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# On a Distributed Cognitive MAC Protocol for IEEE 802.11s Wireless Mesh Networks

**Kaveh Ghaboosi · Matti Latva-aho · Ryuji Kohno**

**Abstract** A distributed frequency agile medium access control (MAC) extension to the IEEE 802.11s for the next generation wireless mesh networks is proposed. The introduced protocol enhancements are capable of concurrent deployment of existing frequency opportunities in order to coordinate simultaneous data transmissions. The root concept is mainly based on the deployment of well-known ISM frequency bands, where the legacy 802.11-based wireless equipments operate, as the common control channel in order to establish contemporaneous transmissions. We apply the aforementioned key concept to the IEEE 802.11s common channel framework to attain two important goals: To improve the channel utilization using the concept of cognitive radio, and to lower the access delay. Through extensive event-driven simulations, taking into account primary user appearance in non-ISM frequency bands, performance of the proposed MAC enhancement is evaluated showing its higher efficiency compared to the existing solutions, in addition to its better wireless medium management.

**Keywords** Medium access control · Mesh networks · Cognitive radio

## 1 Introduction

As wireless networks evolve into the next generation in order to offer better services, a key technology, wireless mesh networks (WMNs), has emerged recently [1,2]. In WMNs, nodes

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K. Ghaboosi (✉) · M. Latva-aho
Centre for Wireless Communications (CWC), University of Oulu, Oulu, Finland
e-mail: kaveh.ghaboosi@ee.oulu.fi

M. Latva-aho
e-mail: matti.latva-aho@ee.oulu.fi

R. Kohno
Division of Physics, Electrical and Computer Engineering, Graduate School of Engineering,
Yokohama National University (YNU), Yokohama, Japan
e-mail: kohno@ynu.ac.jp

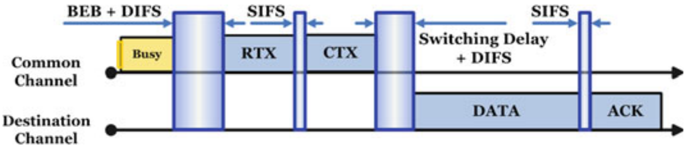

**Fig. 1** Common channel framework (CCF) concept in IEEE 802.11s

are comprised of mesh routers and mesh clients. Each node operates not only as a host but also as a router, forwarding packets on behalf of other nodes that may not be within direct wireless transmission range of their destinations [3,4,6,7].

In the final version of IEEE 802.11s amendment, the so-called common channel framework (CCF) is going to be ratified as a non-compulsory technique to provide higher aggregate channel throughput due to its capability of conducting multiple channels deployment and concurrent data transmissions [1,4,5]. In CCF, mesh points (MPs)[1] utilize a common channel to negotiate for available data channels, which are deployed for link layer communications between source and destination entities.[2] The negotiation phase is accomplished by exchanging two designated control frames named as ready-to-switch (RTX) and clear-to-switch (CTX). According to CCF, the SE sends an RTX frame over the common channel to inform its DE of interest. In addition, the SE should offer an available data channel to DE to be deployed during the whole data transmission between SE and DE. Using a dedicated field in the header of RTX (i.e., destination channel information), SE advertises a particular data channel to the DE. If DE agrees with the advertised data channel, it shall respond using a CTX control frame which is also transmitted over the shared common channel. Subsequent to the intact reception of CTX frame by SE, both involving entities have to switch to the destination channel in order to commence the agreed data transmission. After switching to the agreed data channel, if the wireless medium is sensed idle for at least DIFS[3], the SE starts transmission of data frame(s) to the DE. At the end, an acknowledgement (ACK) frame is delivered through the destination channel back to the SE (see Fig. 1). It should be also reminded that there is a special type of MP named as mesh access point (MAP), which serves also as an access point (AP) in addition to providing the conventional mesh services.

In IEEE 802.11s, it is assumed that MPs are equipped by a single-radio transceiver; hence as an apparent consequence, MPs on data channels are unaware of the network activities taking place on the common channel. In fact, applying cognitive radio techniques to the 802.11s-based WMNs brings several possibilities to improve the overall system performance. In this paper, we propose an architecture by which the cognitive mesh entities establish a cognitive extended service set (CESS) to which both legacy and cognitive mesh entities are allowed to associate. Here, by mesh entity (ME) we refer to any mesh equipment that is part of the wireless mesh network. Thus, an ME can either be an MP or an MAP. In addition, by cognitive mesh entity (CME) we explicitly refer to MEs that have frequency agile capabilities.

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[1] According to the IEEE 802.11s amendment, a wireless device supporting the pre-defined mesh services in a wireless mesh network is called a mesh point (MP). An MP can be either a dedicated infrastructure device or a user appliance that is able to fully participate in both formation and operation of the mesh network simultaneously.

[2] In this paper, source entity (SE) refers to any mesh equipment that intends to commence a data transmission. This entity can either be a mesh point (MP) or a mesh access point (MAP). In addition, by cognitive source entity (CSE) we refer to an SE that has frequency agile capabilities. On the other hand, destination entity (DE) refers to any mesh equipment that is supposed to receive data frame(s) from an SE. Similarly, by cognitive destination entity (CDE) we refer to a DE that has frequency agile capabilities.

[3] DIFS stands for Distributed Inter-Frame Space (see IEEE 802.11-1999).

This includes both cognitive mesh point (CMP) and cognitive mesh access point (CMAP). As a whole, a CESS accommodates CMPs, CMAPs, and possibly non-cognitive MPs and MAPs (i.e., legacy MEs).

Following, in Sect. 2 the proposed medium access control (MAC) enhancement for the next generation frequency agile IEEE 802.11s WMNs is presented and in Sect. 3, the proposed cognitive scheme is evaluated through extensive simulations. Finally, conclusions are stated in Sect. 4.

## 2 Proposed Cognitive MAC Enhancement

### 2.1 Preliminaries

The key concept of the proposed architecture is to establish CESSs on the ISM frequency bands where the legacy 802.11/.11s appliances currently operate. By this essential requirement, all legacy 802.11/.11s equipments are able to detect, probe, and associate to the CESSs. Besides, ISM band can be utilized as a shared common control channel by the cognitive radio entities.

