Hindawi Publishing Corporation
EURASIP Journal on Wireless Communications and Networking
Volume 2011, Article ID 176393, 12 pages
doi:10.1155/2011/176393

Research Article

A Secure and Robust Connectivity Architecture for Smart Devices and Applications

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Received 31 May 2010; Accepted 2 August 2010

Academic Editor: Damien Sauveron

Convergence environments and technologies are urgently coming close to our life with various wireless communications and smart devices in order to provide many benefits such as connectivity, usability, mobility, portability, and flexibility as well as lower installation and maintenance costs. Convergence has brought important change not only in the way we live but also in the way we think. It is the progress towards the attempt to create and to evolve new valuable services through the device convergence and fusion of in-home, office, and various environments around the personal mobile apparatus. Based on the dynamic trends of convergence, it is widely argued that the increased requirements on secure and robust connectivity between a variety of mobile devices and their applications provide us the era of real pervasive computing environment. Thus, in this paper, we present a novel connectivity architecture using RF4CE-(Radio Frequency for Consumer Electronics-) based wireless zero-configuration and enhanced key agreement approach. We analyze the security and performance of our proposed approach by the development of the prototype H/W and the construction of a testbed with CE and mobile devices.

1. Introduction

Nowadays, various smart devices and their applications are rapidly increasing according to the smart grid environment based on the interlocking and controlling of in-home smart appliances. It means that the rapid and explosive increase of the mobile device like smartphone and tablet PC will have a big impact on human life more and more. The enlargement of the mobile devices based on wired and wireless mobile communication technologies becomes one of the important factors that brings into various and new convergence services, and then promotes it. Such recent trends request the innovative paradigm about the various convergence services satisfying the individualized desire and consequently brings into the new converged services and open media platforms. Open platform convergence services between devices evolve into D2S (Device-to-Solution) in the existing D2D (Device-to-Device), and also evolve into M2M (Machine-to-Machine), that is all things' convergence, based on interaction with devices that are not the simple coupling between device-to-device and device-to-solution [1–4]. As the convergence technologies of next generation wireless networks and smart devices are rapidly emerging, secure and easy connection between various mobile devices has become a primary concern and a mandatory requirement in order to ensure dependable, secure communications and simple connectivity services under mobile and wireless network environment to end users. In this sense, IEEE 802.15.4 technologies are presented, as one of the representative convergence connectivity technologies, and favored to be

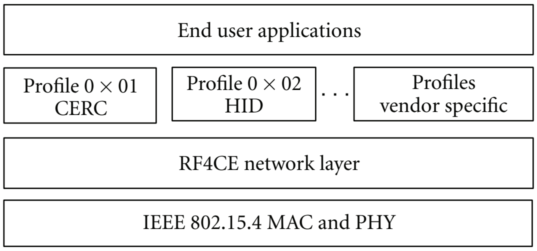


Figure 1: RF4CE protocol architecture.

applied to diversified mobile devices and their WPAN environments. In last March 2009, a principal electronics 4 corp. (Panasonic, Philips, Samsung Electronics, and SONY) and ZigBee Alliance agreed to found the RF4CE (Radio Frequency for Consumer Electronics) consortium which is based on the existing IEEE 802.15.4 radio frequency [5–7]. Thus, the RF4CE standard can be one of the best candidates to fulfill the requirement for connecting heterogeneous mobile devices as well as various CE devices. In the security aspect, the link key generation scheme through exchanging key seeds is supported between the RF4CE enabled devices in order to provide reliable communication. However, the scheme provided by RF4CE standard has a vulnerability like Man-in-the-Middle (MITM) attack that key seed value can be exposed to the third party because the key seed is exchanged as a plaintext, and a third party can acquire and masquerade key seeds to generate link encryption key. Besides, the scheme also has the vulnerability of key seed retransmission and interception. In case key seeds are affected by a network attack like DoS (Denial of Service), additional seed retransmission is required because maximum 255 seeds should always be successively reassembled to generate a link key between nodes for secure communication. In case of Bluetooth, it has the risk of guessing of a PIN (Personal Identification Number) and the exposure of a random number according to a security mode [8, 9].

In this paper, we first address the RF4CE-based zero configuration in order to provide easy control and contents sharing for a smart digital home device and applications. We then propose RF4CE-based enhanced key agreement using certificate-based mutual authentication to prevent cloned or comprised devices from joining RF4CE network and two-phase key seed distribution to provide efficient and robust key seed exchange.

The first contribution of this paper is that the proposed zero-configuration approach provides energy efficient, simple, and easy configuration method to various devices during their connectivity control and data sharing. The second contribution is that the proposed RF4CE-based enhanced key agreement protocol provides a device identification and a forgery prevention using mutual device authentication, and generates a like encryption key without using all 255 key seeds which have the possibility of information disclosure to the third party, and resolves the vulnerability that key seed information is exposed to the third party by applying fundamental key seed encryption. Finally, we present a novel secure and robust connectivity architecture based on RF4CE for smart devices and applications.

This paper is organized as follows. In Section 2, we deal with the introduction of RF4CE and security issues of the existing techniques. In Section 3, the proposed approaches are presented such as the ad hoc and infrastructure configuration and advanced pairing method. In Section 4, the actual system implementation and experiment are illustrated. Discussion about the proposed approach is explained in Section 5. Finally, we draw a conclusion of this paper in Section 6.

2. Background

2.1. Overview of RF4CE. The RF4CE of the ZigBee alliance is one of the defacto WPAN standard technologies determined in March 2009 by the representative electric home appliances enterprises including Panasonic, Samsung Electronics, SONY, and Philips in order to prepare for the rapid increasing demand of bidirectional communication and remote control functionalities in CE market such as TV, home-theater, set-top box, DVD, and so forth.

As shown in Figure 1, RF4CE has the physical and MAC layer function of the IEEE 802.15.4 and it replaces the current IR remote to ZigBee RF4CE remote based on the low power consumption, nondirectional function including the LCD back lighting interference avoidance, and bi-directional communication. In case of the network layer in RF4CE, it has the light-weight structure in comparison with the preexistence ZigBee. Generally the RF4CE topology consists of 2 branch types' nodes as called a target and controller. The target node performs the network initiation as the role of PAN coordinator similar with ZigBee network. In case of a controller node, it can search the network coordinated by the target node and request a connection and it generally works as a remote controller [7, 8].

