ENGINEERING JOURNAL

Review

Multi-Channel Utilization Algorithms for IEEE 802.15.4-based Wireless Network: A Survey

Soamsiri Chantaraskul

The Sirindhorn International Thai-German Graduate School of Engineering (TGGS)
King Mongkut's University of Technology North Bangkok
1518 Pracharat 1 Road, Wongsawang, Bangsue, Bangkok 10800, Thailand
E-mail: soamsiri.c.ce@tggs-bangkok.org

Abstract. In the pass years, IEEE 802.15.4 based Wireless Sensor Networks (WSNs) have received great attention and have been employed in many areas such as inventory checking, local monitoring and alarming etc. One of the key issues affecting WSN's system performance is interference caused by devices operating with the same or different standards on the overlapping frequency within the 2.4 GHz ISM band. This paper addresses the coexistence problem, which is the key motivation for the necessity of flexible channel usage. A review of existing approaches being proposed to date supporting multi-channel utilization in IEEE 802.15.4 based WSNs is categorized and discussed. The paper also presents major functionalities needed in implementing multi-channel utilization.

Keywords: Multi-channel utilization, IEEE 802.15.4, system optimization.

ENGINEERING JOURNAL Volume 17 Issue 3
Received 3 May 2013
Accepted 19 June 2013
Published 1 July 2013
Online at http://www.engj.org/
DOI:10.4186/ej.2013.17.3.119

DOI:10.4186/ej.2013.17.3.119

1. Introduction

The IEEE 802.15.4 has received great attention as the standard supporting Wireless Sensor Networks (WSNs). It is designed for such applications that require short-range communication with low data rate (throughput). Hence, the system can benefit from an efficient energy usage of battery powered end devices.

One of the most considered issues of the IEEE 802.15.4 is the coexistence problems because generally the system operates on the shared and unlicensed ISM band of 2.4 GHz, which is also being used by other systems such as WLAN (IEEE 802.11), Bluetooth, and microwave oven, etc. Large amount of work has focused on the coexistence studies and tried to understand and observe the system performance under the environment when two or more systems (one being IEEE 802.15.4-based system) collocate and operate on the same frequency band. [1][2] and [3] are examples of work examining the mutual effects caused by interference from collocating devices operating on the 2.4 GHz band in particular between IEEE 802.15.4 and other systems such as IEEE 802.11 and Bluetooth. General conclusions gained from the studies show that there are certainly coexistence issues within the 2.4 GHz band and the IEEE 802.11 seems to give more severe impact to the IEEE 802.15.4 devices than other systems sharing the same range of frequency. On the other hand, the IEEE 802.15.4 network will typically have little impact on the performance of IEEE 802.11b/g-based system. Hence, solution to the problems caused by coexistence has been one of the most research-focused areas for wireless network-based on the IEEE 802.15.4 standard.

One of the key ideas proposed to solve previously mentioned problem of coexistence is to make the system more flexible with dynamic channel allocation. The general aim is to make sure that there is no collision caused by multiple systems using exact same frequency range at the same time. This paper provides the review of existing research work in the last years proposing novel algorithms for multi-channel utilization in the IEEE 802.15.4. Common objectives are to improve system efficiency in terms of resource utilization and system performance.

The remainder of the paper consists of the following sections: section two presents the background reason to support the idea of multi-channel utilization. In section three, some important functionalities needed in implementing multi-channel utilization are discussed. Section four provides the review of proposed schemes for multi-channel utilization mechanisms. The paper is concluded in section five.

2. Why Multi-Channel?

The primary objective in WSN design is maximizing node/network lifetime, while maintaining appropriate level of data transfer. The communication of sensor nodes is more energy consuming than their computation. It is a main concern to minimize communication while achieving the desired network operation. Communication in a clear channel is an ideal case. However in reality of the shared spectrum band like the 2.4 GHz ISM band, which is used by the IEEE 802.15.4 devices, collision caused by collocating devices from multiple standards is unavoidable. As a result, sensor devices will have lower performance under interference environment since they need to waste energy on trying to communicate rather than the communication process itself. The more flexible and intelligent functionality that can adapt the system in respond to the interference environment (possible collision) could enhance the system performance leading to an optimization of the node/network lifetime.

