Maximum Throughput Analysis in Ad Hoc Networks

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Abstract. The IEEE 802.11 standard for ad hoc networks uses a distributed access mechanism in the shared medium that attempts to avoid collisions by performing carrier sensing, inter-frame spaces, and a backoff mechanism. This paper aims at deriving an analytical expression for the maximum throughput of a communication between two nodes. The communication is achieved in a multi-hop scenario and the path from the source to the destination consists of a chain of nodes. We analyze the multi-path communication and show that the maximum throughput can be increased with the simultaneous use of two paths: the shortest path and an appropriate alternative path that takes into account the interference problem. We also derive the constraints for this alternative path. The use of multiple alternative paths can be considered in order to achieve a load and energy balancing.

1 Introduction

Nowadays, the IEEE 802.11 [1,2] is the most famous standard in local wireless networks. In the ad hoc mode, it uses the distributed medium access mechanism called DCF (Distributed Coordination Function), which applies the CSMA/CA (Carrier-Sense Multiple Access/Collision Avoidance) access method. The collision avoidance is carried out by carrier sensing, inter-frame spaces and a backoff mechanism that uses a contention window. Furthermore, after each successful transmission, the receiver must send an ACK to the sender indicating the success of the operation. That is necessary because in wireless networks, due to the significant difference between the transmitting and the receiving signal power, only the receiver is able to identify a collision.

The hidden terminal problem is a classical challenge in wireless networks. This problem arises because the carrier sensing is accomplished at the sender, but the transmission success is observed at the receiver. Therefore it is possible that a node senses the medium free and starts transmitting, but in the receiver point of view the medium was busy, which means that there was already a transmission that could not be noticed by the last sender due to the long distance between the two senders. To solve the hidden terminal problem, the DCF proposes the use of RTS (Request To Send) and CTS (Clear To Send) frames. By means of an RTS frame, the sender shows all his neighbors the intention to transmit and the receiver allows the transmission by sending a CTS frame, showing that its neighborhood is free. The DCF mechanism derives another benefit from these frames, making it possible for implementing a virtual carrier sense, by indicating in RTS and CTS frames how long the medium will be busy.

Xu *et al.* [3] analyzed the effectiveness of the RTS/CTS handshake and showed that it cannot completely solve the hidden terminal problem, due to the effect of the interference. This mechanism assumes that all nodes that could interfere with the frame reception, which will be called hidden nodes, are able to receive the CTS too. Xu *et al.* [3] derived an expression showing that the interference range is a variable range depending on the distance from the sender to the receiver and the signal to interference relation at the receiver. Moreover, they showed that when the distance from the sender to the receiver is longer than a threshold value, the interference range becomes greater than the transmission range. That happens because the interfering signal power is much less than the signal power required for a correct reception. As a consequence, we cannot assume that the CTS frame is received by a hidden node.

Saadawi *et al.* [4] considered the performance of the IEEE 802.11 medium access control (MAC) protocol in multi-hop ad hoc networks, through the analysis of a TCP (Transmission Control Protocol) traffic. Although the IEEE 802.11 can support ad hoc networks, they argued that the multi-hop connectivity poses serious problems, degrading its performance.

Gupta *et al.* [5] and Li *et al.* [6] analyzed the capacity of ad hoc networks. They showed that the capacity clearly depends on some local radio parameters, the MAC protocol used, the network size, and the traffic patterns. These characteristics directly affect the efficiency and scalability of the network. If the communications take place distant from each other, then the spatial reuse of the bandwidth increases. In contrast, if neighboring nodes want to send a frame concurrently, they compete for the medium, according to the medium access mechanism. In addition, it is worth mentioning that the average number of hops in the communications also plays an important role.

Li *et al.* [6] analyzed the capacity of a chain of nodes considering the interference range. They showed the maximum utilization achievable for a fixed interference range. Considering that the interference range is actually variable, in this paper we generalize this result for any signal to interference relation required for a successful reception and any distance of neighboring nodes.

In addition, we use multiple paths to increase the throughput of a communication. We show that the maximum throughput is achieved with only two paths to the destination: the shortest path and an appropriate alternative path that takes into account the interference problem. We present the constraints that should be respected by this alternative path. Besides we generalize an expression for the maximum utilization achievable using multiple paths for any signal to interference relation required for a successful reception and any distance of neighboring nodes.

