Cross-Layer Design for Caching Scheme by using Successive Interference Cancellation in Information-Centric Network-based Wireless Sensor Network

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Abstract—**Advanced wireless sensor network technologies, such as the Internet of Things and Machine to Machine, have recently been widely applied to various fields. The network protocol of future wireless networks, however, requires sensing data from the various monitoring values in the large-scale wireless sensor network and, hence, may not be effectively built if based on the current host-centric scheme. We must therefore redesign based on a content-centric concept. From this perspective, we focus on an information-centric network-based wireless sensor network framework. We propose a novel, efficient caching scheme using overhearing phenomena, and boost the proposed caching mechanism by using the successive interference cancellation technique. Moreover, we propose protocol stacking and signal processing based on a cross-layer design. Our numerical result reveals that the amount of stored sensing data can be increased, the number of multi-hops reduced, and the distance of data transfer between the publisher and subscriber nodes improved by using the exhaustive computer simulation.**

Keywords—wireless sensor network; information-centric network; caching scheme; successive interference cancellation; cross-layer design.

I. INTRODUCTION

New WSNs (Wireless Sensor Networks), such as IoT (Internet of Things) and M2M (Machine to Machine), play a primary role in providing global access by using billions of various devices. In general, a WSN system is constructed based on vast amounts of resource-constrained sensor nodes, e.g., a low-performance processor, low-capacity memory, and limited battery. However, we expect that the hardware limitations of current WSN devices will lessen in the near future. Therefore, we believe that it is necessary to redesign not only the radio transmission procedure, but also the network architecture and technologies for an advanced WSN framework. On the other hand, most users are interested in accessing the same contents or information sources, such as Google, Facebook, YouTube, Amazon, and Dropbox, despite the availability of numerous other web services over the last few years. This epidemic trend has led to a new paradigm shift in which the network architecture is designed from a content-oriented aspect. In view of the evolving network framework, the ICN (Information-Centric Network) scheme promotes a new communication model [2][3]. We note that the current WSN's network protocol is founded upon the host-centric and IP-based network architecture, such as the traditional Internet infrastructure. In short, the ICN architecture is fundamentally different from the host-centric network, i.e., the major concept of ICN is an ability to retrieve data independently from the current location where the required sensing data are provided.

ICN design has been investigated not only for wired networks, such as the post/next Internet architecture, but also for wireless and mobile networks. For example, in a cellular telecommunications system, popular content is copied onto several intermediate servers called middle-box gateways or routers [4][5]. As a result, frequent requests for the same content data can be effectively provided without requiring the content providers to transfer the redundant data, thus reducing the number of data transmissions. The concept of an improvement mechanism for the ICN scheme resembles the CDN (Content Delivery Network) technique. In the CDN scheme, mirrored content data are stored and provided by using the in-network content servers of service providers; whereas, in the ICN scheme, the copied content data are cached and distributed by using the cache memory of the individual network node.

As another related topic, for content flow, Higuchi and Hirotsu [6] proposed a novel verification-based flow space management based on the OpenFlow method that is a form of SDN (Software Defined Networking) technology. On the other hand, Zhang et al. and Amadeo et al. [7][8] investigated and surveyed emerging and hot trends in ICN-based and IoT/M2M-oriented WSNs, e.g., naming formulation, name resolution technique, data routing formula, caching mechanism, mobility support, and security protection. In addition, Wang et al. [9] examined two promising technologies: the wireless network virtualization and ICN scheme for the D2D (Device to Device)-assisted cellular network. Based on the above, in this paper, we place particular focus on the caching mechanism in order to share duplicated content data effectively. In general, there are two common principles for caching methodologies: the on-path caching scheme and the off-path caching scheme [10]. In short, in the on-path caching scheme, content data are copied along with the routing path by name resolution requests, whereas, in the off-path caching scheme, the network node located outside the routing path actively and positively executes the caching transaction.

In related studies of the caching mechanism, in the traditional ICN architecture, the DONA (Data-oriented Network Architecture) framework [11] and the NDN (Named

Data Networking) framework [12] support natively based on the on-path caching scheme. On the other hand, Sourlas et al. [13] proposed four online intra-domain cache management algorithms with different levels of automaticity and compared them with respect to performance, complexity, execution time, and message exchange overhead to achieve both the on-path and off-path caching schemes. Wang et al. [14] proposed a collaborative in-network caching scheme that users both the content-space partitioning method and hash-routing technique in order to exploit the built-in caching capability of the ICN framework fully. Hajimirsadeghi et al. [15] investigated joint caching and pricing strategies based on duplicated content popularity with the game theoretic approach. Li et al. [16] proposed a modern dynamic caching mechanism for video streaming in order to guarantee QoS (Quality of Service) in terms of average throughput.

In general, most researchers have utilized an exclusive and additive mechanism for replication of the frequently referred content data, which is undoubtedly a proper solution in a wired network. However, in this paper, we adopt a different approach for WSN; we effectively utilize the specific wireless feature. In our previous study [1], we proposed a novel scratch and blueprint strategy of the efficient caching scheme for the ICN-based WSN. We proposed a new off-path caching mechanism using overhearing phenomena and the SIC (Successive Interference Cancellation) technique [17] in order to boost caching capability. We note that, for the overhearing phenomena, when a sensor node wirelessly transmits any content data, its neighbor sensor nodes located in the transmitter sensor node's coverage area can watch the forwarding content data due to free-space radio propagations, regardless of whether it is necessary. In other words, by using the overhearing phenomena, the proposed scheme can achieve an off-path caching scheme without using alternative exclusive control packets and without introducing additional and sophisticated wireless communication systems.

As another key element technology of the proposed scheme, the SIC technique has been extensively studied as a familiar interference reduction mechanism at the physical layer [18]. SIC application technologies have already appeared as industry solutions for cellular and mobile communication systems, such as Qualcomm's CSM6850 chipset [19]. With the SIC method, the SIC-based receiver decodes the strongest signal in the parallel received signals from several various transmitters. If the strongest signal is successfully recovered, the correct decoded signal is encoded again and the re-encoded signal is subtracted from the received signal. As a result, the decoding performance of the remaining signal can be improved by removing the strongest interference; however, its performance and behavior in the ICN-based WSN remain unknown. Hence, our study can provide significant preliminary evaluations.

