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Mesh-Under Cluster-Based Routing Protocol for IEEE 802.15.4 Sensor Network

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Abstract—**The radio duty cycle (RDC) of wireless sensor nodes can be considered as a crucial factor that determines the wireless sensor network (WSN) lifetime and its service availability. Clustering would be a preferable solution to minimize node radio duty cycle by electing multiple cluster heads (CHs) around the network to schedule node transmissions and collect readings. This paper presents a mesh-under cluster-based routing (MUCBR) protocol that will divide the sensor network into multiple clusters and perform the routing function within the IEEE 802.15.4 platform. MUCBR is implemented via the Contiki operating system (OS). It reschedules the structure of the 802.15.4 standard in order to reduce the RDC of the sensor nodes and minimize the number of collisions. The election of the CHs is density-aware and determined by the routing direction inside the network which in turn reduces the number of hops and minimizes the number of collisions caused by the existence of multiple CHs in a single area. The proposed MUCBR manages to achieve a RDC of 0.08% for non-CH nodes and 1.3% for CH nodes while reducing the impact of collision by 40% as compared to the 802.15.4 standard.**

Keywords—cluster network; Contiki OS; IEEE 802.15.4; mesh-under routing; radio duty cycle.

I. INTRODUCTION

The IEEE 802.15.4 standard is targeted for low-rate wireless personal area networks (LR-WPANs) with devices that are low-data-rate, low-power and short-range radio frequency (RF) transmissions in a wireless personal area network (WPAN) [1] such as wireless sensor networks (WSNs). Basically, this standard defines two types of network topology, star and peer-to-peer. Also, the standard defines two types of devices, reduced-function device (RFD) and full-function device (FFD). The media access control (MAC) protocol exploits two communication modes, beacon-enabled and non beacon-enabled mode. While in the beacon-enabled mode the PAN coordinator transmits a periodic beacon to synchronize the communications between the devices and the coordinator, with the non beacon-enabled mode there is no broadcast beacon and the devices contend with each other to transmit to the coordinator using the unslotted CSMA/CA [2].

Upon the 802.15.4 standard, the 6LoWPAN adaptation layer [3] has been introduced that will facilitate the interoperability between the wireless sensor nodes and the Internet cloud which will drive new scopes of research and open the gate to the world of the Internet of Things (IoT). 6LoWPAN adaptation layer can be presented as the layer 2.5 (between the network and data-link layers) in the OSI network architecture and permits the IPv6 packets to be transferred over the 802.15.4 frames [4]. The rise of the 6LoWPAN layer has inspired the research community to bring a new term of classification to the routing world in the WSN, this classification is based on which layer will make the routing decision and accordingly there will be two types of routing: mesh-under and route-over [5]. Unfortunately, neither IEEE 802.15.4 nor 6LoWPAN define how mesh topology will be achieved to route towards the coordinator, which is considered the sink. Regarding network topology, there is no doubt that cluster-based networks have: better performance and scalability compared to other types of networks [6], lower communication overhead which in turn reduces the energy consumption [7] and can be considered as an energy efficient approach for sensor network routing [8].

All these facts led us to propose a mesh-under cluster-based routing (MUCBR) protocol that provides the following services: clustering technique under the 802.15.4, reduced RDC schedule listening technique, routing to the sink through the shortest path and transmissions with low collisions as compared to 802.15.4 standard.

The clustering process will take into account the density of the nodes within a specific area. The dependency on the density factor is necessary to reduce the number of CHs, since increasing the number of CHs inside a single personal operating space (POS) can increase the number of collisions due to the fact that multiple coordinators within a POS increases the risk of assigning matched time slots and leads to transmission collisions. In addition, the node with the least depth to the sink and the highest weight (according to the MUCBR weighting mechanism) will be elected as CH. This will ensure the election of a CH on the upward edge of each cluster and in turn minimizes the number of hops to the sink. The CH in each cluster (corresponding to the coordinator) will assign a random time reference for each node within its cluster to reduce the inter-cluster interference. This time reference is used by each node to start transmitting or receiving. The idea behind randomizing and spreading nodes access is to reduce collisions encountered in 802.15.4. The proposed algorithm has been implemented within the Contiki operating system (OS) [9] based on the IEEE 802.15.4 platform. The simulations show low RDC and in turn an improved energy efficient routing technique while achieving a shortest path to the sink. Moreover, the collision parameter has been reduced by a factor of 40% as compared to the default 802.15.4.

II. RELATED WORK

Several works have been presented regarding WSN clustering techniques, one of the pioneers within this field is the LEACH [10] protocol. Due to its simplicity and effectiveness it has inspired other contributions that optimized its performance and led to new clustering approaches. Here we will commit ourselves to work that considered the 802.15.4 standard as the underlying infrastructure. Regarding cluster-tree utilization and analysis, Pavkovic *et al.* [11] present directed acyclic graph structure within the beacon-enabled mode to form a cluster-tree WSN. The authors minimize delay and improve the robustness of the network by permitting every node to have more than one parent in order to mitigate the parent/CH failure or sleeping. The paper also indicates that the synchronization process within the beacon-enabled mode can lead to a collision between the superframes with the same depth. According to the authors, although some approaches have been proposed to solve this issue, the problem still exists for data frames.