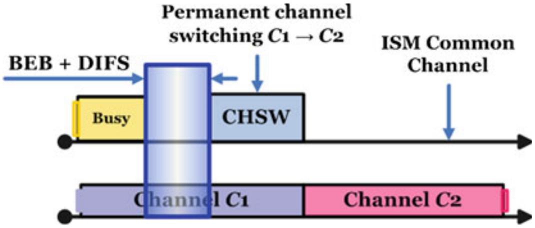
In the proposed architecture, none of the CMEs are allowed to deploy the shared ISM channels for their private data transmissions, except for the case when the CMEs want to communicate with the legacy MEs (i.e., non-cognitive MEs) and vice versa. In these two cases, CMEs are required to operate on the shared ISM channels in order to exchange the intended data frame(s) with the legacy MEs. It is indeed worth to note that by establishing CBSSs on ISM channels, CMEs are able to provide wider network coverage, extra network connectivity, and packet forwarding to the legacy systems on one hand, and on the other hand they are allowed to use shared ISM channels as a common medium to primarily exploit for management and control traffic exchange.

We equip all CMEs by two radio transceivers, named as ISM- and non-ISM transceivers. While the former is particularly dedicated to operate on ISM bands, the latter is specially designed to serve as a cognitive transceiver which is capable of switching within a wide range of non-ISM channels to perform data transmissions. As an obvious result, CMEs will never suffer from the same problem as pointed out earlier regarding awareness about the network activities taking place on common control channel.

In a frequency agile MAC protocol, the main issue of concern is how cognitive radios should be configured in order to utilize frequency opportunities in an efficient fashion. In fact, it is indeed efficient for a CME to choose an available and free of primary users (PUs) non-ISM frequency opportunity, based on a set of pre-defined spectrum sensing criteria, as its long-term residency channel (LTRC). Subsequent to selection of an LTRC, CME should inform all its one-hop neighbours about its chosen LTRC. Furthermore, the CME should tune its non-ISM transceiver permanently on LTRC until based on some criterions it becomes evident that switching to another non-ISM channel is more beneficial. In the case of permanent channel switching, CME is mandated to re-announce the new non-ISM LTRC channel that is going to be utilized right after the switching declaration. Basically, permanent channel switching is announced using a designated frame called channel switching (CHSW). Figure 2 illustrates a simple frame flow to announce a permanent switching from channel $C_1$ to channel $C_2$.

In this paper, source entity (SE) refers to a mesh equipment that intends to commence a data transmission. This entity either can be an MP or an MAP. In addition, by cognitive source entity (CSE) we refer to an SE that has frequency agile capability. Moreover, the destination entity (DE) refers to a mesh equipment that is supposed to receive data frames from

**Fig. 2** Permanent channel switching announcement using CHSW transmitted on the shared ISM channel



an SE. Similarly, by cognitive destination entity (CDE) we refer to a DE that has frequency agile capability. When a CSE wants to commence a data transmission, as it knows the LTRC channel of the CDE, the negotiation phase can be simply eliminated if the CSE is also willing to utilize CDE's current residency channel. To accomplish the intended data transmission, CSE should park its cognitive transceiver on CDE's LTRC. In addition, it should report its on-leave status from its LTRC and the corresponding absence period. Whenever the CME decides to switch to another channel for a planned data transmission, it should use an *e*RTX[4] control frame, sent over the shared ISM channel, in order to attain two achievements:

1. Establishment of link layer connection with the intended CDE,
2. Informing the one-hop neighbours about the on-leave situation and the corresponding absence time duration.

It can be deduced that by aforementioned approach, the exchanged overhead is reduced: using only one control frame, we are able to establish the intended link layer connection, in addition to reporting the on-leave status for a particular time period. More importantly, on-leave information can be also used for the destination non-ISM channel[5] reservation purpose, similar to the Duration/ID field, which is mainly employed for updating network allocation vector (NAV) in 802.11 ISM channels. Here, as the legacy IEEE 802.11 and its .11s counterpart, Duration/ID field of *e*RTX and *e*CTX will be particularly used for the shared ISM channel reservation (i.e., NAV update in ISM channel). In contrast and besides other applications, the on-leave information which is carried by a designated field in *e*RTX and *e*CTX will be used for the destination non-ISM channel reservation where the cognitive data transmission is planned to be accomplished.

While requesting to establish a link layer connection, CSE should mention the CDE's LTRC channel information inside a designated field within the *e*RTX frame. When the prior knowledge of CSE about CDE's current LTRC is correct, upon reception of CSE's *e*RTX, which is carrying the CDE's LTRC, CDE simply responds by an *e*CTX frame, not over the shared ISM channel, but on its own non-ISM LTRC. Moreover, since CSE has already tuned its cognitive transceiver on the CDE's LTRC, it can easily receive the *e*CTX on the CDE's LTRC. In addition to the *e*CTX, both DATA and ACK frames should be also transmitted on the CDE's LTRC. In conclusion, the shared ISM channel (i.e., common channel) is only utilized for cognitive control frame exchange, but no more than an *e*RTX frame.

If CSE has incorrect a priori knowledge about its desired CDE's LTRC, the *e*CTX control frame will be transmitted over the ISM channel. Afterward, CSE receives the *e*CTX frame on the ISM channel and is informed about inaccurate knowledge about the CDE's LTRC. In this case, CDE is required to put the correct information about its LTRC specifications inside

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[4] In this paper, CMEs, instead of RTX/CTX, exchange the so-called *e*RTX/*e*CTX control frames. The new *e*RTX/*e*CTX frames are similar to the conventional RTX/CTX, but with a few extra fields.

[5] Here, by "destination non-ISM channel" we mean CDE's LTRC.

a designated field within its *e*CTX. As a subsequent step, the CSE must resend another *e*RTX frame over the shared ISM channel, but with the updated information. In fact, reception of the *e*RTX frame carrying incorrect information by those CMEs that have no a priori background about the CDE's LTRC distributes incorrect information; thus, such undesirable cases should be addressed as quickly as possible. By sending another *e*RTX frame CSE prevents distribution of inconsistent information within the CESS. Finally, CSE is allowed to commence its data transmission over the CDE's LTRC right after sending the second *e*RTX, plus an extra SIFS.