Furthermore, for introducing the SIC technique into the ICN-based WSN system, it is important to consider the protocol layers holistically and integratively, and the protocol stack must be optimized. To the best of our knowledge, this optimization problem can be solved in a cross-layer design manner [20][21]. Cross-layer design is a new paradigm in network architecture that involves the interaction and sharing of significant information among layers. If we optimize the protocol stack by using the cross-layer design concept, several layers with different functionality performance can collaboratively work together.

Consequently, we summarize the contributions of our paper as follows:

- We formulate an ICN-based WSN framework for adopting the proposed caching mechanism.
- We propose a novel caching scheme based on both the overhearing phenomena and SIC technique.
- We propose a protocol design and procedure of signal processing for the proposed caching mechanism based on the cross-layer design concept.
- We demonstrate the effectiveness of the proposed scheme via exhaustive computer simulation.

The remainder of our paper is organized as follows: Section II describes the manner of the proposed scheme; Section III provides the computer simulation results; and finally, we conclude with our acknowledgments and conclusions.

II. Proposed Scheme

In the ICN-based WSN, the proposed scheme is constructed based on the overhearing phenomena and SIC technique in order to construct an efficient caching mechanism. In this chapter, after presenting our network model and the proposed caching mechanism based on the above two key technologies, we will provide the protocol stack and signal processing procedure for the proposed caching mechanism based on the cross-layer design concept.

A. *Network Model of Information-Centric Network Based Wireless Sensor Network*

In the network model of the proposed scheme, as shown in Figure 1, sensor nodes are distributed on the surface of the observation area and these sensor nodes measure the environmental monitoring values as the sensing data. Unlike the traditional host-centric network model in which the sensing data are gathered in a fusion center or cloud server, in the proposed scheme, the sensing data are managed in the WSN devices and stored among sensor node devices. As a common policy of the ICN-based system, when a sensor node acquires sensing data that have been already requested from other nodes, there is no difference between the original sensing data and the duplicated caching data. Therefore, in the proposed scheme, as shown in Figure 1, the sensor nodes copy and store the sensing data in their cache memories as much as possible.

As the caching transaction trigger, the proposed scheme executes when the sensing data are transferred from the publisher node (source) to the subscriber node (destination). Specifically, when a user wants to acquire the sensing data, the user accesses any nearest and acceptable sensor node located in the proposed WSN system; that is, the sensor node

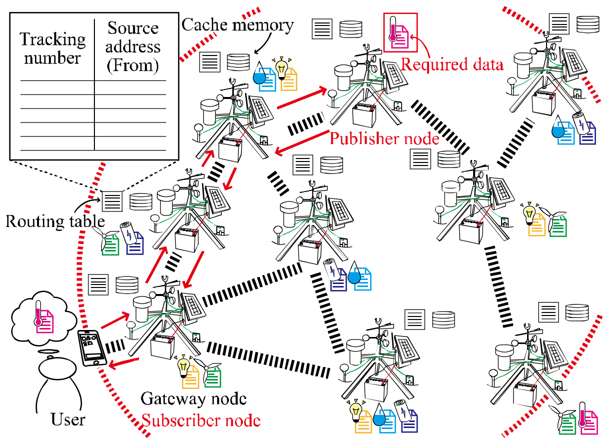

Figure 1. Network model of the proposed ICN-based WSN framework.

works as a gateway node between the proposed WSN system and the users. In addition, the gateway node behaves as the subscriber node instead of the users; that is, the gateway node broadcasts the request message of the sensing data acquisition among the proposed WSN member nodes. When the request message arrives at the sensor node, the sensor node searches for the requested sensing data in its cache memory. If the sensor node finds the target sensing data, the sensor node holding the desired data replies to the subscriber node with its data as the publisher node in the response transaction. Therefore, the proposed scheme establishes a routing path from the publisher node to the subscriber node to transfer the required sensing data, the detailed procedure for which will be described later. In addition, a benefit of the proposed scheme is that the popular sensing data frequently requested by users are cached because of the above procedure. Thus, the proposed scheme promotes effective sensing data acquisition.

As shown in Figure 2, we define and utilize three kinds of packets: the sensing data packet, the find packet, and the response packet. Especially, as shown in Figure 2 (a), the sensing data packet consists of two components—the header section and payload section. In the sensing data packet, the header part contains extra information, e.g., time, location, and sensor node identifier, that operates as searching tags when the subscriber requests their desired sensing data, whereas the payload part should be defined depending on the usage environment of the proposed WSN framework. Moreover, the find packet and the response packet have an identifier number, source/destination address, and the sensing data for the searching transaction, and the response packet also has the replied sensing data, as shown in Figures 2 (b) and (c). On the other hand, every sensor node has not only the cache memory, but also a routing table, as shown in Figure 1. Therefore, since the sensor nodes record both the tracking identifier and the source and destination node information into the routing table when the request messages are flooding in and passing through, we can determine the proper routing path between the publisher node and the subscriber node.

As an addressing rule, the sensor node identifier must be assigned a unique physical address. In typical ICN-based

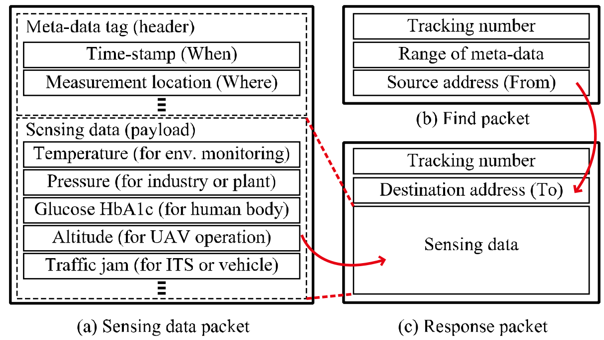

Figure 2. Structure of the sensing data, find, and response packets.

systems, there are two types of naming rules, specifically, the hierarchical and flat naming formula. In the hierarchical naming rule, an individual sensor node is managed based on a hierarchical URI (Uniform Resource Identifier), such as an HTTP (Hyper Text Transfer Protocol)-based website. On the other hand, in the flat naming rule, all sensor nodes are assigned the same and unique namespace. The hierarchical addressing method has the advantage of eliminating the overhead of the aggregations among sensor nodes; hence, the hierarchical naming rule achieves scalable routing. However, if the network structure must be dynamically changed when the sensor node is moved, appended, removed, and renewed, it is hard to adopt hierarchical addressing. As a result, if we define the sensor node that must transfer the sensing data as forwarding content data along the routing path as the relay node, we believe that the relay node can transmit and/or receive from/to the next relay node via the mechanism described above.