2.2. Connectivity Security Issues. The use of interoperation between various consumer electronics, for examples, TV, Set-top box and DVD players, and portable IT devices such as mobile terminals and net-book is highly increasing. The network connectivity among CE and portable IT devices are strongly needed primarily because they have various wireless interfaces. Any service on top of the connectivity, for example, content sharing service between devices is impossible without easy set up of network connection between digital devices. Not much easy set up of network connection is recognized as industry standard. In Wi-Fi alliance [10], Wireless Protected Setup (WPS) provides easy set up between AP (Access Point) and IT device with Wi-Fi interface. By using WPA/WPA2 security module, it near-automatically configures secure connectivity between IT device and AP (Access Point) as long as two devices are certified as Wi-Fi Protected Setup. However, although many options including PBC (Push Button Configuration) and PIN (Personal Identification Number) modes are available for WPS, it is only good for connectivity between AP and IT device, namely, AP infrastructure mode and does not support ad hoc mode. A technical working group for

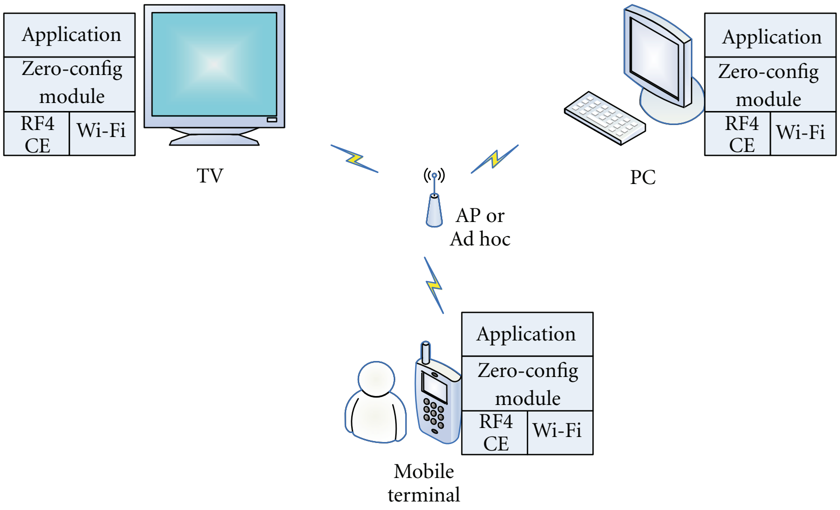


Figure 2: Overall environment of zero configuration approach.

extension of WPS is hence progressing in Wi-Fi alliance [10–13].

RF4CE can provide the basic security functionalities such as frame encryption and data authentication in MAC layer because it is based on IEEE 802.15.4 specification. In the network layer of RF4CE, it first generates 128 bits link encryption key and stores the key in the pairing table after finishing the pairing process, and then the encryption key is utilized for secure data transmission. In the process of distributing the key seeds, it establishes secure channel between nodes. At this time, a controller and target node first performs the pairing process, and then checks the security capability option of the pairing request node. In case the correspondent node supports the security function, a key seed distribution process is performed. During the key seed distribution, the key seed values of the maximum n are delivered to a controller and then the same secret key is generated in an end-to-end. At this time, the maximum n of the transmitted key seed value is 255. In each node, the key seed value is reassembled through the XOR operation and then generates the link encryption key [6, 7, 12, 14]. However, the key seed values have the vulnerabilities such as data interception, masquerading, and denial-of-service by the third party as well as MITM attack because of being transmitted to the plaintext state without providing an encryption or any security functions. Therefore, the key seed wiretapping by malicious users should be fundamentally prevented, and a solution for forgery of seed value itself and a sequence number of a key seed frame is required, too. In order to prevent DoS attack, it is necessary to support tolerant and resilient capability to prepare for interrupting the normal key seed distribution and secret key generation. There is the protection method of the key seed value through an encryption by using a predistributed master key as a simple solution for solving this problem between nodes. However, there remains still security issues like a node capture and distribution the master key safely.

Recently, several researches related to connectivity and control platform such as universal control, home sensor service, and media processing multimedia platforms. In [15], the authors presented RF4CE-based remote control framework, however, it does not describe security analysis and performance analysis to address the proposed architecture's superiority. Some researches [16, 17] showed the multimedia processing platform based on p2p network and PTP/IP. In addition, sensor network platforms are suggested to show the applications using various connectivities in [17, 18]. However, such researches cannot provide enough security aspect and robustness.

3. Proposed Approach

In this section, we present novel connectivity architecture with zeroconfiguration and advanced pairing approach based on RF4CE. The zero-configuration approach is required to provide simple and easy connection between various Wi-Fi supported devices. And the proposed pairing scheme is good alternative for complementing the vulnerabilities of the existing RF4CE key agreement scheme.

3.1. Ad Hoc and Infrastructure Connection Mode. We first show the zero-configuration approach supporting Wi-Fi ad hoc and infrastructure mode. Figure 2 gives an overview of the proposed RF4CE-based zero-configuration approach. The proposed approach consists of three representative devices such as mobile terminal, PC, and TV. It can be applied to various CE and IT devices supported by RF4CE and wireless interface like Wi-Fi.