Another issue that needs to be addressed properly is when a CME decides to perform a *temporary* channel switching while some of its neighbours have already initiated backoff sequences for data transmission intended for CME. Recall that there are two different types of channel switching: *permanent* non-ISM channel switching and *temporary* non-ISM channel switching. While the former is conducted when it becomes evident for the CME that switching permanently to another non-ISM channel is more beneficial, the latter is performed when the CME plans to accomplish a data transmission to one of its neighbouring CMEs. As stated earlier, permanent channel switching is announced using a designated control frame called CHSW while on the other hand, CMEs are required to announce their transition to other non-ISM channels using *e*RTX control frame if the temporary channel switching is intended for a data transmission. Basically, upon reception of switching notification in the form of an *e*RTX frame, those CMEs that have already initiated a backoff cycle to commence data transmission to the switching CME should suspend counting down of their backoff timers until the end of on-leave period, which has been appended to the *e*RTX frame. In contrast to the temporary channel switching, for *permanent* switching there is no need to suspend ongoing backoff sequences since based on the proposed cognitive scheme, we enforce CMEs to follow two essential rules when counting down the backoff counters:

1. If the backoff counter is loaded by an integer value larger than 1, for any subsequent count-down before reaching '1' CME shall perform carrier sensing only on the shared ISM channel.
2. For the final count-down (i.e., counting down from '1' to '0') both ISM common channel and the destination non-ISM channel should be simultaneously sensed 'idle' for at least a time duration equal to DIFS.

The above differences compared to the conventional backoff algorithm leads to lower access delay in comparison to the existing multi-channel MAC protocols. In addition, the proposed scheme is obviously more robust to the hidden terminal problem compared to 802.11s CCF.

### 2.2 Protocol Core Algorithm and Frames Structure

As stated formerly, in IEEE 802.11s two designated control frames, i.e., RTX and CTX, are used by CCF scheme for link layer connection establishment between MEs. We expand RTX/CTX frames functionalities to let the system coordinate cognitive concurrent data transmissions in an efficient way. In this paper, the above control frames are renamed to *e*RTX and *e*CTX respectively.[6] In addition, we refer to the proposed scheme as cognitive common channel framework (CCCF).

Figures 3 and 4 illustrate frame structure of *e*RTX and *e*CTX respectively while, Fig. 5 shows the frame format of CHSW control frame. Similar to the RTX and CTX frames, both

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[6] Note that by introducing *e*RTX/*e*CTX we do not define any new *frame type* to the existing IEEE 802.11s. We simply use the same frame types for the legacy RTX/CTX but with extra appended fields.

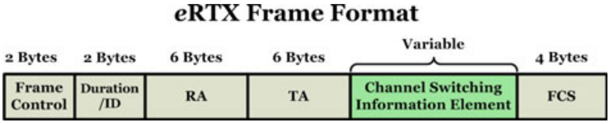

**Fig. 3** *e*RTX frame format in cognitive common channel framework (CCCF)

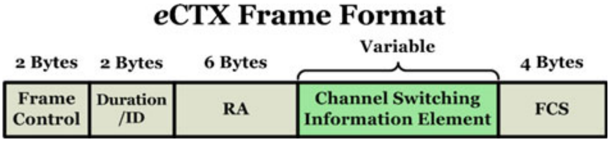

**Fig. 4** *e*CTX frame format in cognitive common channel framework (CCCF)

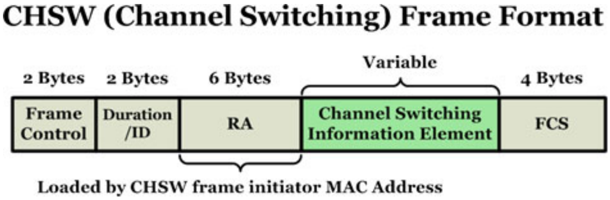

**Fig. 5** Channel switching (CHSW) frame format in cognitive common channel framework (CCCF)

*e*RTX and *e*CTX frames contain 2 Bytes for Frame Control and 2 Bytes for Duration/ID field. Later, we will discuss how the Duration/ID field is set for *e*RTX and *e*CTX. Duration/ID field of *e*RTX and *e*CTX frames is always used for the shared ISM channel reservation and NAV update. On the other hand, the on-leave duration information carried by *e*RTX and *e*CTX is used for the destination non-ISM channel (i.e., CDE's LTRC) reservation.

For *e*RTX and *e*CTX frames, CHSWIE field has variable length depending on the application scenario in which the above control frames are employed. Since CHSW frame is primarily used when a CME decides to change its LTRC channel permanently, the CME simply sends the CHSW over the shared ISM channel for which the receiver address (RA) field is loaded by the switching CME's MAC address. This strategy is similar to the CTS-to-self which is defined in IEEE 802.11g amendment but for a different application.

Figure 6 illustrates the detail structure of CHSWIE field used in *e*RTX, *e*CTX, and CHSW frames. In a CHSWIE, up to two channel information (CI) subfields can be appended. In fact, CI is the place where channel specifications of non-ISM channels are indicated. Each CI has three entries as shown in Fig. 6: Regulatory Class, Channel Mask, and Center Frequency.

The first byte of CHSWIE is called channel control (CC) which is used to control basic structure of CHSWIE and its contents. In CC, the first couple of bits represent "CHSWIE status". When the CHSWIE has no appended CI subfield, the CHSWIE status is simply set to '00' (i.e., Empty CHSWIE); otherwise, the aforementioned bits are loaded by '11' (i.e., non-Empty CHSWIE). Finally, CHSWIE status value of '01' and '10' are reserved. The next three bits in CC are used for future protocol development purposes. The last three bits in CC are altogether called Reason Code: The first bit, i.e., "Permanent/Temporary Switching Flag", is used to specify whether the intended channel switching is permanent or temporary. The

