Dynamic Replication for Secure Mobile Caching: A Control Theoretic Approach

Taek-Young Youn[1]*, Ki-Woong Park[2]†, and Joongheon Kim[3]
[1]ETRI, Daejeon, Republic of Korea
taekyoung@etri.re.kr
[2]Sejong University, Seoul, Republic of Korea
woongbak@sejong.ac.kr
[3]Chung-Ang University, Seoul, Republic of Korea
joongheon@cau.ac.kr

Abstract

This paper proposes a reliable and self-adaptive reliability maximization policy for virtual machine replication in distributed cloud servers. In order to guarantee reliable virtual machine services, cloud computing service providers are operating virtual machine replication into multiple servers in order to provide seamless services even though several servers are out of order. In this replication-based cloud server system, our proposed algorithm controls the number of virtual machine replications for time-average maximization of reliability under server storage capacity limits based on the theory of Lyapunov optimization. As verified through simulation-based data intensive performance evaluation, our proposed algorithm presents desired results.

Keywords: Dynamic replication, Mobile caching, Distributed cloud computing

1 Introduction

In recent years, security and privacy related issues have received significant attention by industry and academia research communities [6, 23, 19, 25, 3, 24, 22, 21, 5]. The proposed security and privacy-preserving algorithms obviously present excellent performances, however higher performance are desired in order to design more robust and secure cloud computing platforms.

In this paper, we consider the case where the distributed cloud computing platform provides remote virtual machine (VM) services to end users. As presented in Fig. 1, when each user creates VM in cloud computing platforms, the platform *replicates* the VM in each distributed cloud servers in order to ensure reliable VM services. If only one VM is created in a single cloud server, the VM service cannot be properly provided when the cloud server is out of order. This kind of replication-based reliability-preserving methods have been actively studied in the literature [25].

In order to design secure and reliable cloud computing service platforms with VM replication-based reliability-reserving, the efficiency on storage capacity utilization should be considered. If the VM replication algorithm is independent to the consideration of storage capacity, the algorithm definitely introduces inefficient utilization of storage memories. Therefore, the storage capacity dependent algorithms should be designed in the resource-constrained computing platforms.

In this paper, we designs a dynamic algorithm which controls the number of VM replications in distributed clod services under the consideration of available storage capacity. In order to guarantee

---

IT CoNvergence PRActice (INPRA), volume: 6, number: 4 (December 2018), pp. 12-20

*Corresponding author: ETRI, 138, Gajeongno, Yuseong-gu, Daejeon, 34129, Korea, Tel: +82-10-6851-3238

†Corresponding author: Sejong University, 98, Gunja-dong, Gwangjin-gu, Seoul, Korea, Tel: +82-10-9165-1624

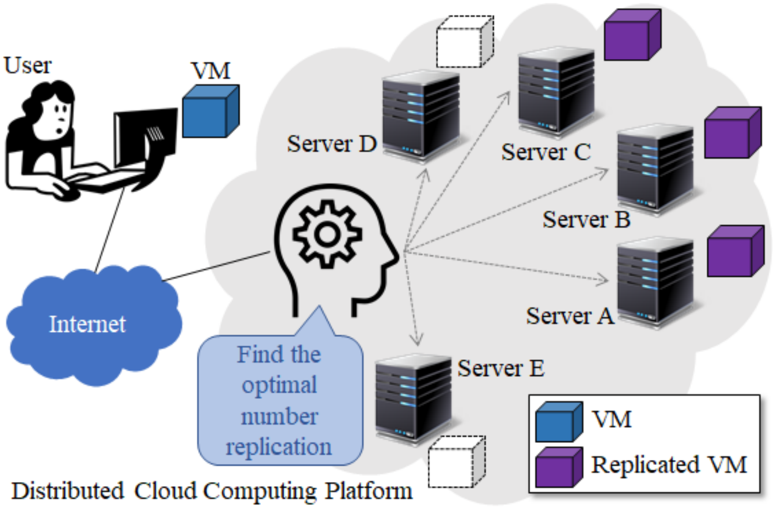


Figure 1: Reference distributed cloud computing server model.

the time-average optimality of reliability maximization under the consideration of storage capacity, Lyapunov optimization framework is used for the dynamic time-average optimization algorithm design [16].