In order to provide zero-configuration functionalities, each device should have multi-RF (RF4CE and Wireless interface like Wi-Fi) zero-configuration core modules, and its application component. In this environment, a mobile terminal (user) can make a connection between TV and PC as well as their turning on and off using RF4CE interface, and then remote control and contents sharing services can be provided by simple Wi-Fi zero configuration. In Wi-Fi zero configuration, the proposed approach can support

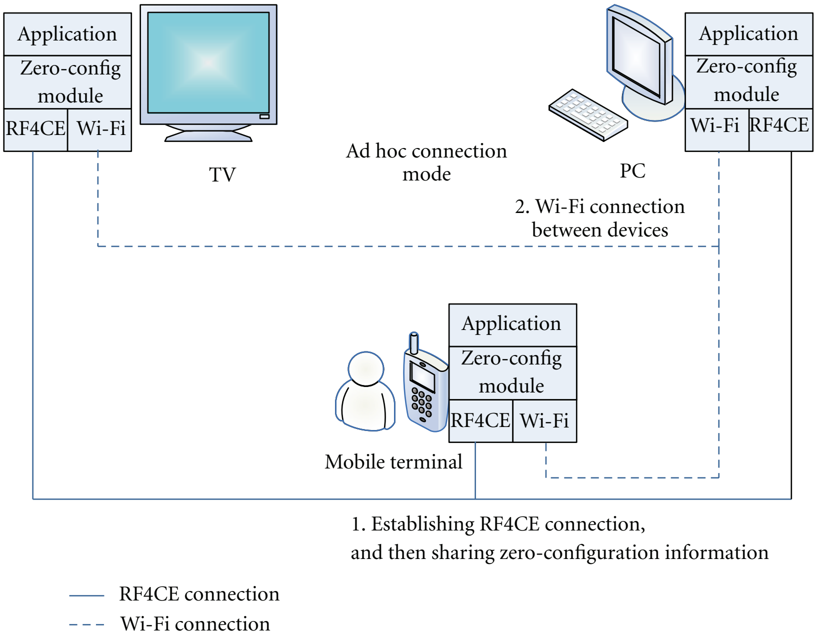


Figure 3: Ad hoc connection mode in zero configuration approach.

both infrastructure mode based on Access Point and ad hoc mode connection. The zero-configuration architecture capabilities can be performed by the distinguished features of RF4CE such as NLOS (No Line-Of-Sight or field of vision limitations) feature, bidirectional capability, reliable communications, power consumption, and true interoperability between vendors' products. In aspects of our implementation, we assume that the architecture has RF4CE and Wi-Fi RF interface. Thus, it can perform energy efficient power control, Wi-Fi zero configuration and exchanging control command by RF4CE and high-speed data transmission by Wi-Fi. The zero-configuration module supports lower layer's RF interfaces, zero-configuration component, and RF interface controller. In other words, the zero-configuration core module performs RF interface control and management, and zero configuration of Wi-Fi network based on RF4CE control channel. Application components have a variety of application service profiles to provide remote control service, energy efficient power control, and content sharing. If more application profiles are added on our devices, they can work with other devices using the same application profile based on the zero-configuration architecture.

As we already mentioned about two kinds of zero configuration modes, there are two connection modes like AP and ad hoc for Wi-Fi zero configurations using RF4CE. The proposed architecture can support ad hoc and Infrastructure modes when a device requires making a connection with other devices with Wi-Fi.

Ad hoc connection mode is described in Figure 3. In ad hoc mode, there is no access point device and only exist RF4CE-based mobile and CE devices. For explanation, we assume that there are mobile terminals, PC, and TV devices. First, a mobile terminal tries to establish RF4CE network performing device discovery and pairing procedure. In case of secure communication, secret key seed values can be shared if each corresponding devices are configured as security enabled. After constructing RF4CE control channel like bold line of Figure 3, a mobile terminal distributes ad-hoc connection information such as private IP, SSID, security material, XML profile, and so on, to already existing RF4CE pairs. Each RF4CE connected devices establish Wi-Fi ad-hoc connection as illustrated in the dotted line of Figure 3.

Infrastructure connection mode is described in Figure 4. In infrastructure mode, we assume that there exists Wi-Fi access point device and at least one device has a preconnected Wi-Fi connectivity. The preexisted Wi-Fi connection is described as the double-dotted line of Figure 4. The overall environment is the same as ad hoc connection mode, however, access point is added. Basically, in infrastructure mode, the discovery and pairing procedure to establish RF4CE network is performed as ad hoc mode. RF4CE control channel is illustrated as the bold line in Figure 4. During RF4CE network establishment, a user's mobile terminal collects an existing Wi-Fi connectivity from the rest of devices in RF4CE network, and then requests the Wi-Fi connection information to the device with Wi-Fi connectivity. After getting Wi-Fi connection information, the mobile terminal distributes the Wi-Fi information such as SSID, authentication mode, security key, XML profile, and so on, to the devices connected by RF4CE. Finally, the device which received Wi-Fi connection information makes a Wi-Fi connection, which is illustrated in the dotted line in Figure 4. If all members in RF4CE network can support security, the Wi-Fi zero configuration data will be delivered by secure communication.

3.2. Advanced Pairing. In this section, we propose advanced pairing approach based on RF4CE key agreement scheme.

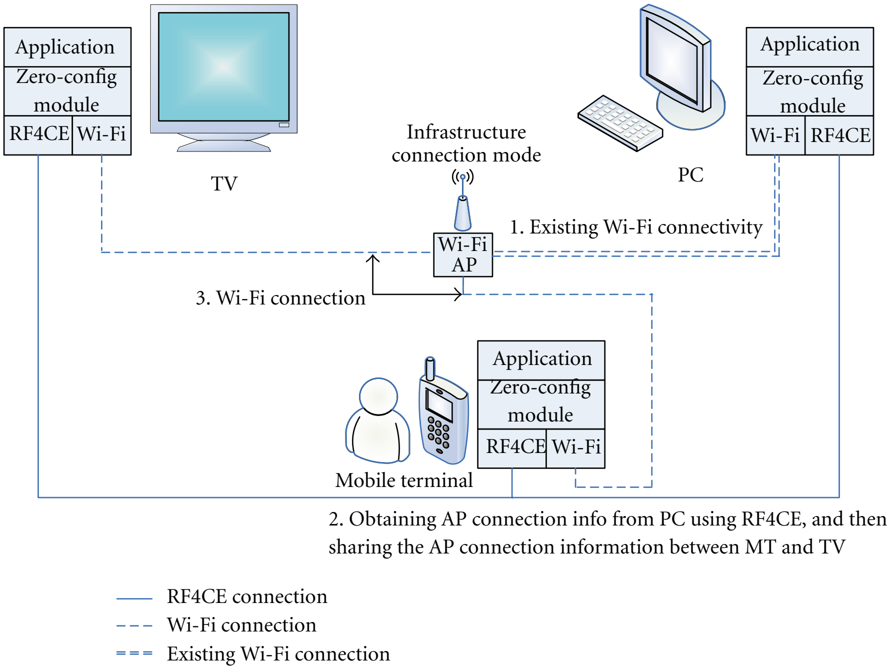

Application
Zero-config module
RF4CE
Wi-Fi
TV
Infrastructure connection mode
PC
Application
Zero-config module
Wi-Fi
RF4CE
1. Existing Wi-Fi connectivity
Wi-Fi AP
3. Wi-Fi connection
Application
Zero-config pairing module
RF4CE
Wi-Fi
Mobile terminal
2. Obtaining AP connection info from PC using RF4CE, and then sharing the AP connection information between MT and TV
RF4CE connection
Wi-Fi connection
Existing Wi-Fi connection

Figure 4: Infrastructure connection mode in zero-configuration approach.