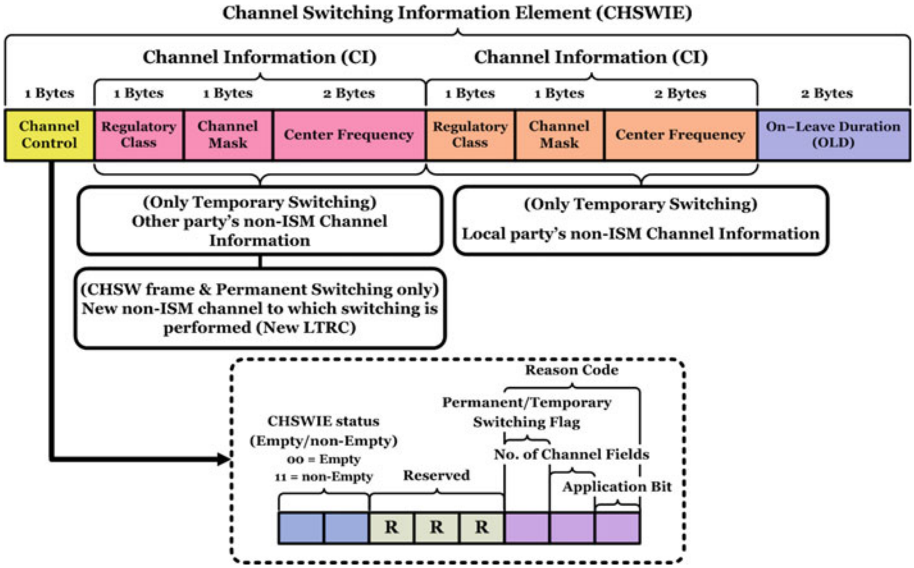

**Fig. 6** Channel switching information element (CHSWIE) structure in *e*RTX, *e*CTX, and CHSW control frames

second bit, i.e., "No. of Channel Fields", specifies the number of appended CIs in CHSWIE. The last bit, i.e., "Application Bit", is usually used in conjunction with its preceding two bits.

For *permanent* switching (CHSW control frame), only one CI can be appended inside CHSWIE field. In this case, the CI subfield carries the information of non-ISM channel to which the permanent switching is going to be accomplished (i.e., new LTRC for the switching CME). In contrast, for *temporary* switching up to two CIs can be appended within a CHSWIE. In this case, the first CI always represents the "other party non-ISM LTRC channel information" while the second one is corresponding to the "local party non-ISM LTRC channel information". Here, by "other party" we mean the CME to which the frame, containing the CHSWIE, is targeted (i.e., frame receptor). Also by "local party" we mean the frame initiator that is transmitting the frame, containing the CHSWIE. As an example, for an *e*RTX control frame the "other party" refers to the CDE and the "local party" refers to the CSE; in contrast, for an *e*CTX control frame the "other party" refers to the CSE while the "local party" refers to the CDE which is supposed to receive the data frames from CSE.

Every CHSWIE is ended by a two-byte on-leave duration (OLD) subfield representing the time interval during which CSE will be absent from its LTRC channel. For a temporary channel switching, this subfield is loaded by a non-zero value between 0000 and FFFF Hex; in contrast, for permanent switching OLD is simply loaded by FFFF Hex.

Duration/ID field in both *e*RTX and *e*CTX is used for the shared ISM channel reservation and NAV update; on the other hand, OLD subfield of CHSWIE in *e*RTX and *e*CTX is not only used for on-leave duration reporting, but also used for channel reservation and NAV update in the destination channel (e.g., CDE's LTRC). Therefore, it is indeed important to define the way by which both Duration/ID field and OLD subfield are tuned when exchanging *e*RTX/*e*CTX control frames. We consider all possible scenarios that take place when a CME wants to commence a data transmission with another CME based on different combinations of Reason Code bit pattern and CHSWIE status:

### *2.2.1 CHSWIE status = 11*

When CSE has prior knowledge about CDE's LTRC, the *e*RTX frame always carries a non-empty CHSWIE; as a result, CHSWIE status bits of CC are loaded by '11'. For an *e*RTX control frame we consider two following cases:

Case I: As the first case, let us assume that Reason Code is set to 000. This set up refers to a temporary switching with only one appended CI subfield. When this configuration is used in an *e*RTX frame, the CI contains the CDE's LTRC channel information. To establish a link layer connection with a CME, CSE needs to switch to CDE's LTRC. By transmitting an *e*RTX frame, CSE sends its request to the CDE and at the same time, it informs its one-hop neighbours about its temporary transition to another non-ISM channel. Obviously in this case, CDE's LTRC channel information should be also included in CHSWIE of *e*RTX.

Case II: As the second case, when the Reason Code is loaded by 010, not only CDE's LTRC but also CSE's LTRC channel information is included in CHSWIE of *e*RTX; both appended CDE's LTRC and CSE's LTRC are based on CSE's local knowledge. It should be noted that inclusion of CDE's LTRC channel information in *e*RTX control frames is always mandatory while enclosure of CSE's LTRC channel information is totally optional. Also note that for the case of 000 the size of CHSWIE is seven bytes while for the case of 010 it is eleven bytes in size (Case II).

For an *e*CTX control frame, we consider the following three cases:

Case I: When the Reason Code is loaded by 000, the single appended CI carries CSE's LTRC. Basically, when CDE's knowledge about CSE's LTRC channel information is incorrect, the only way to get the correct information is to use integrated CSE's LTRC channel information in the received *e*RTX. Actually, the correct information can be obtained via the received *e*RTX if CSE has included its LTRC channel information in the preceding *e*RTX. When CDE notices that its knowledge about CSE's LTRC is inaccurate, it should make the required corrections to its local databases as soon as possible. In fact, CDE will be unable to be informed about its incorrect knowledge unless CSE includes its LTRC channel information inside the *e*RTX frame to be sent to CDE (Recall that inclusion of CSE's LTRC channel information in *e*RTX is optional). Only by this way, CDE is able to find out that its knowledge about CSE's LTRC is incorrect and should be corrected immediately. In addition, CDE is also mandated to inform its neighbours about CSE's LTRC correct channel information. As a matter of fact, it is possible that CDE has already distributed its incorrect knowledge among its one-hop neighbours, resulting in further undesirable distribution of inconsistence/incorrect information. Therefore, when CDE by reception of an *e*RTX frame is notified about its incorrect knowledge about CSE's LTRC, should put the correct information inside the *e*CTX and sends it over the shared ISM channel back to the CSE.