Our proposed algorithm works as follows. First of all, the algorithm checks the available storage capacity. Based on the information, it determines the number of VM replications in distributed servers. If the available storage capacity is huge enough, the algorithm can do the VM replication as much as possible due to the fact that there are enough spaces in distributed servers. On the other hand, if the available storage capacity is not enough, the proposed algorithm reduces the number of VM replications under the consideration of resource-limitation. For this operation, the exact number of VM replications is determined by Lyapunov optimization framework for mathematical time-average maximization of reliability under storage capacity limitations.

The remainder of this paper is organized as follows: Section 2 gives preliminaries and background information. Section 3 explains the details of our proposed time-average expected reliability index maximization subject to storage capacity constraints. Section 4 shows the performance evaluation results which verify the novelty of the proposed algorithm. Section 5 concludes this paper and presents future research directions.

2 Preliminaries

In this preliminary section, our considering reference cloud computing system model is explained in Section 2.1. Lastly, our related work is summarized in Section 2.2.

2.1 Reference System Model

Our considering reference distributed cloud computing platform can be illustrated as shown in Fig. 1. Note that this reference system is widely acceptable in the distributed cloud computing system design and implementation [1, 23].

As presented in Fig. 1, each user is remotely able to generate VMs in distributed cloud computing servers. Suppose that the generated VM is located in the Server A as shown in Fig. 1. If the server A is our of order and also in malfunction/fault due to unexpected situations or natural disasters, the

VM cannot be loaded by the owner user. This situation should be avoided for providing reliable cloud computing services.

One of major approaches to the problem is *replication* [2, 25]. In general, the replication-based reliable algorithms work as follows. Suppose that each user generates VMs in distributed cloud computing servers. Then, the VMs are replicated and stored in multiple servers in the distributed cloud computing platform. In Fig. 1, a user remotely generates a single VM in cloud computing platform; and then the VM is stored into servers A, B, and C. Finally, the three servers have the VM and the replicated VMs are all equivalent to each other.

It is obvious that the most reliable method is the replication of newly generated VM into all existing cloud computing servers (i.e., servers A, B, C, D, and E in Fig. 1). However, it will dramatically increase server storage utilization by the replicated data. This means that the available server storage capacity will rapidly decrease. Thus, we can observe the *tradeoff relationship between reliability and storage capacity*. Thus, we need to design a new dynamic algorithm which can control the number of replications in distributed cloud computing servers. As an example, we can observe that the generated VM is replicated into servers A, B, and C (i.e., the number of replications is 3). On the other hand, servers D and E do not have the replicated VMs. The main objective of this control is the *reliability maximization while avoiding the situation where many replications are conducted even though we have few available storage capacity*.

2.2 Related Work

The stochastic network optimization based drift-plus-penalty (DPP) algorithm which is based on Lyapunov control theory (time-average penalty minimization, i.e., utility maximization, while guaranteeing system/queue stability) [18] is scalable, and thus the algorithm can be used for many applications with simple modifications as follows.

In *multimedia applications*, J. Kim, *et. al.* [8] proposed an algorithm for time-average video streaming quality maximization subject to transmission queue stability in device-to-device (D2D) video delivery. The corresponding Android software implementation is also demonstrated in [12]. J. Koo, *et. al.* [13] proposed a dynamic adaptive streaming over HTTP (DASH) algorithm for time-average video streaming quality maximization under the consideration of energy status, LTE data quota, and transmission queue stability in integrated LTE/WiFi networks. In *Multicore computing applications*, J. Kim, *et. al.* [10, 11, 7] designed an energy-efficient multicore computing platforms for 5G millimeter-wave base station and medical big-data platforms under buffer stability. For *communications applications*, M. J. Neely, *et. al.* [15] designed an energy-efficient multi-hop routing which is for time-average energy consumption minimization subject to node queue stability. Its corresponding practical implementation was presented and discussed in [14, 20, 4]. For the others, The application of Lyapunov optimization framework to dynamic Markov decision process (MDP) policy design is discussed in [17]; and the other application to smart grid consumer satisfaction maximization is presented in [18].