B. *Effective Caching Scheme with Overhearing Phenomena*

In this section, after describing the aim of the caching mechanism and the on-path caching scheme in the proposed scheme, we present the proposed off-path caching scheme based on the overhearing phenomena. Since there is no difference between the original data and the duplicated data from the subscriber node viewpoint, as mentioned above, if lots of sensor nodes have the required data, the hit probability of meeting the target data is improved. As a result, we can eliminate the number of wireless communications; thus, we expect that the proposed caching scheme will reduce energy consumption and radio frequency resources.

Figure 3 shows the proposed caching methods, specifically, the on-path caching scheme and the off-path caching scheme, and the relationship of the overhearing phenomena. For the on-path caching scheme, as with traditional schemes, the proposed scheme is copied and stored along the routing path; i.e., when the response packet is generated and forwarded, the relay node completes the on-path caching transaction. In greater detail, when the relay node receives the response packet, the relay node extracts the sensing data from the received response packet and stores it into the cache memory. After execution of the on-path caching transaction, the relay node sends the response packet to the

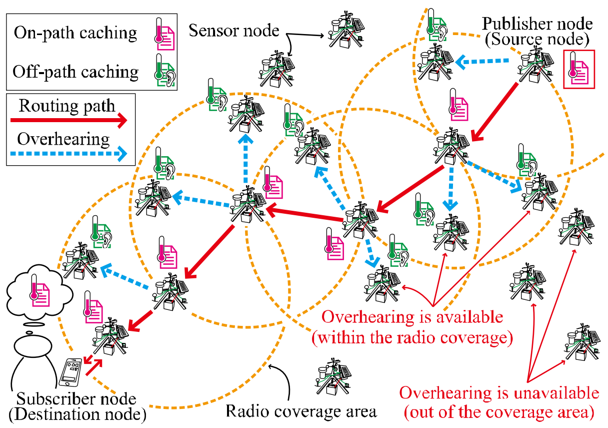

Figure 3. Comparison between on-path caching and off-path caching transactions in the proposed scheme, and the relationship between the off-path caching method and the overhearing phenomena.

neighbor sensor nodes, and the relay node updates the destination address from the current address to the next sensor node's address based on its routing table depending on the tracking identifier. For the off-path caching scheme, we introduce the overhearing phenomena into the proposed scheme without the extra overhead cost of a sophisticated hardware module. Unlike the wired network system, in the wireless network system, the neighbor sensor nodes located within the relay node's radio coverage area receive and acquire the sensing data, which is called the overhearing phenomena, as shown in Figure 3. When the relay node transfers the sensing data, the proposed scheme proactively watches and gathers the cross-talked and surrounded sensing data as the overhearing sensing data. The detailed procedure of the signal processing will be described later on.

In the proposed scheme, the neighbor sensor nodes of the relay node need not communicate with the relay node because of the overhearing phenomena. However, there are two major and considerable drawbacks when the overhearing mechanism works effectively, specifically, an increase in energy consumption of the signal processing for the wireless receiving (overhearing) transaction and additional cache memory capacity for the overhearing sensing data. Formerly, even if the computational energy consumption, e.g., micro-controller processing, memory access, and circuit power loss, is increasing, it is significantly (extremely) smaller than that of the radio transmission. Therefore, the proposed scheme reduces the total energy consumption depending on the decrease the number of wireless communications. On the other hand, for the latter issue, we (and everyone) will expect and experienience a decline in the RAM (Random Access Memory) hardware price under the influence of mass production, broad usage, and price competition, whereas, a shortage in the limited, common, and valuable radio resource will continue infinitely.

Consequently, the proposed scheme has significant and sufficient benefits, such as reduced energy consumption and the effective utilization of radio resources, even with the above two costs.

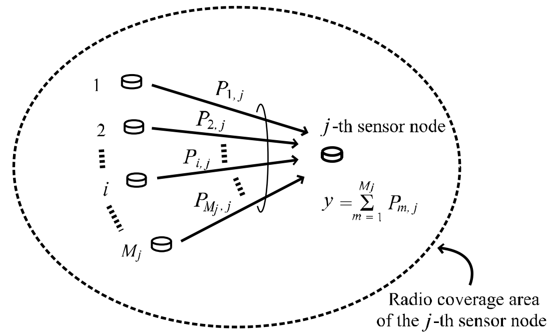

Figure 4. A received signal, $\boldsymbol{y}$, from the neighbor sensor nodes with $\boldsymbol{M_j}$ concurrent transmitter, and its fundamental model.

C. *Effective Caching Scheme with Successive Interference Cancellation*

As mentioned above, the sensor node receives from its neighbor nodes, which is a double-edged sword. In other words, this circumstance is positively applicable as the overhearing phenomena; however, it causes significant interferences, that is, the probability of successful reception is negatively degraded. Therefore, in the proposed scheme, we will not only execute the off-path caching scheme but also reduce the interference by using the cached sensing data based on the overhearing phenomena. Specifically, we utilize the SIC technique in order to eliminate interference. The beauty of the SIC technique resides in its simplicity; it is a purely received-based interference management scheme that does not require sophisticated coordination among sensor nodes. Figures 4 and 5 show the fundamental SIC model. In short, the SIC-based receiver decodes in order of high-power among several received signals. If the strongest signal can be successfully decoded, its decoded signal is encoded again, and then this re-encoded signal is subtracted from the received signals in order to remove the greatest interference; i.e., the SINR (Signal to Interference and Noise Ratio) for the remaining signals is improved. Then, the SIC-based receiver continues to decode the second strongest signal, and so forth, until all signals are decoded or the remaining signals are no longer decodable.

As shown in Figure 4, let $P_{i,j}$ denote the signal strength at the j-th sensor node that is a destination relay node or neighbor nodes based on the overhearing processing from the i-th sensor node that is a source relay node. In addition, let $\mathcal{M}_j$ denote the set of concurrent transmitting sensor nodes that can be heard by the j-th sensor node. As with the traditional wireless reception model, the j-th sensor node treats all interfering signals from other concurrent and non-intended transmissions as a noise signal. When the i-th sensor node transmits the required signal, if its SINR at the j-th sensor node is greater than or equal to a threshold value Λ, the j-th sensor node can be successfully recovered. In other words, let $P_{i,j}$ denote the power level from the i-th sensor node to the j-th sensor node; if the signal from the i-th sensor node to the j-th sensor node can be correctly decoded, $P_{i,j}$ is satisfied with

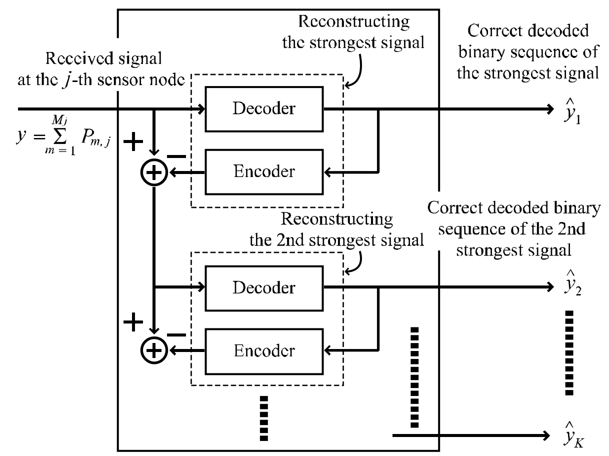

Figure 5. Schematic procedure of the proposed SIC-based receiver side transaction at the j-th sensor node.