Case II: As the next case, consider an *e*CTX with Reason Code loaded by 001: temporary switching with only one appended CI subfield. In this case, the CI carries CDE's LTRC channel information. When CSE transmits an *e*RTX frame over the shared ISM channel, it is required to put its intended CDE's LTRC channel information inside CHSWIE field of *e*RTX. If CDE receives the delivered *e*RTX and notices erroneous appended information about its LTRC, as an obvious consequence, instead of sending the *e*CTX on its non-ISM LTRC, it will send out the

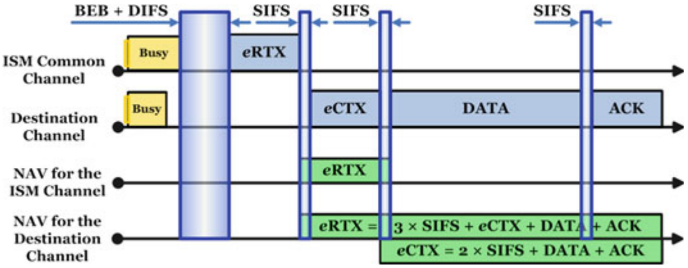

**Fig. 7** Channel reservation using *e*RTX and *e*CTX when CSE's knowledge about CDE's LTRC is correct

*e*CTX over the shared ISM channel. In addition, CDE shall put its correct LTRC channel information inside *e*CTX to inform CSE about its incorrect knowledge. In response, CSE shall respond by another *e*RTX on the ISM channel carrying the correct information. Only after transmission of an *e*RTX with the correct channel information, CSE is allowed to commence its data delivery over the CDE's LTRC.

Case III: Finally, for the case of an *e*CTX carrying a Reason Code loaded by 010, not only CSE's knowledge about CDE's LTRC, but also CDE's knowledge about CSE's LTRC has been incorrect. In other words, this case includes both previous scenarios we just discussed about, i.e. *e*CTX/000 and *e*CTX/001. CDE is required to send the *e*CTX with both CSE's LTRC correct channel information and its own LTRC correct channel information. Apparently this frame should be delivered on the shared ISM channel, and as the next consequence CSE is also required to resend another *e*RTX frame over the shared ISM channel appended by correct CDE's LTRC channel information. Finally, CSE starts sending DATA frame(s) on CDE's LTRC right after completion of sending the second *e*RTX, plus an extra SIFS (Case III).

### 2.2.2 *CHSWIE status = 00*

When CSE has no prior knowledge about CDE's LTRC, *e*RTX frame always carries an empty CHSWIE; as a result, CHSWIE status bits of CC are simply loaded by '00'. In addition as far as the receiver side (i.e., CDE) is concerned, when both appended CDE's LTRC channel information in *e*RTX and CDE's knowledge about CSE's LTRC are correct, CDE is allowed to respond using an *e*CTX with no appended CI transmitted on its own non-ISM LTRC.

## 2.3 CSE and CDE Frame Exchange Patterns

Figure 7 illustrates the regular frame exchange between CSE and CDE when CSE's knowledge about CDE's LTRC is correct.

In this scenario, CSE includes only CDE's LTRC information in CHSWIE field of *e*RTX which is being transmitted over the shared ISM channel. When only CDE's LTRC channel information is included in *e*RTX, the Duration/ID field in *e*RTX is loaded by *e*CTX*time* (with 7 Bytes CHSWIE) + 2 × SIFS while OLD subfield is loaded by *e*CTX*time* (with *no* CHSWIE) + DATA*time* + ACK*time* + 3 × SIFS. The reason CSE reserves ISM channel for the aforementioned time duration is obvious: in fact, CSE should take into account the case when its knowledge about CDE's LTRC is incorrect and its intended CDE responds by an *e*CTX on the shared ISM channel accompanied by a non-empty 7 bytes CHSWIE

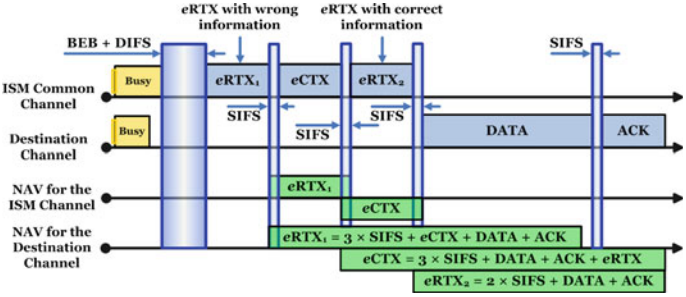

**Fig. 8** Channel reservation using *e*RTX and *e*CTX when CSE's knowledge about CDE's LTRC is incorrect

for the correct CDE's LTRC channel information. In such case, ISM channel should have been reserved by CSE beforehand to prevent any possible loss of channel-control. If the ISM channel is reserved for a time period less than the abovementioned duration, other MEs may acquire control of ISM channel and the tagged CSE is needed to re-initiate the whole *e*RTX/*e*CTX negotiation phase from the beginning. Finally, the transmitted *e*CTX on CDE's LTRC carries an empty CHSWIE for which the Duration/ID field is loaded by '00' and OLD subfield is loaded by DATA*time* + ACK*time* + 2 × SIFS.

Figure 8 shows the case when only CDE's LTRC channel information is appended in *e*RTX while this information is incorrect.

In this scenario, CSE appends only CDE's LTRC channel information in CHSWIE of *e*RTX. In addition, CSE's knowledge about CDE's LTRC is incorrect; therefore, CDE responds by an *e*CTX on the shared ISM channel to inform CSE about its inconsistence knowledge about CDE's LTRC. When CSE receives the above *e*CTX on the shared ISM channel, as a consequence it sends another *e*RTX on the common ISM channel accompanied by the corrected information about CDE's LTRC. Upon successful transmission of second *e*RTX plus an extra SIFS, CSE is allowed to start transmission of data frames on CDE's LTRC. When only CDE's LTRC channel information is included in *e*RTX, the Duration/ID field in *e*RTX is loaded by *e*CTX*time* (with 7 Bytes CHSWIE) + 2 × SIFS while OLD subfield is loaded by *e*CTX*time* (with *no* CHSWIE) + DATA*time* + ACK*time* + 3 × SIFS. On the other hand, based on this scenario the transmitted *e*CTX on the shared ISM channel carries a CHSWIE loaded by CDE's correct LTRC channel information for which the Duration/ID field is loaded by *e*RTX*time* (with 7 Bytes CHSWIE) + SIFS and OLD subfield is loaded by *e*RTX*time* (with 7 Bytes CHSWIE) + DATA*time* + ACK*time* + 3 × SIFS. Finally, for the second *e*RTX, the Duration/ID field is loaded by '00' while OLD is loaded by DATA*time* + ACK*time* + 2 × SIFS.