At last, we consider the implementation of the interference aware alternative path. Since it relies on some location information, it is suggested the use of geographic routing. If the nodes remain always static, as in a rooftop network, or they have a slow moving dynamics, as in sensor networks, then finding a good alternative path is easier. The faster the nodes in the network move, the more difficult becomes the task of finding a convenient alternative path. In this case, attempting to accomplish this task, we suggest the implementation of an anchored path, as it is done by the Terminodes routing [7,8], listing in each packet a list of geographic fixed regions strategically chosen to guide the way a packet is supposed to travel until it gets to the destination.

The remainder of this paper is organized as follows. In Section 2, we present the interference effect. In Section 3, we analyze the maximum utilization of a chain of nodes and derive a generic expression. In Section 4, we show that the use of an alternative path can improve the throughput experienced by the source. It is shown how this alternative path should be and it is calculated the maximum utilization provided by this method. In Section 5, we consider the use of multiple alternative paths. In Section 6, we take into account the implementation of the alternative path. Section 7 presents our conclusions.

2 The Interference Effect

Let us consider a transmission in an IEEE 802.11 network. In order to correctly receive a packet, the signal power at the receiver must be strong enough. Hence, the signal to noise plus interference relation must be greater than the minimum value specified for the receiver equipment. Due to the signal attenuation in the air, increasing the distance from the sender to the receiver results in the reduction of the signal power at the receiver, which means that nodes more distant from the receiver can become hidden nodes.

Let d be the distance from the sender to the receiver, r be the distance from the receiver to a third node that might want to transmit, and SIR_{TH} the minimum value for the signal to interference relation (SIR) required for a successful reception. Xu *et al.* [3] argued that the thermal noise can be ignored when compared to the interference signal; accordingly, we also ignored it in our analysis in this paper. Then Xu *et al.* derived the Equation 1, which implies that every node separated by less than $d\sqrt[4]{SIR_{TH}}$ meters from the receiver can indeed interfere with its reception.

$$SIR = \left(\frac{r}{d}\right)^4 < SIR_{TH}$$
$$r < d\sqrt[4]{SIR_{TH}} \tag{1}$$

Let us define R_{Tx} as the transmission range. It can be easily shown [3] that when the sender and the receiver are more than $\frac{1}{\sqrt[4]{SIR_{TH}}}R_{Tx}$ meters away from each other, the RTS/CTS handshake does not solve the hidden terminal problem.

Let us assume that the nodes N_S and N_R are the sender and the receiver of a transmission, respectively. In Figure 1, the A_{RTS} and A_{CTS} areas are the regions reached by the RTS and CTS frames, respectively sent by N_S and N_R. In Figure 1, the SIR_{TH} is such as $1 < SIR_{TH} < 16$. The A_{Int} area represents the region where hidden nodes might be located. In Figure 1, the sender and the receiver are separated by the maximum distance (R_{Tx}). In this case, the interference range and the $A_{Int} - (A_{RTS} \bigcup A_{CTS})$ area are maximized. Other ad hoc nodes, represented by N_A, N_B, and N_C, might want to transmit during the transmission of N_S. It can be seen at Figure 1 that N_A and N_B would not transmit simultaneously with N_S, since they previously received the RTS and CTS frames, respectively, of the handshake implemented by N_S and N_R. However if N_C, which is not aware of this handshake, wants to send a frame, then it would proceed to its transmission, interfering with the reception of N_R.

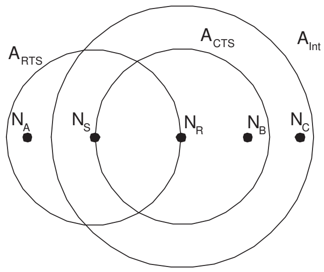

Fig. 1. The interference effect

3 Capacity Analysis of a Chain of Nodes

The highest throughput can be achieved when the destination is in the transmission range of the source, called "direct communication", and the medium is always free. Li *et al.* [6] showed that, for the IEEE 802.11 at 2Mbps, the maximum throughput is 1.7Mbps for 1500 bytes of packet size. The data rate reduction is due to the overhead added by the RTS/CTS/ACK exchange and the inter-frame timings. Furthermore the data rate depends on the packet size. The same considerations can be used in order to calculate the maximum throughput at other rates, such as 11Mbps or 54Mbps. The scenario with only two neighboring nodes can be considered as the simplest chain case and can be taken as a baseline for comparison, giving an upper bound for the throughput of a chain. Hence, in the following analysis, the maximum utilization of a general case is a fraction of this reference value. The general case is a "multi-hop communication" where, due to constraints in the consumption of power, bandwidth, and energy, the nodes need to cooperate forwarding packets from the source to the destination. We will analyze the behavior of a multi-hop chain of nodes transmitting a flow of packets.