Cuomo *et al.* [12] analyze the effect of the number of sinks over the cluster-tree within the beacon-enabled mode. Furthermore, [12] investigates the topological characteristics of the WSN over 802.15.4 in order to identify some key points that the Zigbee alliance might consider during the network formation. The authors address two factors to be considered, the depth of the network (derived by the association procedure) and the criteria by which the nodes select their coordinators.

With respect to clustering techniques and impact on network performance, Tavakoli *et al.* [13] indicate that clustering can reduce the number of collisions in the beacon enabled mode. Hence, the authors suggest allocating different frequency channels to each cluster which can be assigned by the base station. The paper defines a mechanism to elect a CH based on a random value generated by each node and compared to a threshold value that in turn is influenced by: the desired number of clusters, the number of nodes within the network and the number of nodes which have not been CHs before.

Kumar *et al.* [14] provide a performance analysis of a clustered network (based on LEACH and DYMO routing protocol) over a non-clustered WSN network and show an improvement in terms of end-to-end delay but not in terms of energy consumption.

In terms of inter-cluster interference, Abdeddiam *et al.* [15] present a mechanism to reduce collisions by allocating a dedicated channel for the control frames to all the nodes while letting each coordinator select a different frequency channel and indicating this channel through the 'hello' control frames. These frames will be announced via the control channel to allow other nodes to join the network.

Li *et al.* [16] propose an approach to minimize the inter-cluster interference by identifying the nodes that might suffer from collision with other nodes and calling them edge nodes (EN). The authors re-allocate the position of the time slots for these ENs to eliminate interference with adjacent clusters.

Other than clustering, Farook *et al.*[17] analyze the throughput of the Contiki-based RIME [18] network stack over IEEE 802.15.4. The authors enhance the OS throughput by minimizing the CSMA/CA waiting time which is required to perform the clear channel assessment (CCA) prior to transmission. The simulation was based on a single hop network.

III. MESH-UNDER CLUSTER-BASED ROUTING PROTOCOL (MUCBR)

The basic feature of the proposed MUCBR is to provide a routing service within the link layer (mesh-under). This will add an advantage to the network in terms of reduced energy consumption.

As stated earlier, there is a possibility of inter-cluster interference due to the synchronization process of the beacon-enabled mode [11]. In addition, the node's radio has to stay ON within the contention period of the slotted CSMA/CA period until a free slot is located. This will increase the energy consumption. On the other hand, for the non-beacon enabled mode, the nodes have to always be awake to avoid deafness [15] which in turn leads to 100% RDC.

Accordingly, since the 802.15.4 standard does not indicate how the clustering will be achieved [15], our approach is based on clustering the 802.15.4 standard to reduce nodes RDC and minimize collision. The proposed MUCBR resembles the beacon-enabled mode by which the CHs allocate a random *time-reference* to each node. This *time-reference* represents a solid time by which the node will either start sending or receiving (not a time slot) and simulates the guaranteed time slot (GTS) that no other nodes will contend on this timing. During these *time-references*, nodes will transmit to their CHs while the CHs must listen during these reference times. This will gain a significant reduction in the duty cycle for both the non-CH and CH nodes. Fig. 1 shows the basic differences between the patterns of communication carried out by three sensor nodes for the 802.15.4 and MUCBR. T_RA, T_RB and T_RC are time references assigned randomly, for nodes A, B and C respectively by a CH in order to identify the transmission initiation time. Thus, the CH and any member within the cluster will only be required to open radio through T_f intervals. According to our simulation tests through Contiki OS, the value of T_f ranges between (0.54ms for 12-byte) and (4.2ms for 128-byte) while the default slot duration within the 802.15.4 is 15.36ms. On the other side, if node C in the 802.15.4 standard tries to transmit, then it must contend with nodes A and B and if it was not able to utilize slots S_1 and S_2, then it has to open the radio for time duration T_3. Moreover, there is a probability of collision that might occur at a collision point C_p due to the contention. Thus, retransmission is required while a time slot has been lost due to the contention of two nodes.

The dependency of MUCBR on randomly distributed nodes over the beacon interval (BI) will minimize the probability of collisions that might occur at C_p points and eliminate the needs for retransmission, hence saving energy.

