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Article

An Adaptive Beamforming Time With Round Robin MAC algorithm for reducing energy consumption in MANET

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Abstract: The use of Smart Antenna Systems (SAS) in pervasive environments such the Mobile Ad hoc Networks (MANET) has been promoted as the best choice to improve Spatial Division Multiple Access (SDMA) and throughput. Although directional communications are expected to provide great advantages in terms of network performance, directional MAC (Medium Access Control) protocols introduce several issues. One of the most known problems in this context is represented by the fact that, attempting to solve or at least mitigate the problems introduced by these kinds of antennas especially at MAC layer, a large amount of energy consumption is achieved ; for example, due to excessive retransmissions introduced by very frequently issue such as deafness and handoff. The expedients proposed in order to reduce these drawbacks attempting to limit beamforming time of nodes in cooperation with a Round-Robin scheduling, can grant high performance in terms of fairness and throughput. However the overall energy consumption in the network is not efficent due to the static approach. In view of this, we propose an Adaptive Beamforming Time with Round-Robin MAC providing for a dynamic assignment of the beamforming time with the purpose to limit the waste of energy of nodes.

Keywords: Smart Antenna Systems, MANET, MAC, Energy Consumption, Beamforming, Round Robin

1. Introduction

In the latest research studies, relating to wireless network environments, one of the most significant and, at the same time, critical issue is represented by the management of energy consumption of nodes that could highly limit the overall network performance with reference to protocols and application fields. In this regard, several aspects should be considered in order to address the problems implied by main features of this kinds of networks that significantly affect the behaviours at physical, Medium Access Control (MAC) and routing layers. For instance, let us consider Mobile Ad hoc Networks (MANET); they are self-organized networks in which mobile nodes can move independently; the nodes usually move according to a certain mobility pattern model and the movement of a node is not necessarily related to the movement of other nodes in the network. Usually, in MANET, omnidirectional antennas are used for communication among nodes both for transmission as well as for reception; this approach results in very limited performance relating to physical, link and routing layer statistics [1-3]. Omnidirectional antennas, also known as isotropic antennas, radiate and receive equally well in all directions. Main advantages of omnidirectional antennas include: ease of configuration and implementation, low designing cost, very and simple architecture (hardware-less). For instance, in cellular systems, they allow to amplify cell signals from multiple carriers with different cell towers in multiple locations. Nevertheless, despite from these few benefits they introduce a considerable number of drawbacks such as: limited range and coverage (implied by low gain), high energy consumption,

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high interference probability (especially in dense networks), very high performance dependency on the environments in which they are employed (indoor or outdoor); nonetheless, omnidirectional antennas cannot exploit the benefits of cross-polarization because they are vertically polarized. More specifically, this last issue, contributes to increase the probability of interference between communicating nodes in the channel [4]. From a topological point of view, this approach implies that, the signal generated from the transmitter T, reach desired users with only a small percentage of the overall energy sent out into the environment. Due to this huge number of limitations, omnidirectional antennas may not be efficient due to interference caused by the transmission of packets in all directions (other than target direction) and limited range of communications.

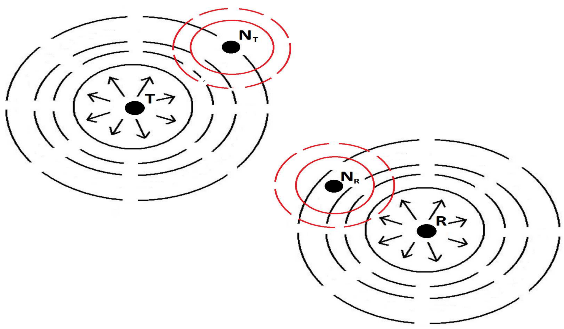
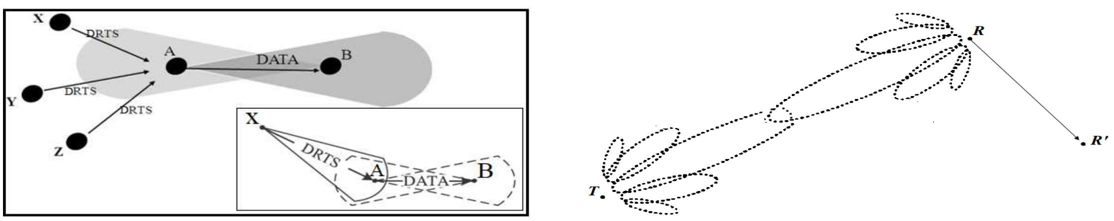


Figure 1. Interference caused by omnidirectional antennas.

The Figure 1 illustrates a wireless network scenario in which nodes use omnidirectional antennas to perform communications. In particular, the transmitter node T sends to the receiver R a communication signal by using an omnidirectional antenna; R attempts to capture the signal with the same antenna model. Because the transmitter signal is radiated in all directions with the same intensity, if there are such nodes in the neighboring of the transmitter/receiver (N_T and N_R) is possible that the radiated signal is captured by these nodes that, in turn, may attempt a communication at the same time. In this case, interferences and collisions can occur; these issues could enhance as the mobility of nodes increases. Nevertheless, in this case, because nodes radiate in the same way toward all directions, a huge waste of the battery life of nodes is certainly achieved. The majority of these issues could be partially mitigated using directional antennas. Directional antennas may be useful to increase network efficiency by directing the transmitted power in the desired/intended direction. Directional antennas have a great number of advantages over omnidirectional antennas in ad hoc networking. By focusing energy only in the intended direction, directional antennas can increase the potential for spatial reuse and can provide longer transmission and reception ranges for the same amount of power. Increased spatial reuse and longer range translates into higher ad hoc network capacity (more simultaneous transmissions and fewer hops), and longer range also provides improved connectivity [5-7]. Different kinds of issues have to be investigated when directional communications occur with respect to the traditional omnidirectional case; problems such as the hidden terminal and the deafness problem have to be properly handled as well as handoff issue implied by mobility of nodes.