We first present a mutual authentication process between devices entering RF4CE network is performed to provide enhanced RF4CE key agreement with two-phase key seed distribution based on a certificate like Mobile WiMAX [1]. In the device authentication of the IEEE 802.16 standard called Mobile WiMAX, it prepared for a forgery attack like a cloned SS by using a certificate applied in the manufacturing process [19–21]. In other words, we concentrate on the authentication of the devices itself, however, it can verify whether a device participating in the RF4CE pairing process is normally manufactured or not. It also decreases the possibility of a masquerading attack in which a compromised controller or target participates in key seed allocation process.

As shown in Figure 5, a controller and target node providing a certificate each other perform a mutual authentication process before the pairing process starts. First, the controller receiving the target certificate confirms whether the certificate is provided from an authenticated target through the verification process of CA (Certificate Authority) signature, and then the controller delivers its own certificate, *UID* (Unique ID) and SEK_*R* (Seed Encryption Key Random number) values which are used during key seed distribution. The *UID* and SEK_*R* is a kind of a random number selected arbitrarily and they are encrypted by target's public key with the signature of a controller after applying hash-function. The *UID* value is used as an argument at the key seed allocation process and the SEK_*R* is used in selecting a key seed encryption function. In a target side, the target certificate is verified, and then the *UID* value, SEK_*R* and a controller's signature are decrypted by the target's private key. In addition, the target verifies the controller's signature to calculate the hash value of *UID* and SEK_*R* for confirming *UID* and SEK_*R* values. Therefore, the target authenticates that the controller is a node requesting a pairing to target through the hash value and signature verification, and then it finishes all mutual authentication process.

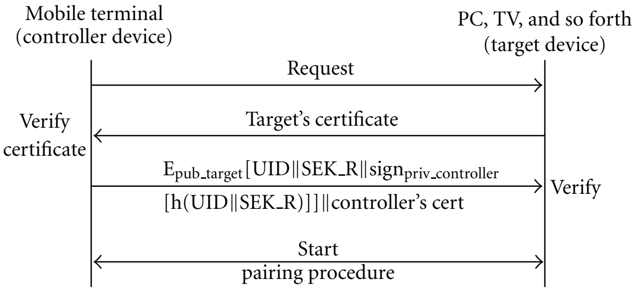

Mobile terminal (controller device)
PC, TV, and so forth (target device)
Request
Verify certificate
Target's certificate
E_pub_target[UID||SEK_R||sign_priv_controller
[h(UID||SEK_R)]]||controller's cert
Verify
Start
pairing procedure

Figure 5: Mutual authentication, key parameters.

After finishing mutual authentication process, the proposed connectivity architecture performs two-phase key seed distribution. Basically, after distributing 255 seed values in the existing method, these values were performed XOR operation to generate the link encryption key of 128 bits. However, the existing method have some problems such as key seeds are sent to a node as a plaintext and all key seed values (maximum 255 seeds) should be guaranteed their successful transmission each time without loss. Therefore, in this paper, we propose two-phase key seed distribution approaches called quick and main mode. In case of quick mode, it can provide DoS resilient capability because it does not need to send maximum 255 key seeds every time. And a main mode can provide the confidentiality of the key seed values using all different seed encryption keys. Current RF4CE standard does not provide any protection during key seed distribution, while our protocol provides the secure protection for the initial key seed distribution. In the pairing phase (Figure 5), controller device can verify target's certificate and obtain the public key of the target. Anyone who eavesdrop the communication cannot know or modify SEK_*R* since SEK_*R* is encrypted with accompanying hashed value. The message from controller device can be easily authenticated by target's private key, while previous methods do not provide the message authentication in this phase.

First, the proposed quick mode is performed with the procedure as described in Figure 6. A target node delivers randomly generated N seeds ($N \le 255$) to the controller. In each side, the controller and target can select the same n ($n \le N$) seeds among N seeds, and then they are used for generating the same link encryption key. In order to select n seeds, each node utilizes the random selection mask function which generates a random number with the size of 255 bits using the address and the *UID* previously shared in the authentication procedure and *IV* assignment process, separately. For example, the bit string of generated 255 bits becomes a criterion of selecting the nth key seed. In other words, each 0 or 1 of *n*th bit can be applied to a simple masking scheme to decide the transmission of a key seed value. In addition, we can transmit the only selected n key seeds by the masking result to a controller as a modified quick mode. The former quick mode is a key seed distribution method to provide the tolerance against DoS or intercept attack in comparison with the existing solution because it makes it difficult for attackers to know which seeds are used for key generation. When compared to a maximum 255 key seed transmissions of the existing key seed distribution, the modified quick mode is a way to focus on the transmission efficiency because of distributing only selected n key seeds. Therefore, the quick mode brings the effect of reducing the computation time since a link encryption key can be generated by using few numbers of seeds. In addition, there is the advantage to make difficult for guessing a link key in case some key seeds are exposed to the third party. In quick mode (Figure 6), the communication overhead is reduced to n ($\le$255) times communications while RF4CE standard requires 255 times communications. In order to generate the shared key using quick mode, an adversary should know n seeds that are randomly selected in 255 seeds. Also, the selection of n seeds needs the shared UID that is securely transmitted in the pairing phase (Figure 5). Thus, our protocol provides more efficiency in key seed distribution than current standard without threaten the security.