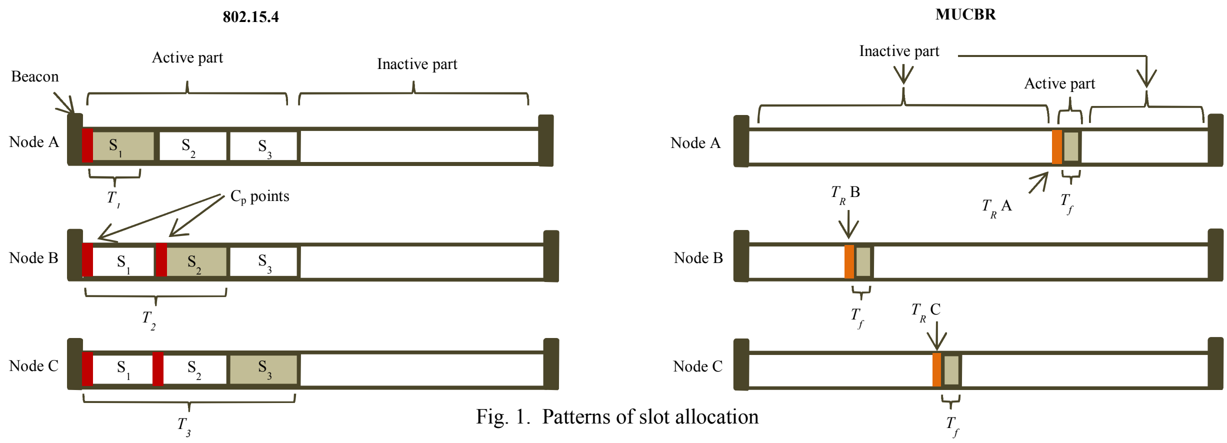

Fig. 1. Patterns of slot allocation

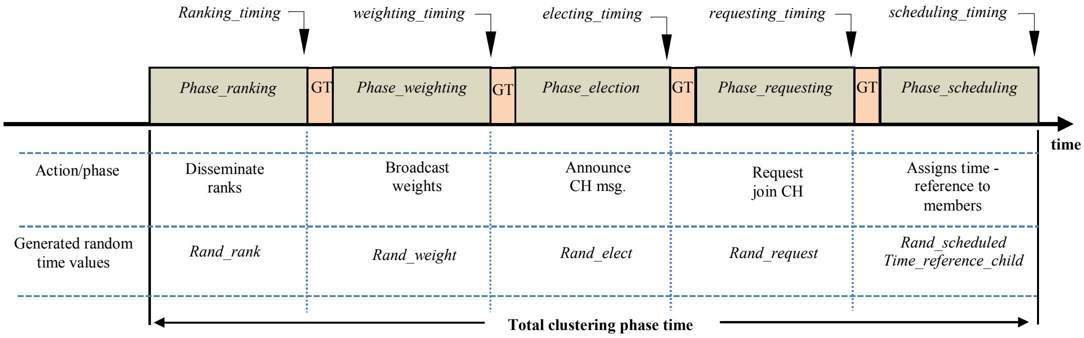

Fig. 2. Clustering Phase Timing

The proposed algorithm is based on the IEEE 802.15.4 infrastructure and appends four types of frames to the defined frame types list in this standard. These frames are: *Establish_Cluster, Broadcast_Weight, CH_Elect* and *CH_Request* as shawn in Table I. The frame type values are reserved for future use within [1]. The amendment 1 MAC sublayer, IEEE std. 802.15.4e™-2012 has not yet been implemented within the Contiki OS environment, so the reserved frame type values of the earlier standard version have been considered.

TABLE I. APPENDED FRAME TYPES VALUES

Frame type value b2b1b0	Frame_type
100	*Establish_Cluster*
101	*Broadcast_Weight*
110	*CH_Elect*
111	*CH_Request*

Seeking to reduce the size of the packets required to initialize the nodes into clusters, the PAN ID compression bit within the frame control field is set to one due to the existence of the source and destination addresses. Hence, the source PAN identifier field in the 802.15.4 frames will be omitted which gains a reduction of two bytes (utilized feature based on the 802.15.4 specifications). Analyses in [17] indicate how the CCA within CSMA/CA can increase the delay, so the MUCBR (during clusters initialization) does not utilize the CSMA/CA technique to access the medium but we devise another approach that will omit the RDC time required for checking medium prior to transmission. Therein, each node will generate a random number that represents a time indicator for transmission called *(rand_tick*) and chosen within the *phase_state* time duration. The *phase_state* represents one of the clustering process stages as depicted in Fig. 2: *phase_ranking*, *phase_weighting*, *phase_election*, *phase_requesting* and *phase_scheduling*. These phases are separated by a guard time (GT). The time duration of any phase is equal to the summation of the GT and preceding timing indicator, subtracted from the current timing indicator, i.e.:

$$phase\_election = election\_timing - (weigting\_timing + \text{GT})$$

The values of *ranking_timing*, *weighting_timing*, *electing_timing*, *requesting_timing*, *scheduling_timing* are adjusted with regards to the number of nodes in the network (the user must adjust these values prior to initialization), high number of nodes leads to choose high timing values in order to decrease the probability of collision. These timing intervals are set fixed for all the nodes and ensure all the nodes to be synchronized and committed to the clustering phases.

Fig. 3 presents the message sequence chart carried out by the nodes to initialize the 802.15.4 network into clusters while Fig. 4 shows a flow chart that represents the process carried out by each node in the network in order to determine clustering. The mechanism of MUCBR which is depicted in Fig. 3 and 4 is as follows. The initialization of the cluster network is basically started by the PAN coordinator (sink) via broadcasting an *Establish_Cluster* message. The message will embed a rank field (1-Byte) which is set to one as an indication to the coordinator, and will be incremented by one