(a) Deafness problem (b) Handoff problem

Figure 2. Directional antennas common issues in MANET

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Referring to directional MAC communications in which Directional Request to Send (DRTS) and Directional Clear to Send (DCTS) are used to perform a transmission/reception flow, a particular node (deaf node) that is engaged in a certain communication, but at the same time is solicited as receiver by another source node arises the deafness problem (Fig. 2(a)). The node that experiences the deafness (the node A in Fig. 2(a)) could try to retransmit many times MAC layer packets, resulting in a large amount of collisions and considerable increase of the network overhead. Furthermore, due to the recurring retransmission attempts from deaf node, a large waste of energy could take place, and consequently this node consumes its battery life in a very short time, highly degrading the overall throughput of the network. Another common issue while using directional antennas is given by the handoff problem that is usually implied by the mobility of nodes in the network. In Fig. 2(b) an example of handoff is illustrated: the transmitter node T is communicating with a node R; during the communication R moves in the position R' and exit out of the transmitter beam and consequently the communication fails and the beams need to be re-pointed. In this case, if the node in the position R' can still be reached by T through a beam switching. If a proper mechanism of synchronization and node position refreshing is not provided, the directional beam remains tuned for a long time in an undesired direction due to node movement; for this reason, again, a lot of energy consumption occurs. Most researchers, in order to mitigate these undesired phenomena in directional contexts, demonstrated that, through the employment of Smart Antenna Systems (SAS) instead of the more traditional directional antennas, it is possible to create an efficient system, exploiting the Spatial Division Multiplexing (SDMA) technique that this kind of devices well provided. Using SAS, higher spatial reuse and better link reliability can be achieved [8-9]. In contexts in which directional Smart Antenna Systems are used, the beamforming issue have to be deeply investigated. The use of DRTS and DCTS frames in association with a Directional Network Allocator Vector (DNAV) information, helps to decrease the large amount of collisions that usually occurs when using omnidirectional antennas, but in environments in which SAS are employed it might not be enough to provide these expedients [10-12]. In the present paper, we propose to reduce these issues by enhancing the works proposed in [13-14] using SAS along with a Round-Robin scheduling in order to address more detailed challenges such as the queue and the time slice problem involved by the use of the Round-Robin. The main purpose of the work is to limit the massive energy consumption in the network and, simultaneously to improve the overall performance when Directional MAC protocols are executed in medium-high mobility environments.

2. State of Art

Relating to MAC layer communications, the most causes of excessive energy consumption in mobile network scenarios include the use of omnidirectional antennas, data processing, high protocol overhead, high level of interferences in the channel. Data processing implies the large usage of Central Processing Unit (CPU), memory, hard drive, etc. To partially solve this issue the most actual solution is to find a tradeoff on energy consumption between data processing and radio communication [16]. For example, data compression techniques are introduced in [15] to minimize packet length and so to obtain an energy saving in radio communication, but the cost of computation is increased. In work [17] authors also highlight the large protocol overhead introduced by this kind of systems. Generally, to make a MAC protocol energy efficient, at least one of the following guidelines are used:

- **Reducing collisions and retransmissions:** One of the most common objective of MAC protocols in order to avoid collisions so that two interfering nodes do not transmit at the same time. The simplest ways for collision avoidance in a general network include code division multiple access (CDMA), time division multiple access (TDMA), and frequency division multiple access (FDMA). Since collision avoidance may translate into a substantial overhead, which will burn more energy, tradeoffs must be explored to achieve reasonable solution.
- **Reducing overhearing:** Wireless mobile nodes deplet battery life because they overhear the transmissions of their neighbors. Therefore, the mobile nodes receive all packets that hit their

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receivers. One possible solution to this problem is the introduction of a control channel for the transmission of control signals that will wake up the nodes only when needed. Authors in [18] propose to broadcast a schedule that contains the data transmission starting times for each mobile nodes. In work [19] two schemes are proposed in order to mitigate the deafness caused by persistent hearing of data and for handling the Short Retry Limit (SRL) in directional environments.

- **Minimize control overhead:** Protocol overhead should be reduced as much as possible, especially for transmitting short packets [20-22]. Due to the large channel acquisition overhead, small packets have disproportionately high energy costs. When mobile nodes request multiple transmission slots with a single reservation packet, the control overhead for reservation can be reduced [23]. A packet delivery scheduling algorithm and two MAC protocols in which nodes uses directional sectorized antennas are proposed in [24]. The scheduler and the protocols are designed with the purpose to prevent the co-site interference problem that could arise in some directional contexts also by limiting the overall overhead in the network.
- **Reducing beamforming time:** In [25] authors, propose a Tone DMAC mechanism that enable the transmission of special packets (Out-of band tones) by nodes in omnidirectional mode; these tones can be processed by neighbors reducing considerably the large backoff time introduced by deafness. In [14] a sectorized antenna model based on a round-robin scheduling algorithm is presented in order to reduce the impact of the deafness in directional communication environments. The Round-Robin mechanism was implemented by an algorithm, that manages the assignment of the beam toward a certain sector also handling the incoming frames that could not temporally be transmitted in the channel (in case they are outside from the current active sector) by using wait queues.

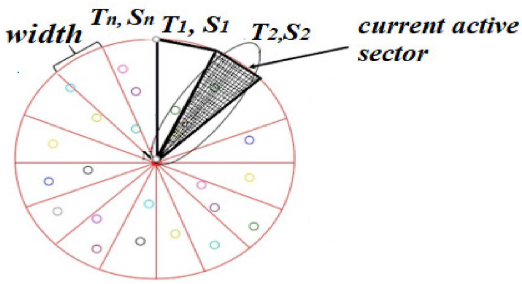

Figure 3. Round-Robin MAC principle.

The Figure 3 illustrates the Round-Robin MAC (RR-MAC) principle. The plane is divided into N equal sectors, each one having a certain amplitude w (sector width) and a beamforming duration time T_i (sector time) with $i = 1...N$; N is the number of sectors in which the plane is divided. Note that all sectors have the same width as well as the same sector time; each node that belongs to a certain sector beamforms with an angle α_i until the sector time is reached, then it switches to the next sector. The sector in which the beam is currently active is defined current active sector.

