbon footprints [1, 67]. Therefore, the proposed strategy investigates the cooperative scheduling of the caching units at the helper nodes during various hours of the day. This strategy abates non-renewable energy consumption and activates caching units in relation to the availability of solar energy and user demand.

The main contributions of this chapter are as follows[1]

- This chapter presents a cooperative content caching technique, which incorporates renewable energy utilization and scheduling of data storage units at the helper nodes. The proposed approach is modeled as an optimization problem, which minimizes non-renewable energy consumption while maintaining average E2E delay standard. This model investigates the optimal scheduling of helper nodes and caches content considering available solar energy and predicted traffic demand.
- Considering the importance of a real-time solution, a heuristic algorithm is developed for cooperative green caching leading to a significant performance gain in reducing non-renewable energy consumption.
- The system performance of the proposed technique is analyzed in the form of non-renewable energy consumption, cache hit ratio, and average E2E delay with respect to the helper node locations, skewness parameter, delay threshold, and total cache size. Simulation outcomes establish that the proposed scheme saves more than 23% on-grid energy compared to the existing green solution [44].

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Chapter 5

Secure and Energy-aware Caching

5.1 Introduction

In the previous chapter, a cooperative caching strategy was designed to reduce non-renewable energy consumption by exploiting intermittent solar energy, network traffic, and the scheduling of caching nodes. However, as discussed in Chapter 2, content caching raises concerns over potential security breaches at the network edge. IIoT content objects in particular are more prone and sensitive to security breaches. On the other hand, energy-efficient network design is also a major requirement of the Industrial systems. Therefore, this chapter jointly considers IIoT content caching for energy-efficient content distributions and trusted system allocations at the network nodes for secure content delivery.

The proposed strategy introduces the concept of TCN, which not only caches popular IIoT content but also provides surveillance and supervisory control to the connected links. The optimal placement of the TCNs ensures security of the content forwarding path and upholds the confidentiality of the IIoT content. However, avoiding the unsecured links may upraise the number of content delivery hops and eventually increase energy consumption. Therefore, this study considers associated energy consumption cost and security damage cost while finding the optimal locations for TCNs placement and caching IIoT content objects. The proposed scheme also determines energy-efficient and secure IIoT-content-delivery paths.

The major contributions of this chapter are summarized as:[1]:

- The proposed study introduces the concept of the TCN which provides both caching and security services to the IIoT systems. To allocate the TCNs optimally and cache popular IIoT content, a unified cost function is defined as a combination of the energy consumption cost and the probable security damage cost. Moreover, this study develops an NLP optimization model and converts it into an ILP. The proposed model minimizes the unified cost and ensures optimal TCN placement, content allocation, and secure content delivery.
- A secure green caching (SGC) heuristic algorithm is also designed to solve the optimization problem. The heuristic achieves a near-optimal solution within a reasonable time span.
- Simulation results present associated costs, percentage of unsecured content delivery, and cache hit ratio as measures of system performance. The research outcomes are compared with the existing approach [58, 212] where the proposed technique shows significant improvement in system performance. Moreover, the caching strategy achieves fully secure content delivery with a lesser number of TCNs than the existing approach.

Chapter 5 is not available in this version of the thesis.

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Chapter 6

Green and Secure Computation Offloading for Cache-Enabled IoT Networks

6.1 Introduction

The IIoT content caching technique presented in Chapter 5 reduces both energy consumption and probable security damage. However, to fulfill different QoE requirements, some of these applications require computation-intensive task offloading. As a result, stat-of-the-art IoT applications not only cache IoT data but also offload computation tasks to the edge servers. Moreover, these IoT tasks are also vulnerable to malicious attacks and tampering. Hence, this chapter designs a green and secure task offloading technique for cache-equipped IoT systems.

The proposed model explores caching, cooperation among the BSs, and security service provisioning to achieve energy savings and reduce probable security-breach cost. Optimal allocation of IoT tasks at the MEC servers ensures faster task execution. On the other hand, optimal allocation of the security services to the offloaded tasks is mandatory to accomplish robust security protection. Nonetheless, the security services also cause overheads in terms of energy and delay. Therefore, the proposed strategy not only reduces energy consumption and probable security-breach cost, but also optimally allocates offloaded tasks and maintains delay requirements.

The key contributions of this study are summarized as follows:[1]

- This chapter introduces a green and secure task offloading technique for MEC in IoT networks. The designed system model incorporates caching, cooperation among the MEC servers, and security requirements of the tasks to improve system performance.
- The proposed MEC technique is formulated as a constrained NLP optimization problem, which jointly reduces energy consumption and probable security damage. After that, the NLP is converted into an ILP. The proposed model also maintains delay threshold and optimally allocates tasks for caching and computing at the MEC servers.
- To reduce the complexity of the solution procedure, the optimization model is decomposed into two sub-problems, and a two-stage heuristic algorithm is developed. The proposed heuristic achieves a sub-optimal solution in polynomial time.
- The study also analyzes the system performance of the introduced technique and compares it with existing solutions [38, 53, 250, 251]. The system performance is measured in terms of energy consumption, probable security-breach cost, and average delay. Numerical results show that, compared to other techniques, the proposed technique achieves significant energy savings and reduction in probable security-breach cost.