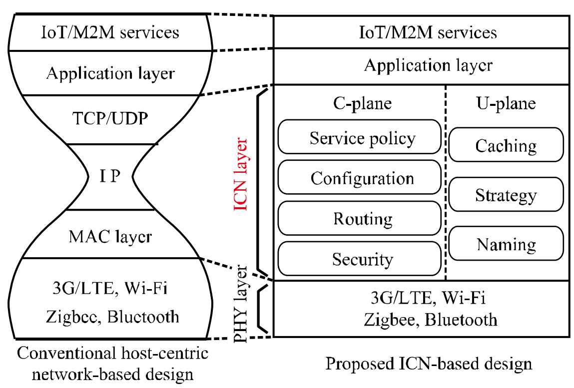

Figure 6. Protocol-stack design of the proposed ICN-based WSN scheme in comparison with the host-centric network architecture.

$$\mathcal{H}:\ \frac{P_{i,j}}{\sum_{k\in\mathcal{M}_j}^{k\neq i} P_{k,j}+\sigma^2} \geq \Lambda \tag{1}$$

where Λ is the power level of the required received signal threshold and σ^2 is the power of the ambient noise, respectively. In short, (1) indicates that the j-th sensor node can store the replicated data of the i-th sensor node, if the SINR is sufficiently large.

In Figures 4 and 5, let y denote the received signal strength of the j-th sensor node, which is expressed as

$$y = \sum_{m=1}^{M_j} P_{m,j} \tag{2}$$

where M_j is the amount of $\mathcal{M}_j$'s elements.

As shown in Figure 5, in the proposed scheme, the decoder works to recover the strongest signal among the input signals of y, such as the received signal in the first transaction. Based on (1), if the strongest signal can be successfully decoded, that is, its SINR is no less than threshold Λ, the decoded signal is subtracted from the aggregate signal. Following this procedure, the j-th sensor node decodes the second strongest signal and so forth until all signals are correctly decoded or the SINR criterion is no longer satisfied. Therefore, when the j-th sensor node decodes the signals based on (1), the received signal can be decoded correctly if and only if

$$\begin{aligned}
&\text{Step 1:} && \frac{\hat{y}_1}{y} = \frac{P_{1,j}}{\sum_{m=1}^{M_j-1} P_{m,j}+\sigma^2} \geq \Lambda \\
&\text{Step 2:} && \frac{\hat{y}_2}{y-\overline{y}_1} = \frac{P_{2,j}}{\sum_{m=1}^{M_j-2} P_{m,j}+\sigma^2} \geq \Lambda \\
&\quad\vdots && \qquad\vdots \\
&\text{Step } K\text{:} && \frac{\hat{y}_K}{y-\sum_{k=1}^{K-1}\overline{y}_k} = \frac{P_{K,j}}{\sum_{m=1}^{M_j-K} P_{m,j}+\sigma^2} \geq \Lambda
\end{aligned} \tag{3}$$

where K denotes the number of correct decoded signals, $\hat{y}_k (k = 1, 2, \cdots, K)$ denotes the correct decoded signal, and $\overline{y}_k (k = 1, 2, \cdots, K)$ denotes the re-constructed transmission signal based on the decoded signal of $\hat{y}_k$, respectively.

In (2) and (3), we assume that both $\overline{y}_k$ and $P_{m,j}$ are in non-decreasing order as $\overline{y}_1 \geq \overline{y}_2 \geq \cdots, \overline{y}_K$ and $P_{1,j} \geq P_{2,j} \geq \cdots \geq P_{K,j}$, respectively. If we achieve the SIC technique as shown in Figure 5, we can formulate the detailed protocol design, which we will describe in the next section.

D. Cross-Layer Design for Protocol Stack

In the proposed scheme, as shown in Figure 6, the ICN-layer is constructed by summarizing the middle layers, which is Srivastava and Motani's cross-layer design concept of 'merging of adjacent layers' [21]. We note that, as mentioned in reference [21], the aim of 'merging of adjacent layers' is to design two or more adjacent layers together and a new super-layer to provide the union services of the constituent layers. Namely, the ICN layer of the proposed scheme corresponds to this super-layer. In addition, this design concept should not require any new interface to be created in the protocol stack; that is, architecturally speaking, the super-layer should be constructed based on the rest of the layers by using interfaces that already exist in the original architecture. Therefore, the proposed scheme inherits the protocol stack of the host-centric network-based framework from the physical (PHY) layer, the application (APP) layer, and the IoT/M2M services layer, as shown in Figure 6.

Regarding the ICN layer's functionality, we examine and implement the separated data aspect, such as the C-plane for the control signal and the U-plane for the sensing data, respectively. As shown in Figure 6, there are lots of key technologies for the ICN-layer feature, and their elemental techniques, e.g., service policy, configuration, routing, security, strategy, naming, and caching, are essential to creating the proposed framework. However, we do not take into account their considerations without the caching scheme

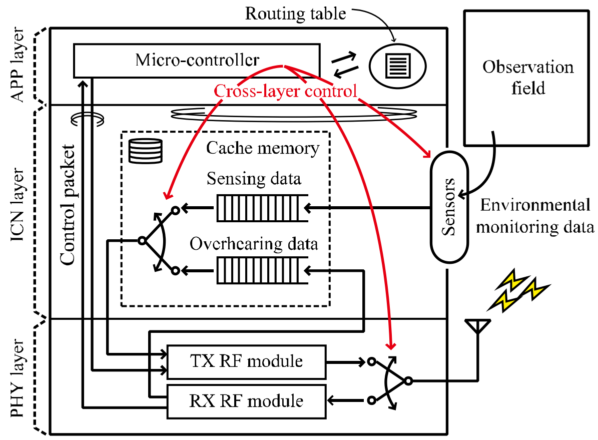

Figure 7. Signal processing procedure of the proposed sensor node device.

as this is outside the scope of this manuscript and will be the focus our future work.