When CSE has no prior knowledge about CDE's LTRC, it simply sends an *e*RTX frame with an empty CHSWIE on the shared ISM channel to inform CDE about its demand to establish a link layer connection. Upon reception of an *e*RTX frame with an empty CHSWIE, CDE simply replies by an *e*CTX on the shared ISM channel carrying its current LTRC channel information. When CSE receives the *e*CTX, it resends another *e*RTX on the shared ISM channel accompanied by CDE's LTRC channel information in CHSWIE field. An SIFS after completion of second *e*RTX transmission, CSE commences data delivery on the targeted non-ISM channel (i.e., CDE's LTRC). Figure 9 illustrates the whole frame exchange corresponding to this scenario.

In this scenario (see Fig. 9), the Duration/ID field of first *e*RTX is loaded by *e*CTX*time* (with 7 Bytes CHSWIE) + 2 × SIFS while OLD subfield is loaded by *e*CTX*time* (with 7

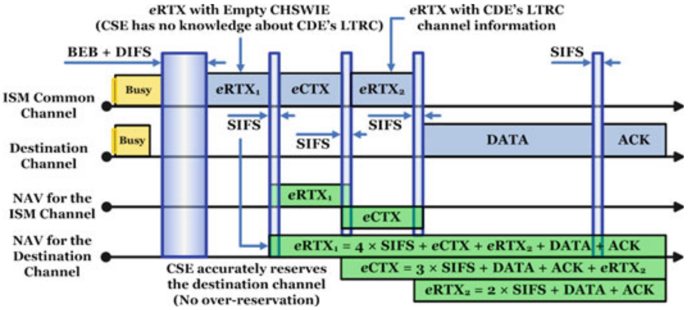

**Fig. 9** Channel reservation using *e*RTX and *e*CTX when the CSE has no prior knowledge about CDE's LTRC

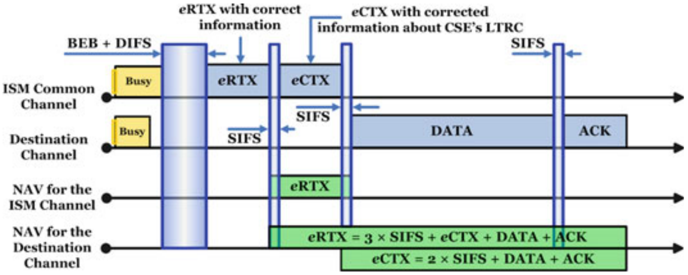

**Fig. 10** Channel reservation using *e*RTX and *e*CTX when the CDE's knowledge about CSE's LTRC is incorrect

Bytes CHSWIE) + *e*RTX*time* (with 7 Bytes CHSWIE) + DATA*time* + ACK*time* + 4 × SIFS. On the other hand, the transmitted *e*CTX on the shared ISM channel carries a CHSWIE loaded by CDE's LTRC channel information for which the Duration/ID field is loaded by *e*RTX*time* (with 7 Bytes CHSWIE) + SIFS and OLD subfield is loaded by *e*RTX*time* (with 7 Bytes CHSWIE) + DATA*time* + ACK*time* + 3 × SIFS. Finally, for the second *e*RTX, the Duration/ID field is simply loaded by '00' while OLD is loaded by DATA*time* + ACK*time* + 2 × SIFS.

Figure 10 shows the scenario when CSE includes both CDE's and its LTRC channel information in the *e*RTX frame to be delivered on the shared ISM channel. In this scenario, it is assumed that the appended CDE's LTRC channel information in *e*RTX is completely correct while CDE's knowledge about CSE's LTRC is incorrect. Since CSE has included its LTRC channel information in *e*RTX, CDE will be able to figure out that its knowledge about CSE's LTRC is incorrect; as a result, CDE responds using an *e*CTX delivered on the shared ISM channel appended by the correct CSE's LTRC channel information. In response and after a SIFS, CSE commences transmission of data frames over CDE's LTRC.

For the scenario shown in Fig. 10, the Duration/ID field of *e*RTX is simply loaded by *e*CTX*time* (with 11 Bytes CHSWIE) + 2 × SIFS while OLD subfield is loaded by *e*CTX*time* (with *no* CHSWIE) + DATA*time* + ACK*time* + 3 × SIFS. On the other hand, the transmitted *e*CTX on the shared ISM channel carries a CHSWIE loaded by CSE's LTRC channel information for which the Duration/ID field is loaded by '00' while OLD subfield is loaded by DATA*time* + ACK*time* + 2 × SIFS.

## 3 Performance Evaluation

To evaluate the performance of the proposed scheme deployed in a WMN, a scenario with 64 MPs and 32 flows is considered, in which each MP has an effective transmission range of 250 m, and the distance between MPs is approximately 200 m. Considering the fact that each MP may interfere with the data reception at another MP, even though they are beyond the transmission range, a 550 m carrier scene range is used in simulations. In addition, the two-ray ground channel model is also adopted and the MPs are placed in a $1500 \times 1500$ square meters simulation area. In addition, we assume that 5 MPs, which are positioned on the top-horizontal side of the considered grid topology, are connected through broadband wired links to the backbone network. We explicitly assume that there is no bandwidth limit in any of the abovementioned broadband connections while the aggregate WMN traffic is being delivered to the backbone side. For the protocol performance analysis, 32 source MPs are considered while, each source MP sends CBR traffic to a randomly chosen MP connected to the backbone network and the traffic load is varied for the simulations. The CBR traffic uses 125 bytes packet size. For each traffic load setup, we averaged the achieved results of 30 successive simulation repetitions.

The IEEE 802.11g OFDM PHY is considered for all simulations. PHY layer modulation mode is set to 64-QAM Modulation, 3/4 Code Rate, 54 Mbps Data Rate, 27 Bytes per Symbol. SIFS and DIFS are set to 16 and 56 μsec, respectively.

We assume that CMEs' PHY has enough cognitive capability in detecting PUs. To deal with PUs, we assume that upon a PU appearance in one of the deployed non-ISM channels and subsequent to an interval equal to 50 μsec, all occupying CMEs release the non-ISM channel, the involved CDEs choose another available frequency opportunity as their permanent LTRC, and then the CSEs re-establish their broken link layer connections from the point they have been interrupted. Apparently, in the case when CDEs inform their new LTRCs prior to *e*RTX frames of CSEs, the scenario illustrated in Fig. 7 will be followed while, in the case when CSEs have higher chance to send their *e*RTX frames before CDEs' CHSW frames, the scenario shown in Fig. 9 is followed consequently.

