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A Multi-Channel MAC Protocol For Wireless Hospital Sensor Networks

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I – INTRODUCTION

Both IEEE 802.15.4 and 802.15.4a standards allow for dynamic channel allocation and use of multiple channels available at their physical layers but its MAC protocols are designed only for single channel. Also, sensor's transceivers such as CC2420 provide multiple channels and as shown in [1-3] channel switch latency of CC2420 transceiver is very short just about 200 μ s.

In order to enhance both energy efficiency and to shorten end to end delay, we propose, in this report, a new MAC protocol allowing multi-channel allocation for 802.15.4a compliant devices.

II – CHANNEL FREQUENCY ALLOCATION INSIDE WHSN (Wireless Hospital Sensor Network)

As shown in the table below, we dispose of 16 physical frequency channels associated with 8 sequence codes to have in total 32 logical channels.

Table .1: Logical channels

	Logical channels	
Index code	Sequence Code	Physical channel
1	SC_1	0, 1, 8, 12
2	SC_2	0, 1, 8, 12
3	SC_3	2, 5, 9, 13
4	SC_4	2, 5, 9, 13
5	SC_5	3, 6, 10, 14
6	SC_6	3, 6, 10, 14
7	SC_7	4, 7, 11, 15
8	SC_8	4, 7, 11, 15

As shown in table and figure below, we note:

- Channel 4 overlaps channels 1, 2 and 3.
- Channel 7 overlaps channels 5 and 6.
- Channel 11 overlaps channels 8, 9 and 10.
- Channel 15 overlaps channels 12, 13 and 14.

- Channels (1,2), (2,3), (5,6), (6,8), (8,9), (9,10), (10,12), (12,13) and (13,14) are adjacent.

And for each physical channel there are two sequence codes (in other terms two logical channels).

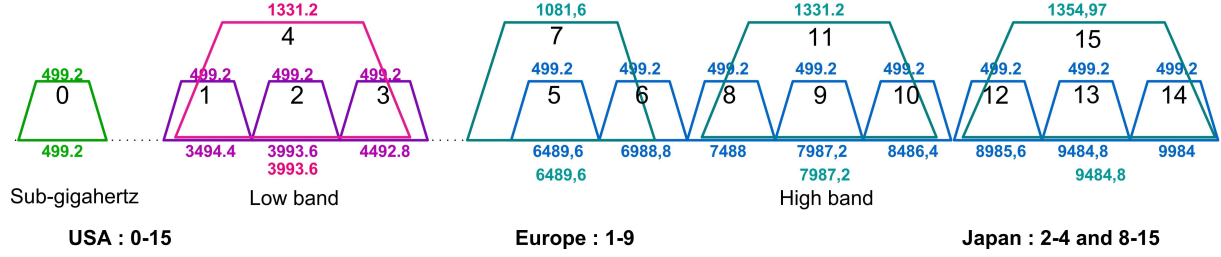


Figure .1: UWB Frequency plan

Important notes

1. According to table 1 and figure 1, we note that all overlapping channels don't share same sequence code. Consequently, logical channels overlapping don't represent co-channels since its sequence codes are different, in this case, the simultaneous use (in close space) of two overlapping channels don't produce co-channel interference.
2. According to table 1 and figure 1, we note that all adjacent channels don't share same sequence code. Consequently, logical adjacent channels don't interfere since its sequence codes are different, in this case, the simultaneous use (in close space) of two adjacent channels don't produce adjacent channel interference.

Table .2: Logical control and data communication channels

Logical channels				Data communication Channel
(SC ₁ , 0)	(SC ₁ , 1)	(SC ₁ , 8)	(SC ₁ , 12)	
(SC ₂ , 0)	(SC ₂ , 1)	(SC ₂ , 8)	(SC ₂ , 12)	
(SC ₃ , 2)	(SC ₃ , 5)	(SC ₃ , 9)	(SC ₃ , 13)	
(SC ₄ , 2)	(SC ₄ , 5)	(SC ₄ , 9)	(SC ₄ , 13)	
(SC ₅ , 3)	(SC ₅ , 6)	(SC ₅ , 10)	(SC ₅ , 14)	
(SC ₆ , 3)	(SC ₆ , 6)	(SC ₆ , 10)	(SC ₆ , 14)	
(SC ₇ , 4)	(SC ₇ , 7)	(SC ₇ , 11)	(SC ₇ , 15)	
(SC ₈ , 4)	(SC ₈ , 7)	(SC ₈ , 11)	(SC ₈ , 15)	
				Control Channel

Our problem is how to optimally allocate logical channels inside our cellular network (*WHSN*).

For a fixed number of cells N_c , each cell or PAN network is characterized by its duty cycle, BSNs (Body Sensor Network which is equivalent to BAN Body Area Network) and routers members.

We assume that all UWB sensors transmit with the same transmitter power levels:

- P_0 : used in control traffic,
- P_i : used in data communication traffic.
-

In other terms, our problem will be to find

- The optimal number of logical control channels (inside WHSN) and minimal distance of control channel reuse,
- The optimal number of logical data communication channels to ensure at least one channel per PAN and minimal distance of data communication channel reuse,
- According to available data communication channels and PANs duty cycle, method of channel allocation to each PAN (suitable sets of logical channels for each cell per elementary time duration).
- Method of time slot and channel frequency allocation inside PAN.
- Method of time slot allocation inside BSN.

II- 1 – FIRST LEVEL OF CHANNEL ALLOCATION

II-1-a Static control channel allocation

We propose, for control traffic (a control channel for each PAN, in other terms a control channel per cell), a fixed or static allocation of the overlapping channels (4, 7, 11 and 15). First, those channels are characterized by its high bandwidth (more than 1GHz) allowing a transmit power of 96,3μW (comparing to 37, μW in the case of non-overlapping channels) permitting an extended range comparing to non-overlapping channels (Since the PSD is fixed to -41.3dBm/MHz for all channel).

Assumptions :

1-/The radius of different cells is the same and equal to the PAN coordinator coverage zone that we assume be circular and all PAN members transmit at the same power transmit P_0 .

The choice of P_0 is done by taking into account the following equation.

$$P_{Rx} = P_0 + Pl(R) / P_{Rx} - Link_margin = Rx_sensitivity \quad (1)$$

Pathloss equation is given in the IEEE 802.15.4a standard [4].

So, in this case all PAN members (precisely PAN members located at or near the cell border) can hear their PAN coordinator control signal (beacon frame,...), and it can be heard by their PAN coordinator (as shown in figures 2.a and 2.b).

Consequently, as shown in figures 2.a and 2.b, the minimum distance D_{min} of frequency reuse must be strictly bigger than R_c :

$$D_{min} > R_c \quad (2)$$

With R_c is given by:

$$R_c = 2R \quad (3)$$

So, from equations (2) and (3) the shortest distance frequency reuse will be :

$$D_{min} = 4 \left[R \left(\frac{\sqrt{3}}{2} \right) \right] = (2\sqrt{3})R \quad (4)$$

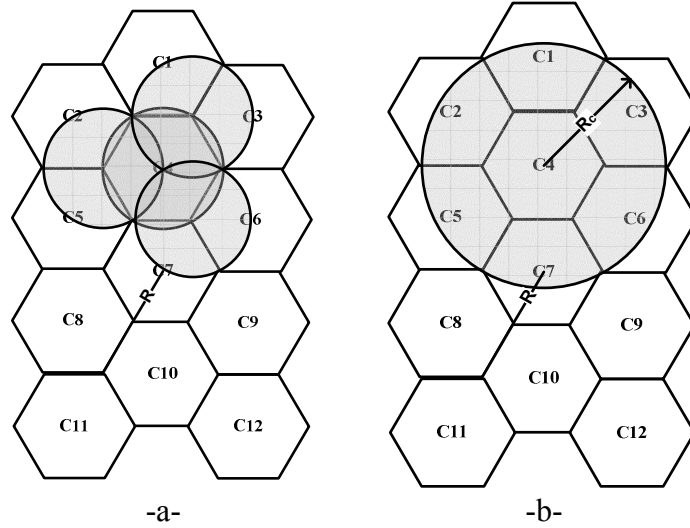


Figure .2: Radio coverage limit of a logical control channel

In this section, we are interested to find the minimal or optimal number of logical control channels $N_{cch-opt}$ ensuring a complete network coverage taking into account frequency reuse.

This problem can be modelled as graph coloring problem (**vertex coloring**).

As shown in figure above, we can represent our network as a $G(V, E)$ graph where:

- Each cell centre (PANc) represents a vertex : V .
- Cells distance separation that is shorter than D_{min} represents edge : E .

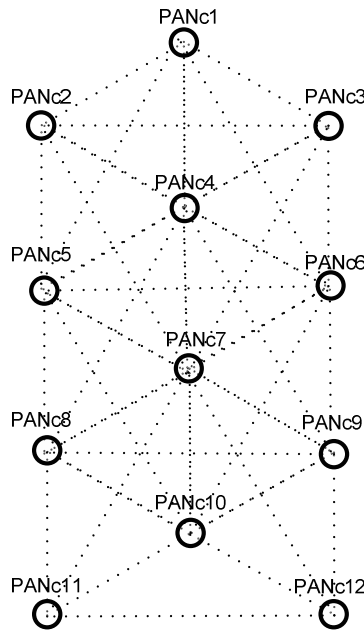
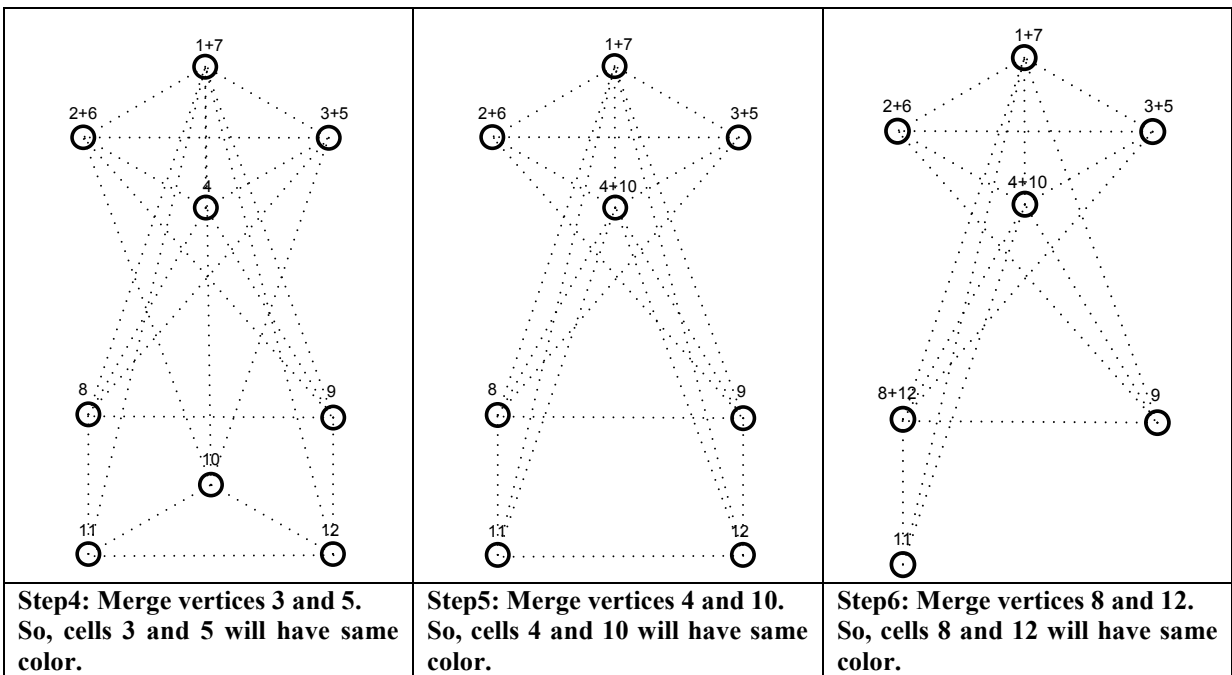
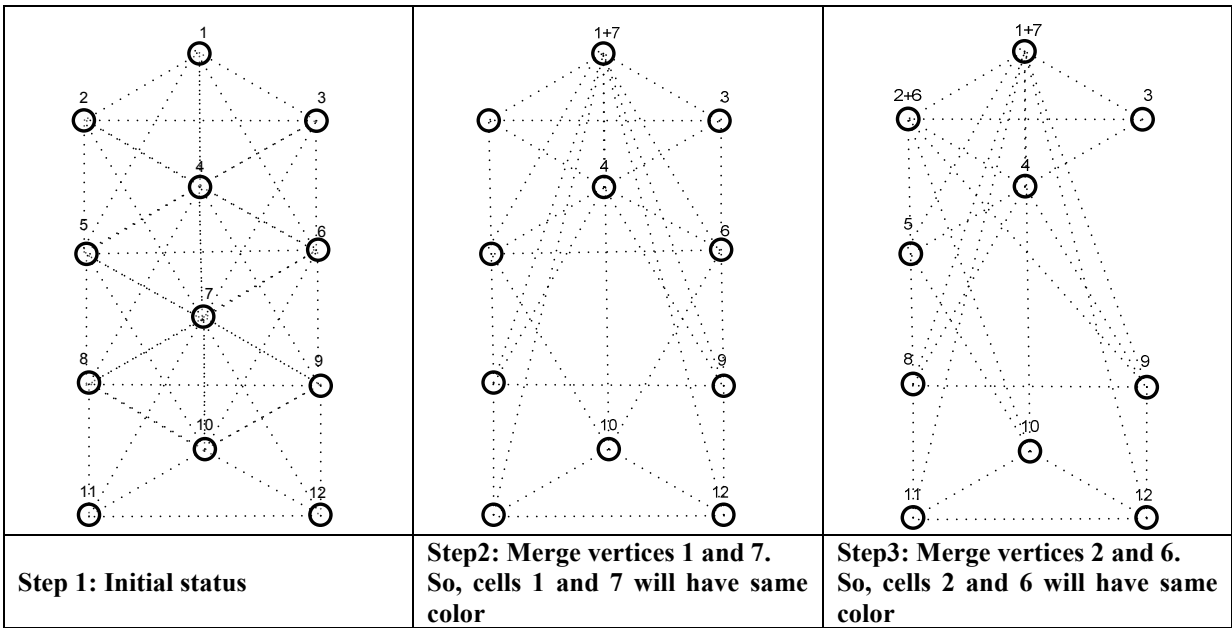