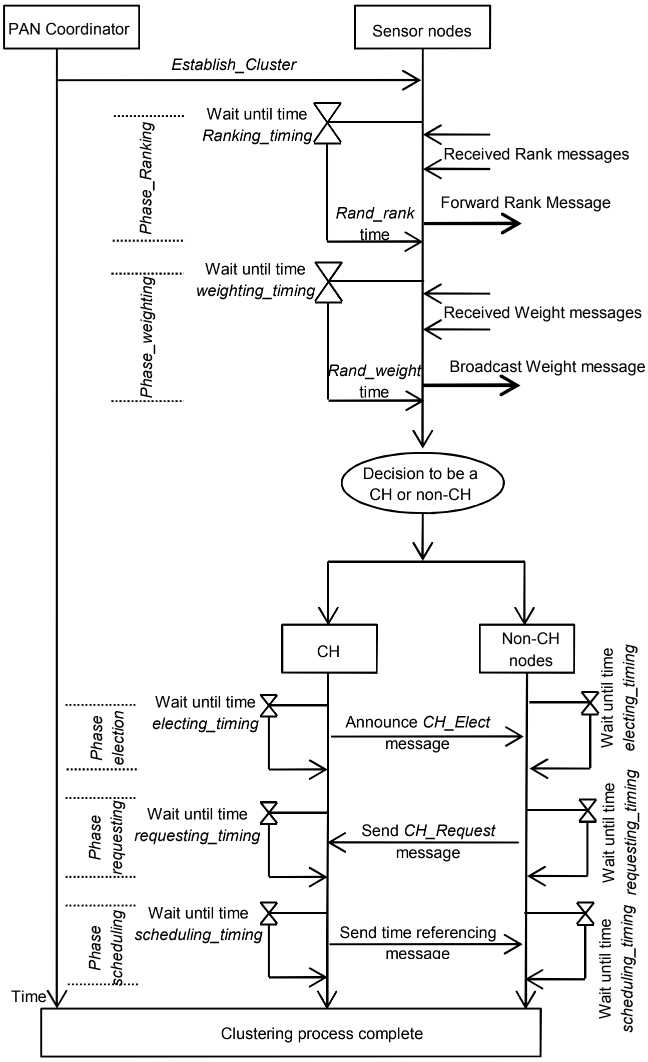

Fig. 3. Clustering Process (Message Sequence Chart)

as passing each hop across the network. Each node within the PAN will first act as FFD device and enter the passive scan mode waiting for the *Establish_Cluster* message. Each node which receives this message has to increment the rank field in the message and store the value as its rank in the network. Once a node has its own rank, it will update the rank field within the message to its rank (*R_current*) and the source address to its short address. Thereafter the node has to retransmit the message to its neighbors at a time tick, called *rand_rank*, which is randomly generated and lies within the *phase_ranking* period. In order to avoid the count-to-infinity routing problem [19], the nodes will not forward any message that carries the same rank or higher while recording these messages. The *phase_ranking* period will ensure that the *Establish_Cluster* message has been forwarded down to all nodes within the network. After the *phase_ranking* time has finished, each node computes its weight and generate a time tick, *rand_weight,* within the *phase_weighting* period to announce its weight at this time. The weight of a node (*W_current*) is equal to the number of *D* (Downward) nodes within the POS.

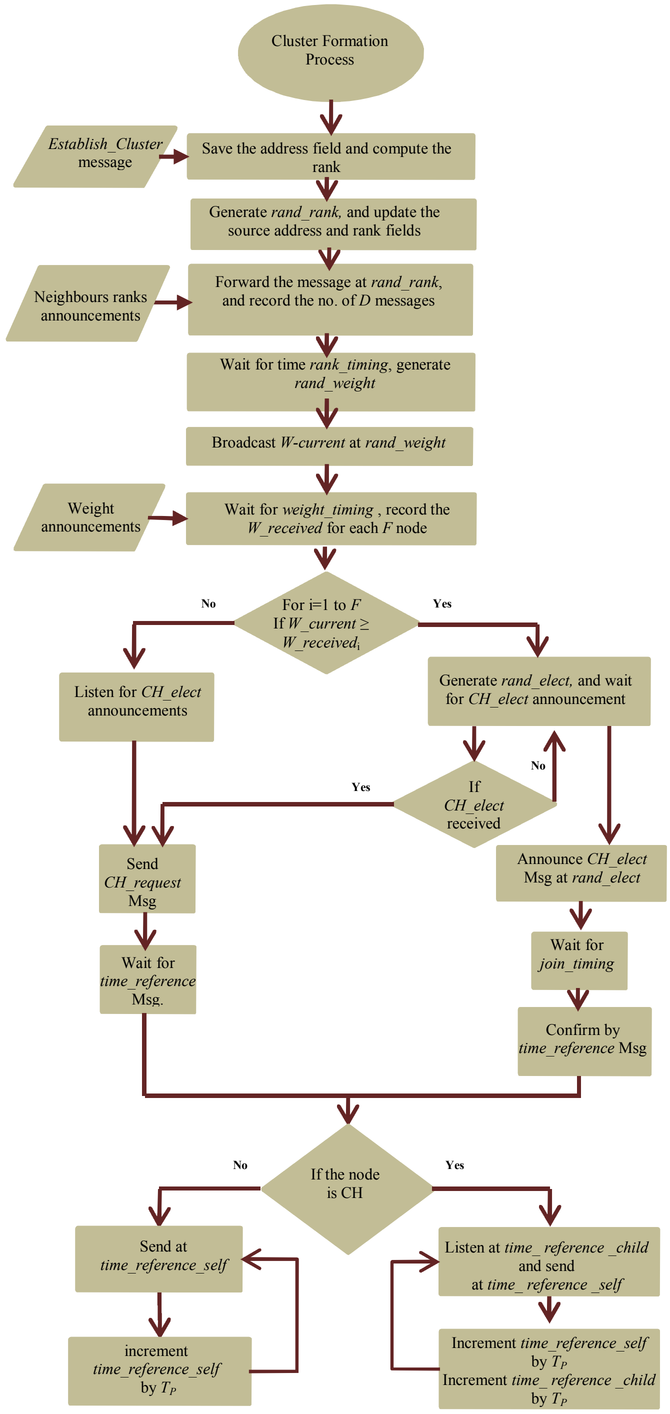

Fig. 4. Clustering Process-(Node-based activity)