In case of the main mode, the proposed main mode is performed with the procedure as described in Figure 7. All key seeds up to 255 are transmitted to a node like the RF4CE standard, however, all seed values are encrypted by using all different SEK (seed encryption key) in order to solve the problem of key seed distribution as a plaintext. We can calculate each seed encryption key by following equations. First, the SEK_1 for encrypting the initial key seed value is derived by (1) using *UID*, *IV*, and SEK_*R* of the mutual authentication procedure as the arguments of $F_{\text{SEK}}()$ function. For the generation of the SEK_n, we can use (2) or (3) with the enumerated SEK_*R* of 254 bits. If the nth bit of SEK_*R* is 0, the $F_{\text{SEK}}()$ function of (2) is applied to make SEK_n of *n*th key seed value. If not, (3) is used. The distributed all key seeds are not only encrypted by using all different encryption keys, but also cause more computation and time cost to guess a SEK_i even in case a special key is exposed by the third party. Thus, the main mode can reduce the threat of key exposure and forgery due to the key seed transmission of plaintext status:

$$\text{SEK}1 = F_{\text{SEK}}(\text{Addr}\|\text{UID}\|\text{SEK\_}R), \qquad \text{Encrypted}_{\text{Seed}_1} = E_{\text{SEK1}}(\text{Seed}_1), \tag{1}$$

$$\text{IF } n\text{th bit } of \text{ SEK\_}R\ is\ 0,$$

$$\text{SEK}_n = F_{\text{SEK}}(\text{Addr}\|\text{UID}\|\text{Seed}_{n-1}), \tag{2}$$

$$\text{Encrypted}_{\text{Seed}_n} = E_{\text{SEK}n}(\text{Seed}_n),$$

$$\text{IF } n\text{th bit } of \text{ SEK\_}R\ is\ 1,$$

$$\text{SEK}_n = F_{\text{SEK}}(\text{Addr}\|\text{UID}\|\text{Seed}_{n-1} + \text{Seed}_{n-2}), \tag{3}$$

$$\text{Encrypted}_{\text{Seed}_n} = E_{\text{SEK}n}(\text{Seed}_n).$$

In main mod (Figure 7), each seed is encrypted using $\text{SEK}_1, \ldots, \text{SEK}_n$. Existing methods have the initial problem since they use the previously sent seed as the encryption key. When the first seed is known, all information is exposed. However, our proposed method uses SEK_*R* for randomization. Depending on each bit of SEK_*R*, computation of SEK_n is decided as in (2) or (3). SEK_*R* is randomly chosen by the controller device, and transmitted as encrypted. The probability that an adversary obtains SEK_*R* is the same as the probability that an adversary breaks the public key cryptosystem. Since RF4CE is based on 802.15.4 ZigBee standard, we could consider deploying existing WSN key distribution methods. However, such protocols require intermediate entities such as base station, while our protocol provide the peer-to-peer key exchange only between controller device and target.

4. Experimental and Implementation Results

4.1. Implementation of Connectivity Architecture. In order to confirm the feasibility of the proposed zero configuration and advanced pairing approach in the connectivity architecture, we implemented the prototype H/W module with zero configuration and advanced pairing functionalities for mobile terminal and PC system. As described in the previous section, the approaches are supported by RF4CE based on IEEE 802.15.4 for all CE appliances and IT devices. In order to confirm and evaluate the feasibility of the proposed RF4CE-based zero-configuration and advanced key agreement system, we fabricated prototypes of RF4CE evaluation board shown in Figure 8. We implemented the RF4CE zero-configuration with ad hoc and infrastructure mode, and the improved RF4CE key agreement protocol with mutual authentication and two-phase key seed distribution on the

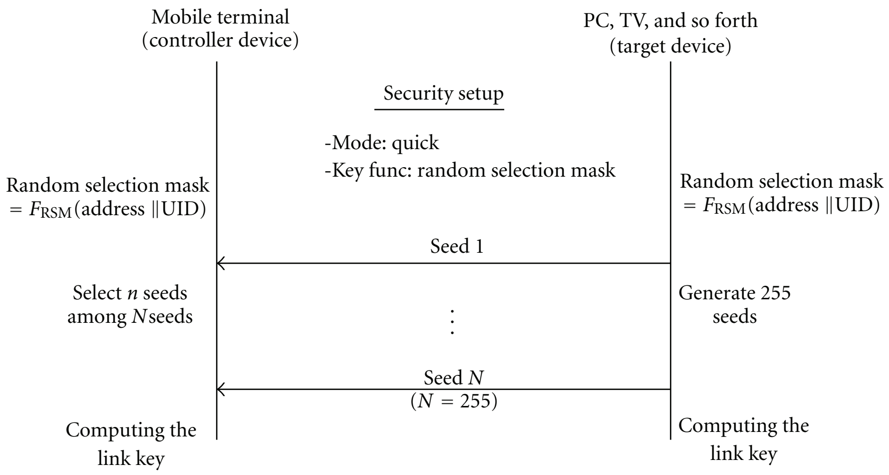


Figure 6: Key seed distribution-quick mode.