E. Cross-Layer Design of Signal Processing Procedure

Figure 7 shows our proposed sensor node device's signal processing procedure. The routing table and cache memory in Figure 7 are the same components as in Figure 1. From a data flow viewpoint, the environmental monitoring data are observed from the target observation area. The micro-controller digitizes them as sensing data via the various sensors; then, the sensing data are stored in the cache memory. Two types of preserving data accumulate data: the self-sensing data that was previously mentioned and the overhearing sensing data that is acquired based on the procedure of the previous section. When the sensor node transmits the stored data, the micro-controller encourages the TX RF module to send the sensing data. On the other hand, when the sensor node carefully watches the radio propagation space at the RX RF module, the adequately received sensing data is stored in the cache memory as much as possible. We note that it is necessary to determine which sensing data should be stored because the cache memory capacity of the sensor node is limited, the consideration of which is outside the scope of this manuscript. However, we believe this decision rule poses a significant problem; in fact, we feel that the frequently requested data should be preferentially stored, and the old and worthless data should be removed.

On the other hand, the micro-controller should not only generate the sensing data and manage the database of the routing table, but also control the cache memory and the RF TX/RX modules. Notably, when the sensor node works as a publisher node for response transactions, the micro-controller produces the response packet and then the generated packet is adaptively transmitted. To achieve this, the proposed scheme constructs and optimizes based on Srivastava and Motani's cross-layer design concept of 'downward information flow' [21]. In short, in the 'downward information flow,' the setting parameters at the lower layer are adaptively controlled

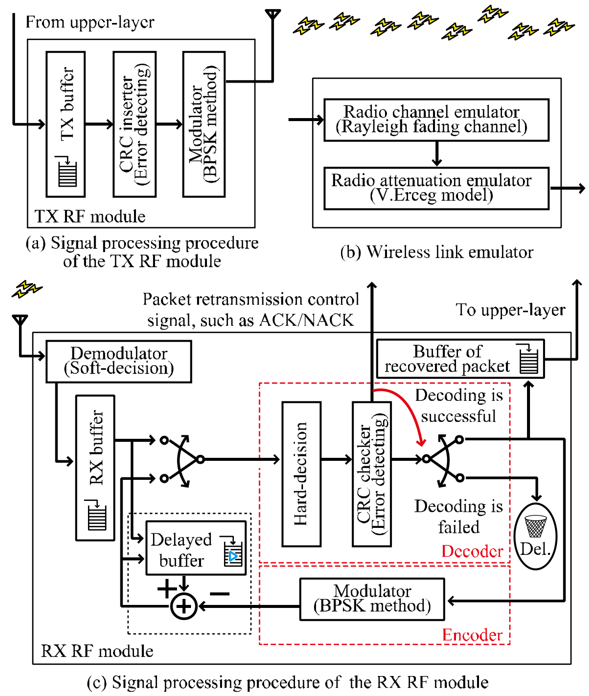

Figure 8. Procedure of signal processing at the transmitter device, the receiver device, and the wireless link emulator.

depending on the upper layer's information as a notification and hint.

Figure 8 shows the procedure of the signal processing for the transmitter, receiver, and wireless link in the proposed scheme. In Figure 8, the TX RF module (see Figure 8 (a)) and the RX RF module (see Figure 8 (c)) have the same components as in Figure 7. A detailed description of the wireless link model (see Figure 8 (b)) is provided in the next section. In addition, as shown in Figure 8 (c), the RX RF module has an encoder and decoder, which corresponds to the SIC-based encoder and decoder in Figure 5.

As shown in Figure 8 (a), in the TX RF module, the transmission packets—the sensing data packet and the control signal packet—are streamed from the upper layers and buffered in the TX buffer in order to adjust the data transmission rate. The CRC inserter appends a sequence based on the CRC code to every packet to detect the packet errors. Then, the transmission bit-stream is modulated by using the modulator based on the BPSK (Binary Phase Shift Keying) method. The transmission signal, i.e., the output signal of the TX RF module, is wirelessly transmitted via radio propagation space. Its model is shown in Figure 8 (b). In the proposed scheme, the wireless link emulator is designed based on radio attenuation model of Erceg et al. [22] and the Rayleigh fading channel model, which are described in the next section.

As shown in Figure 8 (c), in the RX RF module, the demodulator recovers based on the soft-decision decoding formula in order to conduct a signal processing based on the SIC technique, and the demodulated soft-decision information temporarily queues in the RX buffer. The received and detected signal is sent not only to the decoder, but also to the delayed buffer, for which the buffered signal is utilized for the interference removal stage in the SIC technique. In the decoder, the soft-decision information is judged based on the hard-decision metric, i.e., the hard-decision-based detector decides the estimated bit-stream. We note that, if we adopt the FEC (Forward Error Correction) mechanism, we need to add the error control decoder before the hard-decision. After that, the CRC checker verifies the estimated bit-stream sequence in order to detect bit errors and then the correct decoded bit-stream sequence is stored in the recovered packet's buffer. The verification result of the CRC checker can be utilized for the packet retransmission control signal, such as ACK and NACK, if we adopt the ARQ (Automatic Repeat reQuest) mechanism. The properly recovered packet is sent to not only the upper layers, i.e., the cache memory in the ICN-layer, but also the encoder. This is because, for interference reduction based on the SIC technique, the re-encoded signal of the recovered packet in the encoder is subtracted from the buffered signal in the delayed buffer, the detailed mechanism and procedure of which are described in Section II-C.

F. Wireless Link Model

In the wireless channel, as shown in Figure 8 (b), the packet error probability is related to the received signal strength, RSSI (Received Signal Strength Indication), and the received signal strength can be calculated based on the distance between the sensor nodes. Hence, the goal of this section is to expose this relationship. Let P_{TX} and P_{RX} denote the electrical power, let G_{TX} and G_{RX} denote the antenna gain of the wireless communication module, and let L_{TX} and L_{RX} denote the circuit attenuation loss at the transmitter side and the receiver side, respectively. The circuit attenuation loss of L_{TX} and L_{RX} is caused not only by the thermal noise due to the electric-resistive components, but also the impedance mismatching and transmission power losses of high-frequency signals. In addition, let L_{P} denote the radio-wave attenuation over the wireless channel. In general, the relationship among the parameters of P_{TX}, P_{RX}, G_{TX}, G_{RX}, L_{TX}, L_{RX}, and L_{P} are calculated based on

$$P_{\mathrm{RX}} = P_{\mathrm{TX}} - L_{\mathrm{TX}} + G_{\mathrm{TX}} - L_{\mathrm{P}} + G_{\mathrm{RX}} - L_{\mathrm{RX}} \text{ (dB)} \tag{4}$$

where the constant parameters of P_{TX}, P_{RX}, G_{TX}, G_{RX}, L_{TX}, and L_{RX} are provided by the wireless module specification.

