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TOPOLOGY CONTROL IN *AD HOC* NETWORKS: A MAC LAYER SOLUTION

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In *ad-hoc* networks the need for a distributed topology control algorithm is being widely recognized. In this paper we propose TC-ADHOC MAC, a medium access algorithm with topology control capabilities. The proposed algorithm aims at maintaining the minimum number of bidirectional neighbors of any wireless terminal very close to a certain connectivity threshold. The correctness of the algorithm is evaluated through detailed simulation and several test on the impact of different algorithm parameters are carried out in static network scenarios. Furthermore, the ability of TC-ADHOC MAC of reusing the radio resources is assessed by a detailed simulation in a dynamic traffic environment. Our results show that the topology control solution integrated at the MAC layer helps increasing the channel reuse and, consequently, the network efficiency.

Keywords: Topology control; MAC layer solution; TC-ADHOC MAC.

1. Introduction

Wireless *ad hoc* networks are attracting much attention within the researcher community all over the world. Such a success is mainly due to the fact that the design of effective protocols and algorithms for wireless environment poses intriguing challenges to implementers and vendors.

Applications of mobile *ad hoc* networks can range from military ones, where networks need to be deployed immediately without the support of either base stations or fixed network infrastructures, to inter-vehicle communications.

To this extent, the protocols and the algorithm concurring in the provision of the communication services have to be optimized to the wireless scenario: applications must be flexible and distributed; transport layer protocols must provide effective communication services; routing protocols must cope with the high variability in the network topology due to wireless node mobility; MAC layer must effectively handle the access to the scarce and unreliable shared resource; and finally the physical layer must be robust enough to combat the impairments of the physical wireless channel.

Furthermore, the effectiveness of a given algorithm or protocol running at a certain layer is highly influenced by the operation of other protocols running at other logical layers. For this reason, the classical paradigm of designing the different layers separately does not seem suited for *ad hoc* wireless networks any longer. Cross-layering, intended as a stricter interaction among the functionalities provided by different layers, seems to be the best approach.

A typical example of cross-layering issue is represented by power control. Ever since in wireless communications, power control has been a means to determine the quality of the received signal and, as such, an issue belonging to the physical layer. In wireless networks, however, power control also affects higher level performances such as the throughput of a multiple-access channel, a layer two issue, and the topology of ad-hoc networks, a layer three issue, since the transmitted power level determines the maximum distance of neighbors, and thus their number and the network topology. Therefore, depending on the dominant issue, power controlling procedures can be implemented at different logical layers and can be optimized with respect to different targets ranging from energy saving (a physical layer issue), radio resource reuse (a MAC layer issue) and network connectivity (a network layer issue).

In this paper we are interested in power control as a means to determine the network topology with respect to the nodes' connectivity degree K, i.e. the number of neighbors directly connected to a given node through a bidirectional wireless link. There are many reasons why K should be strictly controlled: for example, as all connections share the same bandwidth, increasing K diminishes the bandwidth available to each connection; however, since all nodes in the network also share the same bandwidth, increasing K diminishes the bandwidth reuse, i.e. the bandwidth available to the network. On the other side, a low value for K may lead to network partitions and some destinations may become unreachable from some sources. It is therefore clear that, given a network scenario, an optimal value of K does exist coming from the trade off between network connectivity and network capacity.

[Xue & Kumar, 2004] and [Blough *et al.*, 2003] focus on the issue of connectivity and both provide mathematical theories to obtain the asymptotic value of the number of neighbors needed to get a fully connected network. From these two valuable pieces of work comes that an optimal value of parameter K does exist and should be maintained by some kind of dynamic topology control algorithms.

Within this field [Ramanathan & Rosales-Hain, 2000] propose algorithms that are de facto modified routing protocols with topology control capabilities. The basic idea is to let each wireless node monitor the number of neighbors and modify the transmitted power in order to control connectivity. Similar solutions are proposed in [Gurumohan *et al.*, 2004], [Hu, 1993] and [Shen *et al.*, 2004]. Within this framework, [Wattenhofer *et al.*, 2001] and [Li *et al.*, 2005] propose a cone based topology control algorithm which aims at maintaining the number of bidirectional neighbors within a given angle above a certain threshold.

The general approach of these works is logically composed by two distinct phases: A first phase where each node gathers local topological information on the surrounding nodes, and a second phase where it modifies its transmitted power according to a certain algorithm.

Throughout the paper we refer to the former as to the *Neighbors Discovery Phase* (NDP) and to the latter as to the *Topology Update Phase* (TUP).

[Gerharz *et al.*, 2003, 2005] focus on the TUP assuming a simplified NDP provided by an ideal signalling protocol which runs out of band on an ideal error-free control channel. On the other hand, in [Liu & Li, 2002], [Blough *et al.*, 2003], [Yu *et al.*, 2004] and [Li *et al.*, 2005] the signalling used for the NDP is similar to a layer 3 HELLO protocol, based on layer 2 broadcast. The main drawback of this approach is that the broadcast transmissions used for signalling purposes raise the interference level within the network possibly impairing the capacity of the access mechanism. Furthermore, a common approach used in these works is to resort to maximum power transmissions during the discovery phase, which, again, increases the average interference level. Generally speaking, the proposed algorithms either make simplifying assumption on the implementation of the NDP or resort to layer 3 neighbors discovery protocols based on flooding-like algorithms. In these last solutions the layer 2 is completely blind with respect to local connectivity, thus highly bandwidth demanding broadcast transmissions of signalling packets are needed to gather information on the surrounding neighbors.