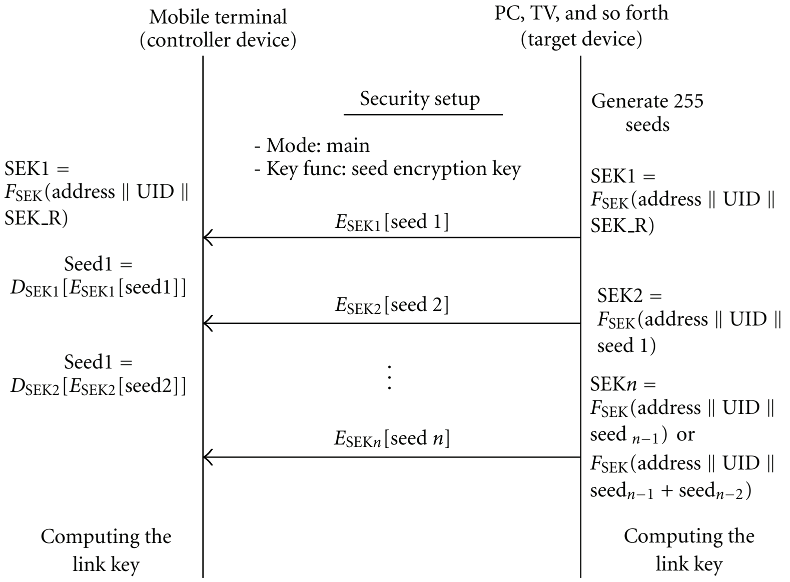

Mobile terminal
(controller device)
PC, TV, and so forth
(target device)
Security setup
Generate 255
seeds
- Mode: main
- Key func: seed encryption key
SEK1 =
F_{SEK}(address \|\| UID \|\|
SEK_R)
SEK1 =
F_{SEK}(address \|\| UID \|\|
SEK_R)
E_{SEK1}[seed 1]
Seed1 =
$D_{\mathrm{SEK1}}[E_{\mathrm{SEK1}}[\mathrm{seed1}]]$
E_{SEK2}[seed 2]
SEK2 =
F_{SEK}(address \|\| UID \|\|
seed 1)
Seed1 =
$D_{\mathrm{SEK2}}[E_{\mathrm{SEK2}}[\mathrm{seed2}]]$
SEKn =
F_{SEK}(address \|\| UID \|\|
seed $_{n-1}$) or
F_{SEK}(address \|\| UID \|\|
seed$_{n-1}$ + seed$_{n-2}$)
$E_{\mathrm{SEK}n}$[seed n]
Computing the
link key
Computing the
link key

Figure 7: Key seed distribution-main mode.

RF4CE test board. In Figure 8, it shows two kinds of RF4CE prototypes such as upper figure is RF4CE prototype with MG2455 RF4CE module [20] and lower figure is the layout of RF4CE prototype board. The specifications of the RF4CE evaluation board are shown in Table 1. MG2455 consists of 2.4 GHz RF transceiver, baseband modem, H/W MAC, 8051 MCU, and flash memory. Moreover, it has timer, UART peripheral, and normal I/O pins. Specifically, the MG2455 provides a few enhanced features as follows: Scalable Data Rate (250 kbps for ZigBee, 500 kbps and 1Mbps for private applications), Voice Codec Support, High RF RX/TX Power, 96 KB Embedded Flash Memory for Program Space, and Power Management Scheme with Deep Sleep Mode Support (under 1 μA). Thus, we implemented H/W modules with IEEE 802.15.4 PHY/MAC as various types in order to be applied to mobile terminal and PC system. Specifically, we used a small-size model with one-chip solution for a mobile terminal (e.g., Omnia phone) and a common model with enough size for multifunctional usage such as ZigBee and other IEEE 802.15.4-based simple applications (PCI board or USB board).

Figure 9 is a real mobile phone with connectivity architecture module in our testbed. In order to make a testbed, we used Samsung Omnia phone (SCH-M490) and the prototype module is embedded as a type of small PCB in a battery case.

Figure 10 is a prototype for PC system and it describes a variety of a built-in type of the prototype modules. It can be installed by PCI extension board or USB connecter board according to the type of PC system. For instance, in case of note-pc type, the prototype module can be installed as an USB connection type extension board because it cannot

Table 1: Specification of RF4CE prototype board.

General features	Board size	30 x 29 [mm2]
	MCU	Enhanced 8-bit 8051 (hardwired MAC and AES-128)
Processor/Radio	P/N	MG2455-F48 (Radiopulse)
	Memory	96 KB flash memory 8 KB SRAM
	Etc.	16 Mhz crystal, 12-bit A/D, D/A converter
	Frequency range	2400–2483.5 [MHz]
	Data rate	250 kbps/500Kbps/1Mbps
	Transmit power	0 dBm (Rx Sensitivity -95 dBm)
	Antenna	Chip antenna
Miscellaneous	Current consumption	28 mA @ RF mode 1uA @ Deep Sleep mode
	Power supply	1.5V alkaline battery (x2) (AA Size)
	RF connector	SMA type RF connector

Table 2: Energy consumption for contents sharing scenario.

	TV status query (times)	Contents list query (times)	Contents delivery (1 Mbytes)	Total energy consumption (mA)
RF4CE + Wi-Fi With Zero-configuration	2 (RF4CE)	2 (RF4CE)	447 (Wi-Fi)	97,991.8
Wi-Fi only	2	2	447	98,769.0
Bluetooth + Wi-Fi	2 (BT)	2 (BT)	447 (Wi-Fi)	98,121.0

have a PCI slot like desktop PC. The prototype for PC system consists of chipcon's CC2420 as a radio chip (2.4 GHz Frequency, 250 Kbps, 0 dBm Output power), TI MSP430 16-bit RISC architecture with 12-bit A/D, and D/A converter as a microcontrol unit. Moreover, 116 Kb flash memories and 8 Kb RAM is installed as an internal memory and the board size of core module is 60 × 32 mm. Figure 10 presents various built-in type of the prototype module in PC system. Figure 10(a) shows that the prototype module is connected by USB extension board to note-pc. In case of normal desktop PC, the module is installed by PCI slot as illustrated in Figure 10(c). During debug and test, it is connected to the development machine by USB port as shown in Figure 10(b).

4.2. Experimental and Demonstration of Connectivity Architecture. In this section we constructed two testbed for zero-configuration approach and advanced pairing approach like Figures 11(a) and 11(b). First, the testbed of a RF4CE-based wireless zero-configuration in connectivity architecture for Smart and Easy Control of CE devices in order to validate the core functionalities with implemented zero-configuration modules has been created in our laboratory. As described in Figure 11(a), the zero-configuration testbed consists of TV (Samsung LED TV 8000), two Mobile terminals (Samsung Omnia phone SCH-M490), and Note-PC (Samsung SENS P50). Each device has RF4CE-based zero-configuration module and Wi-Fi interface. The two mobile terminals have the same application, however, it can be work for twofold: one is only for TV control, the other is for showing contents sharing controller between TV and PC. Users can control TV and PC by using their own mobile terminal, remotely and freely.