Figure .3: Logical control channel allocation graph

So, control channels assignment problem can be translated to: coloring the vertices of the graph above such that no two adjacent vertices share the same color, in other terms no two cells near than D_{min} share the same control channel. For that we can call for one of optimal coloring algorithms such as Zykov's algorithm, branch and bound method, ect. In general, the time required for such algorithms is deterministic polynomial. Steps from 1 to 9 summarise the application of Zykov's algorithm to previous graph.



<p>Step7: Merge vertices 4 and 10. So, cells 4 and 10 will have same color.</p>	<p>Step8: Merge vertices (2+6) and (8+12). So, cells 2, 6, 8 and 12 will have same color.</p>	<p>Step9: Merge vertices (3+5) and (9+11). So, cells 3, 5, 9 and 11 will have same color.</p>

In step 9, we note that we are left with a complete graph (“A complete graph with n vertices obviously requires n colors”[5]).

The optimal solution is given by the complete graph with 4 vertices in which vertices 1 and 7 are allocated to first color, 2, 6, 8 and 12 to a second color 3, 5, 9 and 11 to a third color and vertices 4 and 10 to the fourth. We note that to cover all the network by control traffic without suffering from co-channel interference, we just need 4 different channel frequencies (See figures 4 and 5).

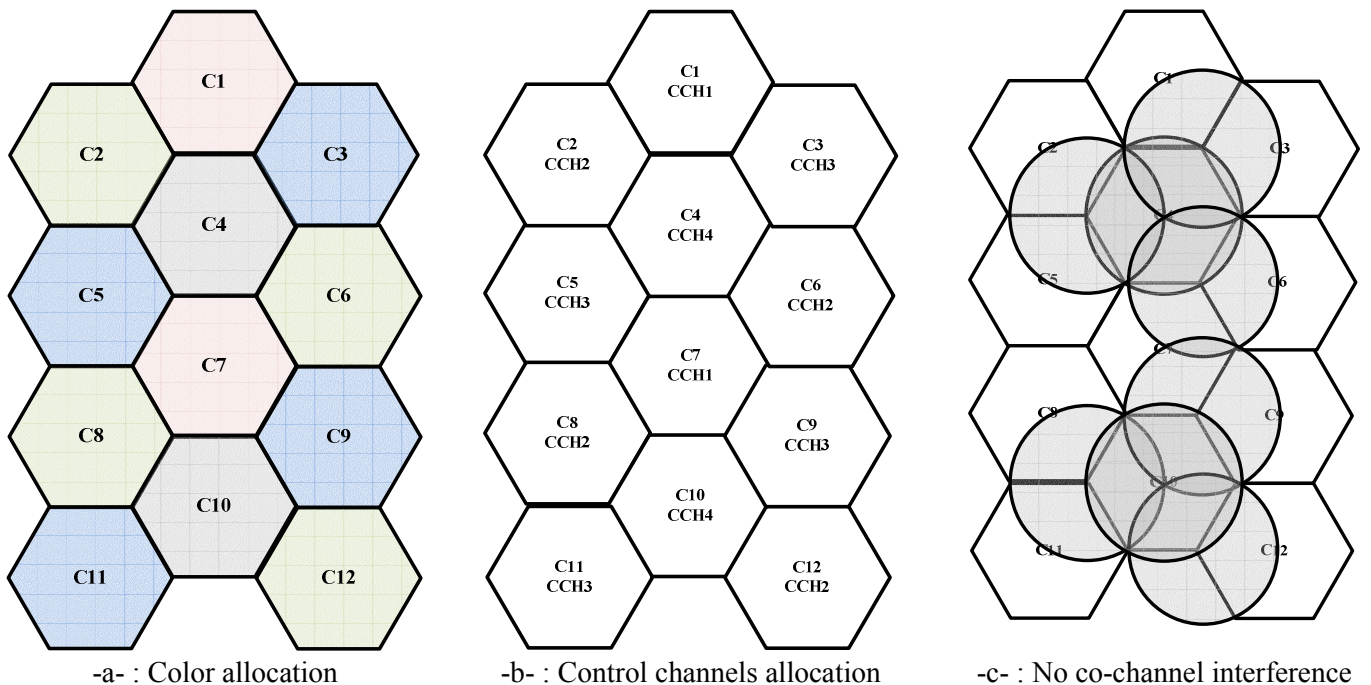


Figure .4: Logical control channel allocation

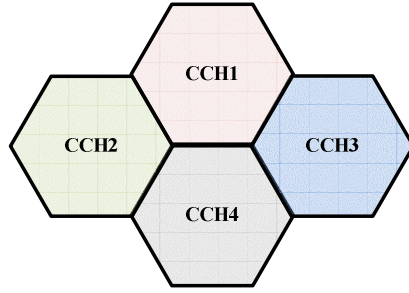


Figure .5: Elementary cluster

The algorithm below gives the method of control channels allocation.

With

- N_c : the total number of cells, (in the example above is 12 cells)
- R : radius of a cell
- $D_{N_c \times N_c}$ distance matrix, distance separating each couple of cell centres
- N_{cch} : set of available control channel, represents a sub set of total control channel set N_{tch} .

$$N_{tch} = \{(4, SC_7), (7, SC_7), (11, SC_7), (15, SC_7), (4, SC_8), (7, SC_8), (11, SC_8), (15, SC_8)\}$$

$$N_{cch} \subseteq N_{tch}$$

According to worldwide UWB regulations:

- For US regulation : $N_{cch} = N_{tch}$, $Card(N_{cch}) = Card(N_{tch}) = 8$,
- For European regulation : $N_{cch} \subset N_{tch}$, $Card(N_{cch}) = 4$,

$$N_{cch} = \{(4, SC_7), (7, SC_7), (4, SC_8), (7, SC_8)\}$$

- For Japan's regulation : $N_{cch} \subset N_{tch}$, $Card(N_{cch}) = 6$,

$$N_{cch} = \{(4, SC_7), (11, SC_7), (15, SC_7), (4, SC_8), (11, SC_8), (15, SC_8)\}$$

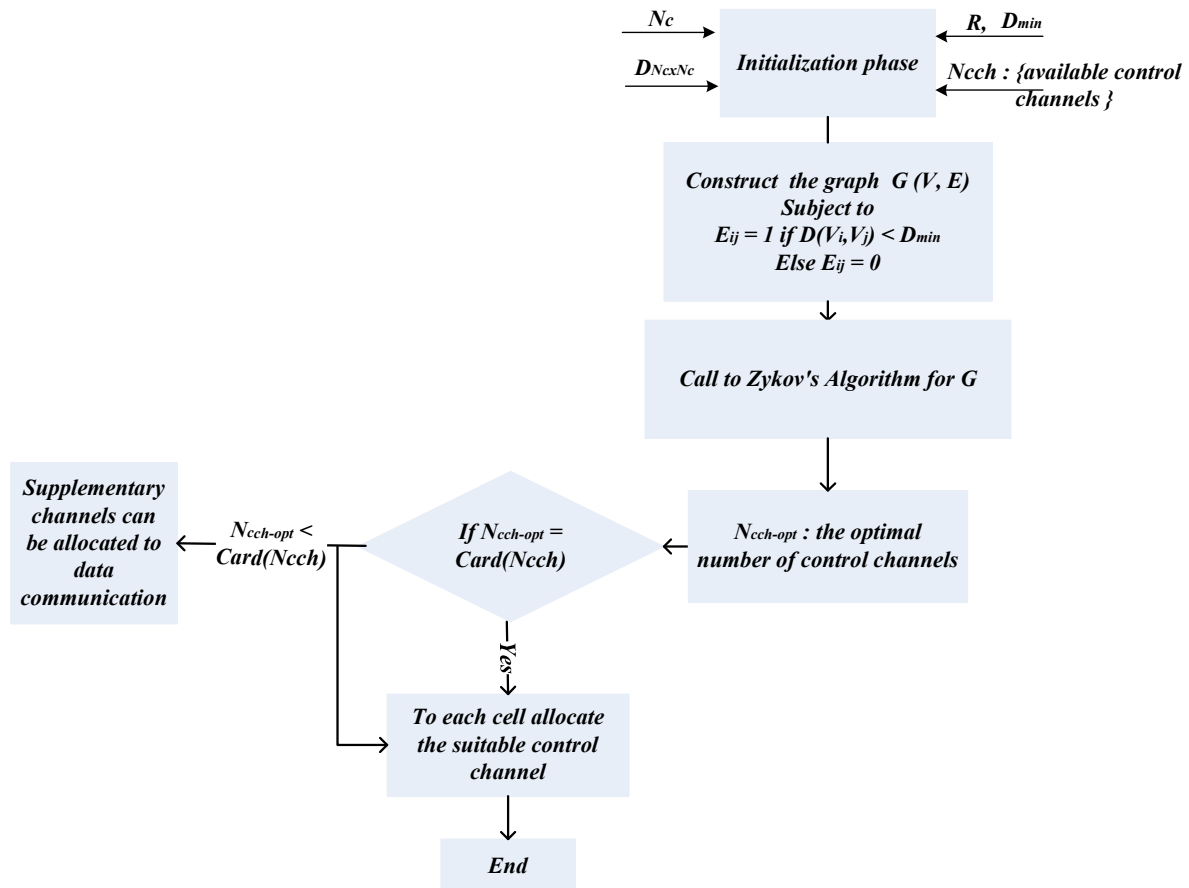


Figure .6: Logical control channel allocation algorithm

To have a general idea about network deployment, we draw the table below. We suppose that the total surface of the network is equal to 3000m² and the link margin is about equal to 3 dB. According to the standard 802.15.4a P_0 cannot exceed 96,3 μW power transmit. We note that the minimum number of cells to cover the totality of the network can't be less than four.