To simplify the way MPs discover in their vicinity all available frequency opportunities, we assume that MPs are perfectly aware of the deployable non-ISM data channels; this means that each MP knows the number of available utilizable non-ISM data channels and their frequency specifications. In addition, we assume that channel mask and regulatory class for all existing data channels are the same and well-defined beforehand. Thus, the Regulatory Class and Channel Mask sub-fields in each CI are loaded by default values and consequently are not checked by the receiving CMEs. Hence, each data channel is uniquely identified by its center frequency. A CSE is only required to identify the intended data channel's center frequency when establishing a link layer connection with its CDE of interest. For the whole simulations, we consider, at any time, the availability of ten non-overlapping non-ISM data channels, which can be utilized by CMEs in an opportunistic fashion. Each channel is assumed to have a bit rate of 2 Mbps.

By increasing the number of deployable data channels, the overall achieved system capacity is increased while the incurred frame latency is decreased due to more radio resource availabilities. To take also into account the possibility of primary users operation in non-ISM data channels, we assume that before commencing any data transmission, a CSE checks its preferred non-ISM data channel for any primary user activity. If the planned channel is found busy due to primary user transmission, CSE should try other frequency availabilities until a non-ISM data channel is discovered free of any primary user. The selection of a non-ISM channel by PU is modeled by a random variable (RV) called *channel deployment*.

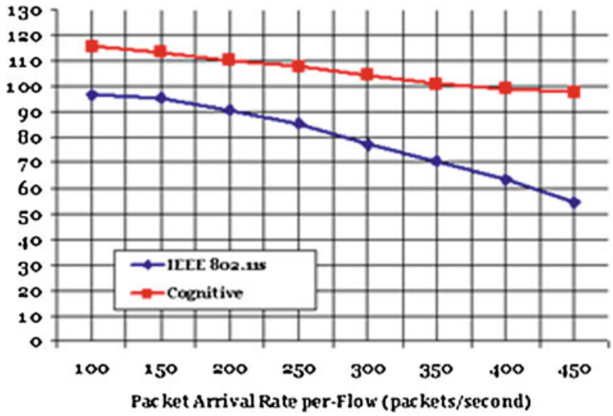

**Fig. 11** Simulation results for the achieved throughput per-flow in Kbps (IEEE 802.11s CCF vs. Cognitive CCF)

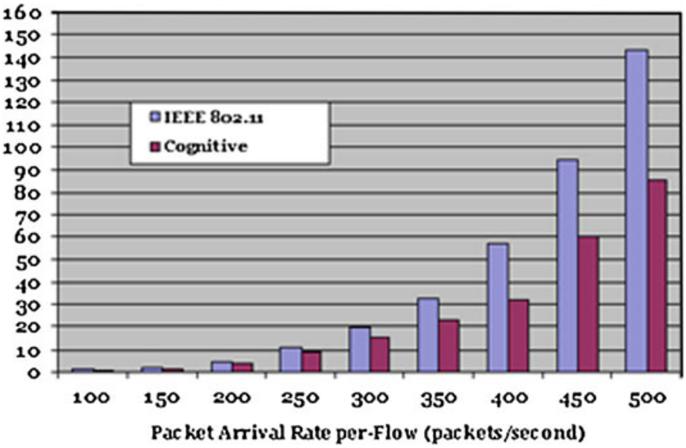

**Fig. 12** Simulation results for the averaged end-to-end delay in milliseconds (IEEE 802.11s CCF vs. Cognitive CCF)

The deployment of a chosen non-ISM channel by PU is also modeled by two other random variables: *channel gaining* RV, and *channel utilization* RV. The former, which is a Poisson RV, represents non-ISM channel acquisition rate by PU since it has finished its last transmission in one of the existing non-ISM channels. The latter, which is also a Poisson RV, represents PU's departure rate from a deployed non-ISM data channel, meaning that it determines for how long PU continues operating in an acquired non-ISM data channel. Basically, when the PU finishes its current data transmission on a non-ISM channel, the *channel gaining* RV is used to determine for how long all non-ISM channels will be free of any PU activity. By the end of this time duration, *channel deployment* RV is used to determine in which one of available non-ISM channels PU should commence a new data transmission. When the target non-ISM channel is chosen, the PU gains the control of that channel and subsequently the *channel utilization* RV is used to determine for how long that channel will be utilized by the PU. At the end of this interval, the above procedure is repeated from the beginning and continued for the whole simulation. For all simulations, we set the PU's acquisition rate to 1/50 $\mathrm{msec}^{-1}$ and its departure rate from a non-ISM data channel to 1/1000 $\mu\mathrm{sec}^{-1}$, which

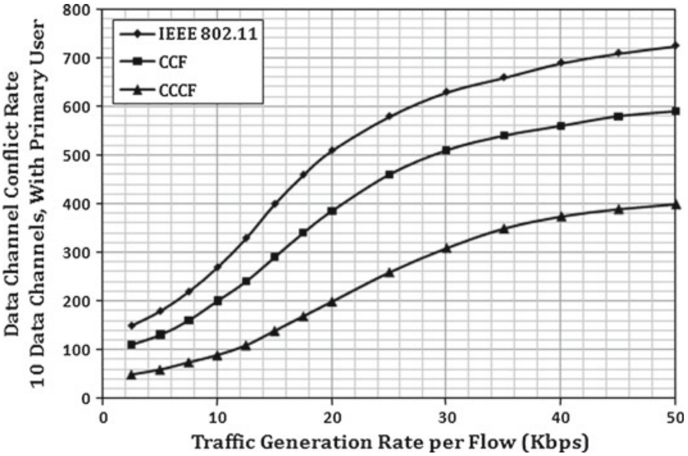

**Fig. 13** Data channel conflict rate versus traffic rate per flow

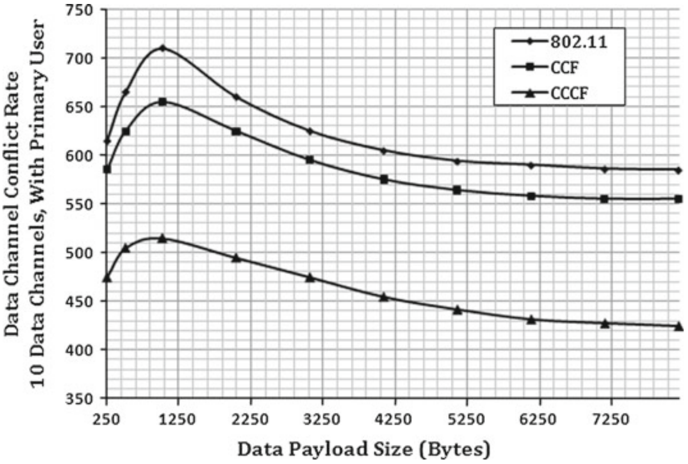

**Fig. 14** Data channel conflict rate versus data payload size

are representing a non-saturated licensed primary system. Figure 11 shows the simulation results for the achieved traffic throughput for different offered traffic loads while, the MAC frame end-to-end delay in milliseconds for both IEEE 802.11s CCF and the proposed cognitive CCF are illustrated in Fig. 12, showing better performance and higher efficiency of the presented frequency agile enhancement.

