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$\Theta(1)$ Time Algorithm for Master Selection in Ad-hoc Wireless Networks

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***Abstract*—This paper details a hardware implementation of a distributed $\Theta(1)$ time algorithm allows to select dynamically the master device in ad-hoc or cluster-based networks in a constant time regardless the number of devices in the same cluster. The algorithm allows each device to automatically detect its own status; master or slave; based on identifier without adding extra overheads or exchanging packets that slow down the network. We propose a baseband design that implements algorithm functions and we detail the hardware implementation using Matlab/Simulink and Ettus B210 USRP. Tests held in laboratory prove that algorithm works as expected.**

***Keywords*—Cluster-based networks, Cluster head selection, Ad-hoc networks, Wireless sensors networks, SDR, USRP, Simulink**

I. Introduction

THE number of IoT devices has been significantly increased during lasts years. Due to its advantages, communication between Devices is mostly enabled by wireless. Wireless technologies are called to adopt new techniques able to optimize latency, bandwidth, coverage, and power consumption regardless the number of devices. Master/slaves architecture is a very popular solution for ad-hoc and cluster-based wireless networks, like Wireless Sensor Networks (WSN), thanks the high level control provided to manage contentions, cooperation and extend the network life time [1]–[4]. However, the weakness of centralized architectures is the dependence on master device. All system goes down if the master runs out of energy or it's out of range or any other failure. Lot of researches [5]–[11] has introduced new techniques allows to select dynamically the master, more precisely cluster-head in cluster-based networks, in order to ensure coverage preservation and increase the network lifetime by sharing the master load with all other nodes . In this paper we detail a solution that enhances the traditional master/slave architecture by introducing the dynamic aspect without adding extra overheads or beacon parquets that slow down the network. The novel technique has been inspired form a parallel computing algorithm able to select the Processor Element (PE) which has the maximum or minimum ID from a set of PEs in constant $\Theta(1)$ time. This algorithm has been introduced for the first time by [12] in 1990, as a new approach in parallel computing field, to resolve nearest neighbor problems on a mesh-connected computer. In 1994, the algorithm has been used to solve the ranking problem in the connected components of images [13]. One year later, in 1995, same algorithm has been used for images decomposition into quadtree and octree on a mesh connected computer [14]. Patent published in 2007 [15] presents the first uses of the algorithm in telecommunications filed as comparison technique retaining a single device in combat process to get access for a shared communication channel. In 2009, the algorithm has been used to ensure access without collision for distributed wireless ad hoc local networks [16]. The proposed method is based on the use of one or more frequency bands. Each of its frequency bands includes a pair of channels. One channel of the pair is used for communication in a limited area under the control of a master device, while the other channel, called protection channel, is used as protection shield where the combat occurs. Combat procedure is based on a comparison technique allows the election of a single master device of the communication zone. Two works has been published in 2014 [17] and 2016 [18] detail and analyze the performance of access methods based on this algorithm. However, all previous works present top level architecture and there is no hardware implementation has been proposed until today. In this paper we propose an enhanced baseband design of physical layer that implements the combat technique for master selection. We develop new architecture adapted for SDR implementation. We use Welch periodogram estimation method [19] for detection module and we implement the design under Simulink and Ettus B210 USRP [20]. Results of tests held on laboratory are shared and prove that the algorithm can be adopted for wireless. We sum up by discussing the result and concluding the advantages and limitations of the proposed method.

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II. Method

The proposed technique is based on a distributed comparison technique able to select the maximum in $\Theta(1)$ time. This technique has been detailed in [16] as a solution to prevent contentions over a shared radio channel. Communication device described in [16] uses two specific RF channels, Protection Channel (PCH) and Communication Channel (CCH), with different scopes. CCH is used to exchange data between several devices within a communication area A_c and covers a range R_c which is the same for all devices. PCH is used to define a protection area A_p which includes the area A_c.