For the radio-attenuation parameters, to determine the parameter of L_{P} in (4), we use model of Erceg et al. [22], which can be calculated based on

$$L_{\mathrm{P}} = \alpha + 10 \cdot \beta \cdot \log_{10}\ (d/d_0) \tag{5}$$

and

$$\alpha = 20 \log_{10}\ (4\pi d_0/\lambda) \tag{6}$$

and

$$\beta = a - b h_0 + c/h_0 \tag{7}$$

TABLE I. Simulation parameters.

Terms		Values
Number of simulation trials		10,000 trials average
Observation area (in rectangular shape)		1,000 m × 1,000 m
Packet length		ℓ = 1,000 bit
Number of publisher/subscriber node pairs		N_{PS} = 100
Sensor node based on XBee [25]	Transmission power	R_{TX} = 0 dBm (1 mW)
	Antenna gain	$G_{\mathrm{TX}} = G_{\mathrm{RX}}$ = 0 dBi
	Circuit power loss	$L_{\mathrm{TX}} = L_{\mathrm{RX}}$ = 0 dB
	Antenna height	h_0 = 0.5 m
	Radio frequency	2.4 GHz (λ = 0.125 m)
	Modulation method	BPSK
Thermal noise (Device temperature)		N_0 = -171.94 dBm (τ_{o} = 1,600 K)
Parameters in reference [22] (Flat ground surface/light tree density)		d_0 = 100, a = 3.6, b = 0.005, and c = 20
Channel model		Rayleigh fading
Probability of correct recovery		p_{e} = 1% (Req. $p_{\mathrm{b}} = 10^{-5}$)

where d denotes the distance between the sensor nodes, λ denotes the radio wavelength, h_0 is the antenna height, and d_0, a, b, and c denote the constant parameters depending on the surrounding environment given by Erceg et al. [22].

In our computer simulation, we calculate the packet error probability based on the signal to noise ratio (SNR) and the theoretical equation of bit error probability. If we utilize the BPSK method for the modulation scheme, we can calculate the SNR, γ, based on

$$\gamma = P_{\mathrm{RX}}\ /\kappa\tau_{\mathrm{o}} \tag{8}$$

where κ (= 4.0×10^{-21} W/Hz) is the Boltzmann's constant parameter and τ_{o} (K) is the absolute temperature of the system device, respectively.

On the other hand, the bit error probability, p_{b}, under the Rayleigh fading channel that is utilized for familiar wireless communication system evaluation, can be theoretically calculated [23] based on

$$p_{\mathrm{b}} = \frac{1}{2} \cdot \left(1 - \sqrt{\gamma/(\gamma+1)}\ \right) \tag{9}$$

Let ℓ denotes the packet length. We can calculate the packet error probability, p_{e}, using (9) based on

$$p_{\mathrm{e}} = 1 - (1 - p_{\mathrm{b}})^{\ell} \tag{10}$$

III. COMPUTER SIMULATION

In this chapter, we evaluate the fundamental performance using computer simulation in terms of three benchmarks—the amount of stored sensing data, the number of multi-hops, and the data transfer distance between the publisher and subscriber nodes.

A. Simulation Setting

In the computer simulation, we implemented the computer simulator by using C++ computer programming language. We

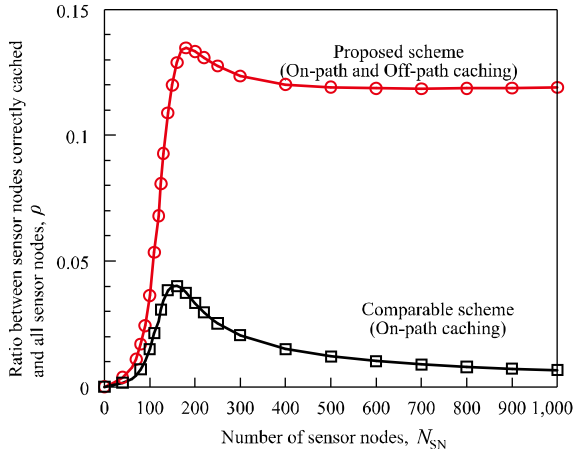

Figure 9. Number of sensor nodes, N_{SN}, versus ratio between sensor nodes correctly cached and all sensor nodes, ρ.

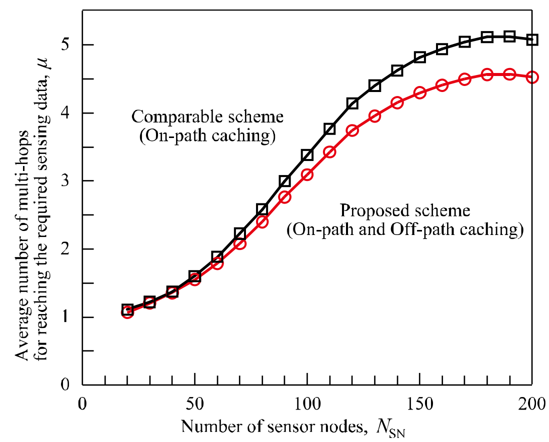

Figure 10. Number of sensor nodes, N_{SN}, versus average number of multi-hops for forwarding the required sensing data, μ.

will evaluate the TX/RX RF module, wireless link, and cache memory as shown in Figures 7 and 8. Table I shows the parameter settings of our computer simulation. In the simulation scenario, the sensor nodes are randomly scattered, i.e., the position of the sensor node is distributed based uniformly. The publisher node and the subscriber node pair is randomly selected; that is, their identifier numbers are distributed based uniformly, and their identifier numbers are different. Let N_{SN} and N_{PS} denote the number of sensor nodes and the number of publisher and subscriber node pairs, respectively, which are provided in Table I. For the routing path decision and calculation, we introduce Dijkstra's algorithm [24]. Dijkstra's algorithm can calculate the optimal path while minimizing the physical distance as a metric of weight links in order to reduce the computational time complexity of our simulation.