Li *et al.* [6] analyzed the capacity of a chain of nodes aligned in a row and separated by 200m from each neighbor. They also simulated it in NS. In the NS, as a means of achieving a realistic model, the physical radio characteristics of each mobile node [9], such as the transmit power, the antenna gain, and receiver's sensitivity, are based on the Lucent WaveLAN model. This way, the transmission range is set to 250m and the SIR_{TH} is set to 10. In the analysis, Li *et al.* assumed a simplification: they considered the interference range fixed at 550m, instead of variable. Besides they considered the carrier sensing range equal to the transmission range; such consideration is also assumed in this paper. Figure 2 presents a chain of 7 nodes, separated by 200m from each neighbor. Since the transmission range is 250m, a packet sent by the node P_S is able to reach the destination P_D, by passing sequentially through the nodes P_1, P_2, P_3, P_4, and P_5.

Li *et al.* [6] argued that the maximum utilization achieved by their chain is $\frac{1}{4}$. As they remarked, nodes P_S and P_1 cannot transmit a frame together, since P_1 cannot send and receive at the same time; and the nodes P_S and P_2 cannot transmit simultaneously, because P_1 cannot correctly receive the frame of P_S if P_2 is transmitting together. Concluding the explanation of a maximum utilization of $\frac{1}{4}$, they justified that P_S and

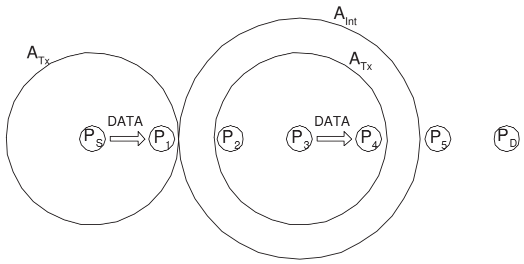

Fig. 2. Chain of 7 nodes separated by 200m from each neighbor. The interference range is according to Equation 1

P_3 cannot transmit at the same time, because the transmission of P_3 would interfere with P_1's reception of the frame sent by P_S. This argument was based on the fixed interference range set to 550m.

Nevertheless, Xu *et al.* [3] showed that the interference range is variable, depending on the distance from the sender to the receiver and the signal to interference relation required for a correct reception. Accordingly, we consider this range variable in this work. Since the distance between two consecutive nodes is 200m, the Equation 1 shows that the interference range is only 356m. Then a transmission from P_3 does not disturb the transmission of P_S because P_3 is separated from P_1 by a distance greater than the interference range, as illustrated in Figure 2. So, as shown by Xu *et al.* [3], the maximum utilization achievable is $\frac{1}{3}$.

Let us define the maximum utilization as U_{max}. Now, we will analyze the maximum utilization of the chain when the distance d between neighbors in the chain is such as $\frac{R_{Tx}}{2} < d \leqslant R_{Tx}$. Our point is that if $d > R_{Tx}$ then it is impossible getting to the destination and if $d \leqslant \frac{R_{Tx}}{2}$ then each node would not send a packet to its closest neighbor, instead each node would send it to its neighbor closest to the destination, as a means of minimizing the number of hops. The arguments which justified that P_S cannot transmit simultaneously with P_1 or P_2 remain valid for any value of d and SIR_{TH}. Then $\frac{1}{3}$ is an upper bound for U_{max}.