On the other hand, the testbed of a simple RF4CE network for validating the fundamental functionalities of the proposed enhanced RF4CE key agreement system has been constructed in our laboratory. As shown in Figure 11(b), the RF4CE testbed is composed of two PCs as a controller and target simulator, and the simulators are connected with RF4CE prototype boards, separately. A discovery or pairing request packet from a controller node is sent to the target node, and then it is delivered to the simulator program using USB interface through UART serial socket. Thus, we can see that PC simulator is connected to RF4CE devices with USB-to-Serial interface, and then each node communicates on IEEE 802.15.4 standard.

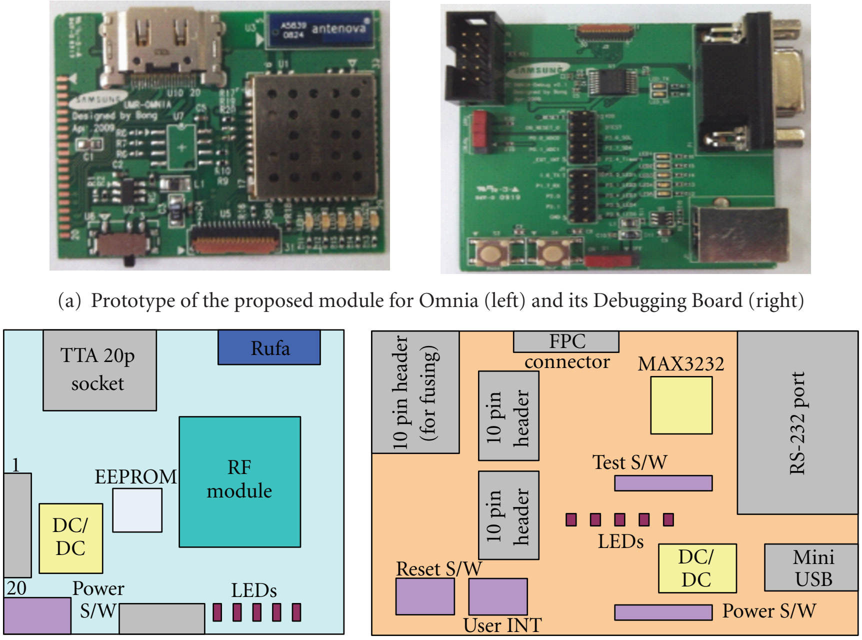
5. Discussion of Secure and Reliable Connectivity Architecture

Based on the proposed zero-configuration approach, we analyzed energy consumption for contents sharing between devices using different types of wireless technologies, that is, RF4CE, Wi-Fi, and Bluetooth. We applied multimedia contents sharing to them separately. For each of these types, we measured the amount of energy consumed and Table 2 shows the comparison results. We retrieved TV status 2 times and a list of contents in PC 2 times, and then issues a data sharing command. In order to measure the energy consumption, we

Table 3: Security analysis and comparisons.

		Existing RF4CE	Bluetooth	Proposed System
Authentication	Feature	None	ECDH(Mode4)	PKC*.
	Storage cost	None	Max2048 bits	Max2048 bits
	Computation cost	None	3E**	3E**
Integrity	Feature	Packet level	Packet level	Packet level and quick mode
	Storage cost	255∗80 bytes	***	≤255*80 bytes
	Computation cost	255 times	***	≤255 times
Confidentiality	Feature	None (Plaintext)	None (Plaintext)	Main mode
	Storage cost	None	None	128 bits
	Computation cost	None	None	<E

*Public Key Cryptosystem; **E denotes the exponentiation; ***BT does not use key seed distribution scheme.



(a) Prototype of the proposed module for Omnia (left) and its Debugging Board (right)

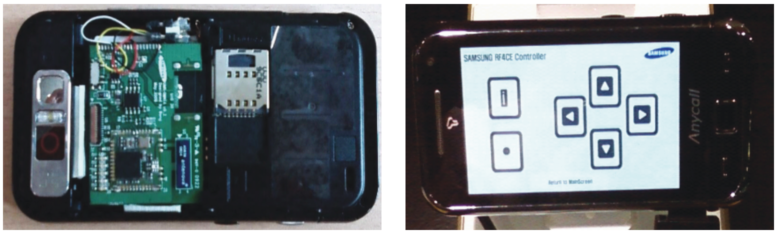
(b) Layout of the prototype and its debugging board

Figure 8: The Prototype of the connectivity architecture.

transmit 1 Mbyte-size content from PC to TV and measure the amount of energy consumed using the current consumption model in [22]. In the case of zero-configuration approach, RF4CE works for multimedia system control and Wi-Fi is used for delivering the content and the same configuration is applied to Bluetooth. But for the case of Wi-Fi, only Wi-Fi is used for both remote control and data sharing. Based on this experiment result, we claim that the RF4CE-based zero-configuration is more suitable to multimedia system control and contents sharing than the other solutions.

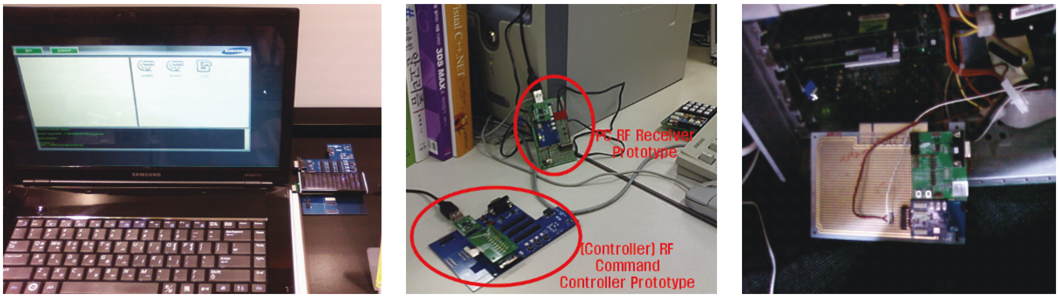
In multimedia communications, energy is mostly consumed while devices exchange data and multimedia communications have not been much used for control. The age of various converged multimedia services is on its way and furthermore various hardware devices for these services are being developed. In light of this, sooner or later, these services and devices will be common in our real life and we are going to use a control unit to remotely control them. As demonstrated in this section, multimedia control communications in using such various converged multimedia services also requires a nonnegligible amount of energy. In this sense, the proposed low-power RF4CE-based zero-configuration architecture can play a key role delivering a new device control experience with the users in the new environment of multimedia converged services

Moreover, we analyze our proposed approach in aspects of the security of authentication, integrity, confidentiality, and the cost for computation and communication. We also analyze the feasibility of our protocol against the known attacks. And then, we compare our proposed system with the existing RF4CE key agreement and Bluetooth pairing process. In Table 3, we tabulate the functional features between the existing RF4CE, Bluetooth, and the proposed system according to above-discussed security analysis.