In the channel model, the constant parameters of P_{TX}, P_{RX}, G_{TX}, G_{RX}, L_{TX}, and L_{RX} in (4) and the RF wavelength, λ, in (6) are determined based on the familiar XBee RF module [25]. On the other hand, in the radio attenuation model, the constant parameters of a, b, and c in (7) are provided by Erceg et al. [22] when the observation area is assumed to be a suburban area with trees and buildings standing sparsely on flat ground. These detailed parameter settings are shown in Table I. In addition, we assume that the control signal is ideally exchanged and we ignore the shadowing for the wireless communications to avoid system complexity.

B. Simulation Result

The numerical result reveals how the proposed scheme improves the caching capability. The proposed scheme reduces the number of multi-hops and the distance of data transfer between the publisher node and the subscriber node.

Figure 9 shows how many sensor nodes hold the duplicated sensing data in the proposed sensor network. Namely, for the evaluation benchmark, we illustrate the ratio between the sensor nodes that are correctly copied and stored as cached sensing data, ρ, and all sensor nodes, as expressed as

$$\rho = \frac{N_{SN}^{*}}{N_{SN}} \tag{11}$$

where N_{SN}^{*} denotes the number of sensor nodes that can copy and store the overhearing sensing data into the cache memory.

As shown in Figure 9, from the qualitative viewpoint, ρ can be improved with increasing N_{SN}, because of the increase in sensor nodes that can store with the overhearing transactions due to increasing dense deployment. In the proposed and comparable schemes, ρ reaches its maximum value at $N_{SN} = 180$ and ρ is degraded in the case of $N_{SN} >$ 180 region. This is because ρ reaches its upper limitations in the case of $N_{SN} = 180$ and then decreases depending on N_{SN} when N_{SN} is sufficiently large. However, in the proposed scheme, N_{SN}^{*} significantly increases in proportion to N_{SN}, which does not increase as dramatically as when $N_{SN} < 180$ region; hence, ρ maintains a constant value when $N_{SN} > 500$ region. On the other hand, from the quantitative viewpoint, the proposed scheme can be improved 1.42, 2.61, 8.85, and 17.0 times over the comparable scheme with any off-path caching mechanism in the cases of N_{SN} = 100, 180, 500, and 1,000.

Figure 10 shows how many multi-hops the response packet transmits from the publisher node to the subscriber node, namely, the number of sensor nodes, N_{SN}, versus the average number of multi-hops for wirelessly forwarding the response packet among the relay nodes, μ. From a qualitative viewpoint, in the proposed scheme, μ is improved in comparison with the comparable scheme. This is because the hit probability of the required sensing data increases depending on if ρ is large; hence, μ can be improved. In addition, when $N_{SN} < 50$ region, the difference of μ between the proposed and comparable schemes is significantly small because of the small ρ difference, and μ reaches its maximum value at $N_{SN} = 180$ by reaching upper limitation, the same as for ρ, as shown in Figure 9. On the other hand, the curve of μ gradually increases depending on N_{SN}, since the multi-hop transmission promotes by increased sensor nodes. From a

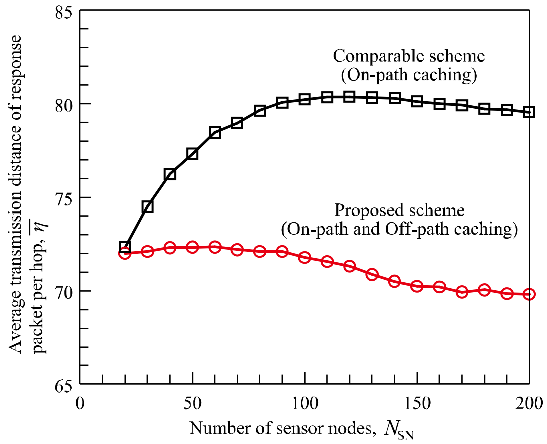

Figure 11. Number of sensor nodes, N_{SN}, versus average transmission distance of response packet per hot, $\overline{\eta}$.

quantitative viewpoint, the proposed scheme can be improved by 3.35%, 8.51%, 10.8%, and 10.9% when N_{SN} = 50, 100, 150, and 200, respectively.

Figure 11 shows how long the response packet takes to transfer from the publisher node to the subscriber node; i.e., the number of sensor nodes N_{SN} versus the average transmission distance of the response packet per hop, $\overline{\eta}$, which is calculated based on

$$\overline{\eta} = \frac{\eta}{\mu} \tag{12}$$

where η denotes the transmission distance of the overall routing path between the publisher and subscriber nodes. In our computer simulation, we utilize Dijkstra's algorithm to obtain the routing path while minimizing η, as mentioned above. Hence, we can calculate η based on the distance metric, which is the summation of the linked weights when the optimal routing path is decided.

As shown in Figure 11, from a qualitative viewpoint, when $N_{SN} < 100$ region, the $\overline{\eta}$ of the comparable scheme worsens, whereas the proposed scheme prevents an increase of $\overline{\eta}$. This is because the probability of holding the target sensing data in the near sensor node becomes large due to the proposed caching mechanism, hence, $\overline{\eta}$ improves. From a quantitative viewpoint, the proposed scheme is improved by 6.46%, 10.5%, 12.3%, and 12.2% when N_{SN} = 50, 100, 150, and 200, respectively.

Consequently, since the proposed scheme improves ρ, as shown in Figure 9, the proposed scheme reduces the number of multi-hops and the data transfer distance between the publisher and subscriber nodes as shown in Figures 10 and 11, respectively. In particular, for the numerical result of Figures 10 and 11, the target sensing data is randomly decided. However, the requested sensing data must have several biases; therefore, we demonstrate our computer simulations in the worst condition, such as an upper (or lower) limitation, and thus expect that the evaluation metrics of ρ, μ, and $\overline{\eta}$ will be significantly more improved in the practical environment.

IV. CONCLUSION

In this paper, we addressed an effective caching mechanism and its cross-layer-design protocol construction for an ICN-based WSN. We proposed a novel caching scheme using the overhearing phenomena and the SIC technique. We also proposed the protocol-stack and mechanism procedure based on the cross-layer design. The numerical result demonstrated that the proposed scheme is improved 2.61 times that of the comparable scheme (without adopting an off-path caching scheme) when $N_{SN} = 180$ for the caching capability. In addition, the proposed scheme can maximally reduce the number of multi-hops and data transfer distance between the publisher and subscriber nodes by 10.9% and 12.3%, respectively. In our future research, we will demonstrate and discuss our work further in a realistic environment using a hardware testbed-based experiment.