On the other hand, we have recently proposed the ADHOC MAC [Borgonovo *et al.*, 2002, 2003, 2004], which is a layer two protocol able to spread reliable connectivity information among nodes.

In this paper we show how the operation of ADHOC MAC can be extended to provide connectivity control, which we name *Topology Controlled ADHOC MAC* (TC-ADHOC MAC), i.e. an "all-layer 2" integrated solution to NDP and TUP problems. We analyze the proposed scheme with respect to the achieved network connectivity, network capacity and convergence time.

The paper is organized as follow: In Sec. 2, we briefly describe the features of the ADHOC MAC layer chosen to suit the topology control algorithm. Section 3 proposes the distributed topology control algorithm describing its properties and parameters. Section 4 presents numerical results on the performance of the TC-ADHOC MAC. Finally, Sec. 5 reports our concluding remarks.

2. The ADHOC MAC Protocol Features

ADHOC MAC operates with a time slotted structure, where slots are grouped into Virtual Frames (VFs) of length N, and no frame alignment is needed. The slot synchronization can be explicitly provided by external sources, such as GPS, or implemented in a distributed way [Ebner *et al.*, 2002a, 2002b].

In ADHOC MAC each terminal, upon activation, acquires a Basic CHannel (BCH) which corresponds to a slot in the VF and that is mainly used for MAC signaling, but can be used also for data that must be broadcast to all neighbors in a reliable way. The BCH is acquired in a distributed way through the Reliable Reservation ALOHA (RR-ALOHA) protocol where, as in R-ALOHA, contention is limited to the access frame and, upon success, the same slot is reserved in the following frames and no longer accessed by other terminals until it is released, i.e. when the terminal deactivates. Since the *ad hoc* environment is not fully broadcast, the information needed for the RR-ALOHA correct operation is provided to all terminals by means of the BCHs.

Each transmission on the BCH contains, besides data and header information, a control field named Frame Information (FI). The FI is a vector with N entries specifying the status of each of the N slots preceding the current transmission, as observed by the transmitting terminal itself. The slot status can be either BUSY or FREE: It is BUSY if a packet has been correctly received from another terminal or transmitted by the terminal itself, otherwise it is FREE. In the case of a BUSY slot the identity of the transmitting terminal is reported.

Consequently, the FIs report the information on the neighbors' activity of the sending terminal as perceived by the terminal itself in the previous VF. Thus, a terminal receiving the FI from one of its neighbors gets aware of its neighbors'neighbors activity. For example, consider the case of terminal 4 in Fig. 1; its FI is received by terminal 1, who gets aware of the neighbors of terminal 4 which it cannot reach directly, i.e. terminals 3, 6 and 7.

Based on received FIs, each terminal marks a slot, say slot k, either as RESERVED, if slot $k - N$ is coded as BUSY in at least one of the FIs received in the slots from $k - N$ to $k - 1$, or as AVAILABLE, otherwise.

As in R-ALOHA, an AVAILABLE slot can be used for new access attempts. Upon accessing an AVAILABLE slot, terminal j will recognize in the next VF its transmission either successful, if the slot is coded as "BUSY by terminal j" in all the received FIs, or failed, otherwise.

According to the aforementioned rule, if just one terminal is attempting access, all terminals receiving the accessed BCH will recognize the transmission and, therefore, all the

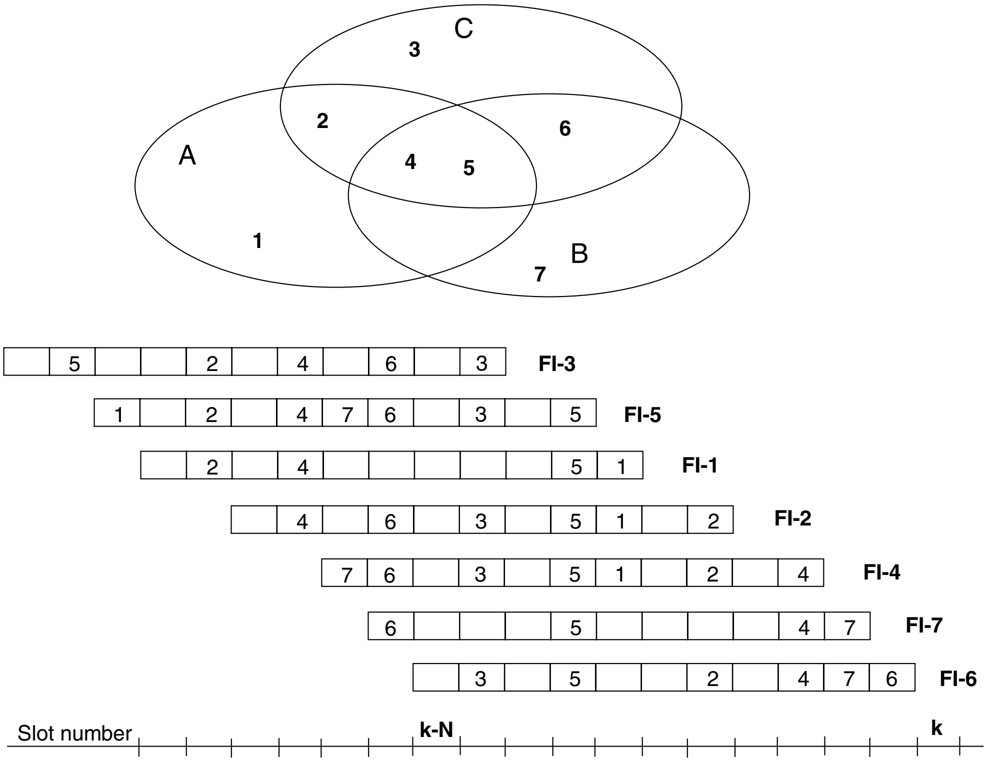

Fig. 1. FIs transmitted in a TH-cluster.