2.1. Mobility issues directional MAC works

Other approaches, such as the work [26], attempt to reduce the handoff issue through an efficient beam system control; a similar work is presented in [27]; in this paper, authors try to mitigate the handoff problem by proposing a predictive location model in order to advance the future position movements of the nodes. Nevertheless, these works are suitable for Vehicular ad Hoc Network (VANET) environments and do not properly address the deafness problem which is very relevant in MANET. In [28] we introduce a predictive location mechanism that also provides for a frame scheduler with priority in order to reduce the handoff problem. However, in this case, the energy consumption of nodes is not considered.

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3. Omnidirectional and Directional antennas vs Round-Robin MAC

As largely mentioned in the previous sections, networks containing nodes equipped with omnidirectional antennas are prone to high waste of energy because the shape of the radiation pattern that does not beamform only a specific direction. Although different proposals there exist with the aim to solve or at least, mitigate the issues derived from the use of omnidirectional and directional antennas at MAC layer, a more deeply analysis is required for highlighting the issues that need to be addressed. For example, let us consider the work [14], that attempts to mitigate the overall network energy consumption using a SAS antenna module along with a Round-Robin scheduler algorithm. Basically, it works fine under two main assumptions:

Assumption 1. *nodes are equipped with high-efficient hardware antennas (SAS).*

Assumption 2. *data traffic and nodes are uniformly distributed among sectors.*

Assumption 3. *the size of the sector queues are fixed and equals for all sectors.*

In order to evaluate the implications of the first assumption it can be useful to analyze the behavior of the RR-MAC in case the omnidirectional antenna is used in place of directional or SAS technologies. For this purpose, we evaluate, through the use of the *Omnet++* Network simulator [29], the energy consumption of nodes of three different run configurations using the same simulation parameters described in [14] (the most of the them are illustrated in table 1 in subsection 5.2 of the present paper); in order to accomplish the analysis, energy simulation modules have been inserted into each mobile node for allowing the emulation of the battery life time behavior. The initial energy value of each node was set to 300 J, the shutdown energy value was set to 0 J; in this way, a node shutdowns when a node completely depletes its battery life. In the first configuration run nodes are equipped with the classical omnidirectional antenna; in the second, nodes use the omnidirectional antenna together with the RR-MAC scheduling; the latest run configuration is similar to the second except from the fact that in this case the antenna is the SAS module designed in [30].

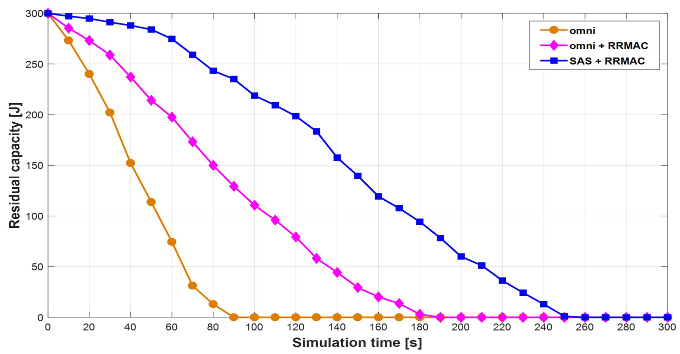


Figure 4. Residual capacity progression.

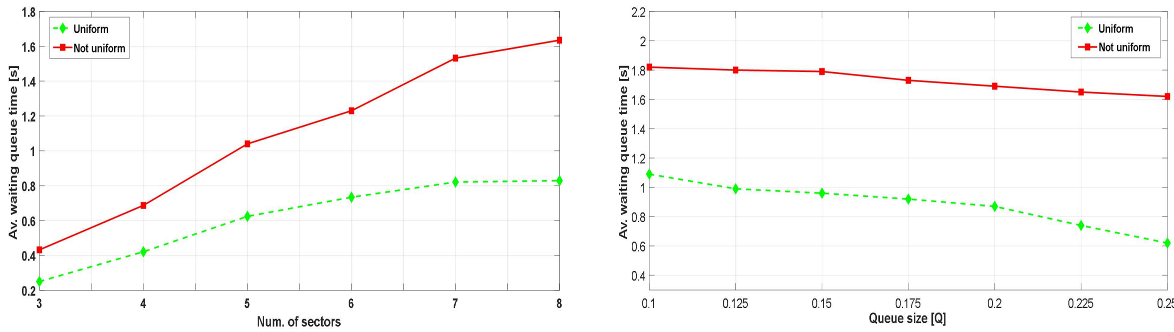
The Figure 4 depicts the residual capacity (averaged by all nodes) plot comparison between the three considered cases. As we can expect, when using the omnidirectional antenna without any energy saving mechanism, nodes deplet their battery life very quickly; when the omnidirectional antennas are used in cooperation with RR-MAC the average depletion time is almost doubled (t=190 s) and improves significantly when SAS are employed by nodes. This is mainly due to the fact that RR-MAC limits the beamforming time for each sector translating into a reduction of the number collisions and interferences. Then, we investigate about the assumptions 2 and 3. In particular, these assumptions imply that the system could be affected from the queue size and the waiting queue time problems [31] that can affect the overall network consumption in the network. We analyze these issues by creating two more run configurations: in the first one mobile nodes are uniformly distributed in the network scenario; also the activity degree of the nodes is uniformly distributed among sectors; in the second, instead, nodes are periodically concentrated in a certain sector (randomly chosen) of the sectorized plane and the activity degree of nodes is unbalanced among sectors. The number of sectors in the plane varies from 3 to 8 while the queue size is evaluated based on the following equation:

$$Queue\,size = Q \times [N + w_Q(N_s)] \qquad w_Q \in \overline{W_Q} \tag{1}$$

The queue size is function of the number of nodes N and the number of sectors N_s in the plane. Q is a value chosen in the interval $0.1 \leq Q \leq 0.25$ in order to maximize the Packet Delivery Ratio performance of [14]. The number of sectors is weighted by the term w_Q that varies from 1 to 6 as the number of sector value increases. In particular, given the number of sector array $\overline{S} = [3,4,5,6,7,8]$, the weight vector $\overline{W_Q}$ is expressed by:

$$\overline{W_Q} = [1,2,3,4,5,6] \tag{2}$$

In order to assess the impact of the two simulation scenarios relating to the queue issues, we compare the waiting queue time of the two running configurations in function of the number of sectors and queue size.