In this paper, our proposed algorithm controls the number of VM replications while observing available storage capacity in order to avoid storage capacity overflow.

3 Replication Adaptation (RA) Algorithm

The basic design concept of the proposed algorithm in this paper is well introduced in Section 3.1; and the details of the algorithm is described in Section 3.2.

3.1 Design Rationale

In our proposed VM replication adaptation algorithm, the number of VM replications is controlled in each unit time depending on the amount of available storage capacity. If the amount of available storage capacity is big enough, more replication can be allowable. On the other hand, the amount of available storage capacity is not big, the number of replication should be controlled in order to avoid the case where the storage capacity becomes fully utilized by the replication. The control of the number of VM replication in the proposed algorithm is managed by Lyapunov optimization framework in order to maximize time-average expected reliability index while avoiding storage capacity overflow.

3.2 Main Algorithm

Our proposed algorithm aims at the time-average expected reliability index maximization subject to storage capacity stability (i.e., avoiding the situation where replication happens even though the storage is fully utilized). This mathematical optimization problem can be formulated as follows:

$$\max : \lim_{t\to\infty} \sum_{\tau=0}^{t-1} \mathbb{E}\left[R(\tau)\right] \tag{1}$$

where

- $R(t)$:reliability index at time t,
- $\mathbb{E}[\cdot]$: expectation,

and the storage capacity constraint (avoiding storage capacity overflow) as follows:

$$\lim_{t\to\infty} \frac{1}{t} \sum_{\tau=0}^{t-1} \mathbb{E}\left[S(\tau)\right] < \infty. \tag{2}$$

where

- $S(t)$: storage occupancy by virtual machine placement at time t,

and this storage occupancy can be mathematically formulated as follows [16]:

$$S(t+1) = \max(S(t) - \mu(t), 0) + \lambda(t) \tag{3}$$

where

- $\mu(t)$: the amounts of total removed virtual machine sizes from the storage at time t (unit: bit) and
- $\lambda(t)$: the amounts of the replicated virtual machine at time t (unit: bit).

According to the Lyapunov optimization theory based DPP algorithm [16], this program can be reformulated as following where $\lambda^*(t)$ is time-average optimal number of VM replications for maximizing expected reliability index:

$$\lambda^*(t) \leftarrow \arg\max_{\lambda(t)\in\Lambda} \left\{V \cdot R(\lambda(t)) - S(t)\cdot\lambda(t)\right\} \tag{4}$$

where $\lambda^*(t)$ is time-average optimal number of VM replications for time-average expected reliability index maximization subject to storage stability, and also the Λ is the set of all possible replication numbers where

$$1, 2, \cdots, M \in \Lambda \tag{5}$$

where M is the number of physical cloud servers in the distributed cloud computing platform. In addition, V is the tradeoff coefficient between reliability performance and stability, respectively. Note that the $\mu(t)$ in (3) is out of control (i.e., the value is not associated with the number of VM replications). Therefore, that can be ignored in Lyapunov optimization framework. Lastly, the $R(\lambda(t))$, i.e., reliability index, is monotonously increasing when the number of VM replications increases. Therefore, it is denoted as a function of $\lambda(t)$ in (4).