Let K be the number of nodes which are in the interference range of the source. Therefore $K = \lfloor \frac{R_{Int}}{d} \rfloor = \lfloor \sqrt[4]{SIR_{TH}} \rfloor$. Then analyzing the successors of P_1, its reception of a frame can be interfered by all its successors until P_{K+1}. In addition, P_{K+2} and its successors cannot interfere with the transmission of P_S. So U_{max} is given by Equation 2 for $\frac{R_{Tx}}{2} < d \leqslant R_{Tx}$:

$$U_{max} = \frac{1}{K+2} \tag{2}$$

The maximum utilization depends on the SIR_{TH}. It can be remarked that the SIR_{TH} must be greater than 1. In this paper, we derive generic equations, but we evaluate $K = 1$ or $K = 2$, constraining the SIR_{TH} value to $1 < SIR_{TH} < 81$ that is a realistic case. For example, if $SIR_{TH} = 10$, then $K = 1$, which implies $U_{max} = \frac{1}{3}$, and if $SIR_{TH} = 20$, then $K = 2$, which implies $U_{max} = \frac{1}{4}$.

Let us assume P_S is transmitting a frame to P_1. Then the RTS/CTS handshake successfully forbids P_1 and P_2 from starting to transmit together. If $SIR_{TH} < 16$, this handshake performs well for achieving the maximum utilization, as P_3 and P_S can indeed send frames concomitantly. But if $SIR_{TH} > 16$, it does not perform as well. The nodes from P_3 until P_{K+1} do not listen to the RTS and CTS frames sent by P_S and P_1, so they will not avoid simultaneous transmissions with P_S. Therefore, increasing the frame rate at P_S beyond U_{max}, the chain will experience collisions, which will force retransmissions and implementation of longer backoff waiting times. Ultimately, it will reduce the utilization and the delivery rate.

4 The Use of an Alternative Path

We propose a way of improving the flow utilization. We define P_S and P_D as the source and the destination of a flow of packets. As illustrated in the Figure 3, let us suppose there is a second path (P_S, A_1, A_2, ..., P_D) to the destination. This path is longer, so a single path routing protocol, executing a minimum hop metric, will keep on using the path P_S, P_1, P_2, ..., P_D.

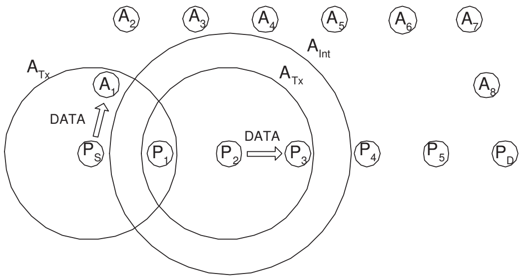

Fig. 3. A default chain and an alternative path

In the chain case, we argued that $\frac{1}{3}$ is an upper bound for the maximum utilization. We argue that we can increase the throughput, taking another way to get to the destination. The flow can be split in two parts using two different paths, as illustrated in Figure 3: the default path, through nodes P_S, P_1, P_2, ..., P_D and an alternative path, through the nodes P_S, A_1, A_2, ..., P_D. The source injects frames into the network, alternating each frame through each path. In this case, we argue that $\frac{1}{2}$ is an upper bound for the maximum utilization, as it will be explained. If P_1 is transmitting, then P_S cannot send a frame, since P_S is able to listen to the transmission and senses the medium busy. In addition, if it is implemented the RTS/CTS handshake then P_S has received the RTS from P_1. But, if P_2 is transmitting, then P_S does not listen to the transmission and also has not listened to the handshake originated by P_2, if the RTS/CTS handshake is used. Therefore, P_S can send a frame simultaneously with P_2. P_S cannot send it to P_1, since P_1 can listen to both P_S and P_2 and will not correctly receive the frame sent by the source. In addition, if the RTS/CTS handshake is applied, then P_1 will not send a CTS in response to the RTS issued by P_S, forbidding the transmission from the source. However if the source has a neighbor, which is not in the interference range of P_2, then P_S can effectively send a frame to this node. This way, in Figure 3, where $1 < SIR_{TH} < 16$, P_2 can send a frame to P_3 while P_S send the next frame to A_1.