(a) Average waiting queue time vs number of sectors

(b) Average waiting queue time vs Queue size

Figure 5. Queue issues with Round-Robin scheduling.

The Figure 5 illustrates the average waiting queue time in function of the number of sectors. The waiting queue time is averaged by varying the Q parameter from 0.1 to 0.25. In Fig. 3 it can be observed that the waiting queue time in the case of not uniform distributed nodes remains higher than the uniform case independently from the number of sector value; in particular, the gap between the waiting queue time of the two considered cases seeks to grow for sector number values higher than 5. The curves in Fig. 4 are plotted in function of the Q parameter that represents a properly index of the queue size; as it can be deduced from eq. 1, the higher is the Q value, the higher is the queue size. As it happens in Fig. 3 the waiting queue time in the case of not uniform traffic lies above the uniform case curve independently from the queue size. However, as opposed to Fig.3, the difference between curves has kept almost constant as the queue size increases. In the uniform traffic case it can be noted how the waiting time slightly decreases for the highest values of Q while, in the not uniform case, the decrease corresponding to the same values is closely negligible. In summary, as the size of the queue grows up the waiting time in the not uniform case does not tend to get smaller, or rather, the decreasing related to high queue size values is not significant. The trends evaluated in Fig. 5 are certainly justified by one of the most common issues implied by a Round-Robin algorithm scheduling: the time slice problem [32-33]; basically, the time slice represents the quantum assigned to each sector (the sector time) in equal portions; therefore, the communications are handled in a circular way among sectors without priority. In case of not uniform distributed traffic if most of mobile nodes are focused in a specific sector of the plane, the communications related to that nodes are enqueued until the beam is allowed in the specific sector; as consequence, the largest is the quantum assigned to each sector the

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largest is the waiting queue time. In the same way, as observed in [14] if the quantum assigned to each sector is too low, the system will provide bad performance in terms of overall throughput; a similar behavior is produced if the quantum assigned to each sector is averaged in a specific interval with increasing the number of sectors which results in largest waiting queue time values as seen in Fig. 3.

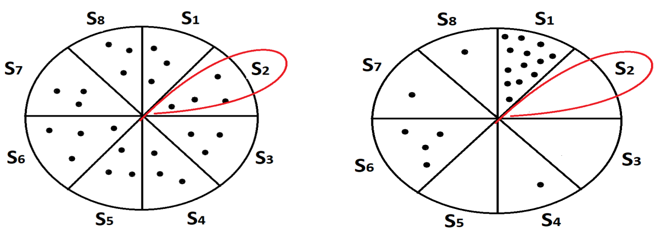
4. Proposed model

4.1. Comparison with RR-MAC and motivations

As explained in the section 3 the main challenges related to the RR approach are referred to the size of the queues and the delay produced by static time slices which cannot be modeled in function of the traffic in the network. However, as observed in [13, 14] the quantum of time assigned for the beamforming process is the same for each sector as well as the amplitude of the width. Therefore, in the work [14] emerges that a proper set of the sector time value affects the overall performance more than the sector width choice; this implies that time slot assigned to sectors needs to be carefully assigned in order to improve the system efficiency. For these reasons we propose an approach that modifies the original Round-Robin algorithm formulation relative to the evaluation of the sector time while keeping unchanged the sectorization of the plane and thus the width of the sectors. In order to understand the modifications introduced with respect to the Round-Robin MAC algorithm we briefly recall the mathematical formulation of this latter:

$$\begin{gathered}\alpha_i = \alpha_j = ... = \alpha \\ T_i = T_j = ... = T_s \\ \alpha_i(T_i) = \alpha_j(T_j) = ... = \alpha(T) \\ \forall i,j = 1,2..N, \quad i \neq j\end{gathered} \tag{3}$$

From formulation given by Eq. 3 it is easy to observe that all sectors have the same width and the same sector time T_s. The use of this approach helps to enhance the MAC performance in terms of reduction of collisions and fairness improving, resulting in a overall decrease of the total amount of energy wasted by nodes. Unfortunately, RR-MAC is a static model and does not adapt itself to the traffic channel conditions; this could represent a limit in scenarios in which nodes are concentrated in a certain sector as verified in the previous section. The goal of the present work is to improve the efficiency of the Round-Robin scheduler in terms of energy management by providing an adaptive beamforming time for each sector that takes into account the size of the waiting queue for each sector. We denoted this novel approach as Adaptive Beamforming Time with Round-Robin MAC (ABT-RRMAC). To figure out the relevance of using an adaptive sector time assignment let us consider the situation discussed in sec. 3 in which two different mobile nodes traffic distribution (uniform and not uniform) in the network are compared:



(a) Uniform node distribution (b) Not uniform node distribution

Figure 6. Uniform node distribution vs not uniform using Round-Robin approach.

The Fig. 6(a) represents a network scenario in which mobile nodes are almost uniformly distributed among sectors of the sectorized plane; the communications are ruled by the Round-Robin

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scheduling; therefore, the current active sector is the sector 2, then the beam is active in that sector. As noticed from the analysis accomplished in sec. 3, assuming a uniform activity degree of nodes, in this case, the waiting queue time is acceptable as well as the MAC layer performance; in Fig. 9b it can be observed that the overall node distribution is unbalanced among sectors as well as the activity degree of nodes. More specifically, most of the mobile nodes are mainly distributed in the sector 1 which, as assumption, has also the highest activity degree among sectors; supposing that the current active sector is again the sector 2 and that sector contains a very small number of nodes with respect to the sector 1 together with a very low burden of active communications, it may occur an under-use of the allocated resources in that sector; in particular, due to the static sector time reservation assignment provided by the Round-Robin algorithm (the assigned sector time is the same for all sectors), the overall beamforming process becomes inefficient resulting in a considerable decreasing of the MAC performance especially in terms of throughput and energy consumption. Indeed, in Fig. 6b it is easy to observe that, due to unbalanced disposition of nodes among sectors, the energy consumption in sectors $S_2, S_3, S_4, S_5, S_7, S_8$ (representing the 80% of the overall plane) is quite inefficient because the beam, in that sectors is performed for a time T_s that is much higher than the required quantum of time required for emptying the queues. Important to highlight that, because we are analyzing the worst condition case, we assume that the scenarios illustrated in Fig. 6(b) remain unchanged for a long time or change very slowly.