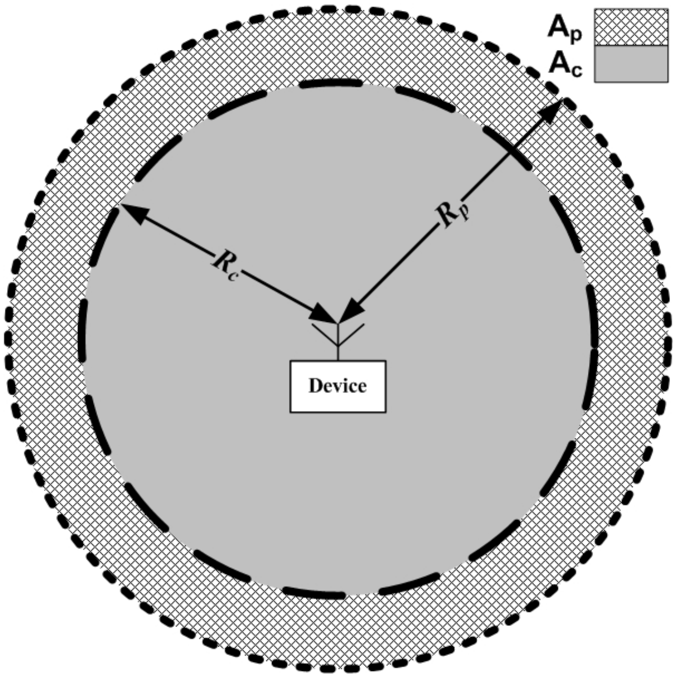

Fig. 1. Cell topology: Communication and protection area

A_p delimits the range of the cell and prevents other external devices outside the cell from disturbing the communication between the devices inside that cell. PCH covers a range R_p bigger than R_c as shown in Fig.1.

All communications inside A_c are under the control of a single communication device which is called master. Any device remains master of its A_c if it wins a combat with the other devices that are in the range of its PCH, whether internal or external to its own A_c. As long as a device is a winner, it remains the master on its own A_c by transmitting to the other devices inside its A_c transmission and reception orders. The combat uses an identifier called General Code of Contention (GCC). Each device has a unique and non-zero GCC. Any device wishes to become or remains the master in its zone Ac must continuously transmit on the PCH signal that reflect the binary elements of its GCC. Each binary element b_i of the GCC is associated with a subcarrier $f_{sc,i}$; which is the same for all devices; broadcasted over PCH. The combat technique is based on a comparison method performed at each device. This comparison retains only one winner device, the one who has the biggest GCC value or the smallest value according to the logic adopted. The hardware implementation of this combat technique is the subject of the rest of this paper.

The top level architecture of the device described in [16] consists of three basic units (Fig.2). The first unit represents the host system which is responsible for processing the data that is exchanged through the two channels PCH and CCH. This unit may consist for example of a microprocessor system. The second unit, called Protection Channel Access Unit (PCAU), allows the host to start election combat on PCH channel. It performs interfacing functions between the host and PCH. This unit itself is composed from several identical subunits Protection Channel Access Sub-Unit ($PCASU_i$) with

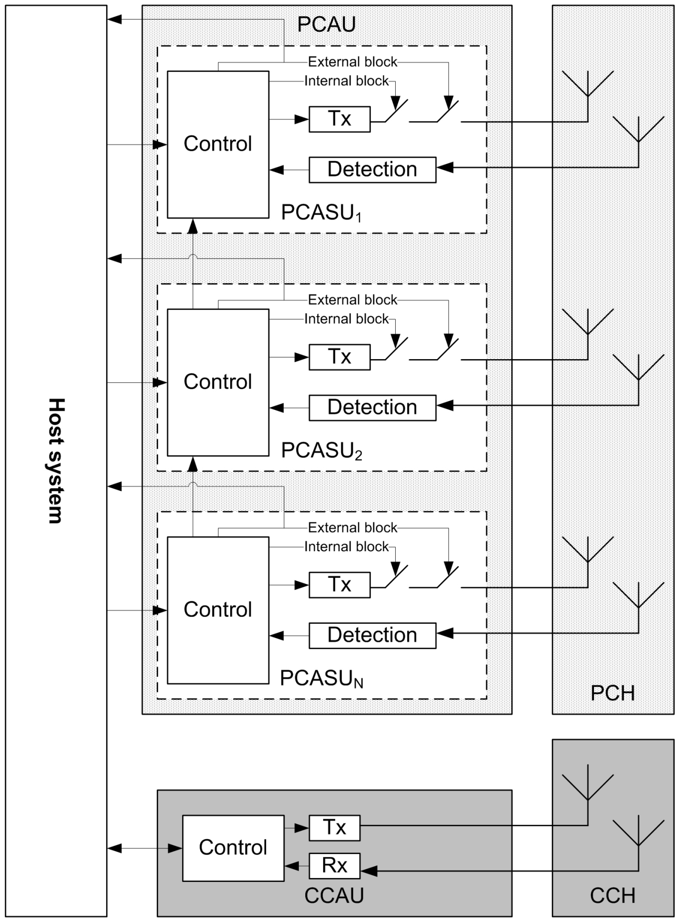

Fig. 2. Communication device: Top level architecture

$1 \leq i \leq N$, where N represents the number of binary elements of GCC. Each of these subunits $PCASU_i$ is associated with a binary element b_i. b_1 is the least significant element (LSB) while b_N is the most significant element (MSB).The third unit , called Communication Channel Access Unit (CCAU), allows the host to access the CCH. It performs the interfacing functions between the host and the CCH. Each $PCASU_i$ subunit is composed of three modules:

- Tx module: Each of these modules transmits a subcarrier $f_{sc,i}$ over the PCH. The transmission of $f_{sc,i}$ can be blocked through a double emission blocking system: an internal locking system and an external locking system.
- Detection module: Detects the presence of subcarrier $f_{sc,i}$. If this carrier is present on PCH, then a detection signal is transmitted to the control module.
- Control module: receives from the host system the binary element b_i of the GCC and from detection module the presence signal of $f_{sc,i}$. The control module outputs the dual blocking signals. On the other hand, this control module transmits to the host system a signal which indicates the blocking state of the carrier.

All $PCASU_i$ units are connected to each other via a serial bus to share the blocking commands between these units. Each control module relating to a $PCASU_i$ unit generates a transmission blocking signal of its own subcarrier if one of the two following situations is present. The first situation is internal blocking state. This state is activated if the corresponding b_i is 0, in this case the control module activates the internal blocking system. The carrier $f_{sc,i}$ is therefore no longer broadcasted on the PCH. The second situation is external blocking state. This state is enabled if one of the following two conditions is satisfied: (1)

1) First condition: the corresponding b_i is 0 in the presence of $f_{sc,i}$ in the PCH, this carrier being produced by other device.
2) Second condition: a blocking order received from a higher order control module via the serial bus.

If at least one of the two conditions is satisfied, the control module performs the following three operations: (1)

1) Transmission of a blocking command, via the serial bus, to the lower order control modules.
2) Activation of the external locking system. The subcarrier $f_{sc,i}$ is muted.
3) Transmitting a blocking indicator signal to the host system which indicates the order of control module that has activated the external blocking system. If this signal is received by the host system for a predefined minimum duration, the device is considered slave.

We propose in next section a hardware implementation of this combat technique by means of SDR. The proposed design keeps the original idea but introduces new architecture adapted for baseband processing.

III. Baseband design

To start the combat, each device must broadcasts an RF signal that represents its GCC. Assuming that GCC is coded in N bits, the RF waveform S_{RF} can be written as a sum of all subcarriers multiplied by the associated binary elements b_i (1). Where f_{RF} is the carrier radio frequency and $f_{sc,i}$ is the i^{th} subcarrier offset.

$$s_{RF}(t) = \sum_{i=1}^{N} b_i.cos(2\pi(f_{RF} + f_{sc,i})t) \quad (1)$$

In complex baseband presentation, the discrete broadcasted waveform $s(n)$ can be written as (2) where f_s is sampling frequency.

$$s(n) = \sum_{i=1}^{N} b_i.e^{2j\pi n \frac{f_{sc,i}}{f_s}} \quad (2)$$

When the combat finishes, only subcarriers related to the master remain on the channel. There is at least one subcarrier muted on slave devices even the corresponding GCC binary element is 1. In order to implement this mechanism using SDR, new architecture is adopted. For all devices, each subcarrier $f_{sc,i}$ is controlled by Tx Unit that contains a local oscillator producing the associated subcarrier and logical valves to mute or broadcast the subcarrier. Fig.3 shows logical model of Tx Unit. Subcarrier produced by local oscillator pass through the first valves which is a simple switch controlled by the associated binary element b_i (bit). Switch-1 shorts the