Table .3: Idea about network provisioning

P_0 (μW)	Rx_sensitivity (dBm)	R (m)	N_c
96,3	-85	16	4
40	-85	13	6
20	-85	10	10
96,3	-80	12	7
40	-80	9	12

II-1-b Dynamic data communication channel allocation

For data communication, we propose the use the non-overlapping channels (0, 1, 2, 3, 5, 6, 8, 9, 10, 12, 13 and 14) and supplementary overlapping channels with their appropriate sequence codes. According to PAN duty cycle and available frequency channels, PAN coordinator can benefit from several data communication logical channels.

The greatest transmitter power used with non-overlapping channel can't exceed 37 μW (PSD \leq -41,3dBm/Mhz).

Assumptions :

1-/ Let us assume

- N_c : the total number of cells with radius R ,
- $D_{N_c \times N_c}$ distance matrix, distance separating each couple of cell centres
- N_{tch} : set of total channels,
- N_{tdch} : set of total data communication channels,
- N_{dch} : set of available data communication channels, it represents a sub set of total data communication channels set N_{tdch} .

$$N_{tdch} = N_{tch} - N_{cch}$$
$$N_{dch} \subseteq N_{tdch}$$

According to worldwide UWB regulations:

- For US regulation : $N_{dch} = N_{tdch}$, $Card(N_{dch}) = Card(N_{tdch}) = 28$,
- For European regulation : $N_{dch} \subset N_{tdch}$, $Card(N_{dch}) = 14$,
- For Japan's regulation : $N_{dch} \subset N_{tdch}$, $Card(N_{dch}) = 20$,

2-/For data communication, we assume that all PAN members transmit at the same transmitter power P_t , in order to have a coverage of r radius.

$$r < \frac{R}{2}$$

The choice of P_t is done by taking into account the following equation.

$$P_{Rx} = P_t + Pl(r) / P_{Rx} - Link_margin = Rx_sensitivity \quad (5)$$

As shown in figures below, taking the example of cell number 4, PAN members, except PAN coordinator, can be located at any position inside its cell. So, we note for the case of sensors located at or near the cell border that can interfere with sensors of neighbor PANs, located at or near its cells border. Consequently, as shown in figures 7.b and 7.c, the minimum distance D'_{min} of frequency reuse must be strictly bigger than R_c :

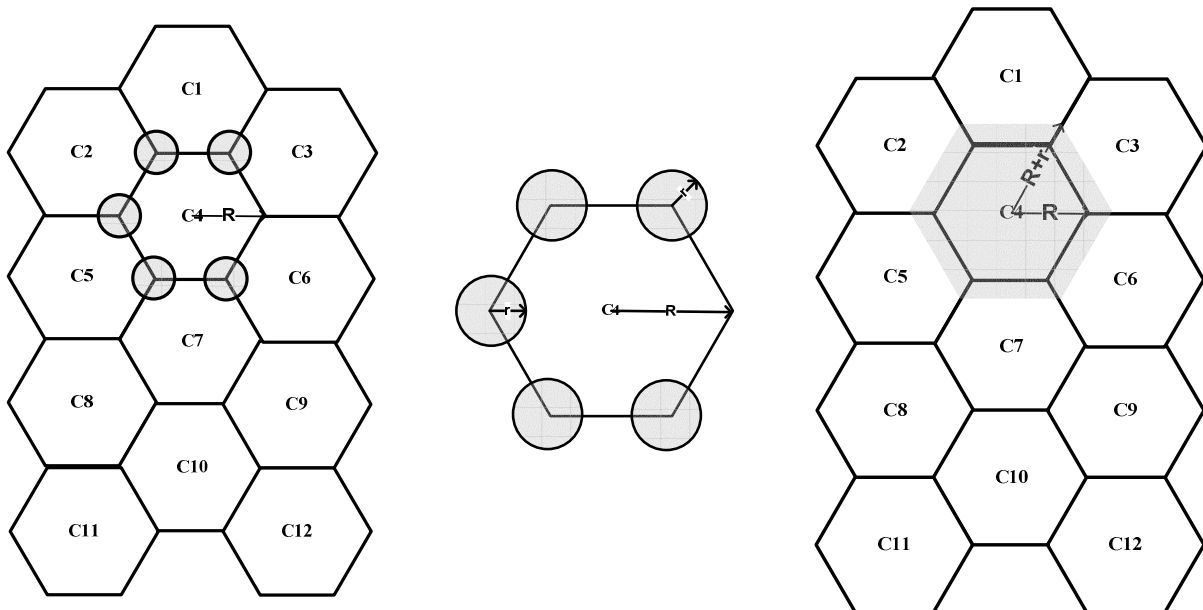
$$D'_{min} > R_c \quad (6)$$

With R_c is given by:

$$R_c = R + r \quad (7)$$

So, from equations (6) and (7) the shortest distance frequency reuse will be :

$$D'_{min} = 3R \quad (8)$$



-a-: Radio coverage of sensors located at cell border

-b-: Radio radius of a data communication

-c-: Coverage limit of data communication inside a PAN

Figure .7: Radio coverage limit of a logical data communication channel

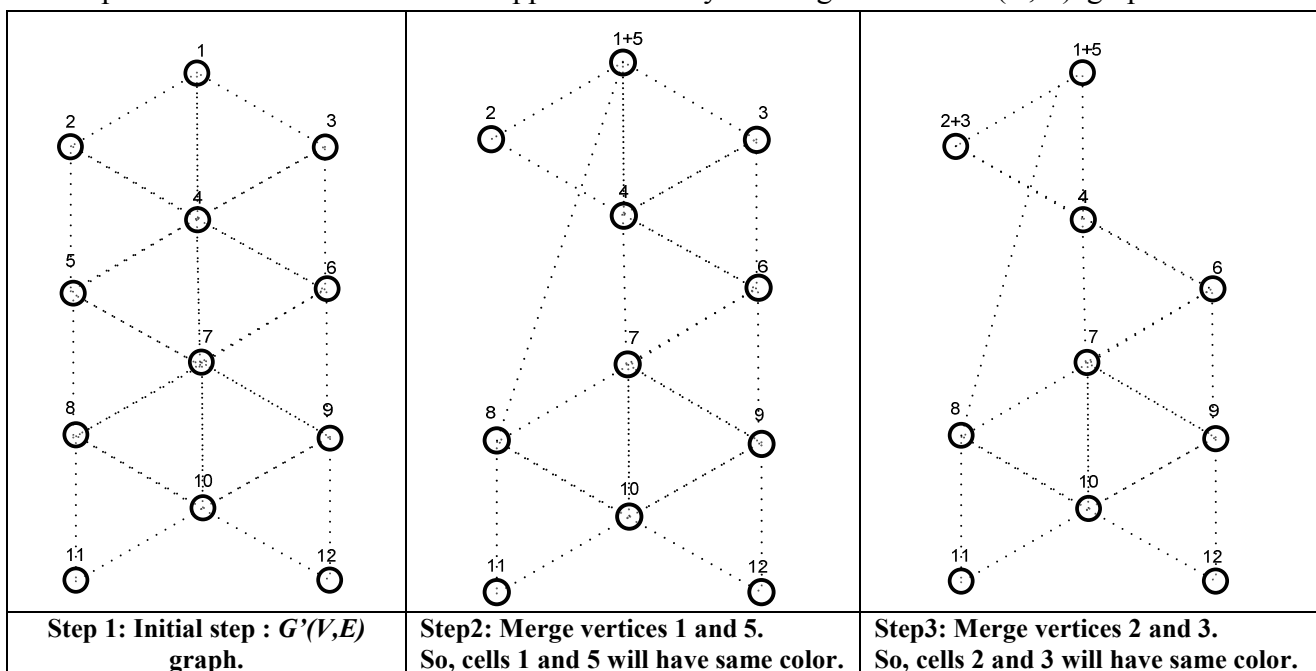
In this section, we are interested to find the minimal or optimal number of data communication channels $N_{dch-opt}$ to covert the global network taking into account frequency reuse.

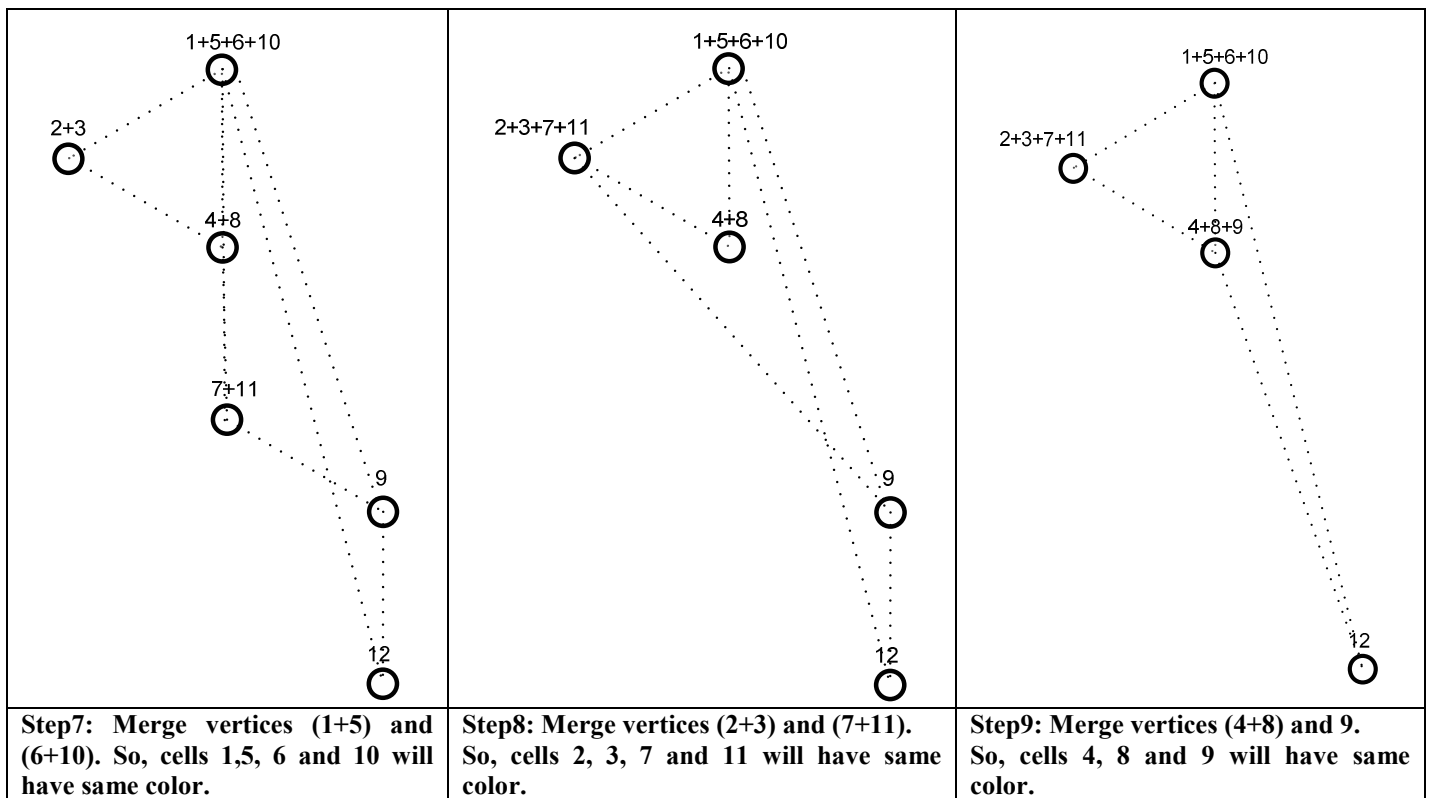
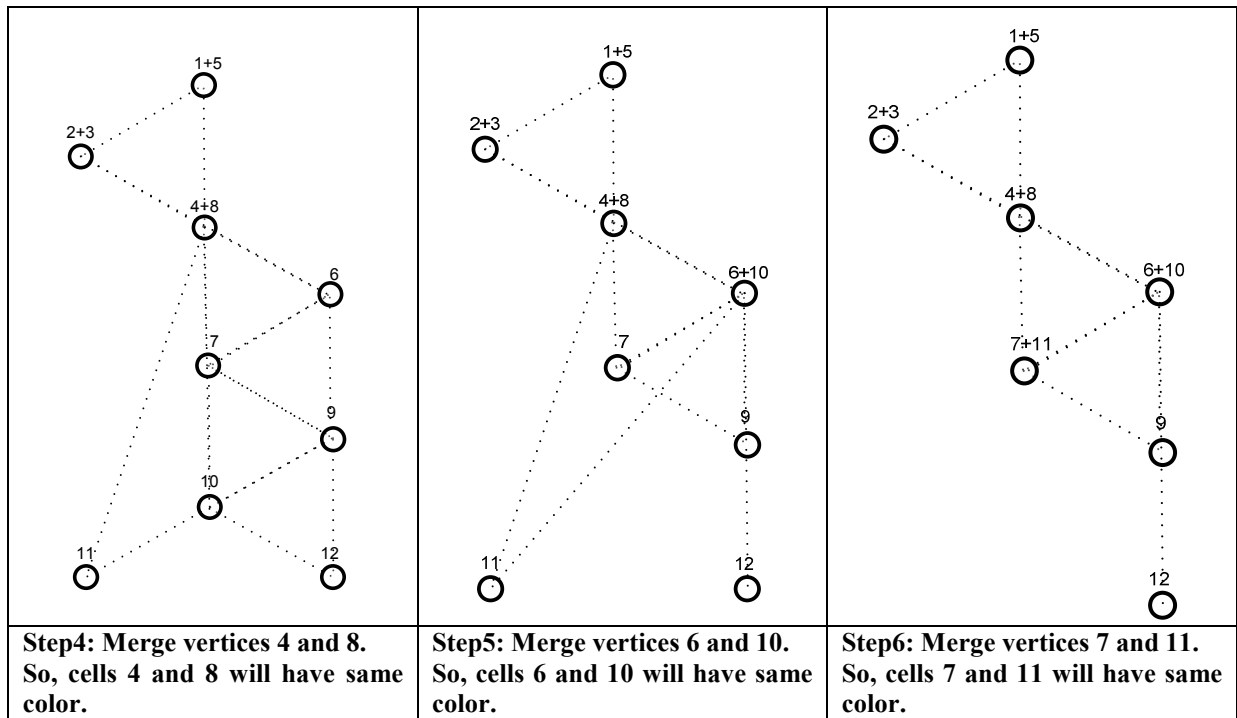
As shown in figure below, we can represent our network as a $G'(V, E)$ graph where:

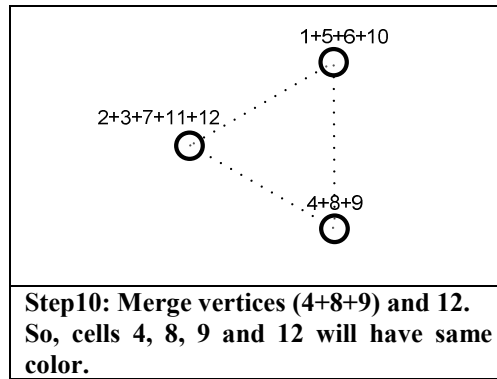
- Each cell centre (PANc) represents a vertex.
- Cells distance separation that is shorter than D'_{min} represents edge.

As the case of static control channel allocation, this problem can be translated to: problem of coloring the vertices of the graph $G'(V, E)$, such that no two adjacent vertices share the same color. For that we can also call to Zykov's algorithm.

Steps from 1 to 10 summarise the application of Zykov's algorithm to $G'(V, E)$ graph.







In step 10, we are left with a complete graph. The optimal solution is given by the complete graph with three vertices in which vertices 1, 5, 6 and 10 are allocated to one color, 2, 3, 7, 11 and 12 to a second color and vertices 4, 8 and 9 to the third.

We note that to cover all the network from (communication traffic) without suffering from co-channel interference, we just need three different channel frequencies (see figures 8 a , 8.b and 8.c).

So, in the present case, the optimal number of data communications channels to cover the totality of the network $N_{dch-opt}$ is equal to three

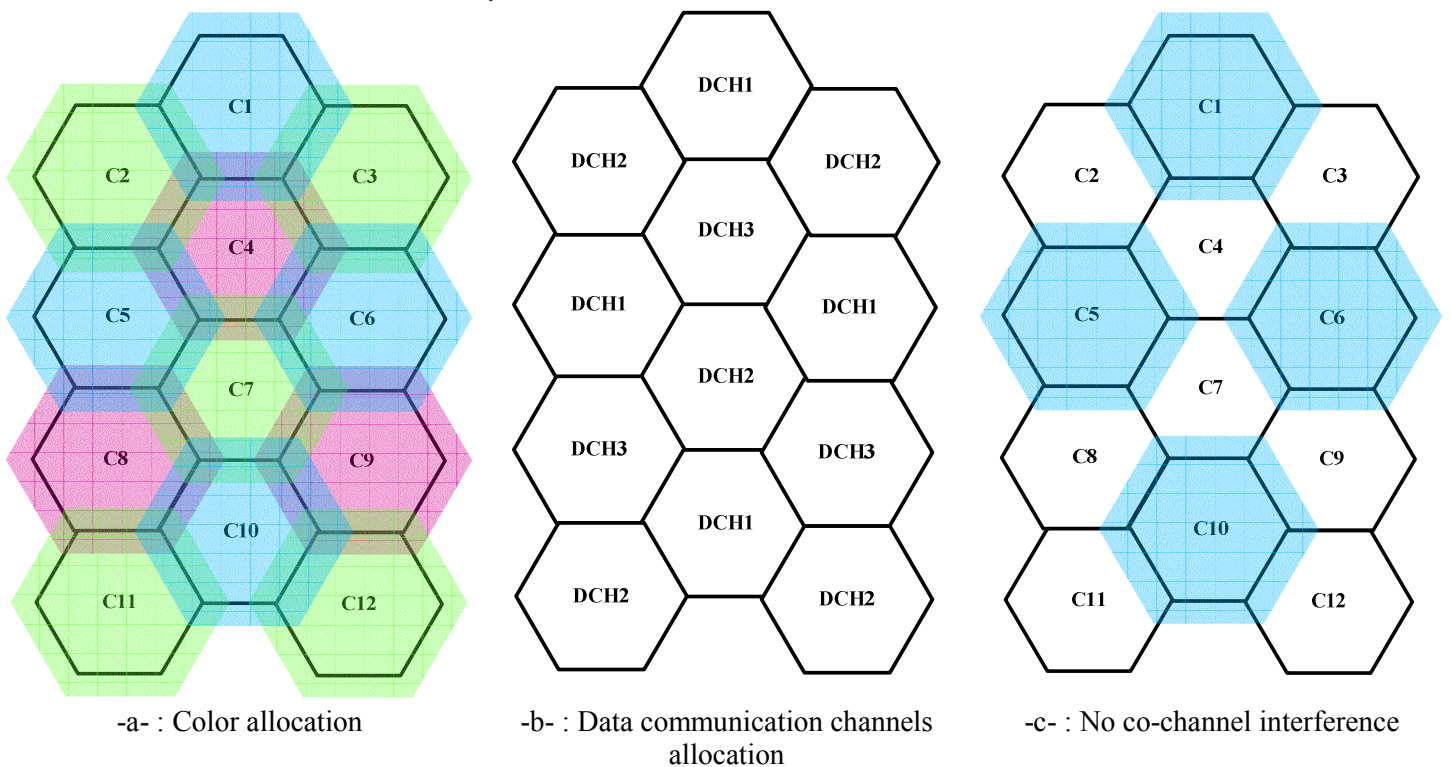


Figure .8: Logical data communication channel allocation

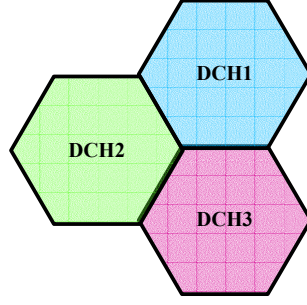


Figure .9: Elementary cluster

We define K as :

$$K = \text{ceil} \left[\text{Card}(N_{dch}) < \text{Div } N_{dch-opt} \right]$$

K represents the number of simultaneous data communication channel frequencies that can benefit each cell or PAN (for the present network for US : 8 data communication channels, Europe: 4 and Japan : 6 channels).

But in reality each PAN is characterized by its duty cycle or superframe duration, as shown below, so, according to PAN duty cycle, K can change.

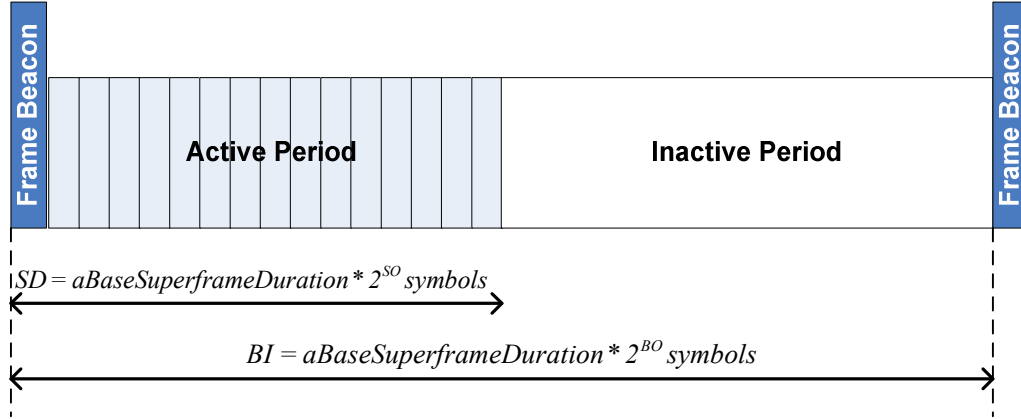


Figure .10: Superframe structure

Let us consider a network composed of a set of N_c cells, in other terms we dispose of N_c PAN coordinators $\{PAN_i = (SD_i, BI_i)\}_{1 \leq i \leq N_c}$ with different superframe durations.

We define \overline{BI}_{maj} , \overline{SD}_{min} and U as respectively the major cycle, the elementary active cycle (or elementary time unit) and the number of elementary active cycle per major cycle.

$$\overline{BI}_{maj} = LCM(BI_1, BI_2, \dots, BI_{N_c}) = LCM(2^{BO_1}, 2^{BO_2}, \dots, 2^{BO_{N_c}}) = \max_{1 \leq i \leq N_c} (2^{BO_i})$$

$$\overline{SD}_{min} = LCD(SD_1, SD_2, \dots, SD_{N_c}) = LCD(2^{SO_1}, 2^{SO_2}, \dots, 2^{SO_{N_c}}) = \min_{1 \leq i \leq N_c} (2^{SD_i})$$

$$U = \frac{\overline{BI}_{maj}}{\overline{SD}_{min}}$$

Let $DC_{N_c \times U}$ and A_U represent respectively the matrix of Duty cycle of all PAN coordinator per elementary time unit and number of active PANs per elementary active cycle.

$$DC_{N_c \times U} = \begin{bmatrix} DC_{11} & DC_{1U} \\ DC_{21} & \\ & DC_{N_c-1U} \\ D_{N_c,1} & \end{bmatrix}$$

$$A_U = \begin{bmatrix} a_i & a_i a_j & a_U \end{bmatrix}$$

Let $D_{N_c \times N_c}$ represents the matrix of distances separating each couple of cells.

$$D_{N_c \times N_c} = \begin{bmatrix} 0 & & D_{1N_c} \\ D_{21} & 0 & \\ & 0 & D_{N_c-1N_c-1} \\ D_{N_c,1} & & 0 \end{bmatrix}$$

So, given $DC_{N_c \times U}$, D'_{min} and $D_{N_c \times N_c}$, we can determine the graph $G'(V, E)_i$ per elementary active cycle and then compute optimal data communication channels $N_{dch-opt}_i$ to convert the totality of the network (as done in section II-1-b, which represents the case of the first elementary active cycle).