Traditionally, solution for wireless devices under interference effect is the transmission power control. The idea is to make sure data is being transmitted with sufficient power to overcome other transmission and noise within the current environment. This method is usually working with the spectrum sharing of homogeneous devices. As mention earlier, devices based on the IEEE 802.15.4 are generally being severely affected by other system like WLAN (IEEE 802.11 based), which has higher transmit power limitation. Hence, the power adaption is not an ideal approach in this case.

Other dimension to the solution of collision problem is then proposed and widely focused, which is the adaption on frequency usage/allocation. Such kind of approaches should therefore be able to solve collision problem caused by collocation of non-homogeneous devices on the shared spectrum band. As a result, many techniques under the umbrella of multi-channel utilization approach have been proposed up to date.

3. General Functions in Implementing Multi-Channel Utilization

In order to implement the multi-channel utilization in IEEE 802.15.4-based system, the system needs to be aware of the interference that occur and also need to be able to reconfigure itself in respond to such situation efficiently. Therefore, the two main features needed to be considered are the interference detection process and the multi-channel usage mechanism. This section majorly discusses on the interference detection methods being used so far and gives introduction to the approaches for multi-channel usage. More detailed discussion and elaboration will be given in section four on different types of approaches for the multi-channel utilization techniques, which have been proposed to date.

3.1. Interference Detection Approaches

Several methods have been discussed for the interference detection. The following approaches are example of rather well-known techniques. They mostly rely on or adapt the existing functions provided by the IEEE 802.15.4 standard.

3.1.1. Energy Detection (ED) is one approach, which is done through the clear channel assessment function available by the IEEE 802.15.4. The energy detection is provided as RSSI (Received Signal Strength Indicator) services in 802.15.4 PHY [4]. The RSSI services can be called periodically or on demand.

3.1.2. Packet Error Rate (PER) measurement and Link Quality Indicator (LQI) value are used in [5] as part of the interference detection. In particular, they are used to initially detect potential interference affecting the system then frequency scanning can be performed to confirm the situation.

3.1.3. Radio Interference Detection (RID) protocols is proposed in [6]. The method makes use of HD-ND detection sequence, which is the transmission of high power detection packet followed by the normal power detection packet. Receiver then uses the HD-ND detection sequence to estimate the transmitter's interference strength.

3.1.4. ACK/NACK based interference detection scheme is presented in [7]. This method utilizes the ACK/NACK report from receivers in respond to the beacon frame sent by the sender. Number of NACKs is being counted and if the value exceeds the threshold, the devices find that they suffer from interference.

3.2. Multi-Channel Utilization Techniques

The second major process for multi-channel utilization is the mechanism to decide on frequency allocation and usage once the interference is detected and notified. Larger amount of works proposes novel multi-channel utilization techniques. The first major group of methods is dedicated to the complete modification of MAC protocol by integrating the entire multi-channel usage mechanism within the multiple access technique. Other proposed methods fall into the second group, which does not modify the current standard MAC protocol. However, they include the interference detection and dynamic channel usage on top of the current stack and also making use of IEEE 802.15.4 available features. Obvious benefit gained by the first group is the freedom in designing new MAC protocol. However, the system evaluation highly relies on analytical model. On the other hand, the second group needs to work around the possible and available functions provided by the IEEE 802.15.4 standard. Nevertheless, they gain from the possibility of real system adaption and real environment testing.

4. Proposed Schemes for Multi-Channel Utilization Mechanisms

As introduced in the previous section, number of mechanisms for multi-channel utilization for IEEE 802.15.4 standard has been proposed to date. Here, they are grouped into three major categories including multi-channel MAC approach, adaptive channel allocation, and multi-channel utilization in large scale networks.