The *D* value corresponds to the number of received announcements (*Establish_Cluster* messages) that have a rank value (*R_received*) larger or equal to the rank of the current node *R_current*. In accordance with the computed weight *W_current*, the node will announce its weight at *rand_weight* time using the *Broadcast_Weight* frame and waits for *phase_weighting* period to finish while recording the received nodes weights (*W_recived*) for *F* (Forward) nodes. *F* nodes are those where *R_received* ≤ *R_current*. Considering only *F* nodes is necessary to select a node with a highest weight on the upward direction of a cluster to achieve the shortest path to the sink.

Regarding the received announced weights from F nodes, each node will check if $W\_current \geq W\_recived$. If the current node has a higher weight than F nodes, then it will announce itself as CH (because it's the only node with highest weight and shortest path for the D nodes) and broadcasts the *CH_Elect* message at time *rand_election*, randomly generated within the *phase_election* interval. For nodes which have the highest weight within their POS and did not receive any *CH_Elect* message, they have to broadcast the *CH_Elect* message and act as CHs to wait for the association request messages *CH_request* from adjacent nodes. Thus only one CH within each POS will be elected. When nodes receive *CH_Elect* announcement they will decide to which CH to connect, based on the rank value indicated by each *CH_Elect* announcement and send a *CH_Request* message at *rand_request*, randomly generated within the *phase_requesting* time duration. The destination address in the *phase_requesting* is set to the source address of selected CH. Any node that has not received a *CH_Elect* announcement (deserted node) will send CH_*Request* to one of the neighbor nodes, the intended node then acts as CH to this unconnected node and proceed to the next step. The last step is determined by the CH, which will generate a random time reference (*time_ reference_child*) for each member in the cluster, where $0 < time\_reference\_child < T_P$. T_P is the period that nodes are programmed to transmit and resemble the beacon interval (BI) value. This randomness with an adequate T_P value will reduce the inter-cluster interference. Subsequently, the probability of a collision-free clustered network is:

$$P_{collision\text{-}free} = (1 - (D_{pos} / (T_P / T_f)) \qquad (1)$$

D_{pos} indicates the density of sensor nodes within a POS and T_f is the required time to transmit a single frame.

The T_P is limited by the interval of the adjusted period timing to transmit readings and matches the BI impact in 802.15.4 beacon-enabled mode. A low value of BI will increase collisions while a high value increases the delay. The CH (during the sensing phase) switches its radio ON only during time references that are generated for its members.

Meanwhile, the CH transmits the collected readings of the members along with its reading within a specified time reference (*time_ reference_self)* allocated by a CH which it has been connected to.

During the remaining time the radio is OFF. Each member node upon the received *time_reference_child,* will transmit strictly at this time and next at ($time\_reference\_child + T_P$). After each transmission, the nodes will increment this value by the transmission period time (T_P). The issue of rotating the CH task around the nodes, which utilizes the residual energy of each node as factor for CH election, has not been addressed by this work. Prior to the initialization process all nodes were assumed to have fixed residual energy.

IV. SIMULATION AND ANALYSIS

The proposed MUCBR protocol has been implemented via the Contiki OS and validated through the Cooja simulator [20]. All the nodes within the network are running the Contiki OS 2.6 and 100 nodes are deployed randomly utilizing the Contiki OS Cooja simulator while only one sink exists at the edge of the network. Table II presents the basic network parameters utilized in the MUCBR simulations.

TABLE II. NETWORK MODEL PARAMETERS

Parameter name	Value
OS	Coniki 2.6
MAC Protocol	NullMAC
Radio duty cycling algorithm	NullRDC
No. of nodes	100
Scattering area size in meter	400*400
Ave, No. of nodes within POS	6
Transmission range	50m
Interference range	100m
Sensor mote type	Sky mote

The performance of the MUCBR is compared with the implemented version of RPL routing protocol within Contiki [21] and the RIME network stack [18].

The RPL and RIME implementation within the Contiki OS are based on the ContikiMAC [22] RDC technique, which is a sampled RDC listening technique and considered as low power RDC MAC protocol. The analysis will highlight the importance of the scheduled RDC listening technique (utilized by MUCBR) over the sampled RDC listening technique (utilized by RPL and RIME implementations within Contiki).

The analyses are based on three classifications: Route-over/sampled-listening (RPL), Mesh-under/sampled-listening (RIME) and Mesh-under/scheduled-listening (MUCBR). The implementation of the RPL within Contiki is said to be route-over since it utilizes the IPv6 protocol. The derivation of this classification will state the differences between two basic important design aspects (mesh-under over route-over) and (scheduled-listening over sampled-listening). Our analyses differentiate between the basic two types of nodes in the network: leaf/non-CH (RFD nodes) and router/CH (FFD nodes). Furthermore, these analyses will address the two life-time phases of the WSN, initialization (clusters formation) and sensing (basic readings forwarding).