Again, let us assume that each node is separated from its neighbors in each path by a distance d, such as $\frac{R_{Tx}}{2} < d \leqslant R_{Tx}$. Let the function $dist(P_A, P_B)$ denote the distance from the node P_A to the node P_B. Again, let K be $\lfloor \sqrt[4]{SIR_{TH}} \rfloor$, which is the number of nodes that are in the interference range of the source. In the chain case, we allowed the concomitant transmission of P_S and P_{K+2} or any of its successors, but we forbade the simultaneous transmission of P_S and P_{K+1}, since $dist(P_1, P_{K+1}) \leqslant R_{Int}$. Aiming at increasing the throughput, now we allow this concomitant transmission, if P_S can send a frame to a neighbor A_1, such as $dist(A_1, P_{K+1}) > R_{Int}$. An equivalent law should be respected by the nodes P_1 and A_{K+1}. An analogous procedure is recommended at the end of the process, when the two paths get closer to each other. And in the middle of the chain, we recommend that a distance greater than R_{Int} should be guaranteed. This procedure, which will be called $Proc_{Alt}$, is implemented as an example in Figure 3.

In fact, allowing the simultaneous transmission of P_S and P_{K+1} with $Proc_{Alt}$ is the best option we have, since the simultaneous transmission of P_S and P_K would imply a lot of collisions, degrading the performance. Since $dist(P_S, P_K) \leqslant R_{Int}$, if the nodes are not synchronized (and we cannot assume such synchronism in the DCF mechanism of IEEE 802.11), then both P_S and P_K will often experience problems at accomplishing the DATA/ACK (or the RTS/CTS/DATA/ACK) handshake. Not receiving the ACK means to the sender a failure and forces the retransmission of the DATA frame. And if the RTS/CTS handshake is implemented, not receiving the CTS forces the retransmission of the RTS; in addition, it forbids the transmission of the DATA frame until the correct reception of the CTS. At last, if we allow the simultaneous transmission of P_S and P_{K-1} or any other node in the chain between P_S and P_{K-1}, then it is impossible finding a neighbor of P_S, which is not interfered by the concomitant transmission of this distant node. In addition, P_S is also in its interference range.

$Proc_{Alt}$ allows nodes P_S and P_{K+1} (and also nodes P_S and A_{K+1}) to transmit simultaneously. Then Equation 3 gives the maximum utilization achievable by $Proc_{Alt}$.

$$U_{max} = \frac{1}{K+1} \tag{3}$$

From Equations 2 and 3, we notice that the achievable gain is $100\left(\frac{K+2}{K+1} - 1\right)$ in percentage, where $K \geqslant 1$. If $1 < SIR_{TH} < 16$, then $Proc_{Alt}$ gives a 50% gain, achieving a maximum utilization of $\frac{1}{2}$, which is already the upper bound for the utilization. And if $16 \leqslant SIR_{TH} < 81$, then $Proc_{Alt}$ achieves a gain of 33% and a maximum utilization of $\frac{1}{3}$.

In Figure 4, it is presented the beginning of a default and an alternative path. The two paths are respecting $Proc_{Alt}$, so they will end in an analogous way. Let us assume that the nodes P_S, A_1, ..., A_{K+1} of the alternative path are also aligned as a row. Let

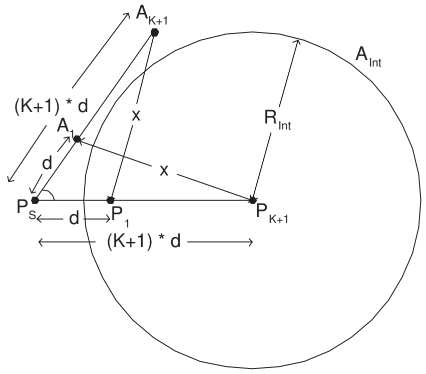

Fig. 4. Angle used to choose an alternative path with $Proc_{Alt}$

the angle $P_S \angle P_1, A_1$ be α. The triangles $\triangle P_S, A_1, P_{K+1}$ and $\triangle P_S, P_1, A_{K+1}$ are equivalent because

$$
\begin{aligned}
dist(P_S, P_1) &= dist(P_S, A_1) &&= d; \\
dist(P_S, P_{K+1}) &= dist(P_S, A_{K+1}) &&= (K+1)d; \\
P_S \angle A_1, P_{K+1} &= P_S \angle P_1, A_{K+1} &&= \alpha.
\end{aligned}
$$

Therefore $dist(P_1, A_{K+1}) = dist(A_1, P_{K+1})$, which we define as x. Let us define β as $P_S \angle A_1, P_{K+1}$ when $x = R_{Int}$. Then, by the cosine law, Equation 4 gives the value of β. To increase the throughput, avoiding collisions due to the interference, we have to choose α, such as $x > R_{Int}$, then $\beta < \alpha < 360 - \beta$.