In last step, we compute the number of simultaneous data communication channels K_i per active PAN for the relative elementary time unit

$$K_i = \text{ceil} \left[\text{Card}(N_{dch}) \text{Div} N_{dch-opt}_i \right]$$

In conclusion, considering the available data communication channels N_{dch} , $DC_{N_c \times U}$, $D_{N_c \times N_c}$, D'_{min} , we can compute the matrix of sub set of data communication channels per cell per elementary active cycle.

$$N_{dch_{N_c \times U}} = \begin{bmatrix} N_{dch_{11}} & N_{dch_{1U}} \\ N_{dch_{21}} & \\ & N_{dch_{N_c-1U}} \\ N_{dch_{N_c,1}} & \end{bmatrix}$$

For example $N_{dch_{11}}$ represents the set of data communication channels used by the first PAN (ID=1) during the first elementary active cycle, where $\text{Card} \left[N_{dch_{11}} \right] = K_1$.

The algorithm below gives the method of data communication channels allocation inside the WHSN.

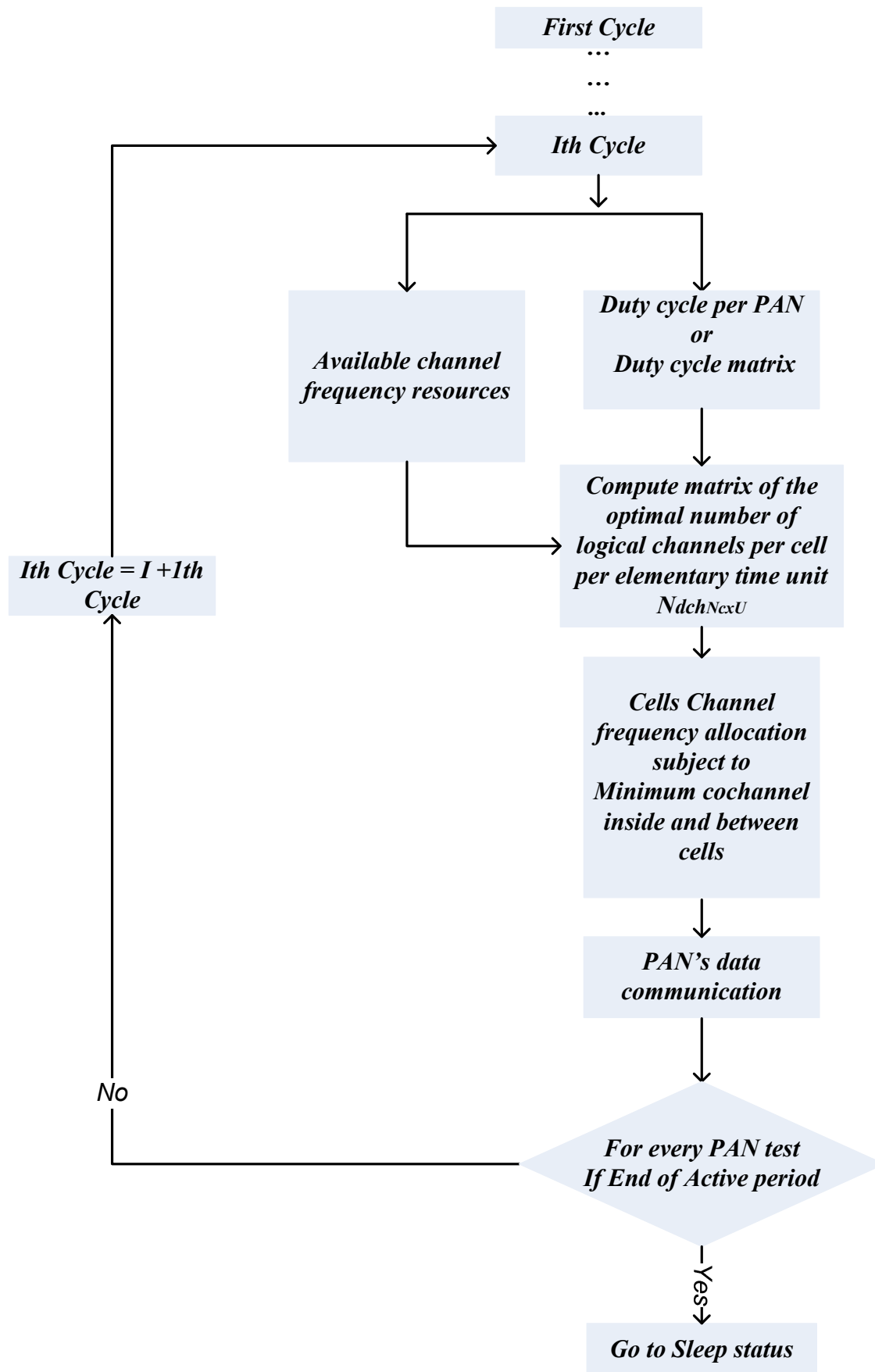


Figure .11: Data communication channels allocation inside WHSN

II-1-b .1 Study case of dynamic allocation inside an example of 12 cells WHSN

Ideal case : Synchronised Network

Let us consider a WSN of 12 cells ($N_c = 12$) of radius R and each PAN is characterized by the following superframe duration (See table below). We assume that all PAN coordinators are synchronised between them, so the beginning and the finish of each elementary cycle are the same at each PAN coordinator as shown in figure 12.

Let us assume that the European regulation is adopted:

$$N_{cch} = \{(4, SC_7), (7, SC_7), (4, SC_8), (7, SC_8)\},$$

$$N_{dch} = \left\{ \begin{array}{l} (1, SC_1), (2, SC_3), (3, SC_5), (5, SC_3), (6, SC_5), (8, SC_1), (9, SC_3), \\ (1, SC_2), (2, SC_4), (3, SC_6), (5, SC_4), (6, SC_6), (8, SC_2), (9, SC_4) \end{array} \right\}$$

Example of PAN configuration

PAN coordinators	SD	BI
PANc1	2	16
PANc2	2	16
PANc3	4	16
PANc4	1	8
PANc5	4	32
PANc6	2	8
PANc7	4	32
PANc8	1	8
PANc9	2	16
PANc10	2	8
PANc11	8	32
PANc12	1	32

So,

$$\overline{BI}_{maj} = 32$$

$$\overline{SD}_{min} = 1$$

$$U = \frac{\overline{BI}_{maj}}{\overline{SD}_{min}} = \frac{32}{1} = 32$$

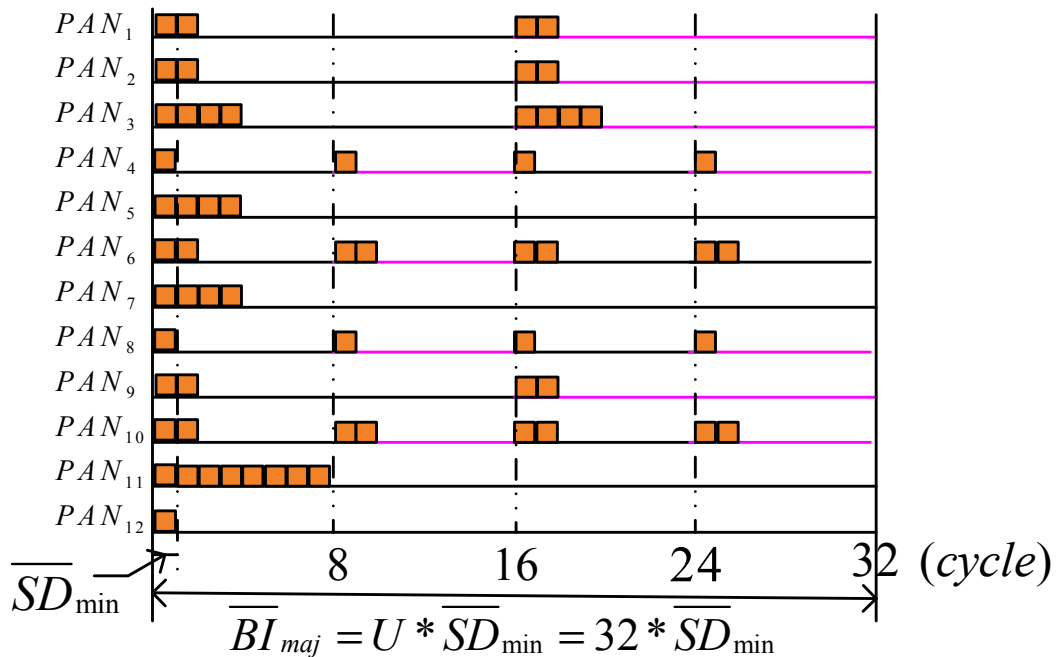


Figure .12: Example of PAN configuration

The following matrix represents the duty cycle matrix

$$DC_{12 \times 32} = \begin{bmatrix} 1 & 1 & 0 & 00 & 0 & 0 & 00 & 0 & 0 & 00 & 0 & 0 & 01 & 1 & 0 & 00 & 0 & 0 & 00 & 0 & 0 & 00 & 0 & 0 & 0 \\ 1 & 1 & 0 & 00 & 0 & 0 & 00 & 0 & 0 & 00 & 0 & 0 & 01 & 1 & 0 & 00 & 0 & 0 & 00 & 0 & 0 & 00 & 0 & 0 & 0 \\ 1 & 1 & 1 & 10 & 0 & 0 & 00 & 0 & 0 & 00 & 0 & 0 & 01 & 1 & 1 & 10 & 0 & 0 & 00 & 0 & 0 & 00 & 0 & 0 & 0 \\ 1 & 0 & 0 & 00 & 0 & 0 & 01 & 0 & 0 & 00 & 0 & 0 & 01 & 0 & 0 & 00 & 0 & 0 & 01 & 0 & 0 & 00 & 0 & 0 & 0 \\ 1 & 1 & 1 & 10 & 0 & 0 & 00 & 0 & 0 & 00 & 0 & 0 & 00 & 0 & 0 & 00 & 0 & 0 & 00 & 0 & 0 & 00 & 0 & 0 & 0 \\ 1 & 1 & 0 & 00 & 0 & 0 & 01 & 1 & 0 & 00 & 0 & 0 & 01 & 1 & 0 & 00 & 0 & 0 & 01 & 1 & 0 & 00 & 0 & 0 & 0 \\ 1 & 1 & 1 & 10 & 0 & 0 & 00 & 0 & 0 & 00 & 0 & 0 & 00 & 0 & 0 & 00 & 0 & 0 & 00 & 0 & 0 & 00 & 0 & 0 & 0 \\ 1 & 0 & 0 & 00 & 0 & 0 & 01 & 0 & 0 & 00 & 0 & 0 & 01 & 0 & 0 & 00 & 0 & 0 & 01 & 0 & 0 & 00 & 0 & 0 & 0 \\ 1 & 1 & 0 & 00 & 0 & 0 & 00 & 0 & 0 & 00 & 0 & 0 & 01 & 1 & 0 & 00 & 0 & 0 & 00 & 0 & 0 & 00 & 0 & 0 & 0 \\ 1 & 1 & 0 & 00 & 0 & 0 & 01 & 1 & 0 & 00 & 0 & 0 & 01 & 1 & 0 & 00 & 0 & 0 & 01 & 1 & 0 & 00 & 0 & 0 & 0 \\ 1 & 1 & 1 & 11 & 1 & 1 & 10 & 0 & 0 & 00 & 0 & 0 & 00 & 0 & 0 & 00 & 0 & 0 & 00 & 0 & 0 & 00 & 0 & 0 & 0 \\ 1 & 0 & 0 & 00 & 0 & 0 & 00 & 0 & 0 & 00 & 0 & 0 & 00 & 0 & 0 & 00 & 0 & 0 & 00 & 0 & 0 & 00 & 0 & 0 & 0 \end{bmatrix}$$