FIs received by the terminal itself in the following VF will denote the slot as BUSY by the accessing terminal. Access is successful in this case.

An access collision happens if two or more terminals attempt transmission on the same slot. In this situation, the receiving terminals that cannot decode the signals because of the collision, will signal the slot as FREE in their FIs in the following VF, and the accessing terminals will interpret it as a negative acknowledgment.

It may also happen that some terminals correctly decode one transmission out of multiple concurrent ones due to a capture effect and consequently signal the slot as BUSY in their FIs. In this case, the slot is assigned to a given accessing terminal if all the FIs it receives signal that slot as BUSY by the terminal itself, whilst the other contending terminals will discover their failure. Thus, the FIs transmission provides a constant and periodical acknowledgement for the transmissions of the BCHs.

In the ADHOC MAC terminology, we define One Hop (OH) cluster a set of mobile terminals whose transmissions are correctly received by all the terminals within the OH cluster itself. In other words, a OH cluster is a fully connected set of terminals. Further on, a Two Hop (TH) cluster is the union of non disjoint OH clusters, i.e. the union of all the OH cluster with a common subset of terminals. Figure 1 shows three OH clusters (A, B and C) forming a single TH cluster.

According to the rules of the RR-ALOHA protocol we can state the following properties.

Property 1: *Transmissions of terminals belonging to disjoint OH-clusters cannot collide, and the slots can be reused.*

The proof of this property is straightforward.

Property 2: *All terminals belonging to the same TH-cluster mark the slots in the same way within their FIs.*

Proof. All the terminals receive the FI generated by the terminals belonging to the common TH-cluster set (terminals 4 and 5 in Fig. 1) and such FI concerns all the transmissions in the TH cluster itself. A single BUSY code is enough to force a RESERVED slot. Similarly, any slot signaled as BUSY is recognized as RESERVED by all the terminals in the TH-cluster and therefore, since a RESERVED slot cannot be accessed, no other terminal within the TH-cluster can transmit, and no collision will occur.

It is worth noticing that, since OH-clusters can overlap, the slot reuse in an OH-cluster can still be constrained if the same slot is in use in a non disjoint OH cluster. Thus it can be seen that the procedure achieves the proposed goal of setting up channels with no interference if the cluster configuration does not change.

However, when the clusters merge because of terminal mobility or activation, collisions can still happen. The RR-ALOHA procedure enables the colliding terminals to become aware of any collision. When a collision is discovered, the slot is released and a new set up procedure is started. The frequency of this situation depends on the activation of new terminals and the mobility of the active ones.

More details of ADHOC MAC and the description of the others features can be found in [Borgonovo *et al.*, 2004], while [Borgonovo *et al.*, 2003] and [Borgonovo *et al.*, 2005] present the performances evaluation of the broadcast services in static and mobile scenarios respectively.

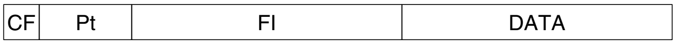

Fig. 2. Fields of a BCH slot: Connectivity Flag (CF), transmitted power (P_t), Frame Information (FI) and data field.

Besides the FIs, each BCH must contain other signalling information for the proper implementation of the topology control algorithm. In details, two pieces of information must be included:

- The transmitted power level, P_t.
- A *connectivity flag* to signal the connectivity status of the transmitter.

Figure 2 shows the fields of a BCH slot.

Thanks to the information carried by the received BCHs, each terminal can gather reliable information on its connectivity situation, namely, it can be aware of:

- its neighbors (identity, transmitted and received power);
- the neighbors of its neighbors (identities and number).

This connectivity information provided at layer two allows a straightforward implementation of an effective topology control algorithm, which is described in the next section.

3. Topology Control Algorithm at the MAC Layer

Hereafter we give the details of a layer 2 topology control algorithm which implements at the link layer both the *Neighbors Discovery Phase* (NDP) and the *Topology Update Procedure* (TUP).

In the following we assume that two terminals are connected by a bidirectional link if and only if they are within the transmitting range one another.

The algorithm works in a fully distributed way by updating the transmitting power of each terminal in order to maintain the number of bidirectional links M equal to a given value K. However, since this is not always possible, depending on the topology, a terminal is allowed to have more than K bidirectional links if this is needed to let a neighbor satisfy the connectivity constraint ($M = K$).

In Sec. 3.1 we define the setting parameters of the algorithm and comment on the implementation of the NDP, while in Sec. 3.2 we give the rules of the TUP.

3.1. *The Neighbors Discovery Phase (NDP)*

The algorithm is driven by five parameters:

- P_{max}: Maximum value of transmission power level;
- P_{step}: The minimum amount of power increase;
- P_{rec}: The reception threshold power;
- K: The target number of bidirectional links;
- *PCP*: The Power Control Period, occurrence period of the power updates.

The NDP can be easily performed exploiting the information carried by the received BCH transmissions.