Semantically, this (4) can be evaluated as follows:

- *Sufficient spaces in available storage capacity:* Suppose that $Q(t) \approx 0$. Due to (4),

$$\lambda^*(t) \leftarrow \arg\max_{\lambda(t)\in\Lambda} \{V \cdot R(\lambda(t)) - 0 \cdot \lambda(t)\} \tag{6}$$

$$= \arg\max_{\lambda(t)\in\Lambda} V \cdot R(\lambda(t)) \tag{7}$$

thus we have to select $\lambda(t)$ which can maximize reliability index $R(\lambda(t))$. It is obvious that the biggest number of VM replications guarantees the maximum reliability index, i.e.,

$$P(\lambda_1(t)) \geq P(\lambda_2(t)), \text{ when } \lambda_1 \geq \lambda_2. \tag{8}$$

Therefore, it can be verified that $\lambda^*(t)$ will be the maximum value among the elements of Λ. This is semantically true because it is beneficial to select the maximum number of VM replications to maximize time-average reliability of the system.

- *Insufficient spaces in available storage capacity:* Suppose that $Q(t) \approx \infty$. Due to (4),

$$\lambda^*(t) \leftarrow \arg\max_{\lambda(t)\in\Lambda} \left\{ \underbrace{V \cdot P(\lambda(t))}_{\text{much smaller than } \infty} - \infty \cdot \lambda(t) \right\} \tag{9}$$

$$\approx \arg\max_{\lambda(t)\in\Lambda} -\lambda(t) \tag{10}$$

$$= \arg\min_{\lambda(t)\in\Lambda} \lambda(t) \tag{11}$$

thus we have to select the minimum number of VM replication among the elements of Λ, i.e., $\lambda^*(t) = 1$. This is semantically true because it is better to select the minimum number of VM replications if the available storage capacity is almost not available.

Therefore, our proposed replication control algorithm with closed-form equation (4) should work in each unit time after observing available storage capacity $S(t)$ and it is mathematically proven that it can guarantee time-average reliability maximization subject to system stability. Based on this nature, it can be said that our proposed algorithm is self-adaptive because it can control its own reliability automatically.

4 Performance Evaluation

This section consists of simulation settings (refer to Section 4.1 and simulation results depending on various setting of tradeoff coefficients (refer to Section 4.2).

4.1 Simulation Setting

In order to evaluate the performance of the proposed dynamic VM replication algorithm, we implemented the matlab-based simulator for that.

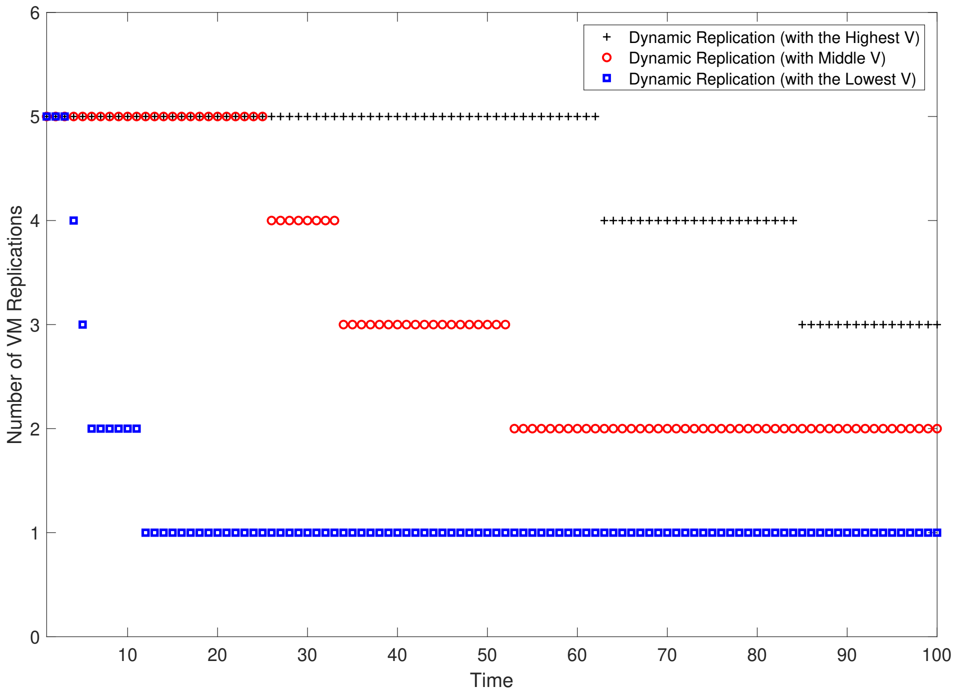


Figure 2: Simulation results – Dynamics on the number of VM replications.