The vector A represents the number of active PANs per elementary active cycle:

$$A = [12 \ 9 \ 4 \ 41 \ 1 \ 1 \ 14 \ 2 \ 0 \ 00 \ 0 \ 0 \ 08 \ 6 \ 1 \ 10 \ 0 \ 0 \ 04 \ 2 \ 0 \ 00 \ 0 \ 0 \ 0]$$

According to the matrix $DC_{12 \times 32}$, we note that:

- For the first elementary active cycle, we are in front of the case presented in section II-1-b, where each PAN can benefit simultaneously from four channels.
- For the second, seventeenth and eighteenth elementary active cycles as the first elementary time unit each PAN can benefit also from four channels.
- For the third, fourth, ninth and twenty-fifth elementary active cycles each PAN can benefit from seven channels (complete graph is composed by two vertices with two edges).
- For the fifth, sixth, seventh, eighth, nineteenth and twentieth elementary active cycles, only one PAN (ID = 11 or 3) is active, so, during this six time units the active PAN can benefit simultaneously from all available channels (14 channels according to European regulation).
- For the tenth and twenty-sixth elementary active cycles only two PANs (ID = 6 and 10) are active so, during this two time units those PANs can benefit simultaneously from all available channels because the distance separating this two PANs is greater than D'_{min} .

With our protocol, the minimum number of allocated channels per PAN is four; as we can see through the two selected examples given in figure 13, the 4th PAN and 11th PAN can benefit during specific active cycles from supplementary channels which are initially been allocated to some other PANs. In this way we can ensure, on the one hand, an efficient and fair channels allocation between PANs permitting an enhancement of QoS (delay decrease and throughput increase) inside each PAN and energy saving, and on the other hand, a maximization of channel utility.

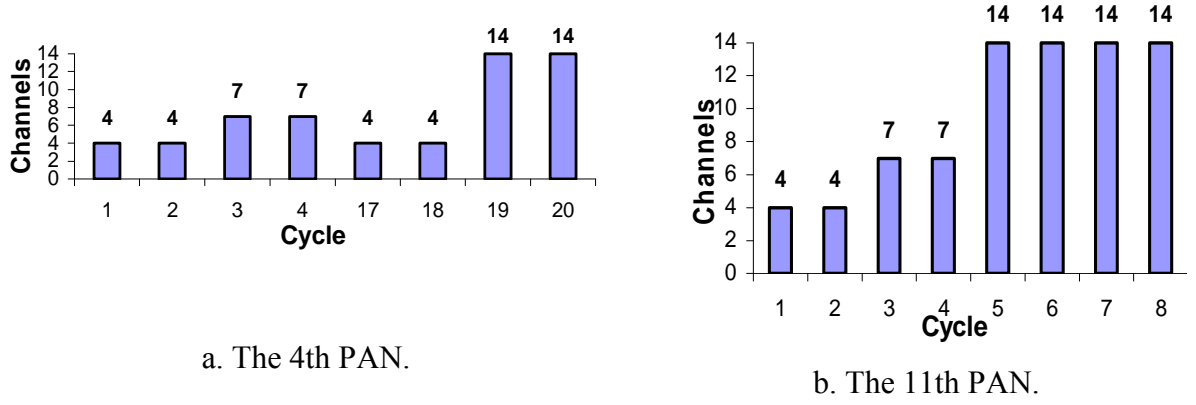


Figure.13:Data communication channels allocation during active elementary cycle

Real case : with margin of synchronization

In reality the network isn't perfectly synchronised; which can deteriorate the performance offered by our scheme. For that reason we introduce a margin of synchronisation ξ before each elementary active cycle to synchronise the network (all PAN coordinators) as shown by the figure below:

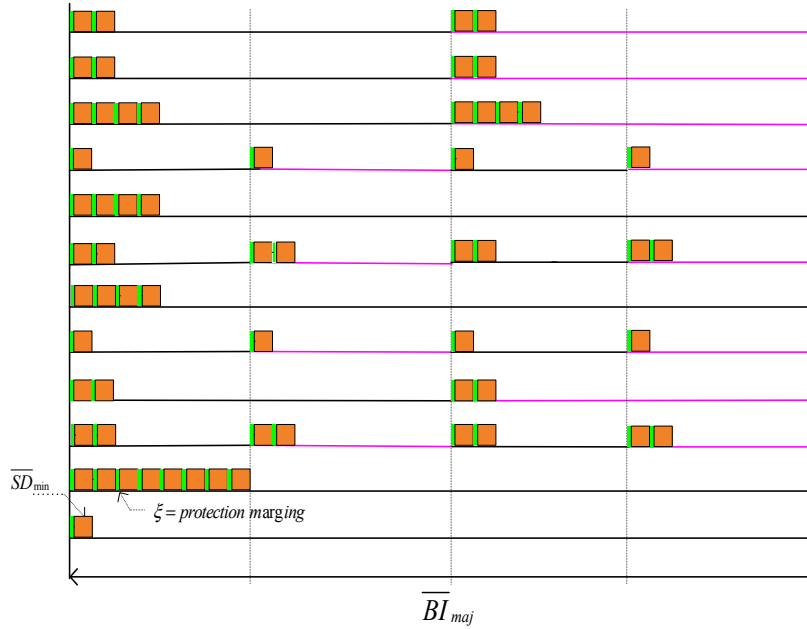


Figure .14: PAN configuration with synchronisation margin

Where

$$\xi = \max \{ \xi_i \}_{2 < i < N_c}$$

ξ_i : Error of synchronisation between the i^{th} PAN coordinator and the first PAN coordinator.

II- 2 – SECOND LEVEL OF CHANNEL ALLOCATION COMBINED WITH TIME SLOT ALLOCATION

We will discuss, in this part, the method of channels and time slots allocation inside a PAN and BSNs.

During the first elementary active cycle, channels allocation inside our WHSN (case of 12 cells) can be represented as shown in figure below:

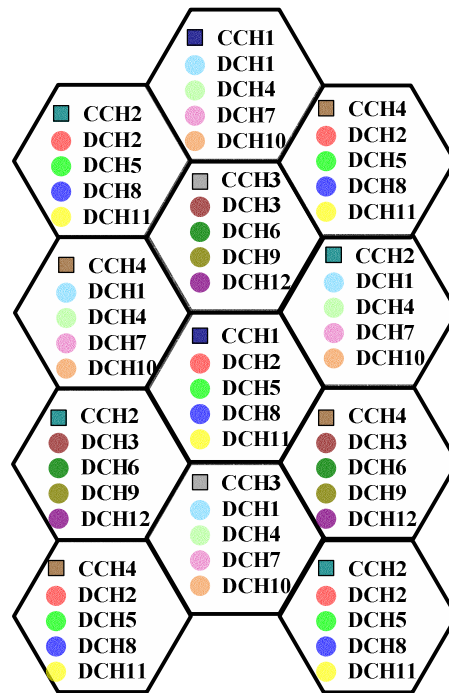


Figure .15: Control and data communication channels allocation inside WSN during the first elementary time unit

II-2-a Principle of channels and time slots allocation inside a PAN

The principle of channels and time slots allocation inside a PAN is based on the three phases:

1. Phase of time slots requests,
2. Phase of allocation of available time slots per available channels in response to previous requests,
3. Phase of channels/time slots use.

II-2-a.1 Phase of time slots requests

This phase must precede every PAN active period; it is divided into two sub steps, in order to synchronize the PAN in first time, then in second step, to collect all PAN members requests using the control channel.

In the first step, by listening to the beacon frame, PAN members adjust their wakeup clocks.

The second step represents a set of equal time slots, during which, the PAN coordinator is listening to PAN member requests. So, inside each PAN, according to the number of members, PAN coordinator assigns to each member a specific time slot according to its ID. Earlier time slot for shorter ID. As shown in the figure below, just following the reception of the beacon frame, each PAN member waits for its own time slot in order to send its request packet.

Synchronization step

		Request transmission step												
PANc: ID=1	Beacon frame	R	R	R	R	R	R	R	R	R	R	R	R	R
ID=11	R	Rq1	S	S	S	S	S	S	S	S	S	S	S	S
ID=12	R	S	Rq0	S	S	S	S	S	S	S	S	S	S	S
ID=13	R	S	S	Rq0	S	S	S	S	S	S	S	S	S	S
ID=14	R	S	S	S	Rq0	S	S	S	S	S	S	S	S	S
ID=15	R	S	S	S	S		S	S	S	S	S	S	S	S
ID=16	R	S	S	S	S	S	Rq1	S	S	S	S	S	S	S
ID=17	R	S	S	S	S	S	S	Rq1	S	S	S	S	S	S
ID=18	R	S	S	S	S	S	S	S		S	S	S	S	S
ID=19	R	S	S	S	S	S	S	S	S	Rq0	S	S	S	S
ID=20	R	S	S	S	S	S	S	S	S	S	Rq0	S	S	S
ID=21	R	S	S	S	S	S	S	S	S	S	S		S	S
ID=22	R	S	S	S	S	S	S	S	S	S	S	S	Rq1	S

Figure .16: Synchronization and time slots requests steps

As shown in figure below, a request packet is composed of six fields:

- TYPE : type of packet « Packet of resource allocation request»
- Rq ID : request Identifier
- Rq type : type of resource allocation request:
 - Rq⁰: For communication inside BAN
 - Rq¹: For routing communication inside PAN
- Time Slot : number of Time slot requested per request
- @Source : @ of the demander of the request
- @Destination : @ of flow destination in the case of routing communication. If Request type = 0 (Rq⁰), Destination @ = 0

TYPE	Rq ID	Rq type	P	Time Slot	Source @	Destination @
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Figure .17: request packet structure

II-2-a.2 Phase of channels/time slots allocation

This step is transparent to all members of PAN except the PAN coordinator which is the responsible of the execution of the related process.

According to the diagram given by figure 22, after reception of all PAN members requests, the coordinator tries to schedule it. Once the list of requests is scheduled, the coordinator passes to the phase of time slots and channels allocation. For each request, it tries to find the first available time slot per channel, next it assigns the earliest one to the suitable request.

At the end of time slots and channels allocation process, PAN coordinator registers a trace of requests which aren't served in queue in order to be analysed during the next cycle and then inserts into the next beacon frame the answers relative of served requests.

So, the first beacon frame following the phase of channels/time slots allocation must contain inside its beacon payload field the necessary information relative to this step, as shown in figure below.

Rq ID	logical Channel Number	Begin slot Number	duration 'Time slot unit'	Source @	Destination @
-------	------------------------	-------------------	---------------------------	----------	---------------

Figure .18: Necessary information that must be enclosed in beacon payload

Where

- Rq ID : request Identifier
- Logical Channel Number : to precise to source and destination the logical channel to be used
- Beginning slot Number: the index of the beginning time slot
- Duration 'Time slot unit': number of allocated time slots
- @source,
- @destination

II-2-a.3 Phase of time slots requests

After listening to the beacon frame, the members of PAN can have an idea of the requests feedback, then each concerned sensor switches to the suitable channel at the suitable time slot and it can begin sending or receiving of its frames for the accorded duration.