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Chapter 7

Conclusion and Future Recommendations

7.1 Concluding remarks

The unprecedented uptake of global Internet traffic has forced the telecommunication industry to rethink their traditional approach to delivering broadband services. Content caching is envisioned as a key enabling technique to address this challenge. In caching, the content delivery distance is reduced, and user requests are served locally. As a result, both transmission latency and backhaul congestion are significantly reduced. The deployment of caching units at the network edges creates concerns related to energy consumption and network security. Energy-efficient caching solutions exhibit remarkable potential to minimize operational costs, on-grid energy demand, and greenhouse gas emissions. Furthermore, cached objects at the edges are vulnerable to spoofing, eavesdropping, and malicious attacks. In addition, preventive security services also cause overheads in terms of energy and QoE. Although these topics are of paramount importance, very few of the existing studies adequately investigated them.

This thesis presented novel strategies to improve the energy-efficiency of a caching system and reduce the probability of content breach in a cache-equipped network. To reduce the energy consumption, this thesis exploited intermittent renewable energy supply. The surplus renewable energy was utilized to serve the user requests at the peak traffic hours by designing a cost-effective technique and a cooperative caching node activation mechanism without degrading QoE. As energy-efficient edge caching contributes to higher security threats, this thesis introduced countermeasures to ensure secure content delivery and investigated energy-security trade-offs. The optimal placement of the TCNs and security-aware link selection were designed to protect IIoT networks from cyber-attacks. Another cooperative method intelligently allocated caching, computing, and security resources while satisfying delay requirements. These studies achieved energy savings and improved security stringency.

7.2 Contributions of the thesis

The major findings of this thesis are as follows:

- Chapter 3 introduced a proactive content caching technique, which utilizes renewable energy to store popular content at the network edge. This thesis formulated the research problem of finding the optimum time for proactive caching as an optimization problem and minimized energy-related costs. Simulation results showed that the proposed model reduced energy related cost by 12%. In addition to the economic benefits, this research also reduces the peak-to-average disparity of the energy load and the Internet traffic load.
- In Chapter 4, a cooperative caching strategy was presented to power up the edge nodes by utilizing renewable energy and reduce the on-grid energy requirements. The target of the proposed model was to activate caching nodes according to network traffic demand and exploit intermittent solar energy. The content load across helper nodes varies with time. Thus, cooperative scheduling of the caching nodes using renewable energy reduces aggregate non-renewable energy consumption for content caching. The thesis developed the model as an optimization problem, which was solved using both ILP solvers and heuristic method. The proposed scheme achieves a substantial reduction in on-grid energy consumption by 23% over the existing green solution.

- Chapter 5 introduced an optimal method for TCNs placement and security-aware content forwarding. The purpose of this technique was to find the best route which jointly considered energy requirements and probable security breach. In this study, an optimization model minimized a unified cost function, which combined both energy consumption and probable security damage cost. A heuristic algorithm also solved the problem in real time. The study not only reduces the unified cost, but also achieves fully secure content transmissions with the help of a minimum number of TCNs.

- Mobile edge computing integrated with IoT applications offloads computation intensive tasks to the servers at the network edge. This technique shows remarkable potential in reducing energy consumption and delay. However, the offloaded tasks are exposed to multiple users and vulnerable to malicious attacks and eavesdropping. In Chapter 6, a green and secure MEC technique, which combined caching, cooperative task offloading, and security service assignment for IoT networks, was introduced. The study formulated an optimization model, which minimized both energy consumption and probable security-breach costs while maintaining delay conditions. To solve the problem in polynomial time, a two-stage heuristic algorithm was also developed. The proposed model significantly improves energy savings and reduces security breach costs compared to other existing techniques.

7.3 Future research direction

This thesis has introduced a new research direction in the field of green communications where researchers can work to optimize the synergy between available renewable energy and content caching. Optimal security service allocation and trade-off investigation related to energy consumption and probable content leakage have also been addressed to design secure content caching and transmission. However, there are provisions for further investigations based on following considerations:

The intelligent management of the cache storage units and user participation can be considered to ensure the diversity of content and limit redundancy using an auction-based game. In the proposed model, households with solar services will cache popular content in data storage units and serve content to the users on behalf of service providers. The households will bid to the service providers for permissions. Furthermore, to serve the interests, the service providers will allocate a content object to a specific household within a predefined coverage area.

In future, a model can be designed to identify the untrusted MEC servers at the edge and allocate the confidential tasks only to the secure edge servers for caching and offloading. This strategy will operate the MEC servers using solar energy and reduce content delivery delay subject to predefined security conditions. Moreover, the strategy will also consider parallel task processing.

Another security-aware caching model can be developed on the basis of graph-theory models to address the cascading failures in a cache-equipped network. If there is any failure at a node, the proposed model will update the capacity of the serving caching nodes by activating additional data storage units.

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