4.2. ABT-RRMAC formulation

In light of the previous considerations our ABT-RRMAC approach modifies the original Round Robin algorithm formulation regarding the evaluation of the sector time without affecting the plane sectorization and thus the width of the sectors. Basically, the idea is to assign a portion of time for each sector that is proportional to the size of the queues, that in this case is not fixed for each sector and can vary dynamically.

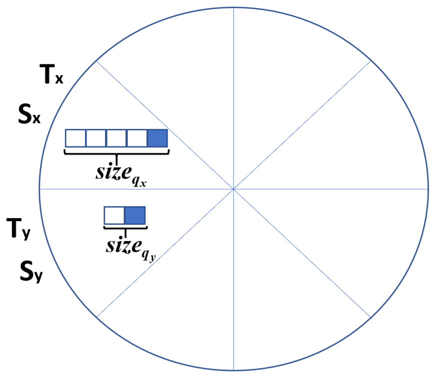

Figure 7. Adaptive Beamforming Time RR-MAC example.

In Figure 7, an example of the ABT-RRMAC application is shown. The plane is normally sectorized into equals amplitude sectors as well as the Round Robin MAC. However, in this case, we consider traffic pattern that is not uniformly distributed among nodes; in Fig. 7, it is assumed that, two particular sectors denoted S_x and S_y respectively have different size of the frame waiting queues; in this regard, the term $size_{q_i}$ denotes the size of the waiting queue related to the *i-th* sector. While considering the situation in Figure 7, assuming that T_X and T_Y are the beamforming (sector) times related to the sector x and y respectively, the ABT-RRMAC assigns the beamforming times as follows:

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$$\begin{cases} T_1 = \frac{size_{q_i}}{\sum_{i=1}^{N} size_{q_i}} \times \overline{T} \neq T_s \\ \dots \\ \dots \\ T_N = \frac{size_{q_N}}{\sum_{i=1}^{N} size_{q_i}} \times \overline{T} \end{cases} \Rightarrow T_1 \neq T_2 \neq .. \neq T_N \iff size_{q_1} \neq size_{q_2} \neq .. \neq size_{q_N}$$

Where:

$$\overline{T} = \sum_{i=1}^{N} \frac{T_i}{N} \quad (4)$$

The term $\overline{T}$ denotes the mean beamforming time averaged by all sectors. Initially, the beamforming times are the same for all sectors and set to T_s (RR-MAC); after a training phase set to 10 s (the time of convergence of the RR-MAC), the mean beamforming time and then sector times are updated periodically in order that for each sector is assigned a quantum of time that is proportional to the size of the queue of that sector multiplied by the mean beamforming time. In this way, sector times can be different and unbalanced among them and the major fraction of time is assigned to the sector having the biggest queue size. For instance, if we consider the example of Figure 7, because $size_{q_x} > size_{q_y}$ then the ABT-RRMAC will assign sector times such that $T_X > T_Y$. The motivation of this choice is due to fact that $size_{q_x} > size_{q_y}$ the serving queue rate of S_X is lower than the serving queue rate of S_Y; consequently, S_X needs for a beamforming time higher than S_Y in order to empty its queue. Among other things, this choice will optimize the energy consumption of nodes in the network; in fact, the undesired waste of energy caused by the classic Round-Robin due to the static model is limited by the dynamic beamforming time assignment.

4.3. ABT-RRMAC implementation

The ABT-RRMAC algorithm is implemented in the Omnet++ Network Simulator in the *DcfUpperMAC* module, that is the main class in which the most important operations at MAC layer are provided, such as frame and collisions management; therefore, as explained in [14] the sectorization of the plane is managed by the SAS antenna module (*PhasedArray* module). The following pseudo-code enhances the original Round-Robin MAC formulation:

Algorithm 1 ABT-RRMAC pseudo-code (part 1)

```
procedure INIT(numSectors)
    numQueues ← numSectors
    CREATEQUEUES(numQueues)
end procedure

procedure ASSIGNSECTORTIME(trainingPeriod, updatePeriod, numQueues)
    if Sim.Time () < trainingPeriod | | Sim.Time()< updatePeriod then
        averageSectorsTime = 0;
        for i=1; i< numQueues; i++ do
            sectorTime[i] = T_s;
        end for
    else
        averageSectorsTime = computeAverageSectorsTime()
        for i=1; i< numQueues; i++ do
            sectorTime[i] = size_{q_i} / (Σ_{i=1}^{N} size_{q_i}) × averageSectorsTime;
        end for
    end if
end procedure
```

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Algorithm 2 ABT-RRMAC pseudo-code (part 2)

```
procedure STARTTRANSMIT(frame)
    int frameSector=getFrameSector(frame);
    int currentActiveSector=getCurrentActiveSector();
    if currentActiveSector != frameSector then
        queueSector[frameSector].insert(frame)//queuetheframe
    else
        transmissionQueue.insert(frame);
        transmitFrame ← queueSector[activeSector].front()
        queueSector[activeSector].pop()
        CONFIGUREANTENNA(activeSector)
    end if
end procedure

procedure STARTRECEPTIONSTATE
    CONFIGUREANTENNA(omnidirectional)
    MAC in reception Mode
    SCHEDULEEVENT(CSMATimer)
end procedure

procedure RECEPTIONFRAME(frame)
    orientation ← GETORIENTATION(frame)
    sector ← GETSECTOR(orientation)
    CONFIGUREANTENNA(sector)
end procedure

procedure RECEIVEFRAMEFROMUPPERLAYERS(frame)
    sector ← GETSECTORFRAME(frame)
    queueSector[sector].push_back(frame)
end procedure

procedure MACPROCCESS
    INIT(NumSectors)
    STARTRECEPTIONSTATE
    loop
        WaitEvent
        if Event Is Upper Frame then
            RECEIVEFRAMEFROMUPPERLAYERS(frame)
        else if Event Is Lower Frame then
            RECEPTIONFRAME(frame)
        else if End Transmission then
            STARTRECEPTIONSTATE
        else if EndCSMA ∧ QueueSector ≠ empty then
            STARTTRANSMIT(frame)
        else
            STARTRECEPTIONSTATE
        end if
    end loop
end procedure
```