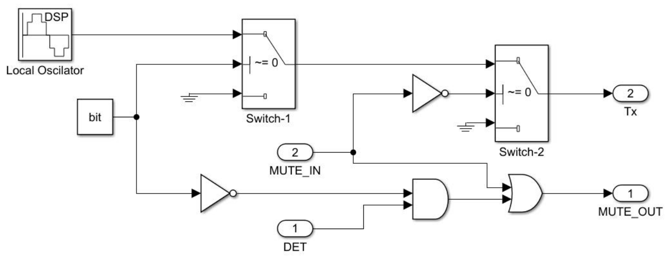

Fig. 3. Tx unit: Logical model

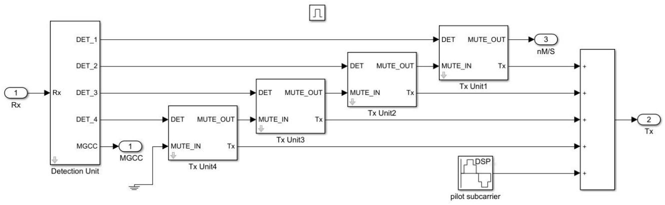

Fig. 4. PCAU: Top level when N=4

subcarrier to the ground if the binary element is 0. Otherwise, subcarrier signal is selected. The second valve is switch-2. It mutes the subcarrier if a mute order produced by a higher order Tx Unit is received at MUTE_IN port. Otherwise, the first input is selected at the output. Finally, TX port outputs subcarrier signal if binary element b_i is 1 and there is no mute order received from higher order Units. Otherwise, it is shorted to the ground. Tx Unit must also produce mute order to the lower units. The mute order is produced if detection signal is received in DET input port while b_i is 0 (which means that the related subcarrier is produced by other remote device) or a higher order mute is received at MUTE_IN port.

In order to generate the broadcasted waveform $s(n)$, all Tx units are cascaded in a serial manner from the higher order to the lower (MUTE_IN port of the highest order unit is connected to the ground), then a sum is performed for all TX outputs. Fig.4 shows the top level architected of PCAU in the case of GCC is coded in four bits ($N = 4$). There are four Tx units and one detection unit. Detection unit provides four detection signals which indicate the presence or no of each subcarrier to the corresponding Tx units through the port DET.

Detection unit uses Welch method [19] to estimate the Power Spectrum Density (PSD) of received signal. Fig.5 shows the logical model of detection unit. Periodogram block estimates the PSD from a set of N_{spd} samples (N_{spd} is the number of samples per detection). After fftshift block, vector (noted E_{psd}) representing the estimated PSD (in logarithmic scale) is centered about 0. At a given sampling rate f_s, the first sample in the frame at fftshift output $E_{psd}(1)$ represents the power quantity of frequency $-f_s/2$ in received signal, while sample in the middle $E_{psd}(N_{spd}/2)$ represents the continuous component and the last one $E_{psd}(N_{spd})$ represents $+f_s/2$. In general, the k^{th} sample represents the estimated power of frequency f_k. Relation (3) shows the link between k, N_{spd}, f_s and f_k.

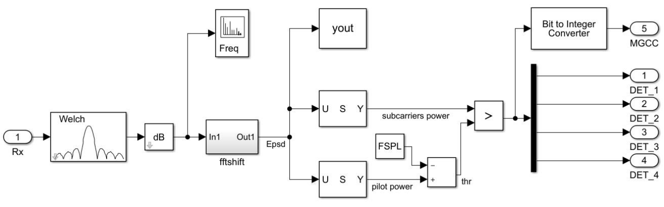

Fig. 5. Detection unit: Logical model

$$f_k = -\frac{f_s}{2} + \frac{k-1}{N_{spd}} f_s \tag{3}$$

To get the estimated power of the corresponding GCC subcarriers, the appropriate samples are selected based on the relation between the index idx_i and the frequency $f_{sc,i}$ (4).

$$idx_i = 1 + (\frac{1}{2} + \frac{f_{sc,i}}{f_s}) N_{spd} \tag{4}$$

Each power measurement is than compared to a detection threshold. If the power measurement is higher than detection threshold, the presence of subcarrier is asserted. In order to set detection threshold corresponding to a given range R_p, a pilot subcarrier f_p is added to the transmitted signal (see pilot subcarrier block in Fig.4). The permanent transmission of pilot subcarrier allows to each device to set automatically and dynamically the detection threshold corresponding to its own range R_p based on Free Space Path Loss (FSPL) formula (5) where $c_0 = 3.10^8 \ m.s^{-1}$ is the radio wave propagation speed [21]. The measured power of subcarriers $E_{psd}(idx_i)$ is compared by detection threshold (noted det_{thr}) which is the difference between measured power of pilot $E_{psd}(idx_{pilot})$ and desired A_{fspl} (6). If it's bigger, the corresponding detection signal det_i is 1 and subcarrier $f_{sc,i}$ is assumed present. Otherwise, det_i is 0 and $f_{sc,i}$ is assumed absent (7).