In the performance evaluation, we set that the number of cloud servers is 5 (i.e., $\Lambda = \{1,2,3,4,5\}$). In addition, the reliability index depending on the number of VM replications are computed as follows:

$$R(n) \triangleq 100 \times \frac{\log_e(n)+1}{\log_e(M)+1} \tag{12}$$

where n stands for the number of VM replications, M stands for the maximum number of VM replications which is equivalent to the number of distributed cloud servers (i.e., $M = 5$ in this simulation study), and $R(x)$ stands for the reliability index, respectively. Notice that this formulation is inspired by the quality of video streaming (which is the index for the quality/reliability of transmission over lossy video streaming) [9]. In addition, note that our proposed Lyapunov control based algorithm can work even though different types of reliability functions are used (instead of (12)) for simulation-based performance evaluation.

4.2 Simulation Results

For simulation-based performance evaluation, we operate our proposed dynamic replication algorithm with various V settings (the highest, middle, and the lowest) and perform the simulations in terms of the dynamics on the number of VM replications.

4.2.1 Dynamics on the number of VM replications

For the first simulation results as presented in Fig. 2, we measure the dynamics on the number of VM replications depending on various V value settings.

When we have high V setting in our proposed closed-form equation, i.e., (4), the control algorithm should work with more weights on reliability, rather than storage stability. Therefore, we can observe that our algorithm with the highest V pursues the highest reliability index values rather than the others, as presented in Fig. 2.

On the other hand, when we have low V in (4), our control algorithm works for more conservative operation in order to manage available storage capacity. Therefore, certain amounts of reliability are sacrificed due to the reduction of the number of VM replications. Therefore, we can observe that the dynamic replication with the lowest V in Fig. 2 shows the smallest number of VM replications rather than the other approaches.

5 Concluding Remarks and Future Work

In this paper, we propose a secure and reliable virtual machine (VM) management algorithm for distributed cloud servers. When a user remotely generates VM into distributed cloud computing platforms, the platform stores the generated VM into physical cloud servers. For reliable service provisioning, there are many approaches and one of the major approaches is the replication of the generated VM into multiple cloud servers. Even though it is true that many replication introduces more reliability, it is not efficient in terms of storage memory management. Therefore, it is important to find the optimal number of VM replications which is for the joint optimization of reliability and storage management efficiency. Based on this observation, we designed a dynamic algorithm which can control the number of VM replication under the consideration of storage capacity limits for time-average reliability maximization, inspired by Lyapunov optimization framework. As verified with simulation-based performance evaluations, we can insist that our proposed algorithm works as desired.

Acknowledgment

This work was supported by National Research Foundation of Korea (NRF Korea) [2016R1C1B1015406] and Electronics and Telecommunications Research Institute (ETRI) grant funded by the Korean government. [18ZH1200, Core Technology Research on Trust Data Connectome]. T.-Y Youn and K.-W. Park are corresponding authors of this paper.

References

[1] M. F. Bari, R. Boutaba, R. Esteves, L. Z. Granville, M. Podlesny, M. G. Rabbani, Q. Zhang, and M. F. Zhani. Data center network virtualization: A survey. *IEEE Communications Surveys & Tutorials*, 15(2):909–928, September 2012.

[2] A. G. Dimakis, K. Ramchandran, Y. Wu, and C. Suh. A survey on network codes for distributed storage. *Proceedings of the IEEE*, 99(3):476–489, February 2011.

[3] H. Goudarzi and M. Pedram. Energy-efficient virtual machine replication and placement in a cloud computing system. In *Proc. of the 2012 IEEE Fifth International Conference on Cloud Computing (CLOUD'12), Honolulu, Hawaii, USA*, pages 750–757. IEEE, June 2012.