Each terminal collects all the BCHs transmissions of the VF preceding the end of a PCP. Upon reception of the BCH from terminal j, the generic terminal i evaluates the attenuation gain from the transmitting terminal according to the formula:

$$\beta_j^i = \frac{P_{ji}^r}{P_j^t}, \tag{1}$$

where P_j^t is the power level transmitted by node j as specified in the BCH and P_{ji}^r is the power level received by node i out of the transmission by node j on the BCH. A transmission from node j is correctly received by node i if:

$$P_{ji}^r \geq P_{rec}. \tag{2}$$

Therefore, assuming symmetric links among nodes, if inequality 2 holds and node j transmission is correctly received by node i, also node i transmissions are correctly received by node j.

The attenuation gains towards all the transmitters are ordered from the highest to the lowest and stored in an ordered set $\alpha_i = \{\beta_1^i, \beta_2^i, \ldots, \beta_M^i\}$.

Besides the attenuation gain, for each neighbor recorded in the set α_i, the following data are available:

- the neighbor's ID;
- the transmitted power level;
- the *connectivity flag* as reported in the corresponding BCH transmission;
- the content of the corresponding FI.

3.2. *The Topology Update Procedure (TUP)*

The purpose of the Topology Update Procedure is to adjust the transmitted power level of every terminal in a distributed way in order to match the connectivity constraint of having K bidirectional links always active.

At each PCP, the generic terminal i checks the content of the set α_i. If $M = |\alpha_i|$ is the cardinality of such set and $P_i^t(k)$ the transmitted power level used by terminal i at the current PCP k, terminal i adjusts its transmitting power for the next PCP $k+1$ according to the following rules:

Rule 1: If $M < K$, the terminal increments its transmission power of P_{step} according to:

$$P_i^t(k+1) = max[P_M^t(k), P_i^t(k)] + P_{step}, \tag{3}$$

where $P_M^t(k)$ is the power level used by the Mth terminal in set α_i; terminal i further signals that $M < K$ by setting the connectivity flag to 0 in its own BCH transmission.

This is the case when the number of neighbors is below the connectivity threshold, thus the transmitted power must be incremented in order to reach terminals farther away. In our approach, the transmitted power is incremented according to a power ramping procedure.

The *connectivity flag* set to 0 signals that the transmitting terminal is below the connectivity threshold.

Rule 2: If $M = K$, the terminal sets its transmitting power so that to reach the Kth neighbor in its list:

$$P_i^t(k+1) = P_M^t(k). \tag{4}$$

It further signals that $M = K$ by setting the connectivity flag to 1 in its own BCH.

Rule 3: If $M > K$, for each of the last $M - K$ neighbors in list α_i, terminal i adds the neighbor to a subset F if in the neighbor's connectivity flag is set to 0 or is set to 1 and the ID of terminal i appears in the neighbor's FI. Terminal i then adjusts its transmitted power according to:

$$P_i^t(k+1) = \begin{cases} P_M^t(k) & \text{if } |F| = 0 \\ P_j^t(k), \quad j = argmin_{m \in F}[\beta_m^i] & \text{otherwise.} \end{cases}$$

If subset F is empty terminal i sets its transmission power to reach the Kth neighbor of the ordered list and the connectivity flag is set to 1, otherwise it sets its transmission power to reach the most distant neighbor belonging to subset F and sets the connectivity flag in its own BCH to 2.

Figure 3 helps clarifying the basic idea of the TUP. Five nodes are represented in the figure with their bidirectional neighbors linked by bi-directional arrows. Suppose $K = 2$. Nodes **a**, **b** and **c** match the connectivity requirements since they all have 2 bidirectional neighbors, whereas nodes **d** and **e** just have one bidirectional neighbor each. According to Rule 2, node **d** will increase its transmission power with the ramping procedure, being $M < K$, until reaching node **a**. The same will happen for **e**. In this way node **a** will receive $M = 3$ FIs, two from nodes **b** and **c** and one from node **d** and will adjust its transmission power according to Rule 3 so that to reach node **d** even if its connectivity requirement is already satisfied. The same thing happens for node **e**.

A "cooperative" approach similar to ours is used in [Gerharz *et al.*, 2003, 2005] with the difference that the connectivity constraint is defined as an interval, i.e. power update procedures are applied whenever the number of bidirectional neighbors falls outside a given interval $[K, K_{max}]$. Furthermore, each node explicitly signals when its bidirectional neighbors are below the connectivity threshold ($M < K$) and, upon receiving such signaling, any neighbor node updates its transmitted power to reach the new requiring neighbors even if it has already matched its connectivity requirement. Whenever the connectivity constraint is reached, nodes stop signalling $M < K$.

The above approach generally provides a more rapid convergence, but, on the other hand, it has a negative impact on the network capacity as we show in the next section. Furthermore, this implementation can bring to oscillatory behaviors. In fact, in the case of

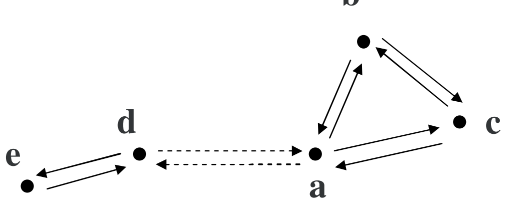

Fig. 3. Operating mode of the Topology Update Procedure (TUP).

Fig. 3 upon receiving the signalling $M < K$ from node **d** node **a** updates its power to reach node **d**. The next power control period node **d** has matched its connectivity requirements thus quit signalling $M < K$. Consequently, **a** receives three transmission and none of them signalling any urgency thus reduces its transmission power cutting off node **d**. This brings to an oscillatory operation according to which node **a** keeps modifying its transmission power every power control period.

On the other hand, in our proposal the oscillation is prevented by Rule 3. As a matter of fact, node **a**, upon checking the received FIs, does not reduce its power because this would force neighbors **d** and **e** to fall below the connectivity threshold.