DOI:10.4186/ej.2013.17.3.119

4.1. Multi-Channel MAC Approaches

Considerable number of works has been proposed for the multi-channel MAC approaches. [8], [9], [10] and [11] try to put them into categories. Most of the methods focus on the mechanism used for the channel selection, agreement and notification among network devices. Since method under the type of multi-channel MAC modification approach is not restricted to the IEEE 802.15.4 standard MAC protocol, authors are free to design and completely modify the MAC protocol. The only major drawback would be in terms of system evaluation, which is most likely confined to the analytical or simulation based analysis.

Focusing on the channel negotiation mechanism, [12][13][14][15] propose methods utilizing dedicated control channel for the transmission of control packets. These control packets are used for the purpose of channel negotiation and notification. The method is simple, however reducing spectral efficiency from the use of one channel purely for the management purpose. It is also necessary that the device needs to have two radios so one can be tuned to listen to the control channel at all time while the other one is used for data communication. This leads to higher cost and complication on the end devices. Fig. 1 illustrates an example of channel usage for this dedicated control channel approach.

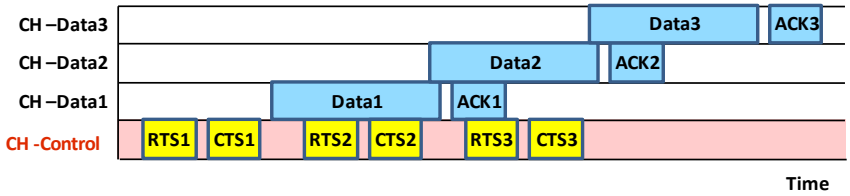


Fig. 1. Dedicated control channel approach.

For the methods that require only one radio for each device, slightly different approach is presented in [16][17][18]. In this technique, the channel negotiation process is performed on a control channel however within a specified timeslot. The communication can then be carried out in the next timeslot (dedicated for data transmission) on the agreed channel. This agreed channel can also be the same as the control channel since the data transmission and control packet transmission are assigned in different time period. The method is based on time division approach to separate time into the control period and the communication period. In this type of methods, timing synchronization is necessary. Nevertheless, the approach benefits from the use of all available channels for data communication in the data transmission timeslots avoiding the single control channel bottleneck especially when number of available channel is low. Example of channel usage over time is shown in Fig. 2.

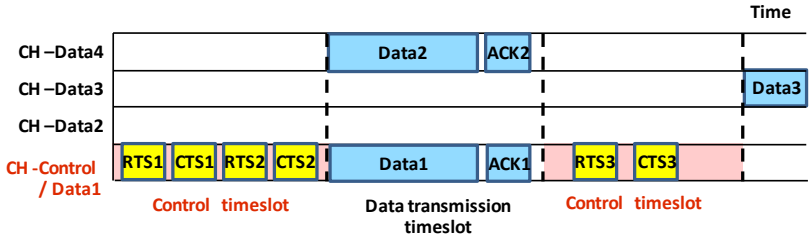


Fig. 2. Time division approach.

The last major approach under the umbrella of multi-channel MAC protocol is the use of common channel hopping sequence. The approach does not require any dedicated control channel or the channel negotiation process. Proposed in [19][20], the channel hopping approaches are used. Devices do not negotiate on the operating channel. On the other hand, they hop from one frequency to another together using the known channel hopping sequence. As a result, only one radio is needed. However, timing synchronization becomes very curtail. Further adaptations to originally proposed idea are also presented in [21] and [22], where several hopping sequences are employed. The hopping patterns are previously set or generated randomly. Shown in Fig. 3 is an example of the common sequence channel hopping approach.