Figure 13 illustrates data channel conflict rate versus traffic generation rate per flow for 802.11, 802.11s CCF, and the proposed CCCF mechanism. As it could be predicted, CCCF shows the lowest conflict rate while 802.11 demonstrates the worst performance. The conflict rate for the proposed CCCF begins from 50 at 2.5 Kbps traffic generation rate per flow and continues increasing up to almost 400 at the traffic rate of 50 Kbps traffic rate per flow. In fact, lower data channel conflict rate of CCCF gives an insightful observation on why it achieves higher aggregate throughput. Encountering less data channel conflict, CCCF conducts smarter channel allocation among contending radio stations, leading to higher aggregate throughput and lower average end-to-end frame delay.

Figure 14 illustrates data channel conflict rate versus data payload size in bytes for CCCF, CCF, and 802.11. Interestingly, for all protocols the channel conflict rate exhibits a bell shape. Larger payload size offsets protocol overhead more effectively, and thus, leads toward higher throughput, while longer data packets keep nodes on data channels longer, and hence, fewer nodes are able to initiate new communication on the control channel, which reduces the possibility of channel conflicts.

## 4 Conclusions

In this paper, we proposed a frequency agile medium access control protocol for the next generation IEEE 802.11s wireless mesh networks which is capable of coordinating concurrent multi-channel data communications in a totally distributed fashion. Through simulations, which are also taking into account primary user appearance, the proposed scheme has been evaluated showing its noteworthy better performance in comparison to the CCF framework in the IEEE 802.11s amendment.

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## Author Biographies

**Kaveh Ghaboosi** received his B.Sc. degree from the University of Tehran, Iran, in 2002, the M.Sc. degree from the Sharif University of Technology, Tehran, Iran, in 2004, and the Ph.D. degree in Centre for Wireless Communications (CWC) at the University of Oulu, Finland, all in Electrical Engineering. He is currently a Post-doctoral research fellow at the Centre for Wireless Communications. His research interests include mobile computing, cognitive radios, medium access control protocols for broadband access networks, radio resource management for Femtocell networks, as well as Smart Grids.

**Matti Latva-aho** was born in Kuivaniemi, Finland, in 1968. He received the M.Sc., Lic.Tech., and Dr. Tech. (Hons.) degrees in electrical engineering from the University of Oulu, Finland, in 1992, 1996 and 1998, respectively. From 1992 to 1993, he was a Research Engineer with Nokia Mobile Phones, Oulu. During 1994–1998, he was a Research Scientist with the Telecommunication Laboratory and Centre for Wireless Communications (CWC), University of Oulu. Currently, he is a Professor of Digital Transmission Techniques, University of Oulu. He was the Director of the Centre for Wireless Communications, University of Oulu, during 1998–2006. Dr. Latva-aho is also an Adjunct Professor at Rice University, Houston, TX, USA. His research interests include future broadband wireless communication systems and related transceiver algorithms. He has published more than 150 conference or journal papers in the field of wireless communications. Dr. Latva-aho has been TPC Chairman for PIMRC'06, TPC Co-Chairman for ChinaCom'07, and General Chairman for WPMC'08. He acted as the Chairman and vice-chairman of IEEE Communications Finland Chapter from 2000 to 2003. He has received the following awards: the Best Doctoral Thesis prize of Technical Sciences in Finland in 1998, Electrical Engineering Foundation (EIS) Award for the development of CDMA Techniques in Finland in 2000, and the Best Paper of the year in the area of Wireless Communications (Mountbatten Premium) award.

**Ryuji Kohno** received the B.E. and M.E. degrees in computer engineering from Yokohama National Univ. (YNU) in 1979 and 1981, respectively and the Ph.D. degree in electrical engineering from the Univ. of Tokyo in 1984. Since 1998 he has been a Professor in YNU. During 1984–1985 he was a Visiting Scientist in Dept. EE, Univ. of Toronto. Since 2007, he is also a Finnish Distinguished Professor (FiDiPro) in Univ. of Oulu, Finland. Moreover, he was also a director of SONY ATL during 1998–2002 and was a director of the UWB Tech. Inst. during 2002–2006, currently a program coordinator of Medical ICT Inst. of National Institute of Information and Communications Technology (NICT), and a principal leader of MEXT 21st century COE program on "Creation of Future Social Infrastructure Based on ICT" during 2002-2007 and is currently a principal leader of MEXT Global COE program on "Innovative Integration between Medicine and Engineering Based on ICT," during 2008–2013 as well as a director of Medical ICT Center in YNU. Prof. Kohno was elected to be a BoG member of the IEEE Information Theory Society three times on 2000, 2002, and 2006. He was an editor of the IEEE Trans. Information Theory during 1995–1998, currently is that of the IEEE Trans. Communications since 1994 and that of the IEEE Trans. Intelligent Transport Systems since 2000. He is a fellow of IEICE (Institute of Electronics, Information, Communications Engineers), and was a vice-president of Engineering Sciences Society of IEICE, an editor-in chief of the IEICE Trans. Fundamentals and also the vice-president of SITA (Society of Information Theory and its Applications). Prof. Kohno has contributed for organizing many international conferences, such as a TPC co-chair of the IEEE ISSSTA'92, PIMRC'93, Information Theory Workshop (ITW'93), PIMRC'99, IWUWBS'03, and a general chair of IEEE ISIT'03, UWBST&IWUWB'04, IWUWBST'05, ISMICT'06&07, ISSSTA&ISITA2010 and so on. He is also a chair of International Steering Committee of ISSSTA. He was awarded IEICE Greatest Contribution Award and NTT DoCoMo Mobile Science Award in 1999 and 2002, respectively.