[4] L. Huang, S. Moeller, M. J. Neely, and B. Krishnamachari. LIFO-backpressure achieves near optimal utility-delay tradeoff. *IEEE/ACM Transactions on Networking*, 21(3):831–844, July 2012.

[5] G. Karame, M. Neugschwandtner, M. Önen, and H. Ritzdorf. Reconciling security and functional requirements in multi-tenant clouds. In *Proc. of the 5th ACM International Workshop on Security in Cloud Computing (SCC'17), Abu Dhabi, United Arab Emirates*, pages 11–18. ACM, April 2017.

[6] G. Kim, H. Park, J. Yu, and W. Lee. Virtual machines placement for network isolation in clouds. In *Proc. of the 2012 ACM Research in Applied Computation Symposium (RACS'12), San Antonio, Texas, USA*, pages 243–248. ACM, October 2012.

[7] J. Kim. Buffer-stable adaptive per-module power allocation for energy-efficient millimeter-wave modular antenna array (MAA) platforms. In *Proc. of the 2016 IEEE Conference on Computer Communications Workshops (INFOCOM'16), San Francisco, California, USA*, pages 820–821. IEEE, April 2016.

[8] J. Kim, G. Caire, and A. F. Molisch. Quality-aware streaming and scheduling for device-to-device video delivery. *IEEE/ACM Transactions on Networking*, 24(4):2319–2331, July 2015.

[9] J. Kim, S. C. Kwon, and G. Choi. Performance of video streaming in infrastructure-to-vehicle telematic platforms with 60-GHz radiation and IEEE 802.11ad baseband. *IEEE Transactions on Vehicular Technology*, 65(12):10111–10115, March 2016.

[10] J. Kim, J. J. Lee, J. K. Kim, and W. Lee. Energy-efficient stabilized automatic control for multicore baseband in millimeter-wave systems. *IEEE Access*, 5:16584–16591, August 2017.

[11] J. Kim and W. Lee. Stochastic decision making for adaptive crowdsourcing in medical big-data platforms. *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, 45(11):1471–1476, April 2015.

[12] J. Kim, F. Meng, P. Chen, H. E. Egilmez, D. Bethanabhotla, A. F. Molisch, M. J. Neely, G. Caire, and A. Ortega. Adaptive video streaming for device-to-device mobile platforms. In *Proc. of the 19th ACM International Conference on Mobile Computing and Networking (MobiCom'13), Miami, Florida, USA*, pages 127–130. ACM, September-October 2013.

[13] J. Koo, J. Yi, J. Kim, M. A. Hoque, and S. Choi. REQUEST: seamless dynamic adaptive streaming over HTTP for multi-homed smartphone under resource constraints. In *Proc. of the 2017 ACM Multimedia Conference (MM'17), Mountain View, California, USA*, pages 934–942. ACM, October 2017.

[14] S. Moeller, A. Sridharan, B. Krishnamachari, and O. Gnawali. Routing without routes: the backpressure collection protocol. In *Proc. of the 9th ACM/IEEE International Conference on Information Processing in Sensor Networks (IPSN'10), Stockholm, Sweden*, pages 279–290. ACM, April 2010.

[15] M. J. Neely. Energy optimal control for time varying wireless networks. *IEEE Transactions on Information Theory*, 52(7):2915–2934, July 2006.

[16] M. J. Neely. *Stochastic Network Optimization with Application to Communication and Queueing Systems*. Morgan & Claypool, 2010.

[17] M. J. Neely and S. Supittayapornpong. Dynamic Markov decision policies for delay constrained wireless scheduling. *IEEE Transactions on Automatic Control*, 58(8):1948–1961, April 2013.

[18] M. J. Neely, A. S. Tehrani, and A. G. Dimakis. Efficient algorithms for renewable energy allocation to delay tolerant consumers. In *Proc. of the 1st IEEE International Conference on Smart Grid Communications (SmartGridComm'10), National Institute of Standards and Technology, Gaithersburg, Maryland, USA*, pages 549–554. IEEE, October 2010.