The nodes for the three protocols were adjusted to transmit a fixed payload size every 2 seconds. Fig. 5 demonstrates the energy consumption of the two radio states of operations (transmitting and receiving) regarding CH nodes (in MUCBR) and router nodes (in RIME and RPL), all having three childs/members. Fig. 6 considers the non-CH and leaf nodes. During the clustering initialization time (first 7 seconds), MUCBR consumes more power than RIME and RPL because of the 100% radio activity required to initialize the nodes into clusters. Then subsequently the nodes will act either as CH or non-CH nodes which will reduce RDC power. After running the sensor nodes for 1000 seconds, the required radio energy of MUCBR (CH/ router) is only 43% of the required energy by RIME and 21% of the consumed energy by RPL. Moreover, the radio energy of MUCBR (non-CH/leaf) is only 38% of the consumed energy by RIME and 29% of the required energy by RPL. Fig. 7 and 8 depict the radio duty cycle through the initialization phase of the three protocols for the CH/router and non-CH/leaf nodes.

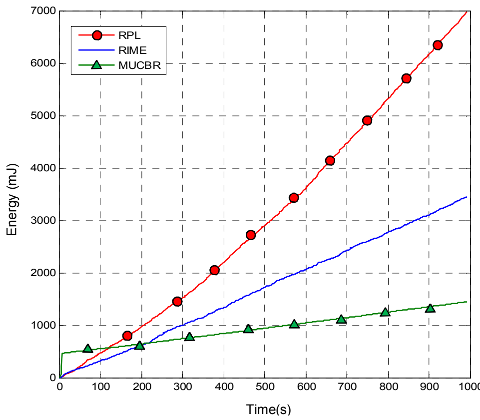

Fig. 5. CH/Parent energy consumption

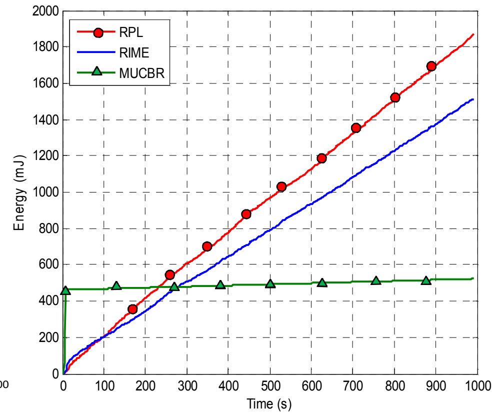

Fig. 6. Non-CH/leaf energy consumption

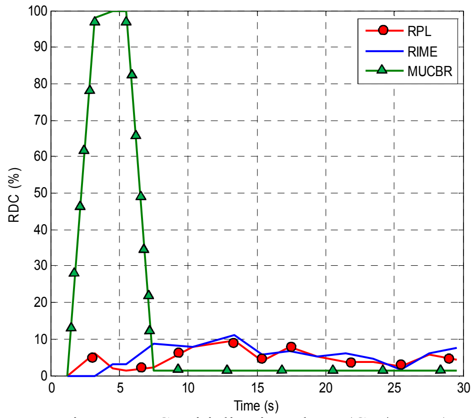

Fig. 7. RDC-Initialization phase (CH/Parent)

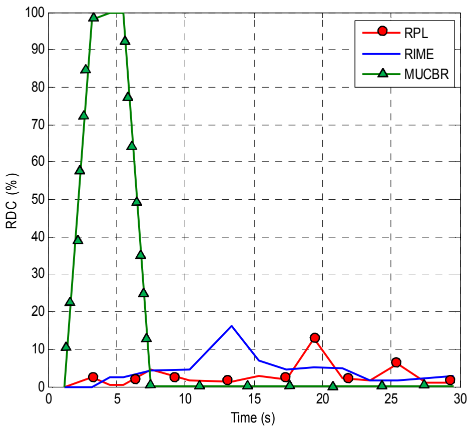

Fig. 8. RDC-Initialization phase (Non-CH/leaf)

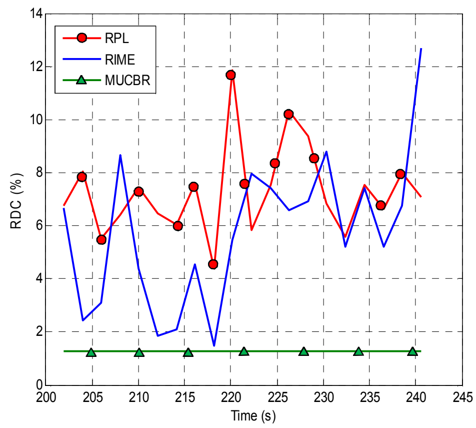

Fig. 9. RDC-sensing phase (CH/Parent)

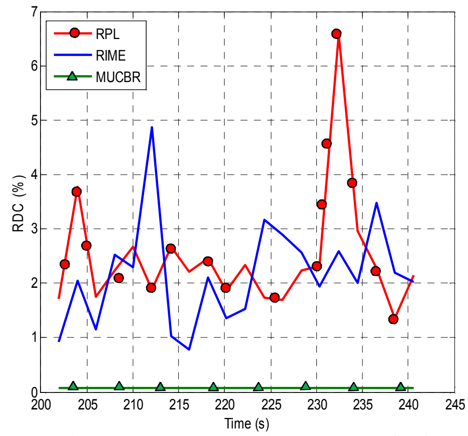

Fig. 10. RDC-sensing phase (Non-CH/leaf)