(a) (b)

Figure 9: Mobile Phone (Omnia) and its embedded prototype module.



(a) (b) (c)

Figure 10: Installed zero-configuration modules for PC extension (USB connection and PCI extension).

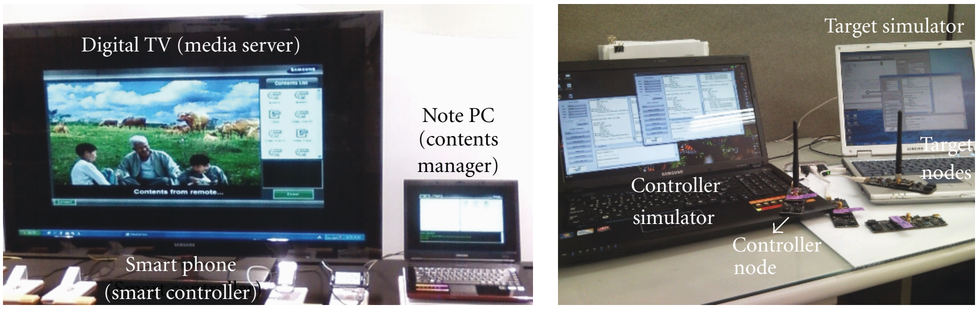
(i) Authentication. While the existing RF4CE standard does not consider any authentication method for the pairing and the key seed distribution, the proposed approach employs the authentication scheme that is used for the wireless network standards such as IEEE 802.16. Applying our approach, two entities in RF4CE communication can mutually authenticate each other during initial pairing with the preinstalled certificate issued by CA. Thus, the proposed approach is secure against not only the unauthorized device from attaching any authorized devices, but also any malicious entity from compromising or forging the node. In case of the Bluetooth, the PIN (Security mode 2, 3) or ECDH (Security mode 4) are deployed for the mutual authentication. Our proposed protocol has the additional computation cost of three exponentiations for supporting PKC (Public Key Cryptosystem) as same as the ECDH (security mode 4) of Bluetooth. In case of the computation cost, our proposed approach has the computation cost of three exponentiations due to the public key operation in the mutual authentication procedure. It means the public key operation is prevailed against other security operations. Thus, the authentication row in Table 1 only has the computation cost and it shows the same level of burden compare to the cost of Bluetooth (mode 4).

(ii) Integrity. Integrity of key seeds shared among the nodes in RF4CE networks is guaranteed by FCS (Frame Check Sum) initially supported by RF4CE MAC Frame and MIC (Message Integrity Code) provided to packet in Network layer (NWK). Bluetooth also supports similar level of packet integrity. However, the previous methods could not guarantee the security against modification or loss of the key seeds considering the integrity of transmitting max 255 number of key seeds. Instead, the proposed protocol provides the higher level of integrity than the previous methods by choosing n number of key seeds randomly from max 255 key seeds in quick mode. Note that we do not consider the integrity and confidentiality of key seeds of Bluetooth that does not use the key seed distribution. Thus, the existing RF4CE support a packet/frame level integrity function by the standard specification. And the proposed approach decreases the threat of the packet loss/interception and storage size (under 255*80 bytes) by providing selective transmission of key seeds.

(iii) Confidentiality: The main mode of our proposed protocol provides the high level of confidentiality in comparison with the previous methods that key seeds are transmitted in plain text during the key seed distribution, since every key seed is encrypted by different keys using 128 bits AES algorithm. In case of Bluetooth, it still has the vulnerability that *IN_RAND* for generating Link Key is transmitted in a plain text in modes 2 and 3.

6. Conclusion

In this paper, we proposed a novel RF4CE-based zero-configuration and advanced pairing approach for a novel connectivity architecture of various CE and IT devices and applications. Deploying the proposed architecture enable users to control a variety of devices and share data, and save the power consumption in comparison with the existing



(a) Zero-configuration testbed (left)

(b) Advanced pairing testbed (right)

Figure 11: Testbed setup for the demonstration experiment (TV-Phone-PC).

Wi-Fi-based zero-configuration methods since RF4CE-based zero configuration is working on IEEE 802.15.4 standard technology. In case of advanced pairing, the novel approach to enhance RF4CE key agreement is presented according to these recent convergence trends. Our improved key agreement approach supports the mutual authentication using RF4CE device certification in order to resolve the threat of counterfeited or cloned devices. The quick mode of the proposed key seed distribution increases the possibility of the secure generation of a link encryption key against the disclosure to the third party and the DoS attack by providing the transmission of the selected key seeds. Key selection information is only shared between the paired nodes. The main mode solves the vulnerability of plaintext transmission through encrypting all transmitted seeds with different keys.

In order to verify the zero-configuration and advanced pairing approach in the connectivity architecture, we implemented the prototype's networking stack and its various prototypes H/W such as Samsung's "Omnia" dongle for a mobile terminal and PC/note-PC side dongles. We presented the implementation results with various verification scenarios using Omnia terminal, LED TV, and Note PC. The experimental scenarios demonstrated that the proposed architecture enables to construct a simple and easy control for an efficient smart home network between various devices. Moreover, we verified the feasibility and compared with the existing solutions of the proposed approach through analyzing security of Authentication, Integrity, Confidentiality, and Known Attacks. From the various security analysis and real implementation, we can say that the proposed RF4CE key agreement approach is more robust than any other previous schemes and works efficiently with RF4CE nodes. Therefore, to the best of my knowledge, these results show the potential to bridge the convergence environments with smart devices and applications to our life using the proposed connectivity architecture with RF4CE-based Wi-Fi zero-configuration and advance pairing approach.

Acknowledgment

This research was supported by the Basic Science, Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education, Science and Technology (2010-0017023).

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