[19] H. Roh, K. Kim, S. Pack, and W. Lee. Flow and virtual machine placement in wireless cloud data centers. In *Proc. of the 12th International Conference on Heterogeneous Networking for Quality, Reliability, Security and Robustness (QSHINE'16), Seoul, South Korea*, volume 199 of *Lecture Notes of the Institute for Computer Sciences, Social Informatics and Telecommunications Engineering*, pages 138–148. Springer, July 2016.

[20] A. Sridharan, S. Moeller, and B. Krishnamachari. Making distributed rate control using Lyapunov drifts a reality in wireless sensor networks. In *Proc. of the 6th IEEE International Symposium on Modeling and Optimization in Mobile, Ad Hoc, and Wireless Networks and Workshops (WiOpt'08), Berlin, Germany*, pages 452–461. IEEE, April 2008.

[21] C. Wang. Some challenges on enabling encrypted cloud media centre. In *Proc. of the 3rd ACM International Workshop on Security in Cloud Computing (SCC'15), Singapore*. ACM, April 2015.

[22] C. Wang, K. Ren, and J. Wang. Secure optimization computation outsourcing in cloud computing : A case study of linear programming. *IEEE Transactions on Computers*, 65(1):216–229, March 2015.

[23] M. Wang, X. Meng, and L. Zhang. Consolidating virtual machines with dynamic bandwidth demand in data centers. In *Proc. of the 2011 IEEE International Conference on Computer Communications (INFOCOM'11), Shanghai, China*, pages 71–75. IEEE, April 2011.

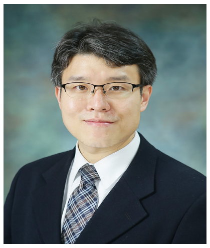
[24] Y. Zheng, H. Cui, C. Wang, and J. Zhou. Privacy-preserving image denoising from external cloud databases.

IEEE Transactions on Information Forensics and Security, 12(6):1285–1298, January 2017.

[25] A. Zhou, S. Wang, B. Cheng, Z. Zheng, F. Yang, R. N. Chang, M. R. Lyu, and R. Buyya. Cloud service reliability enhancement via virtual machine placement optimization. *IEEE Transactions on Services Computing*, 10(6):902–913, January 2017.

Author Biography

Taek-Young Youn received his BS, MS, and Ph.D from Korea University in 2003, 2005, and 2009, respectively. He is currently a senior researcher at Electronics and Telecommunications Research Institute (ETRI), Daejeon, Korea. From 2016, he serves as an associate professor in University of Science and Technology (UST), Daejeon, Korea. His research interests include cryptography, information security, authentication, data privacy, and security issues in various communications.



Ki-Woong Park received the BS degree in computer science from Yonsei University in 2005, and the MS and PhD degrees in electrical engineering from KAIST in 2007 and 2012, respectively. He is currently an assistant professor in the Computer and Information Security Department at Sejong University. He worked as a researcher at the National Security Research Institute in 2012. His research interests include system security issues for cloud and mobile computing systems as well as the actual system implementation and subsequent evaluation in a real computing system. He received a 2009-2010 Microsoft Graduate Research Fellowship. He is a member of the IEEE and the ACM.

Joongheon Kim (M'06–SM'18) has been an assistant professor with Chung-Ang University, Seoul, Korea, since 2016. He received his B.S. (2004) and M.S. (2006) in computer science and engineering from Korea University, Seoul, Korea; and his Ph.D. (2014) in computer science from the University of Southern California (USC), Los Angeles, CA, USA, with two additional M.S. in electrical engineering and computer science (specialization in high performance computing and simulations). In industry, he was with LG Electronics Seocho R&D Campus (Seoul, Korea, 2006–2009), InterDigital (San Diego, CA, USA, 2012), and Intel Corporation (Santa Clara, CA, USA, 2013–2016). He is a senior member of the IEEE; and a member of the ACM and IEEE Communications Society.