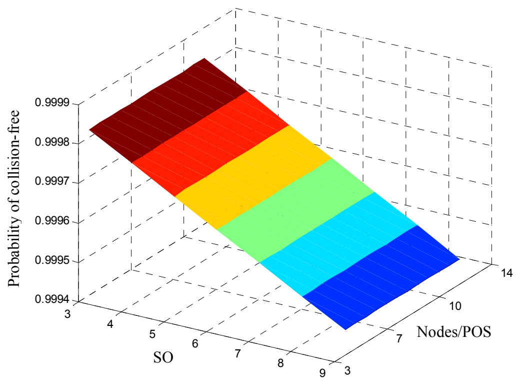

Fig. 11. Probability of Collision-Free (MUCBR)

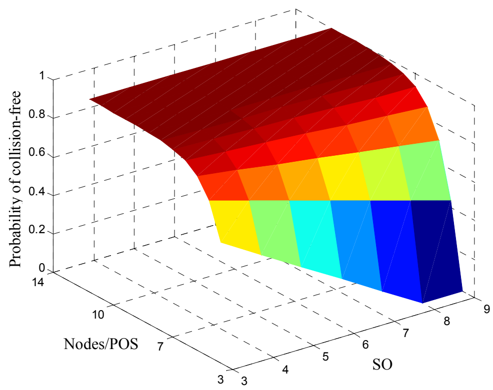

Fig. 12. Probability of Collision-Free (802.15.4)

MUCBR requires 100% RDC through the first 7 seconds to initialize the network and lead to maximize the total radio energy consumption. The MUCBR enters the steady state operation of the RDC in the 8th second where the scheduled radio operation took place; therein the CH nodes will transmit and receive only during defined time indicators and the non-CH nodes will transmit to their CHs also within a defined time reference. Fig. 9 and 10 show the RDC through steady state (sensing period) time of the three protocols. The CHs nodes within MUCBR achieved 1.3% RDC while the router nodes in RIME have an average 5.7% RDC and 7.5% RDC in RPL. Similarly, the non-CH nodes in MUCBR achieved 0.08% RDC while the leaf nodes in RIME have an average 2.2% RDC and 2.8% RDC in RPL. The analyses indicate the advantage of the scheduled-listening considered by the MUCBR over the sampling-listening technique. The excessive energy consumption of transmission for RIME and ContikiRPL is due to the sampling-listening technique which requires the sender to continuously transmit readings in order to permit correct message reception. Fig. 11 and 12 show the probability of collision-free for both of the 802.15.4 and the MUCBR with respect to nodes density and *macSuperframeOrder* (SO) while *beacon order* (BO) has been set to 7. The SO value determines the active slot *superframe duration* (SD) while the BO determines the *beacon interval* (BI) duration [1]. 802.15.4 is fully dependent on the SO value (besides the nodes density and

BI), increasing this parameter will reduce the impact of collision but in term of high RDC and high energy consumption. On the other hand, the MUCBR is only affected by the nodes density and BI while achieving high probability of collision-free due to randomly distributed transmissions across the BI rather than restricting the transmission to only SD duration.

The comparison between the two routing techniques points to the superiority of the mesh-under technique (utilized by MUCBR and RIME) over the route-over technique (utilized by ContikiRPL) in terms of energy consumption. The basic reason behind the high energy consumption is the packet size. The routing within the IPv6 network layer (route-over) will add extra packet header load to the 802.15.4 frames which dramatically increases energy consumption. Moreover, the probability of collision will increase due to maximizing T_f in equation (1). Finally, our analyses show how the clustering technique can minimize the energy consumption by reducing the sensor nodes RDC.

V. CONCLUSION

The proposed MUCBR protocol presents a mesh-under routing technique that utilizes the clustering topology principle in order to divide the WSN into CH nodes and non-CH nodes. Therefore, the RDC has been minimized by allocating the nodes in each cluster random time references instead of time slots to communicate with the CH and in turn route the data to the sink utilizing the shortest path (through CHs). In addition, routing within the link layer has a real advantage in terms of energy consumption that could be utilized for applications that require a timely-event based data aggregation within a single LoWPAN. The proposed MUCBR manages to provide 0.08% RDC for non-CH nodes and 1.3% RDC for CH nodes with timely-based transmissions of one message every two seconds and CHs with an average of three members. Our results clearly show that the scheduling listening techniques provide a better power efficiency. It also disapproves the assumptions that the power requirements of the network setup in scheduling techniques are always higher than the power savings achieved by it. Furthermore, the randomness of time references which are allocated to the members in each cluster reduces both the inter-cluster and intra-cluster interference with an appropriate value of T_P and with respect to node density. Thus, the collision impact has been reduced by 40% as compared to 802.15.4. Finally, the MUCBR CH election scheme provides a chain of connected CHs via a single-hop link and eliminates the need for a bridge node to connect two adjacent clusters and ensure connectivity to the sink through the shortest path.

REFERENCES

[1] "IEEE Standard for Local and metropolitan area networks--Part 15.4: Low-Rate Wireless Personal Area Networks (LR-WPANs)," *IEEE Std 802.15.4-2011 (Revision of IEEE Std 802.15.4-2006),* pp. 1-314, 2011.