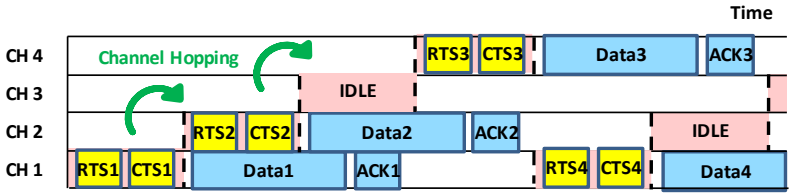


Fig. 3. Common sequence channel hopping approach.

Apart from the three major groups mention above, there are ideas proposed for further improvement of multi-channel MAC protocol such as [23]. The authors present MMSN multi-frequency MAC protocol based on a slotted CSMA. Lightweight frequency assignment is proposed instead of using pair-wise RTS/CTS handshake with assumption that many nodes are static. HYMAC and MC-LMAC are presented in [24] and [25], respectively. The key idea is to employ hybrid TDMA/FDMA for timeslot and frequency assignment.

4.2. Adaptive Channel Allocation

In this category of multi-channel utilization mechanisms, major different from the previous category is that all approaches in this category do not required the modification of MAC protocol defined by the standard. The mechanisms are integrated into the system, which is based on the IEEE 802.15.4 standard system. Most proposals include two main processes: interference detection process (illustrated in section 3) and the interference avoidance process. Each proposal came up with own method for both processes, which will be further discussed in this section. Basic functions provided by the IEEE 802.15.4 standard are generally being used as part of the adaptation.

Channel switching scheme is presented in [26]. In this work, LQI is used together with the ED measurement for the interference detection and PAN coordinator informs other devices to do channel switching through beacon frame. Then, the entire network switches to the new channel.

Frequency agility algorithm is proposed in [5] for the IEEE 802.15.4 cluster-tree networks. The method is claimed to provide reliability, scalability, and energy efficiency. There are two operations involved including interference detection and interference avoidance. PER measurement and LQI are used for the interference detection while the ED and active scan are employed in the interference avoidance phase to identify available channel to switch to. Similar to previous approach, the entire network will switch to the new channel together.

Similar to that proposed in MAC modification approach by using common channel hopping (described in section 4.1), [27] proposed the channel scheduling for multi-channel usage, in which all devices need to synchronize with the common channel hopping pattern. Although all devices need to switch channel with the fixed interval at all time, the system is benefit from no continuous channel detection needed. However, the approach is based on the hopping pattern with fixed number of channels. Therefore, assigned number of multiple channels influents system performance and one fixed pattern may not be suitable for changing interference environment.

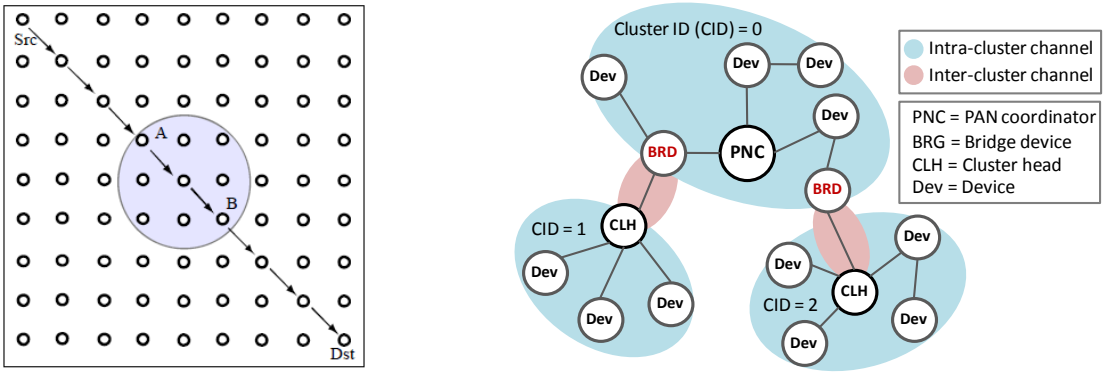
4.3. Multi-Channel Utilization in Large Scale Networks

For the large scale networks, one additional issue to be considered would be the interference distribution across the entire network. Sensor nodes in one area may experience different interference condition from other nodes located at the other end of the network. Hence, treating all nodes with the same frequency allocation may not be the best solution. Several works have been dedicated to the development of mechanisms to provide more flexible approaches of using multiple channels in larger scale networks.