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REFERENCES

[1] S. Mori, "A Study on Off-path Caching Scheme by using Successive Interference Cancellation for Information-Centric Network-based Wireless Sensor Network," *Proc. IARIA the 16-th Int. Conf. Networks (ICN'17)*, Apr. 2017, pp. 42–45.

[2] J. Choi, J. Han, E. Cho, T. Kwon, and Y. Choi, "Survey on Content-Oriented Networking for Efficient Content Delivery," *IEEE Commun. Mag.*, vol. 49, no. 3, pp. 121–127, Mar. 2011.

[3] B. Ahlgren, C. Dannewitz, C. Imbrenda, D. Kutscher, and B. Ohlman, "Survey of Information-Centric Networking," *IEEE Commun. Mag.*, vol. 50, no. 7, pp. 26–36, July 2012.

[4] X. Wang, M. Chen, T. Taleb, A. Ksentini, and V. C. M. Leung, "Cashe in the Air: Exploiting Content Caching and Delivery Techniques for 5G Systems," *IEEE Commun. Mag.*, vol. 52, no. 2, pp. 131–139, Feb. 2014.

[5] C. Liang, F. R. Yu, and X. Zhang, "Information-Centric Network Function Virtualization over 5G Mobile Wireless Networks," *IEEE Network*, vol. 29, no. 3, pp. 68–74, May–June 2015.

[6] S. Higuchi and T. Hirotsu, "A Verification Based Flow Space Management Scheme for Multi-Tenant Virtualized Network," *Proc. IARIA the 11-th Int. Conf. Digital Society and eGovernments (ICDS'17)*, Apr. 2017, pp. 24–29.

[7] Y. Zhang, D. Raychadhuri, L. Grieco, E. Baccelli, J. Burke, R. Ravindran, and G. Wang, "ICN Based Architecture for IoT-Requirements and Challenges," *IETF Internet Draft*, Nov. 2014.

[8] M. Amadeo, C. Campolo, J. Quevedo, D. Corujo, A. Molinaro, A. Iera, R. L. Aguiar, and A. V. Vasilakos, "Information-Centric Networking for the Internet of Things: Challenges and Opportunities," *IEEE Network*, vol. 30, no. 2, pp. 92–100, Mar. –Apr. 2016.

[9] K. Wang, F. R. Yu, H. Li, and Z. Li, "Information-Centric Wireless Networks with Virtualization and D2D Communications," *IEEE Wireless Commun.*, vol. 24, no. 3, pp. 104–111, June 2017.

[10] M. Zhang, H. Luo, and H. Zhang, "A Survey of Caching Mechanisms in Information-Centric Networking," *IEEE*

Commun. Surveys and Tutorials, vol. 17, no. 3, pp. 1473–1499, Third-quarter 2015.

[11] T. Koponen, M. Chawla, B. Chun, A. Ermoliskiy, K. H. Kim, S. Schenker, and I. Stoica, "A Data-Oriented (and beyond) Network Architecture," *Proc. ACM Annual Conf. Special Interest Group on Data Commun. (SIGCOM'07)*, Aug. 2007, pp. 181–192, doi:10.1145/1282427.1282402.

[12] http://www.named-data.net/ [retrieved: Nov. 2017]

[13] V. Sourlas, L. Gkatzikis, P. Flegkas, and L. Tassiulas, "Distributed Cache Management in Information-Centric Networks," *IEEE Trans. Network and Service Management*, vol. 10, no. 3, pp. 286–299, Sept. 2013.

[14] S. Wang, J. B. J. Wu, and A. V. Vasilakos, "CPHR: In-network Caching for Information-Centric Networking with Partitioning and Hash-routing," *IEEE/ACM Trans. Networking*, vol. 24, no. 5, pp. 2742–2755, Oct. 2016.

[15] M. Hajimirsadeghi, N. B. Mandayam, and A. Reznik, "Joint Caching and Pricing Strategies for Popular Content in Information Centric Networks," *IEEE J. Sel. Areas in Commun.*, vol. 35, no. 3, pp. 654–667, Mar. 2017.

[16] W. Li, S. M. A. Oteafy, and H. S. Hassanein, "Rate-Selective Caching for Adaptive Streaming over Information-Centric Networks," *IEEE Trans. Computers*, vol. 66, no. 9, pp. 1613–1628, Sept. 2017.

[17] S. Sen, N. Santhapuri, R. R. Choudhury, and S. Nelakuditi, "Successive Interference Cancellation: A Back-of-the-Envelope Perspective," *Proc. ACM Annual Conf. Special Interest Group on Data Commun. (SIGCOM'10) WS Hot Topics in Networks*, Oct. 2010, pp. 1–6, doi:10.1145/1868447.1868464.

[18] J. G. Andrews, "Interference Cancellation for Cellular Systems: A Contemporary Overview," *IEEE Wireless Commun.*, vol. 12, no. 2, pp. 19–29, Apr. 2005.

[19] S. Sambhwani, W. Zhang, and W. Zeng, "Uplink Interference Cancelation in HSPA: Principles and Practice," *QUALCOMM Inc. White Paper*, 28 pages, San Diego, CA, USA, 2009.

[20] S. Shakkottai, T. S. Rappaport, and P. C. Karlsson, "Cross-Layer Design for Wireless Networks," *IEEE Commun. Mag.*, vol. 41, no. 10, pp. 74–80, Oct 2003.

[21] V. Srivastava and M. Motani, "Cross-Layer Design: A Survey and the Road Ahead," *IEEE Commun. Mag.*, vol. 43, no. 12, pp. 112–119, Dec. 2005.

[22] V. Erceg, L. J. Greenstein, S. Y. Tjandra, S. R. Parkoff, A. Gupta, B. Kulic, and A. A. Julius, "An Empirically based Path Loss Model for Wireless Channels in Suburban Environments," *IEEE J. Sel. Areas in Commun.*, vol. 17, no. 7, pp. 1205–1211, July 1999.

[23] J. G. Proakis, *Digital Communications 5-th Edition*, McGraw-Hill, Jan. 2008.

[24] E. W. Dijkstra, "A Note on Two Problems in Connection with Graphs," *J. Numerische Mathematrik*, vol. 1, no. 1, pp. 269–271, Dec. 1959.

[25] http://www.digi.com/ [retrieved: Nov. 2017]