$$A_{fspl} = 20.log_{10}(\frac{4\pi.R_p.f_{RF}}{c_0}) \tag{5}$$

$$det_{thr} = E_{psd}(idx_{pilot}) - A_{fspl} \tag{6}$$

$$det_i = test(E_{psd}(idx_i) \geq det_{thr}) \tag{7}$$

Based on this proposed design, the device is able to auto detect its own status based on MUTE_OUT signal of the lower order Tx Unit. If it's equal a 1, which means there is at least one mute order has been generated, the device is not a master and the master GCC noted MGCC can be deducted from detections signals according to equation (8). Otherwise, there is no mute order generated, and the device is the master and the device GCC is equal to the restored MGCC.

$$MGCC = \sum_{i=1}^{N} det_i.2^{i-1} \tag{8}$$

IV. SDR IMPLEMENTATION

The implementation of detailed model is shown in Fig.6. The hardware part of communication device in our case is build by Ettus B210 USRP [20] and two omnidirectional antennas VERT 400 [22] for transmitting and receiving. The

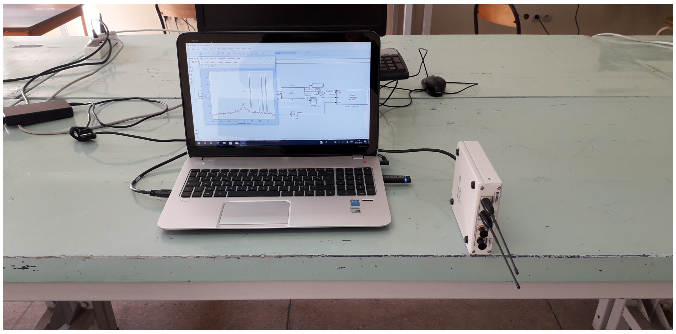

Fig. 6. Communication device: Hardware components

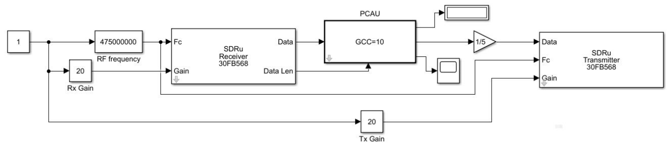

Fig. 7. Communication device: Simulink model interfacing with B210 USRP

software part is implemented in a personal purpose computer using Matlab and USRP® Support Package from Communications Toolbox. Simulink model executed in computer side communicates with Ettus B210 USRP through SDRu Receiver and SDRu Transmitter blocks (Fig.7). Data received from USRP; when it's available; are sent to the PCAU for processing. Samples produced by PCAU are divided by 5 (GCC coded in 4 bits) to prevent saturation in USRP (the module of input Data in SDRu transmitter must be lower or equal to 1) before they are sent to USRP for radio broadcasting. Transmitter and receiver are set at the same adjustable radio frequency. PCAU provides also MGCC which is the GCC of the master and the status of the device master or slave (0 for master and 1 for slave).

Model parameters are set as follows. Sampling frequency f_s is set to 80 kHz. The number of samples of detection N_{spd} is set to 1024. The pilot sub-carrier f_p is 10 kHz. The corresponding GCC sub-carriers $f_{sc,1}$, $f_{sc,2}$, $f_{sc,3}$, $f_{sc,4}$ are set respectively to 15 kHz, 20 kHz, 25 kHz and 30 kHz. The gain of transmitter and receiver is kept under 20 dB to avoid harmonics generation. RF signal carrier f_{RF} is set to 475 MHz. A_{fspl} is set to 46 dB which equivalent in this case to a range R_p of 10 m. In order to mitigate noise, detection periodogram is calculated using Welch method and Kaiser Window with β equal to 38 [23] and 32 spectral averages [19].

Fig.8 shows the estimated spectrum of received signal when there is only one device ($GCC = 10$). It's clear that f_p, $f_{sc,2}$ and $f_{sc,4}$ have approximately the same power level (above detection threshold), while $f_{sc,1}$ and $f_{sc,3}$ are muted (under detection threshold) because the corresponding binary elements are 0. Based on the estimated noise floor, the