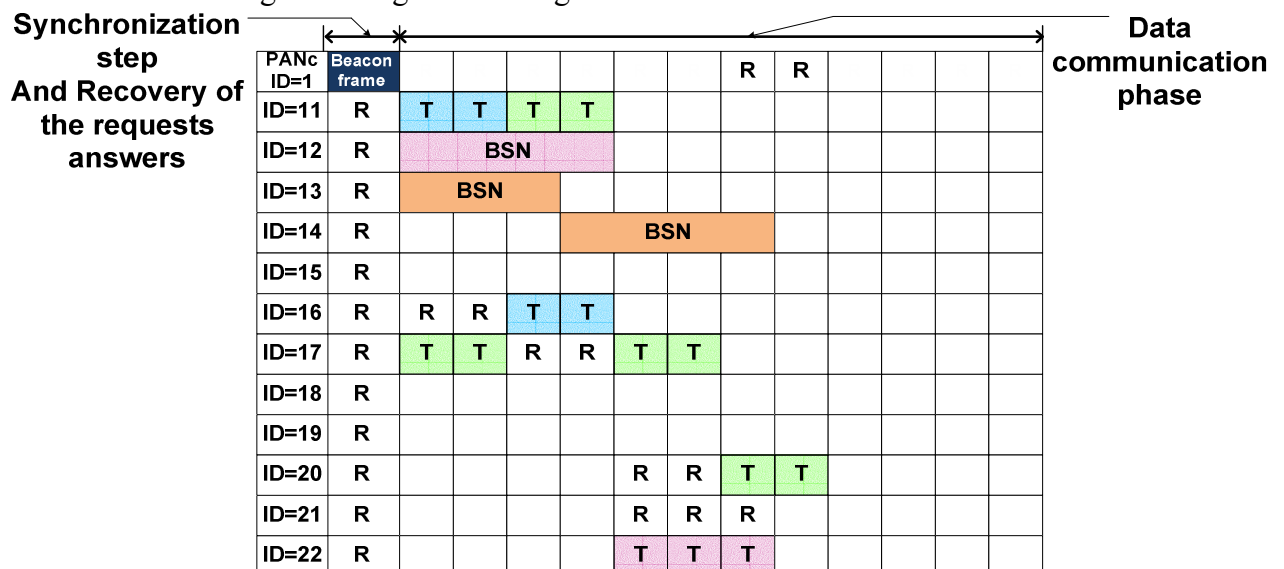


Figure .19: Reception of beacon frame and beginning of data communication phase

Note

During synchronisation step – frame beacon – channel used is the accorded Control channel (CCH1 for the case of PAN1) and the data rate used is the mandatory data rate of 850kbps. During data communication phase, used channels are the accorded data communication channels (DCH1, DCH4, DCH7 and DCH9 for the case of PAN1), mandatory and optional data rate can be used.

R : Reception
T : Transmission
BSN : BSN's communication.

The diagram below details the process of available resources allocation. So, for each cycle, PAN coordinator collects all the resource allocation requests of the members of its PAN. Then, during the stage of "Demande of channel resources", it can know the number of channels that it can benefit during the present cycle (elementary active cycle). Next, it tries to allocate available time slots per channel in response to collected requests. Finally, concerned sensors passed to data communication phase.

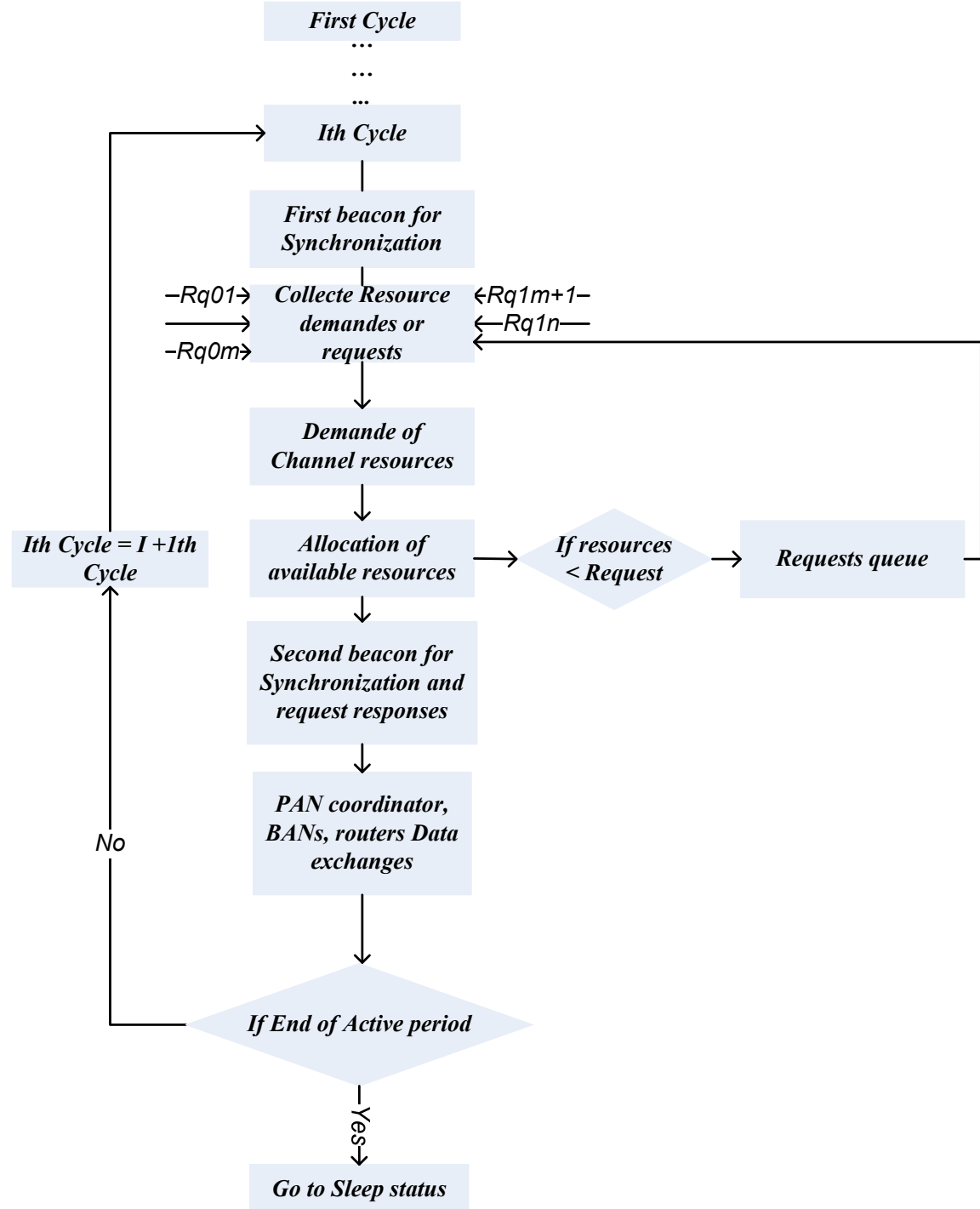


Figure .20: General time slots and channels allocation process inside a PAN

The following diagram details the “Demande of channel resources” block given in previous diagram.

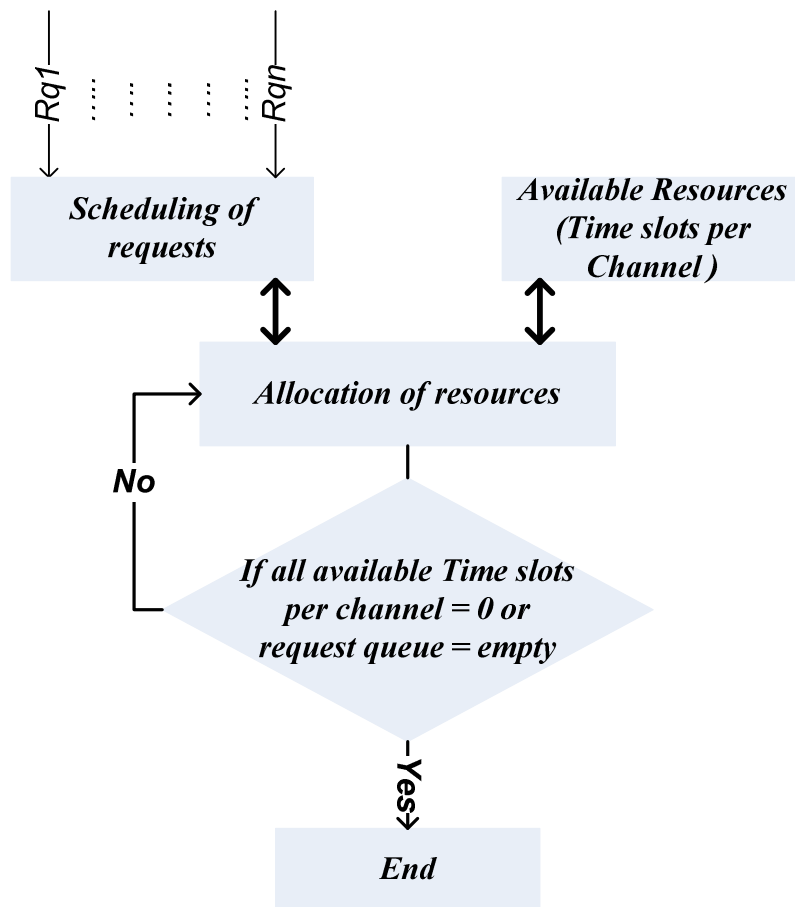


Figure .21: Requests scheduling

Finally, the last diagram, given in figure 22, details the requests scheduling process.

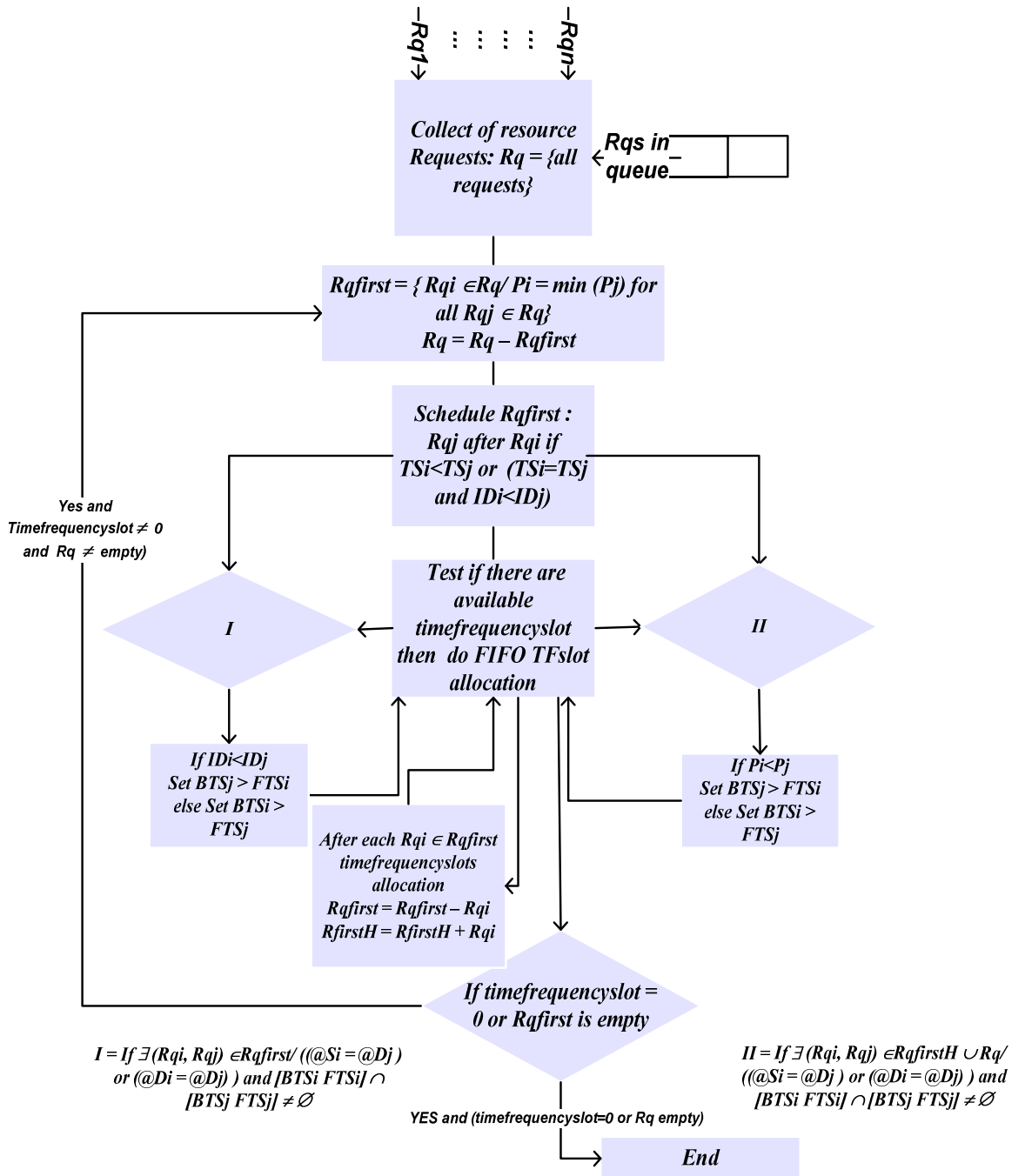


Figure .22: Details of the requests scheduling process

Where, Rq , P , TS , ID , BST and FST denote respectively set of requests, request level priority, demanded time slots, request identifier, beginning slot time and finished slot time.