$$
\begin{gathered}
d^2 + (K+1)^2 d^2 - 2d(K+1)d \cos\beta = d^2 \sqrt{SIR_{TH}} \\
\beta = \arccos\left(\frac{(K+1)^2 + 1 - \sqrt{SIR_{TH}}}{2(K+1)}\right) \qquad (4)
\end{gathered}
$$

Figure 5 presents the value of β when the SIR_{TH} is varied. The lower is β, the greater is the neighborhood area of P_S which is not interfered by P_{K+1}, and also the greater is the range of values that α can assume. If the nodes are not previously ranged in a convenient way, instead they are randomly set in the scenario, then it is important having lower values of β (specially for not dense networks), because it results in a greater probability of finding an alternative path respecting $Proc_{Alt}$. As expected, in each interval limited by the fourth power of two integer values, the value of β increases, when the SIR_{TH} gets greater. Just after switching to the next interval, the node P_{K+1}, that can transmit simultaneously with P_S, gets one hop farther from the source. Therefore the maximum utilization gets lower, but, at this moment, the neighborhood area of the source disturbed by the interference is also reduced, explaining the reduction of β. In the extreme case when the SIR_{TH} is the fourth power of an integer value, β gets equal to zero. Accordingly, P_1 is the only neighbor of the source, which is in the interference range of P_{K+1}.

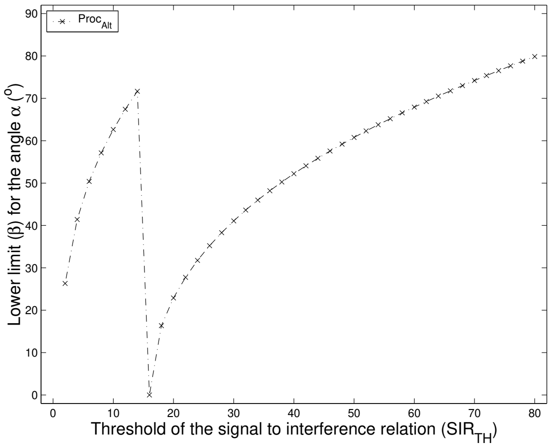

Fig. 5. The lower limit (β) for the angle α

5 Multiple Alternative Paths

As $dist(P_S, P_{K+1}) > R_{Int}$ and $dist(P_S, A_{K+1}) > R_{Int}$, it results that β is always less than 90^o, in accordance with Figure 5. Then it may be implemented more than one alternative paths. In fact, it can be generalized that it is possible to use a maximum of $\lceil \frac{360}{\beta} - 1 \rceil - 1$ alternative paths, if we have enough nodes located in a convenient way.

Assuming that the paths begin and end as aligned rows, to implement the interference awareness between the paths, the angle between each row should be greater than β. In Figure 6, where β is assumed less than 45^o, it is presented four alternative paths (ALT_1, ALT_2, ALT_3, and ALT_4), using $Proc_{Alt}$. All of them begin and end with a direction shifted by at least 45^o from each other and the default path. And, in the middle, it is guaranteed a distance greater than R_{Int} between all the paths.

Using multiple alternative paths allows a better load and energy balancing, which are two scarce resources in wireless networks. With a more equal consumption of energy by the ad hoc nodes, the network can last much longer. Supposing a network with different communications taking place simultaneously, it may be the case that the flow of traffic is concentrated in a region or a group of regions. Then it may be very interesting taking alternative paths, trying to bypass the overloaded paths. Nevertheless, if the network area is approximately equally loaded, then the use of only one alternative path is enough for getting the maximum utilization. That is because the moment when the source can switch from the first alternative path to a second one is also the moment when it can go back to the default path, which is attractive, since it uses less nodes. In this paper, we calculated the maximum utilization achieved by a source, when there is no other source of traffic. Then, in this case, the load balancing with the use of more than one alternative paths is not necessary.