4. Performance Evaluation

In order to test the performance of the proposed protocol, we have built a C++ simulator which operates on a square network area with edge length equal to 1 km. We adopt a wrap-around surface in order to avoid border effect in the interference calculation.

The terminals are placed in the simulation area according to a uniformly distributed probability density and contend with the rules of the RR-ALOHA protocol in order to gain their BCHs. A Virtual Frame (VF) is assumed to be composed by N transmission slots.

Since our main focus is on performance evaluation of the topology control algorithm and its effect on the MAC layer, we ignore both fading and shadowing phenomena, so the connectivity among terminals is simply determined by the Euclidean distance and errors on transmissions can be only due to collision. This assumption widely adopted in the literature [Gupta & Kumar, 2000; Haas *et al.*, 2002] is equivalent of considering a range propagation model, i.e. each transmission is correctly received if transmitter and receiver are within a given distance.

The performance of the TC-ADHOC MAC have been tested in two different traffic configurations: **static** and **dynamic**.

In the **static configuration** a number of terminals, M, is randomly generated within the network at time 0 and the TC-ADHOC MAC algorithm is applied. The simulation is stopped when convergence is reached, i.e. when the transmission power of all the terminals within the network does not change for 50 consecutive VFs. Depending on the particular topology control algorithm and on the network load, it may happen that some terminals can never get their BCHs. In order to prevent these terminals from degrading the overall performances due to their continuous unsuccessful attempts of accessing the channel, we allow them a fixed number of attempts, B, after which, if unsuccessful, they are declared to be in outage and their activity is suspended. The results are averaged over multiple simulation runs to get average performance figures.

In the scenario above we validate the correctness of the topology control algorithm and test the impact of different approaches to the TUP on the capacity of the channel access scheme.

In the **dynamic scenario** new terminals are generated according to a Poisson process with intensity Y [new terminals/s]. Each terminal has a random lifetime, geometrically distributed with mean L [frames]. Both L and Y are input parameters of the simulator, and they identify the offered traffic. A measure of the offered traffic is given by G_{Net}, defined as the average number of terminals per slot in the network. In this configuration we test the capability of TC-ADHOC MAC to fulfill the connectivity requirements in a dynamic scenario. We also determine the single hop broadcast throughput of the network in more realistic circumstances where the interference due to concurring access attempts is present.

The common framework of simulation parameters comprises the length of frame VF $= 100\,\mathrm{ms}$, the terminals lifetime $L = 300$ frames in the dynamic scenario, the number of slots within a frame $N = 30$, the power step P_{step} corresponding 1 m distance increase, the outage parameter $B = 10$, $PCP = 5$ frames and P_{max} set to reach a distance of $d_{max} = 250\,\mathrm{m}$ in a square wrap-around simulation area with edge equal to 1 km. We will refer to this simulation setting throughout the paper as *Standard Setting*.

4.1. *Static analysis*

As already pointed out in the previous sections, many of the topology control solutions presented in the literature propose to resort to maximum transmitted power whenever the number of perceived bidirectional neighbors falls below the connectivity threshold [Liu & Li, 2002; Blough *et al.*, 2003; Yu *et al.*, 2004]. On the contrary, we argue that such approach can impair the performance of the channel access mechanism since it tends to increase the average level of interference within the network and reduces the available bandwidth.

In order to validate this intuition, we compare TC-ADHOC MAC with the Power Ramping (PR) procedure against a modified version resorting to Maximum Power (MP) whenever the number of neighbors is below the connectivity threshold.

Figures 4 and 5 compare the TC-ADHOC MAC with Power Ramping (PR) procedure against a modified version resorting to Maximum Power (MP) whenever the number of neighbors falls below the connectivity threshold. Figure 4 gives the average number of the installed bidirectional links versus the parameter K for different values of terminals density ($T = 100, 300, 500$ terminals/km^2), whereas Fig. 5 reports the outage probability versus K.

As expected, the topology control algorithm with the ramping mechanism adapts the transmitted power according to the terminals' density and provides in all the cases the

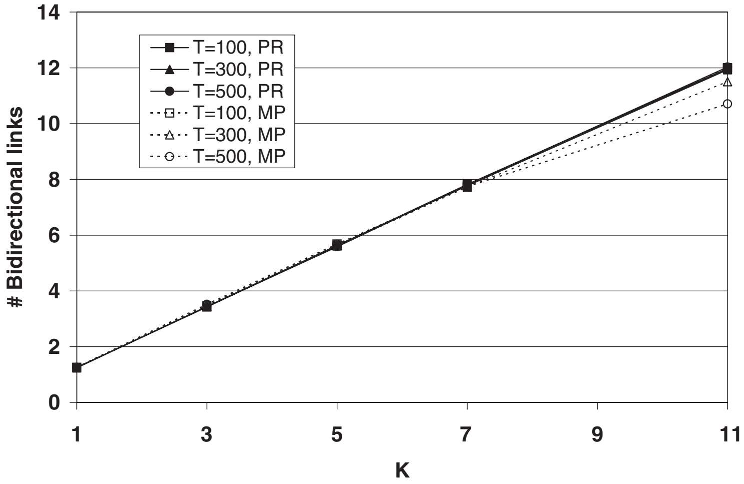

Fig. 4. Number of installed bidirectional links versus the parameter K with different densities of terminals when using power ramping procedure and maximum power transmissions. Standard setting of the simulation parameters.