II-2-b Case study of channels/time slots allocation inside a PAN

For reason of simplification, we will interest to the case of the first PAN during the first elementary active cycle, and then we can generalize the idea to all PANs and during different elementary active cycle.

Taking the example of the first PAN during the first elementary active cycle.

- CCH1 represents the allocated control channel for the first PAN
- DCH1, DCH4, DCH7 and DCH10 represent the four allocated data communication channels for the first PAN during the first elementary time unit.

As shown in figure below, for the first elementary unit time or the first elementary cycle, cell C1 is formed by :

- PAN coordinator : ID = 1,
- Four BSNs :
 - BSN1 coordinator, ID = 11, Priority = 1, with ten biosensors members.
 - BSN2 coordinator, ID = 12, Priority = 1, with ten biosensors members.
 - BSN3 coordinator, ID = 13, Priority = 2, with six biosensors members.
 - BSN4 coordinator, ID = 14, Priority = 3, with eight biosensors members.
- R1, R2, R3, R4, R5, R6, R7 and R8 : router, with ID respectively = 15, 16, 17, 18, 19, 20, 21 and 22.

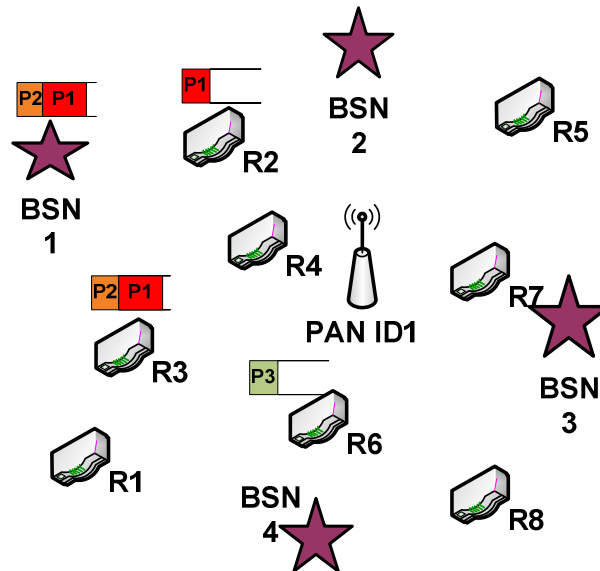


Figure .23: The two D representation of the first PAN during the first elementary cycle

Let us assume that during the 1st cycle :

1. BSN2 (ID = 12): demands 4 slots with priority of P1, for data communications inside its BSN. (Rq_1^0)
2. BSN3 (ID = 13) : demands 3 slots with priority of P1, for data communications inside its BSN. (Rq_2^0)
3. BSN4 (ID = 14): demands 4 slots with priority of P2, for data communications inside its BSN. (Rq_3^0)
4. BSN1 (ID = 11): demands 2 slots with priority of P1, for data routing toward router R2 and 2 slots with priority of P2, for data routing toward router R3. (Rq_4^1) (Rq_5^1)
5. R2 (ID = 16): demands 2 slots with priority of P1, for data routing toward router R4. (Rq_6^1)

6. R3 (ID = 17): demands 2 slots with priority of P1, for data routing toward router R4 and 1 slot with priority of P2, for data routing toward router R6. (Rq¹₇) (Rq¹₈)
7. R6 (ID = 20): demands 2 slots with priority of P3, for data routing toward router PAN coordinator. (Rq¹₉)
8. R8 (ID = 22): demands 3 slots with priority of P3, for data routing toward R7. (Rq¹₁₀)

So there are 10 resource requests.

Request demander	Nb of Time Slots	Type of request	Priority
BSNc2	4	Data communication inside BSN2 :Rq ⁰ ₁	P1
BSNc3	3	Data communication inside BSN3: Rq ⁰ ₂	P1
BSNc4	4	Data communication inside BSN4: Rq ⁰ ₃	P2
BSNc1	2	routing toward R2: Rq ¹ ₄	P1
	2	routing toward R3: Rq ¹ ₅	P2
R2	2	routing toward R4: Rq ¹ ₆	P1
R3	2	routing toward R4: Rq ¹ ₇	P1
	1	routing toward R6: Rq ¹ ₈	P2
R6	2	routing toward PANc: Rq ¹ ₉	P3
R8	3	routing toward R7: Rq ¹ ₁₀	P3

According to algorithm given by the figure 22, the requests are scheduled as following:

1. P1 : (Rq¹₄), (Rq¹₆)*, (Rq¹₇), (Rq⁰₂), (Rq⁰₁),
* : BST_{Rq6} > FST_{Rq4}
2. P2 : (Rq¹₅), (Rq¹₈)*, (Rq⁰₃),
* : BST_{Rq8} > FST_{Rq5}
3. P3 : (Rq¹₉), (Rq¹₁₀).
* : BST_{Rq9} > FST_{Rq8}

The figure below illustrates the first cycle inside PAN (ID = 1) :

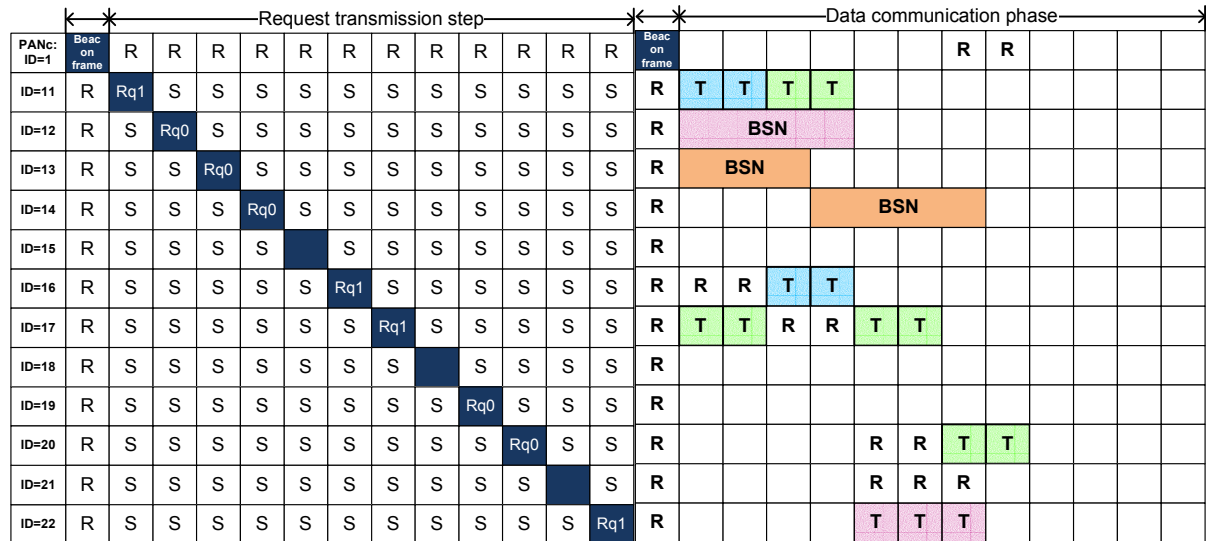


Figure .24: First PAN during its first elementary cycle

We note that all data communications inside the first PAN during the first elementary active cycle finish after eight time slots, where with a single channel can take more than 26 time slots.

As shown in figure 25, if we apply the previous scenario (the ten requests), to the 4th PAN during its first, third and nineteenth active cycles, we note that, compared to single channel use, data communication can be shortened of 2.25 times with four data communication channels and of 3.33 times in the case of seven and fourteen channels. So, we note that multi-channel use can reduce PAN idle period and increase sleep duration that can prolong network lifetime. Without forgetting that simultaneous communications inside each PAN can significantly improve QoS requirements by reducing latency and increasing throughput.

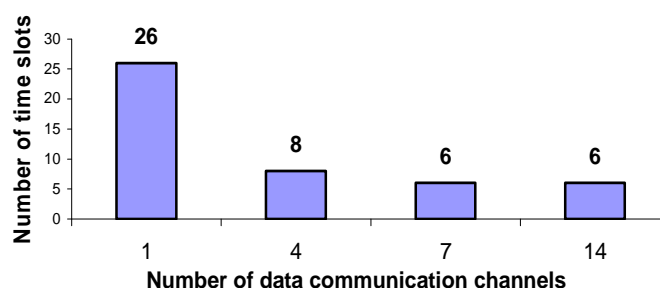


Figure.25: Time slots saving inside the 4th PAN

II-2-b .1 Case study of the second BSN

Let us take the case of the second BSN (ID = 12).

We remind that a BSN is organized in start topology where all members can communicate only with its BSN coordinator. So in this case, we just need only of two logical channels inside a BSN one for control traffic and another for data communication.

According to the figure below, during synchronisation step, BSN coordinator sends beacon frame over the accorded control channel (CCH1 for the case of PAN1) and with the mandatory data rate of 850kbps. During data communication phase, sensors communicate (TA : communication in slotted ALOHA, GTS : communication using guaranteed time slots) using the accorded data communication channel (DCH7), and with optional data rates of 6 or 27Mbps in order to shorten communications.

Each node:

- If it hasn't data toward its BSN coordinator, then it stay in sleep status
- Else, if it has very urgent data ,in this case it can demand the allocation of one or several GTS time slots,
- Else, it can transmit its data without sensing the medium directly after a random time slot units (without reaching ALOHA transmit period)

BSNc: ID=12	CCH 1	DCH7												CCH 1	
	Stotted ALOHA						GTS Allocation								
	BF	R	R	R	R	R	R	R	R	R	R	R	R	R	BF
ID=121	R	TA													R
ID=122	R						GTS	GTS							R
ID=123	R		TA			TA									R
ID=124	R														R
ID=125	R								GTS	GTS	GTS				R
ID=126	R		TA		TA										R
ID=117	R														R
ID=118	R											GTS	GTS		R
ID=119	R														R
ID=200	R			TA											R

Figure.23: BSN superframe

I – CONCLUSION

As pronounced in the beginning of this report, the MAC protocol has an important impact on the network performance. We note that the proposed scheme guarantees, on the one hand, the delay decrease and consequently energy consumption reduction, on the other hand, fairness and optimal resource allocation. As given in section II, the proposed MAC protocol ensures good results by avoiding control congestion, maximising bandwidth utilisation or channel utility and prolonging sleep period. Finally, our scheme comes to reach our goals in terms of energy consumption reduction, delay decrease and throughput increase.

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