At the beginning of the process, after the plane is sectorized into equal width sectors, the same quantum of time is assigned for all sectors (Round-Robin). If the *trainingPeriod* has elapsed the *averageSectorsTime* denoting the mean beamforming time averaged by all sectors, can be computed; remember that this parameter is updated periodically after an *updatePeriod* (that we set to 10 s) has passed; from the first time that the *averageSectorsTime* is computed, the beaforming times of the sectors are assigned according to expression given by Equation 4. The whole of these operations are included in *AssignSectorTime* function. The transmission of frames is ruled by *StartTransmit* function in which the system checks if the sector for which is destined the current frame is the *current active sector*. If true, it inserts the frame in the transmission queue and transmit the frame, otherwise the frame is queued in its waiting sector queue, and delayed until its sector does not become the current active sector. The reception of the frame is performed by *ReceptionFrame* and*ReceiveFromUpperLayers* functions in which, the receiver antenna is configured in omnidirectional mode and the information about the orientation of the transmitter antenna is retrieved in order to achive the synchronization during communication process. Other coordination functions are performed by *MacProcess* procedure.

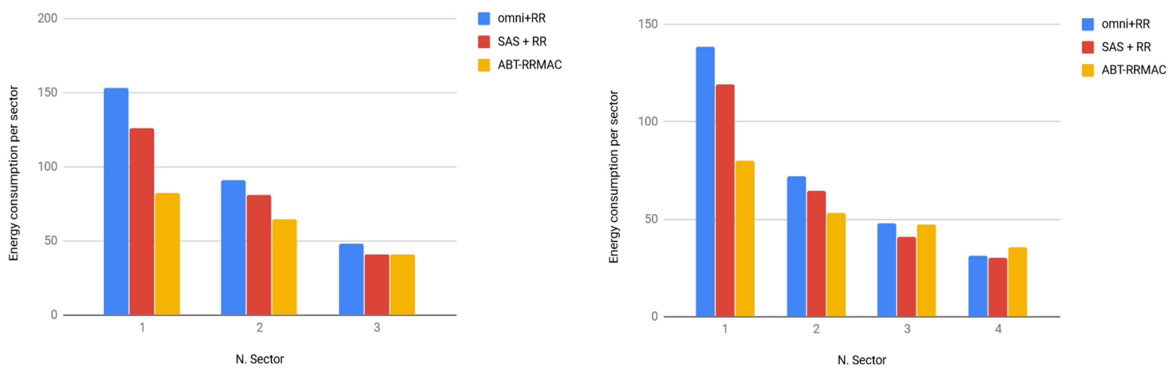
5. Performance evaluation

In order to evaluate the contribution of the ABT-RRMAC we perform simulations by considering three different configurations of antennas in the nodes: omnidirectional with Round-Robin scheduling, SAS with Round-Robin (RR-MAC), and our proposed ABT-RRMAC that uses SAS adaptive array antennas; Simulations are accomplished by varying the number of sectors and then, node mobility speed. The following table summarizes the main simulation parameters:

Table 1. Main simulation parameter set.

Parameter	Value
SAS Array Elements Spacing	0.5 λ
Steering angle	45°
Transmission Rate	54 *Mbps*
Message Length	512 *Byte*
Mobility model	Random Waypoint
Node Mobility speed	from 1 to 10 mps *mps*
Routing Protocol	AODV
Network Load	50 %
Simulation Area Size	500 x 500 *m*
Simulation Time	300 *s*
Number of Sectors	3,4,6,8
Initial battery capacity	300 J

Simulations have been accomplished by using 20 different seeds and extracting the confidence intervals obtained by the repetitions considering a confidence level set to 95 %. The traffic is represented by UDP (User Datagram Protocol) data packets randomly generated (based on the simulation seed) by different couples of nodes. The number of nodes is set to 50 and couples of nodes involved in the data traffic exchange is one half with respect to the total number of nodes in the network. In addition, the channel is moderately affected from noise (-80 dBm), with SAS that have the main beam towards 45°. For the first set of simulations we consider an unbalanced distribution of data (worst conditions) traffic by concentrating the main fraction of communications in the first sector of the plane; therefore, nodes move very slowly (2 mps) in the network and the size of the queues is set to 5. The first evaluated statistic is the energy consumption of nodes by varying the number of sectors.



(a) Energy consumption comparison, $N_s = 3$ (b) Energy consumption comparison, $N_s = 4$

Figure 8. Energy consumption per sectors vs number of sectors (part 1)

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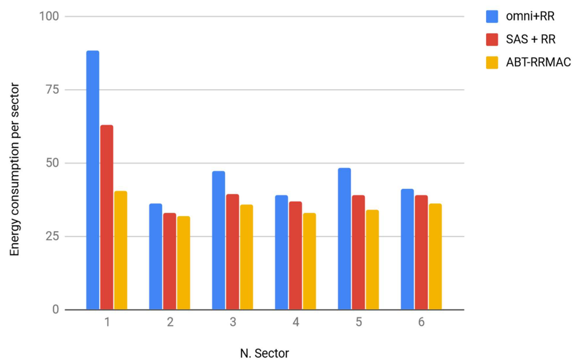
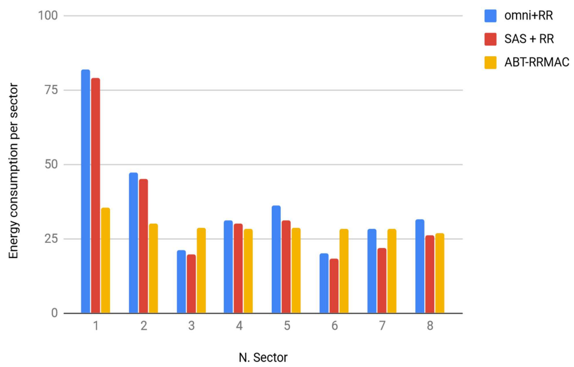