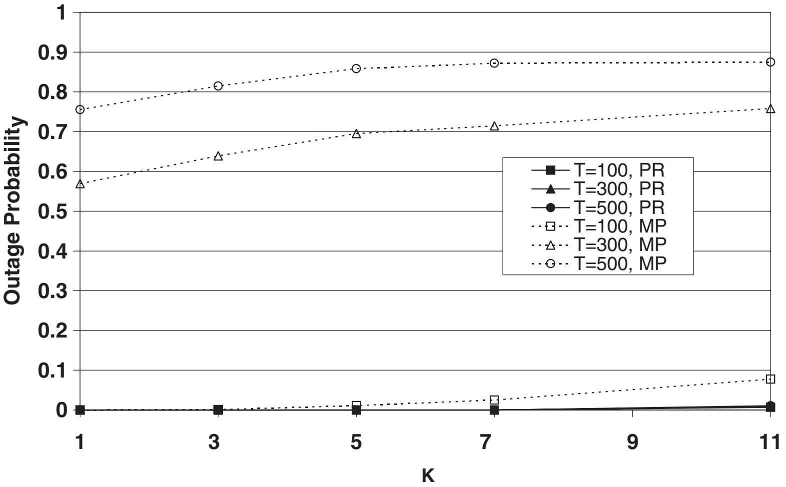

Fig. 5. Outage probability versus K with different densities of terminals when using power ramping procedure and maximum power transmissions. Standard setting of the simulation parameters.

same number of installed bidirectional links. For $K \geq 7$ a minimal fraction of terminals suffer outage due to the fact that with the chosen frame length available slots begin to lack (remember that the slots in the frame are used also by the neighbors of the neighbors).

On the other hand, when the maximum power procedure is applied outage is always present due to the increased interference level, although, for those acquiring the BCH, the connectivity target is reached for $K \leq 7$. The high value of the outage, however, makes this solution not suitable for values of terminal density greater than 100 terminals/km^2.

The concept behind this result is that an increase in the transmitted power leads to an increase in the number of neighbors and consequently, to an increase in the number of contenders during the channel access phase.

Now we compare the cases where the connectivity constraint is defined by a simple inequality ($M \geq K$) with the case where the connectivity constraint is defined by in interval ($M \in [K, K_{max}]$).

Figures 6, 7 and 8 show respectively the number of established bidirectional links, the average transmission radius normalized to the maximum coverage radius and the outage probability versus $K = K_{min}$, for different values of terminals' density, when $K_{max} - K_{min} = 6$.

From Fig. 6, the use of the connectivity interval leads to install a number of bidirectional links close to K_{max} for all the values of terminals' density. This outcome impacts on the efficiency of the channel access mechanism since the average transmission radius is increased for all the values of terminals' densities (Fig. 7). Consequently, the access resource suffer a shortage, as clear from Fig. 8.

These results lead to the conclusion that the transmitted power should be kept as low as possible when matching the connectivity constraint. To this goal, the interval specifying the connectivity constraint $[K, K_{max}]$ needs to shrink with K_{max} eventually getting equal to K.

On the other hand, larger connectivity interval can lead to faster convergence of the topology control algorithm. Figure 9 compares the convergence time of the TC-ADHOC MAC using as connectivity threshold K with the one of topology control algorithm using a

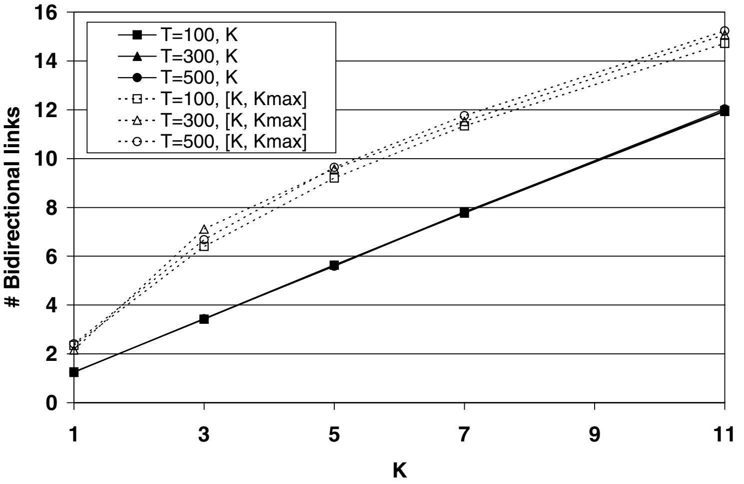

Fig. 6. Number of installed bidirectional links versus K when using different definitions for the connectivity constraint. Standard setting of the simulation parameters.

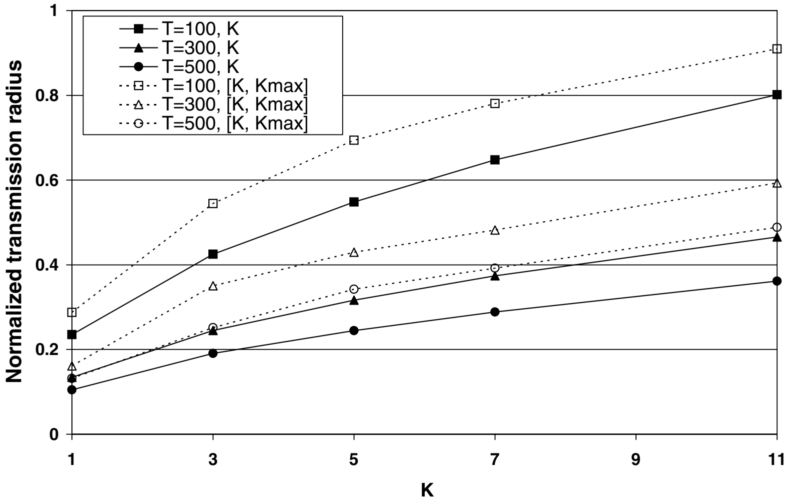

Fig. 7. Normalized transmission radius versus K when using different definitions for the connectivity constraint. Standard setting of the simulation parameters.