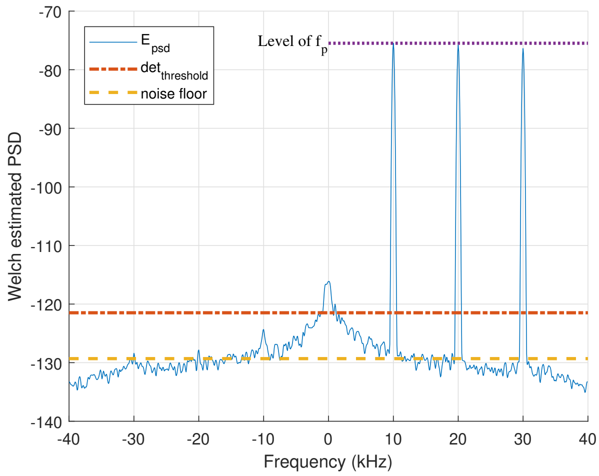

Fig. 8. Estimated PSD: One device with GCC=10

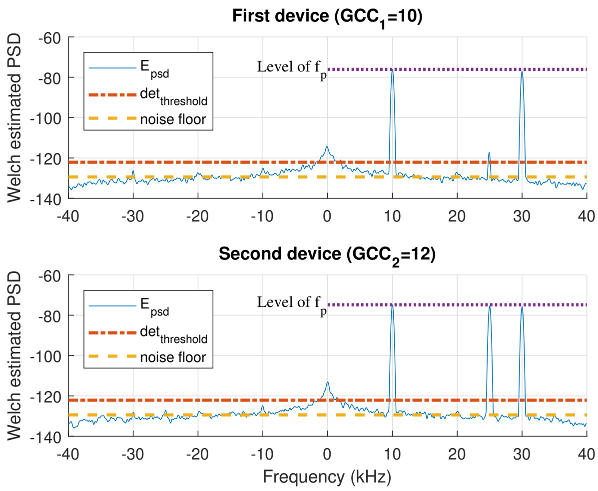

Fig. 10. Estimated PSD: Two devices spaced by 3 m with GCC1=10 and GCC2=12

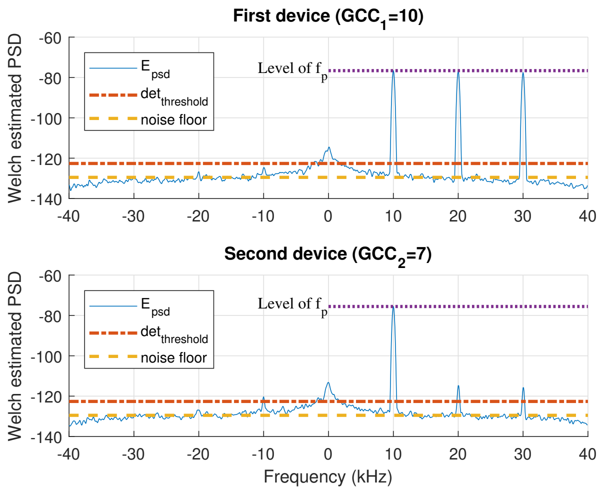

Fig. 9. Estimated PSD: Two devices spaced by 3m with GCC1=10 and GCC2=7

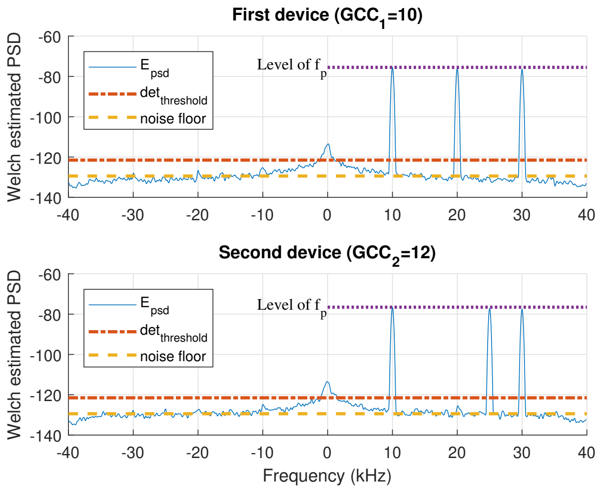

Fig. 11. Estimated PSD: Two devices spaced by 40 m with GCC1=10 and GCC2=12

maximum detectable FSPL with this device configuration is about 55 dB which is equivalent to a range R_p of 30 m. The model is able to detect that device is master because there is no mute order has been generated and recover the master GCC which equal to 10.

Second test has been lunched with allowed $A_{fspl} = 46$ dB ($R_p = 10$ m) while keeping the same configuration parameters. We introduce new device with $GCC_2 = 7$ while GCC_1 is always 10 ($GCC_1 > GCC_2$). Fig.9 shows the results at a distance of 3 m. The first device ($GCC_1 = 10$) is always the master and remained sub-carrier on PCH are $f_{sc,2}$ and $f_{sc,4}$ at the same level of its own f_p .The second device sets automatically itself as slave and mutes subcarriers $f_{sc,1}$, $f_{sc,2}$ and $f_{sc,3}$. The estimated PSD by second device shows the remained subcarriers are $f_{sc,2}$ and $f_{sc,4}$ with a level lower than its own pilot subcarrier f_p which confirm that they are generated by a remote device (the first device).