(a) Energy consumption comparison, $N_s = 6$



(b) Energy consumption comparison, $N_s = 8$

Figure 8. Energy consumption per sectors vs number of sectors (part 2)

The plots in Figure 8 illustrate the energy consumption of nodes (expressed in Joule) in function of the number of sectors (observe that the term "*N. Sector*" used in plots of Figure 8 is related to the progressive number id assigned to each sector and does not identify N_s). In Fig. 8(a) it can be observed how the main fraction of consumption is related to the sector 1, that is the sector in which the traffic is mostly focused with respect to others. When omnidirectional antennas and the Round Robin scheduler are used the distribution of energy consumption among sectors is very unbalanced; this trend is mainly due to the static time slot assigned by the scheduler, that, in this case is the same of all sectors; this feature results in a not efficient distribution of the energy in the sectors and consequently, the total energy consumption is considerable (almost 298 J). However, the same behavior is maintained in Fig. 8(b) in which, when SAS module are used it can be highlighted a better distribution of the consumed energy among sectors. In Fig. 8(c) it appears clear, how, as the number of sector increases the maximum amount of consumed energy is reduced, but in the case of omnidirectional antennas the imbalance remains unchanged; however the use of the SAS allows to decrease considerably the maximum energy amount that is further reduced when ABT-RRMAC approach is employed (44,54 against 88,27 registered in the omnidirectional case). Finally, the Fig. 8(d) emphasizes even more the impact of the proposed approach flowing in a overall balancing of the energy consumption. In summary, the dynamic allocation of the beamforming time allows, independently from the number of sectors, to optimize the distribution of the energy also leading to a reduction of the overall consumed energy; indeed the registered values of total consumed energy in the RR-MAC case in function of the number of sectors are 248.33, 255.14, 250.91 and 272.32 J against values of 187.89, 216.26, 211.81 and 235.37 J registered when ABT-RRMAC is used. For a further investigation, it is possible to evaluate the standard deviation (averaging values by sectors) of the energy consumption by increasing the number of sectors for all of the configurations:

Table 2. Energy consumption: standard deviation vs number of sectors.

Number of sectors	omni + RR	SAS + RR	ABT-RRMAC
3	52.96	42.79	20.55
4	47.02	39.6	19.03
6	19.04	20.69	3.03
8	18.71	18.15	2.62

The Table 2 collects standard deviation values by varying number of sectors for all of the considered approaches; the use of SAS slightly enhances the omnidirectional case, however, observe how ABT-RRMAC contributes to dramatically decrease values when the number of sectors improves with respect to other considered configurations; this trend confirms that our proposed approach seeks to efficiently distribute the energy consumption among sectors as already noticed in plots of Figure 8.

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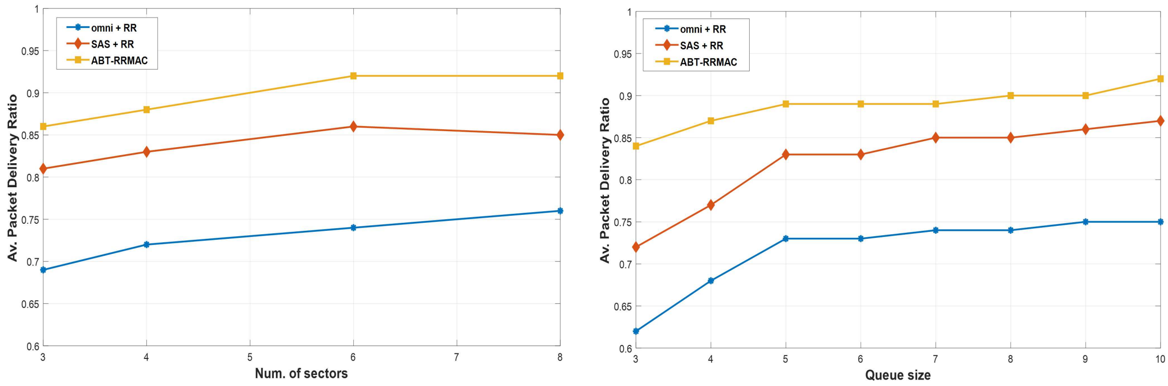
Therefore, energy consumption is very related to Packet Delivery Ratio (PDR) and could represent an helpful indication of the overall network performance; for this purpose next figure illustrates PDR comparison extracted by *rcvdPkts* and *sentPkts* statistics collected by Omnet++:



(c) Average PDR vs Num. of sectors (d) Average PDR vs Queue size

Figure 9. Packet Delivery Ratio comparison.

In Figure 9, the average (averaged with respect to nodes) PDR is plotted both in function of the number of sectors and the queue size. The Fig. 9(a) simply reflects the situation verified in Figure 8, in fact, the lowest is the energy consumption the highest is the PDR; therefore, when the number of sector is high, ABT-RRMAC is able to provide a PDR of about 0.92 against 0.85 registered in the RR-MAC configuration. The same statistic can be evaluated by increasing the size of the queues; in Figure 9(b) (values are averaged with respect to number of sectors) it seems clear that PDR performance are quite sensitive to queue size, indeed, low moderately values of PDR are obtained when omnidirectional antennas are used; SAS contributes to increase the minimum PDR from 0.62 to 0.72, however the minimum PDR value, when our proposed approach is used, is 0.84; this value slightly improves together with the queue size and tends to begin almost uniform for highest queue size values. More specifically, especially for critical queue size cases (from 3 to 5) the difference between RR-MAC and ABT-RRMAC is very significant; this result suggests that our proposed algorithm provides for a great robustness also when the queue size are small, allowing quite acceptable performance in case of limited resource allocation. The latest set of simulations is accomplished with the aim to test our proposal in condition of mobility of nodes; for this purpose we evaluate the energy consumption of nodes by increasing the node mobility speed from 1 to 10 *mps*; in this case, results are obtained by averaging energy consumption values with respect to number of sectors. In addition, we compared the worst queue size case (queue size = 3) and the best queue size case (queue size = 10).