connectivity interval $K_{max} - K = 6$, when $K = 5$. The convergence time is measured as the number of power control periods to be performed to reach convergence assuming a cold start situation, i.e. with all the terminals entering the network at the same time. As clear from the figure, in a cold start situation the convergence time of TC-ADHOC MAC is similar to the one obtained using $K_{max} - K = 6$ for low values of network densities (100, 150 terminals/km^2), and is twice bigger for higher values of density. Furthermore, both the curves tend to decrease for increasing values of terminals' density, since the power ramping phase duration decreases when the number of terminals within the network augments.

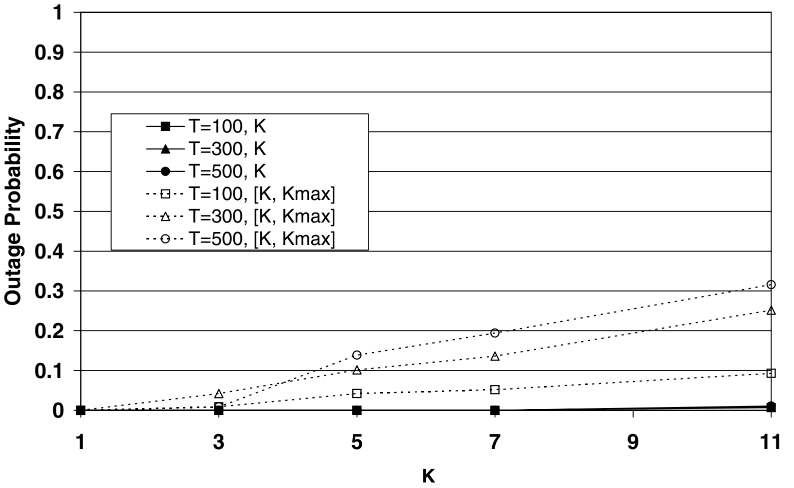

Fig. 8. Outage probability versus K when using different definitions for the connectivity constraint. Standard setting of the simulation parameters.

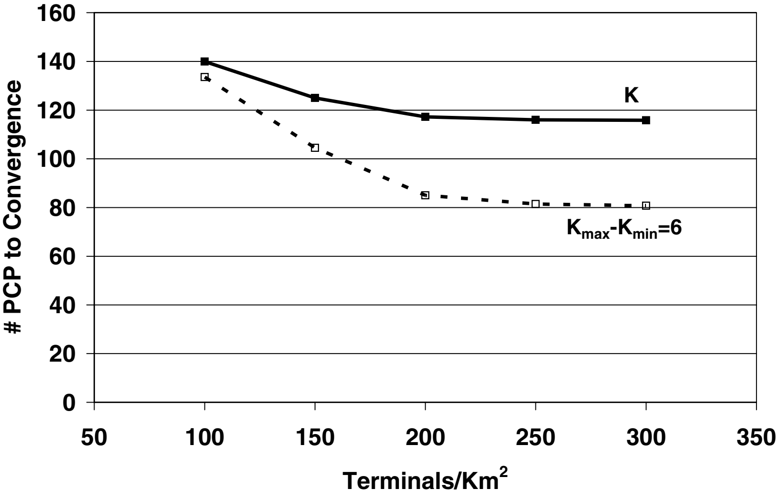

Fig. 9. Number of Power Control Periods (PCPs) to convergence versus the density of terminals. Standard setting of the simulation parameters.

4.2. *Dynamic analysis*

The behavior of the network under dynamic traffic is depicted in Figs. 10, 11 and 12. The first one compares the maximum single hop broadcast throughput obtained in the case of Fixed transmission Power ADHOC MAC (FP ADHOC MAC) with the throughput achieved by TC-ADHOC MAC as a function of the network traffic G_{Net}, when varying the parameter K. The throughput S_{Net} is defined as the number of active transmissions per slot in the network. The throughput curve for FP ADHOC MAC, previously obtained in

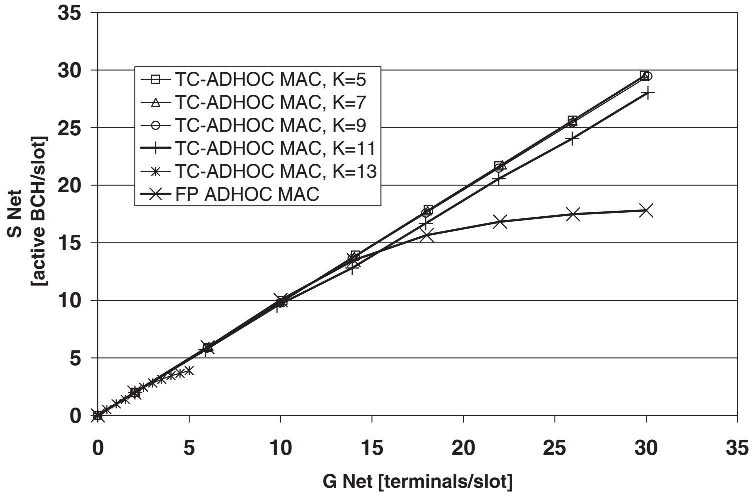

Fig. 10. Network throughput of the BCHs versus network offered traffic for different values of K in the standard setting of simulation parameters. Comparison between the Topology Controlled ADHOC MAC and the Fixed Power ADHOC MAC.