After setting the GCC_2 to 12 ($GCC_1 < GCC_2$) the situation is inverted (Fig.10). First device sets itself as slave and mutes subcarrier $f_{sc,2}$. Remained subcarriers are $f_{sc,3}$ and $f_{sc,4}$ which represents the master GCC ($GCC_2 = 12$) have different levels. Subcarrier $f_{sc,4}$ has the same level of f_p because is also generated by the first device ($GCC_1 = 10$) and it's the higher order unit (didn't received any mute order). Subcarrier $f_{sc,3}$ has a lower level because it is generated by the remote device. Second device sets itself a master and the remained subcarriers are at the same level of its own pilot subcarrier. After moving the second device to a distance of 15 m which is higher than R_p, both devices are masters of its own area and the result on both devices is similar to the first test (Fig.11).

Third test has been lunched with three different devices inside the range R_p of each others as shown in Fig.12. The first device is at the right of the picture, the second is in the left and the third is in the middle. Test has been lunched three times with different GCC configuration. The first case is $GCC_1 = 10$, $GCC_2 = 12$ and $GCC_3 = 7$. Fig.13 shows the estimated peridograms at each device for different

Fig. 12. Real test configuration for three devices

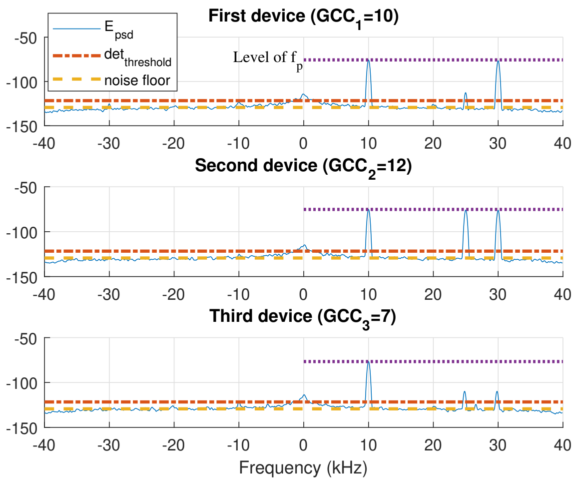

Fig. 13. Estimated PSD: Three devices with GCC1=10, GCC2=12 and GCC3=7

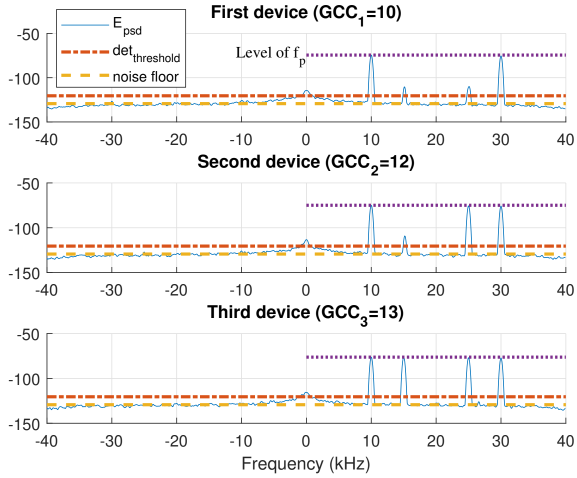

Fig. 14. Estimated PSD: Three devices with GCC1=10, GCC2=12 and GCC3=13

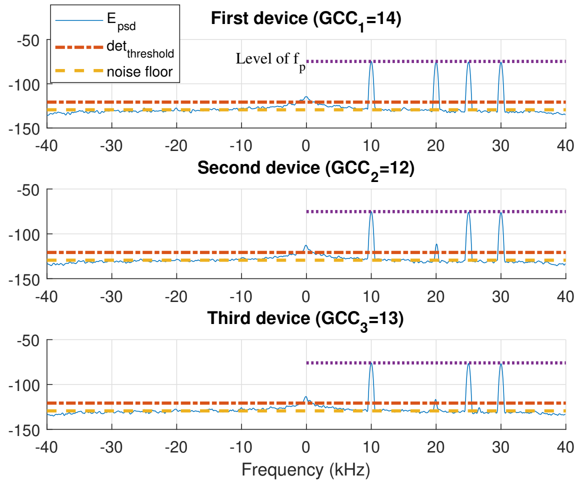

Fig. 15. Estimated PSD: Three devices with GCC1=14, GCC2=12 and GCC3=13

GCC configuration. It's clear that the remained subcarriers are always at the same level of pilot subcarrier in the PSD calculated by the second device which is the master, while they are at lower levels for slave devices. The second case is $GCC_1 = 10$, $GCC_2 = 12$ and $GCC_3 = 13$. The third device becomes automatically master while the first and the second set themselves as slaves (Fig.14). The third case is $GCC_1 = 14$, $GCC_2 = 12$ and $GCC_3 = 13$. The first device becomes master while the second and third set themselves as slaves (Fig.15).

V. Discussions

Tests held for different situations prove that the algorithm can be adapted for wireless networks. For example, the algorithm can be used for a cluster of devices connected witch each other via WiFi, Bluetooth, ZigBee, LoRaWAN or any other protocol. The proposed technique can be implemented separately in a different RF channel located in low band frequency in order to cover more ranges with low transmitted power. The master device will be the one who has the biggest GCC which can be the physical address or combination from physical address and other parameters. For example, in the case of cluster-based network formed by identical drones fly as group and cooperate to accomplish a mission. We can concatenate the binary elements representing the battery level with MAC address to from the GCC. In this case, drones that have low battery level will be always slaves. If the battery level of the cluster head (CH)/Master becomes