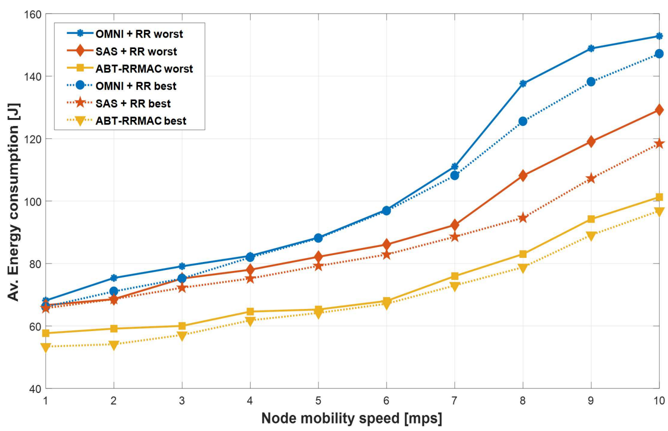


Figure 10. Energy consumption vs Node mobility speed.

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Figure 10 displays comparison curves related to energy consumption of nodes in function of the mobility speed by considering the worst and the best registered case in function of the size of the queues. Note that continued-line curves depict the worst case plots while dashed-line curves are related to the best case plots. As regards omnidirectional case, the overall consumption remains tolerant until 7 *mps* and then whereupon increases widely; this is mainly due to link failures occurring for high mobility speed values that results in enhancement of protocol overhead. However this rapid increase is weak limited in the best omnidirectional case. When using SAS in cooperation with Round-Robin, disruptive impacts due to growth of node mobility speed, are quite mitigated with respect to omnidirectional case, especially for high mobility values. Therefore the effects of directional high-gain beamforming are quite straightforward; in particular, by considering the best and worst cases, the energy saving amount in the case of RR-MAC gives from 23 to 29 J compared to omnidirectional. Nevertheless, ABT-RRMAC, thanks to dynamic sector time assignment, improves, performance of RR-MAC extending battery life of nodes of about 21% (on average) compared to the latter. This effect seems to keep uniform also as the mobility speed of nodes grows up. Note that, for ABT-RRMAC curves related to best and worst case are almost overlapped, indeed, the effect of queue size results mitigated compared to other considered cases.

6. Conclusions

We proposed an Adaptive Beamforming Time with Round-Robin MAC approach with the goal to improve benefits in terms of energy consumption introduced by the employment of Round-Robin scheduling in directional antenna MANET contexts [14]. This work has been mainly motivated by the fact that, although a RR approach is able to counteract main directional antenna issues which usually can occur at MAC layer, the energy consumption distribution is not well distributed among sectors. Basically, the unbalanced energy distribution, due to problems introduced by Round-Robin such as the time slice and queue issues, promotes a not negligible waste of energy which can lead to limit the overall network performance especially in terms of Packet Delivery Ratio. In order to attempt to mitigate these problems, we proposed a solution which aims to eliminate the static assignment of the beamforming (or sector) time for sectors that could bring to a not efficient energy distribution among sectors. The presented solution provides of a dynamic assignment of the beamforming time by considering the current size of the sector queues and the average beamforming time; all parameters are updated periodically. The main advantage of that dynamic assignment is that, when data traffic is unbalanced in the simulation scenario, the slowest is a certain sector to empty its queue (that is directly related to the size of the queue) the highest is the quantum of time assigned to that sector. The ABT-RRMAC has been compared to the classic omnidirectional MAC exploiting the Round-Robin principle and with the RR-MAC presented in [13-14] that uses SAS instead of omnidirectional antennas. Results, in terms of energy consumption of nodes, by considering different configuration cases related to number of sectors, have shown how ABT-RRMAC is able to reduce of about 37% on average, the maximum energy consumption amount per sector, with respect to RR-MAC and even 50% compared with omnidirectional case; furthermore, our proposed approach contributes to level the energy consumption of nodes by uniformly distributing the total amount among sectors. For a further investigation, PDR of all considered cases has been evaluated in function of the number of sectors and queue size; with reference to queue size ABT-RRMAC provides for a minimum PDR of 0.84 that considerably improves the value of 0.72 obtained in RR-MAC. This result is significant because reduce the dependency of the PDR with queue size. Finally, our approach has been evaluated in terms of energy consumption by considering mobility of nodes; in this regards, result have been highlight that ABT-RRMAC outperforms RR-MAC; this trend remains almost uniform independently from the size of the queues.

Table 3. List of symbols used in this manuscript

Symbol	Explanation
Q	term referred to the queue size
N	number of nodes
N_s	number of sectors
w_Q	queue weight
$\overline{W_Q}$	queue weight vector
S_i	i-th sector
T_i	i-th sector time
T_s	sector time
α_i	i-th sector angle
$size_{q_i}$	i-th sector queue size
$\overline{T}$	mean beamforming time
λ	wavelength
s	seconds
m	meters
mps	meters per seconds
J	joules
dBm	decibel-milliwatts

Abbreviations

The following abbreviations are used in this manuscript:

SAS	Smart Antenna Systems
MAC	Medium Access Control
OMNI	Omnidirectional
DMAC	Directional Medium Access Control
RR-MAC	Round Robin MAC
ABT-RRMAC	Adaptive Beamforming Round Robin Medium Access Control
MANET	Mobile ad Hoc Network
VANET	Vehicular ad Hoc Network
SDMA	Spatial Division Multiple Access
DRTS	Directional Request to Send
DCTS	Directional Clear to Send
DNAV	Directional Network Allocator Vector
CPU	Central Processing Unit
FDMA	Frequency Division Multiple Access
TDMA	Time Division Multiple Access
CDMA	Code Division Multiple Access
SRL	Short Retry Limit
PDR	Packet Delivery Ratio
AODV	Ad Hoc On Demand Distance Vector

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