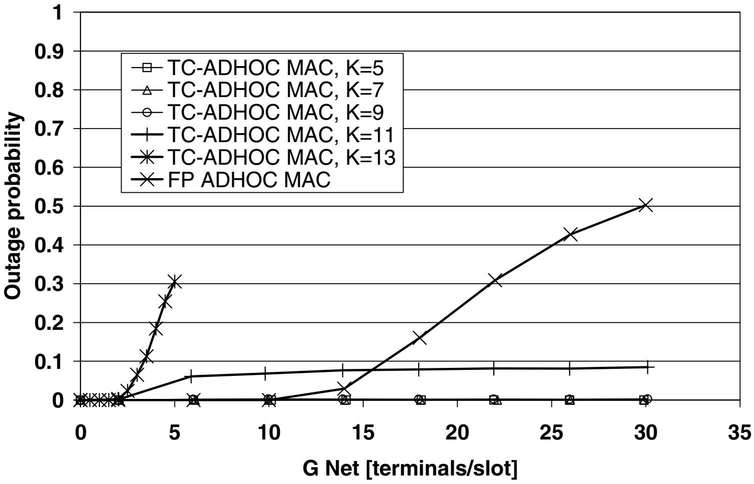

Fig. 11. Outage probability versus the network offered traffic for different values of K in the standard setting of simulation parameters. Comparison between the Topology Controlled ADHOC MAC and the Fixed Power ADHOC MAC with the topology control.

[Borgonovo *et al.*, 2003], shows a linear increase until capacity is reached. Beyond this point, the fraction of terminals in outage increases (see Fig. 11) and the throughput saturates.

As far as TC-ADHOC MAC is concerned, under ideal conditions, we would observe a straight line $S_{Net} = G_{Net}$ for any G_{Net} value. In fact, the protocol adapts the transmitted power to an increase of the offered traffic by shrinking the transmission radius to match the connectivity degree. In this case the throughput in the coverage area remains the same and equals the offered traffic in the same area if the frame is large enough to accommodate

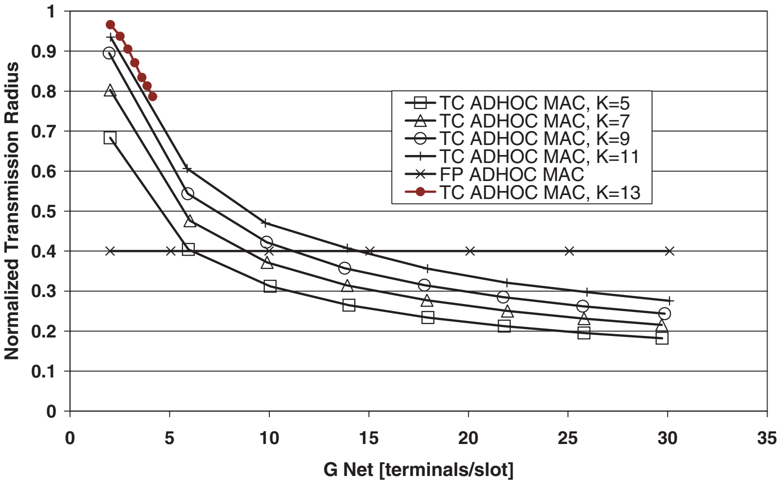

Fig. 12. Normalized transmission radius versus network offered traffic for different values of K in the standard setting of simulation parameters. Comparison between the Topology Controlled ADHOC MAC and the Fixed Power ADHOC MAC.

all the terminals. In practice, as we have already noticed in the static case, the frame length can accommodate a finite number of terminals, $K = 7$, without outage. For $K = 11$ the bandwidth is still sufficient to accommodate all but a small fraction of terminals (11), thus the throughput still grows along a straight line with the offered traffic, but with a smaller slope. For $K = 13$ the bandwidth is clearly not sufficient to accommodate all the connections, and the fraction of terminals in outage sharply increases with the offered traffic.

5. Conclusions

The topology of any wireless network can have a dramatic impact on the network performances in terms of connectivity, reuse and energy efficiency. In *ad hoc* networks the topology may be highly variable due to terminals' mobility and wireless link variability. In this scenario, an effective topology control algorithm is central to determine the success of those kind of networks.

In this paper, we have proposed a novel topology controlled MAC algorithm, i.e. the TC-ADHOC MAC, able to dynamically adapt to network changes due to terminal mobility. The topology update phase of the algorithm is performed by exploiting connectivity information provided at the link layer by the ADHOC MAC protocol, and aims at maintaining the number of bidirectional links below a given connectivity threshold.

We have validated the topology control mechanism by testing its behavior in static traffic environment gathering interesting guidelines for the parameter setting. In details, we have proved through simulation that using maximum power when searching for neighbors leads to an increase of the average level of interference and, consequently, to a reduction of the network reuse. Furthermore, we have evaluated the impact of different connectivity constraint driving the topology update phase.

Finally, we have tested the TC-ADHOC MAC in a dynamic scenario where mobile terminals enter and leave the network according to a time varying process. In this environment, we have shown that TC-ADHOC MAC reduces the interference perceived by each terminal thus providing a higher reuse gain with respect to the basic ADHOC MAC, i.e. using fixed transmission power.

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