Authors of [28] have proposed the method for adaptive radio channel allocation in the IEEE 802.15.4 system, which is designed for a multi-hop large scale mash network. This type of networks can be affected by inference in particular area within the entire network's coverage area, shown in Fig. 4(a). The aim is to reduce system performance degradation from routing path change in order to avoid an interfered area. The interfered path is instead maintained however using multiple channels where the interfered nodes switch to different channel with some border nodes performing channel conversion for the interfered nodes (group). For this type of network topology, the system needs to perform additional functions (besides interference

detection and multi-channel usage), which is the group formation and tear-down process. The group formation process will allow nodes located in the same interference area to form a group then change to new channel together. The tear-down process is executed when interference is diminished. The authors provide simulation result showing the reduction in coexistence effect on 802.15.4 in terms of packet delay in comparison with traditional system.

For the cluster-tree topology networks based on the IEEE 802.15.4 standard, [4] has proposed method so called adaptive interference-aware multi-channel clustering algorithm to solve coexistence problems. The method is designed to adaptively reconfigure the usage of multiple channels to avoid interference from WLANs. Devices in each cluster use the same frequency channel and can move together to different channel when interference occurs. The channel to move to is obtained by using a pseudo random sequence generator with predefined key. The method is highly distributed with the use of this predefined channel changing scheme for each cluster, which is set as a basic group of devices that utilize the same channel. The method is verified through network testbed experiments. Similar to the method proposed by [8] for the large scale mash network, there is a need for channel conversion into and out of the interfered cluster, which is done by the bridge node, see Fig. 4(b) for example of cluster-tree network topology.



(a) Multi-channel allocation in mesh network [28] (b) Multi-channel clustering in cluster-tree network [4]

Fig. 4. Multi-channel usage with channel conversion.

Also designed to support cluster-tree topology in 802.15.4 wireless sensor networks, [29] proposed MCCT (Multi-Channel Cluster Tree), which is a cluster-tree construction protocol for nodes operating with IEEE 802.15.4 beacon-enabled mode. The aim is to reduce collisions between control and data frames by multiplexing transmissions across orthogonal channels.

[30] proposes the distributed selection algorithm for large-scale sensor networks, which is based on the frequency scanning. This algorithm requires the scanning of the current channel and an extra random channel. The authors also present the system enhancement method based on addition of learning.

In general sense, these approaches is aimed at providing more channel utilization flexibility, which could be very beneficial to a large scale network. However, more complicated monitoring and controlling mechanisms are involved especially for node performing bridging functionality.

5. Conclusion

This paper has introduced the review of techniques in multi-channel utilization for IEEE 802.15.4 based WSNs. Coexistence problem, which is the motivation towards the need for more flexible frequency allocation is addressed as well as important functionalities needed in implementing multiple channel usage. Proposed techniques are categorized by the implementation nature into multi-channel MAC approaches, adaptive channel allocation schemes, and multi-channel utilization in large scale networks. While the first category relies on the modification of the standard IEEE 802.15.4 MAC protocol, the last two categories make use of the current MAC protocol with an adaptations based on embedded and available functionalities within the system. Adaptive channel allocation schemes are rather simple however only suitable for small scale and less complicated topologies. Nevertheless, techniques under multi-channel

utilization in large scale networks could provide better system performance in respond to different interference distributions, which is usually the case of sensor networks with large coverage area.

References

[1] A. Sikora, "Coexistence of IEEE802.15.4 with other Systems in the 2.4 GHz-ISM-Band," in *Instrumentation and Measurement Technology Conference, 2005 (IMTC 2005),* May 2005.