lower, new CH will be selected. However, broadcasting an address of 64 bits (e.g LoRAWAN) is costly in terms of power consumption and bandwidth occupation. For a separation of 5 kHz between subcarriers, assuming the pilot subcarrier is transmitted just in device initialization for calibration purpose, the required band to broadcast an address of 64 bits is 320 kHz. To overcome this limitation, two solutions are proposed. The first one is decreasing the separation between subcarrier. Because of subcarriers are constant tones, small separation is allowed if a large detection period is used. With this solution, we have to deal with a tradeoff between bandwidth and detection time. Narrow bandwidth requires longer detection time. In fact, detection time is two times the time required to estimate PSD. The first PSD estimation produces muting orders and the resultant spectrum will be available after the second

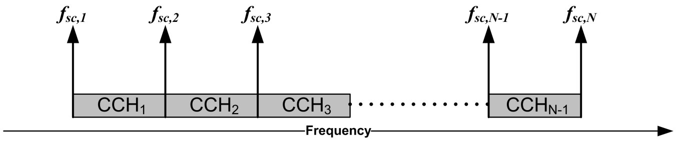

Fig. 16. Proposed spectrum pattern for PCH and CCH

estimation. Therefore, the time (noted T_c) required by the algorithm to elect a master is given by (9). For N_{spd}= 1024 and f_s=80 kHz, the required time is 25.6 ms (same situation as tests held on laboratory). If $f_{sc,1}$, $f_{sc,2}$, $f_{sc,3}$, $f_{sc,4}$ are set respectively to 1.5 kHz, 2.0 kHz, 2.5 kHz and 3.0 kHz, assuming f_s=8 kHz and N_{spd}= 1024, the required time is 256 ms. To reduces this value, we can also decrease the number of samples used for PSD estimation without impacting the certainty of detection.

$$T_c = \frac{2N_{spd}}{f_s} \tag{9}$$

The second solution is using the idle bands between subcarriers for exchanging data using an appropriate modulation scheme. In the case of 64 bit address, there are 63 idles bandwidth available for data communication (Fig.16). Otherwise, new protocol or addressing approach must be adopted by limiting the number of allowed nodes. An address of 8 bits is sufficient to cover 255 nodes which are enough in most cases. If we take Bleutooth network as example, it consists of small subnets or piconets. A piconet consists of two or more connected nodes sharing the same channel. Every piconet have one master and up to 7 slaves [2], [3]. In this situation 4 bits are enough to affect a unique GCC to each device within the same piconet which reduce the bandwidth and power requirement.

VI. Conclusion

The proposed design has been implemented and tested successfully by means of SDR. Due to the lack of resources, the solution has been tested on a set of two and three devices. Results show that there is always one master device elected without any conflict detected. This method can be fitted to any wireless networking situation where a master election from a set of devices is required like cluster-based networks. The method is also decentralized and executed in a constant time regardless the number of devices. However, a tradeoff between the bandwidth and detection time must be considered when using this technique. Otherwise developing new addressing strategy is recommended to take advantages from this technique.

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