[2] N. Salman, I. Rasool, and A. H. Kemp, "Overview of the IEEE 802.15. 4 standards family for low rate wireless personal area networks," in *7th International Symposium on Wireless Communication Systems (ISWCS),* York,UK, Sept. 2010.

[3] N. Kushalnagar, G. Montenegro, and C. Schumacher, "IPv6 over low-power wireless personal area networks (6LoWPANs): overview, assumptions, problem statement, and goals," IETF, *RFC4919, August,* 2007.

[4] G. Montenegro, N. Kushalnagar, J. Hui, and D. Culler, "Transmission of IPv6 packets over IEEE 802.15. 4 networks," *Internet proposed standard* IETF, *RFC 4944*, 2007.

[5] A. H. Chowdhury, M. Ikram, H.-S. Cha, H. Redwan, S. Shams, K.-H. Kim, *et al.*, "Route-over vs Mesh-under Routing in 6LoWPAN," in *Proceedings of the International Conference on Wireless Communications and Mobile Computing: Connecting the World Wirelessly*, *Germany*, June 2009, pp.1208-1212.

[6] X. Wang and H. Qian, "Constructing a 6LoWPAN Wireless Sensor Network Based on a Cluster Tree," *IEEE Transactions on Vehicular Technology,* Vol. 61, no. 3, pp. 1398-1405, 2012.

[7] S. Bandyopadhyay and E. J. Coyle, "Minimizing communication costs in hierarchically-clustered networks of wireless sensors," *Elsvier Journal of Computer Networks,* vol. 44, no. 1, pp. 1-16, Jan 2004.

[8] L. Karim and N. Nasser, "Energy efficient and fault tolerant routing protocol for mobile sensor network," in *IEEE International Conference on Communications (ICC),* Japan, June 2011, pp. 1-5.

[9] A. Dunkels, B. Gronvall, and T. Voigt, "Contiki-a lightweight and flexible operating system for tiny networked sensors," in *the First IEEE Workshop on Embedded Network Sensors,* Florida, USA, Nov. 2004.

[10] W. R. Heinzelman, A. Chandrakasan, and H. Balakrishnan, "Energy-efficient communication protocol for wireless microsensor networks," in *Proceedings of the 33rd Annual Hawaii International Conference on System Sciences,* Jan. 2000.

[11] B. Pavkovic, W.-J. Hwang, and F. Theoleyre, "Cluster-Directed Acyclic Graph Formation for IEEE 802.15. 4 in Multihop Topologies," in *5th International Conference on New Technologies, Mobility and Security (NTMS),* Istanbul, May 2012.

[12] F. Cuomo, S. Della Luna, E. Cipollone, P. Todorova, and T. Suihko, "Topology formation in IEEE 802.15. 4: cluster-tree characterization," in *Sixth Annual IEEE International Conference on Pervasive Computing and Communications, PerCom,* Hong kong, March 2008.

[13] H. Tavakoli, J. Misic, M. Naderi, and V. B. Misic, "Interaction of clustering period and event sensing reliability in IEEE 802.15. 4 based WSNs," in *9th International Wireless Communications and Mobile Computing Conference (IWCMC),* Sardinia, July 2013.

[14] V. Kumar, A. Raghuvansi, and S. Tiwari, "Performance study of beacon-enabled IEEE 802.15. 4 standard in WSNs with clustering," in *International Conference on Power, Control and Embedded Systems (ICPCES),* Allahabad, Nov. 2010.

[15] N. Abdeddaim, F. Theoleyre, F. Rousseau, and A. Duda, "Multi-Channel Cluster Tree for 802.15. 4 Wireless Sensor Networks," in *23rd International Symposium on Personal Indoor and Mobile Radio Communications (PIMRC),* Sydney, Sept. 2012.

[16] L. Li and J. Zhao, "Reducing inter-cluster TDMA interference by slot-pre-allocation-protocol in sensor networks," in *2nd International Conference on Industrial and Information Systems (IIS),* Dalian, July 2010.

[17] M. O. Farooq and T. Kunz, "Contiki-based IEEE 802.15. 4 node's throughput and wireless channel utilization analysis," in *Wireless Days (WD), IFIP*, Dublin, Nov. 2012.

[18] A. Dunkels, F. Österlind, and Z. He, "An adaptive communication architecture for wireless sensor networks," in *Proceedings of the 5th international conference on Embedded networked sensor systems*, *SynSys '07*, USA, 2007, ACM.

[19] J. W. Hui and D. E. Culler, "IPv6 in low-power wireless networks," *Proceedings of the IEEE,* vol. 98, no. 11, pp. 1865-1878, 2010.

[20] F. Osterlind, A. Dunkels, J. Eriksson, N. Finne, and T. Voigt, "Cross-level sensor network simulation with cooja," in *31st IEEE Conference on Local Computer Networks,* Florida, Nov. 2006.

[21] N. Tsiftes, J. Eriksson, and A. Dunkels, "Low-power wireless IPv6 routing with ContikiRPL," in *Proceedings of the 9th ACM/IEEE International Conference on Information Processing in Sensor Networks*, Sweden, April 2010.

[22] A. Dunkels, "The contikimac radio duty cycling protocol," *Technical Report T2011:13, Swedish Institute of Computer Science,* 2011.