[2] D. Yang, Y. Xu, M. Gidlund, "Coexistence of IEEE802.15.4 based networks: A survey," in *36th Annual Conference on IEEE Industrial Electronics Society, 2010 (IECON 2010)*, 2010, pp. 2107-2113.

[3] K. Shuaib, M. Boulmalf, F. Sallabi, A. Lakas, "Co-existence of Zigbee and WLAN, A Performance Study," *in Wireless Telecommunications Symposium (WTS '06)*, April 2006. pp. 1-6.

[4] M. S. Kang, J. W. Chong, H. Hyun, S. M. Kim, B. H. Jung, and D. K. Sung, "Adaptive Interference-Aware Multi-Channel Clustering Algorithm in a ZigBee Network in the Presence of WLAN Interference," in *2nd International Symposium on Wireless Pervasive Computing, 2007 (ISWPC '07)*, Februare 2007.

[5] P. Yi, A. Iwayemi, and C. Zhou, "Developing ZigBee Deployment Guideline Under WiFi Interference for Smart Grid Applications," *IEEE Transection on Smart Grid*, vol. 2, issue 1, pp. 110-120, 2011.

[6] G. Zhou, T. He, J. Stankovic, and T. Abdelzaber, "RID: Radio interference detection in wireless sensor networks," in *24th Annual Joint Conference of the IEEE Computer and Communications Societies (INFOCOM 2005)*, pp. 891-901, 2005.

[7] S. M. Kim et al., "Experiments on interference and coexistence between ZigBee and WLAN devices operating in the 2.4 GHz ISM band," in *NGPC*, Nov. 2005, pp. 15-19.

[8] M. X. Gong, S. F. Midkiff, S.-W. Mao, "A Combined Proactive Routing and Multi-Channel MAC Protocol for Wireless Ad Hoc Networks," in *IEEE BROADNETS'05*, Oct. 2005, pp. 479-488.

[9] J. Mo, H.-S. So, and J. Walrand, "Comparison of Multichannel MAC Protocols", *IEEE Transactions on Mobile Computing*, vol. 7, issue 1, pp. 50-65, Jan. 2008.

[10] J. Mo, H.-S. So, and J. Walrand, "Comparison of Multi-Channel MAC Protocols", in *ACM MSWiM'05*, Oct. 2005.

[11] M. Wang, L. Ci, P. Zhan, and Y. Xu, "Multi-channel MAC Protocols in Wireless Ad Hoc and Sensor Networks," in *ISECS International Colloquium on Computing, Communication, Control, and Management*, Aug. 2008.

[12] S.-L. Wu, C.-Y. Lin, Y.-C. Tseng and J.-P. Sheu, "A New Multi-Channel MAC Protocol with On-Demand Channel Assignment for Multi-Hop Mobile Ad Hoc Networks," in *The International Symposium on Pervasive Systems, Algorithms, and Networks 2000 (ISPAN 2000)*, 2000, pp. 232-237.

[13] M. X. Gong, S. F. Midkiff, S.-W. Mao, "A Combined Proactive Routing and Multi-Channel MAC Protocol for Wireless Ad Hoc Networks," in *The Second International Conference on Broadband Networks IEEE (BROADNETS'05)*, Oct. 2005, pp. 479-488.

[14] Y.-C. Tseng, S.-L. Wu, C.-Y. Lin, and J.-P. Sheu, "A Multi- Channel MAC protocol with Power Control for Multi-hop Mobile Ad-hoc Networks," in *International Conference on Distributed Computing Systems Workshop*, 2001, pp. 419-424.

[15] W. C. Hung, K. L. Eddie Law, and A. Leon-Garcia, "A Dynamic Multi-Channel MAC for Ad-Hoc LAN," in *21st Biennial Symposium on Communications*, 2002, pp. 31-35.

[16] J. So and N. Vaidya, "Multi-Channel MAC for Ad Hoc Networks: Handling Multi-Channel Hidden Terminals Using A Single Transceiver," in *the Fifth ACM International Symposium on Mobile Ad Hoc Networking and Computing (ACM MobiHoc'04)*, 2004.

[17] J. Chen, S. Sheu and C. Yang, "A New Multichannel Access Protocol for IEEE 802.11 Ad Hoc Wireless LANs," in *14th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC2003)*, vol. 3, 2003, pp. 2291-2296.

[18] J. Chen, and S. Sheu, "Distributed multichannel MAC Protocol for IEEE 802.11 ad hoc wireless LANs," *Computer Communications*, vol. 28, pp. 1000-1013, 2005.

[19] A. Tzamaloukas and J. J. Garcia-Luna-Aceves, "Channel hopping multiple access," in *International Conference on Communications (IEEE ICC'00)*, 2000, pp. 415-419.

[20] Hoi-Sheung Wilson So, Jean Walrand, and Jeonghoon Mo, "McMAC: A Parallel Rendezvous Multi-Channel MAC Protocol," in *IEEE Wireless Communications and Networking Conference 2007 (IEEE WCNC'07*), Mar. 2007, pp. 334-339.

[21] P. Bahl, R. Chandra, and J. Dunagan, "SSCH: Slotted Seeded Channel Hopping for Capacity Improvement in IEEE 802.11 Ad-Hoc Wireless Networks," in *ACM MobiCom'04*, Sept.-Oct. 2004, pp. 216-230.
[22] H. W. So and J. Walrand, "McMAC: A Multi-Channel MAC Proposal for Ad-Hoc Wireless Networks," Technical Report, Apr. 2005.
[23] G. Zhou, C. Huang, T. Yan, T. He, J. A. Stankovic, and T. F. Abdelzaher, "MMSN: Multi-frequency media access control for wireless sensor networks," in *25th IEEE International Conference on Computer Communications (IEEE Infocom 2006)*, Apr. 2006.
[24] S. Mastooreh, S. Hamed, K. Antonis, "Hymac: hybrid tdma/fdma medium access control protocol for wireless sensor networks," in *18th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC'07)*, 2007, pp. 1-5.
[25] O. D. Incel, L. van Hoesel, P. Jansen, and P. Havinga. "MC-LMAC: A multi-channel MAC protocol for wireless sensor networks," *Ad Hoc Network*, vol.9, issue 1, pp. 73-94, January 2011.
[26] J. Yun, B. Lee, J. Li, and K. Han, "A Channel switching scheme for avoiding interference of between IEEE 802.15.4 and other networks," in *2008 International Multi-symposiums on Computer and Computational Sciences (IMSCCS'08)*, Oct. 2008, pp. 136-139.
[27] K.L. Hwang, S.-S. Yeo, and J.H. Park, "Adaptive Multi-Channel Utilization Scheme for Coexistence of IEEE802.15.4 LR-WPAN with Other Interfering Systems," in *11th IEEE International Conference on High Performance Computing and Communications*, 2009.
[28] C. Won, J.-H. Youn, H. Ali, H. Sharif, and J. Deogun, "Adaptive Radio Channel Allocation for Supporting Coexistence of 802.15.4 and 802.11b," in *IEEE 62nd Vehicular Technology Conference (VTC2005-Fall)*, 2005.
[29] N. Abdeddaim, F. Theoleyre, F. Rousseau, and A. Duda "Multi-Channel Cluster Tree for 802.15.4 Wireless Sensor Networks," in *IEEE 23rd International Symposium on Personal Indoor and Mobile Radio Communications (PIMRC'12)*, 2012, pp. 590-595.
[30] S. Pollin, M. Ergen, M. Timmers, A. Dejonghe, L. van der Perre, F. Catthoor, I. Moerman, and A. Bahai, "Distributed cognitive coexistence of 802.15.4 with 802.11," in *International Conference on Cognitive Radio Oriented Wireless Networks and Communications (CROWNCOM'06)*, 2006, pp. 1-5.