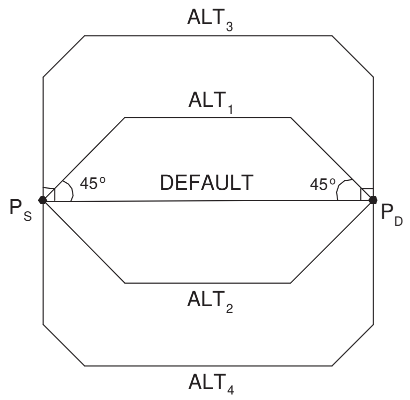

Fig. 6. Multiple alternative paths to the destination

6 Implementation of the Alternative Path

The implementation of the alternative path with an interference range aware procedure depends on some location knowledge. Hence, we suggest it should be based on a geographic routing paradigm. Implementing it in a distributed way is not trivial. It is made easier for static networks. For example, in an ad hoc rooftop network, used when the infra-structure is not properly working, the nodes remain still. We can even assume that a node previously knows the position of the other nodes, making the whole process easier. In this case, a source routing can be applied, where the source indicates in the packet all the nodes in the path to the destination, just like DSR [10] (Dynamic Source Routing) does. In an urban area (e.g. Manhattan), it rather be quite easy to find an alternative path able to improve the utilization. In addition, in a sensor network, it is common having slow moving nodes and a large density of nodes, then the process of finding an appropriate alternative path is also more easily accomplished.

We can also attempt to apply this procedure for rather faster nodes and evaluate its performance. In this case we suggest the use of an anchored path, as it is implemented by the Terminodes routing [7,8]. Instead of listing all nodes in the path to the destination, as it is done by the source routing paradigm of DSR, it can be listed some geographic fixed regions, called anchors, that will guide the way a packet is supposed to travel bypassing the interference.

In Figure 7, P_S and P_D are the source and the destination of a flow of packets, respectively; $DEFAULT$ and ALT are the default and the alternative paths respectively; $Anch_1$ and $Anch_2$ are two anchor regions strategically chosen. The anchor regions are calculated based on the angle α, which is relevant to the beginning and the end of the alternative path, and the necessity of respecting a distance greater than R_{Int} between the two paths in the middle of them. This way, in Figure 7, the alternative path, which passes by $Anch_1$ and $Anch_2$ before getting to the destination, is respecting the $Proc_{Alt}$ procedure. In the header of all the packets supposed to travel through the alternative path, it will be specified that the packet should go firstly to a point in the $Anch_1$

region, after it should go to a point in the $Anch_2$ region, and, at last, it will go to the destination. Between each of these areas, the packet will be routed in a greedy manner, trying to approach the desired position as fast as possible. In the header of the packets that go through the default path, it is specified only the position of the destination. They find their way in a greedy basis, with no need of anchors. In Figure 7, it is illustrated a simplified case where all the nodes are conveniently aligned. In this case, the greedy routing is able to get to each desired position in straight lines.

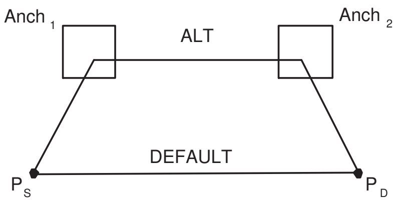

Fig. 7. Implementation of the anchored path to the destination

The faster the nodes move, the faster the links will break. But if we use anchors and we have a sufficiently high density of nodes well distributed over the total area, since geographic areas do not move, the path will be much more stable. Moreover the anchors are very appropriate to implement the bypassing of the default path.

7 Conclusions

In ad hoc wireless networks, the bandwidth is a scarce resource. In this work, we aimed at increasing the throughput verified by a source of traffic.

Analyzing the symptoms experienced by a chain of nodes is relevant, since the forwarding of packets is a frequent activity in ad hoc networks, where the nodes are expected to cooperate. If the source is transmitting, then its next two successors in the chain cannot transmit concomitantly. That reduces the maximum utilization of a chain to $\frac{1}{3}$ in the optimum case. If the signal to interference relation required for a good reception (SIR_{TH}) is greater or equal to 16, then, due to the hidden terminal problem, this optimum utilization cannot be achieved. We analytically derived Equation 2, which gives the maximum utilization in terms of the SIR_{TH}.

We analytically showed with Equation 3 that the simultaneous use of a default and an appropriate alternative path can increase the utilization of the chain. This way, if $1 < SIR_{TH} < 16$, then the maximum utilization gets $\frac{1}{2}$ and if $16 \leqslant SIR_{TH} < 81$, then the maximum utilization gets $\frac{1}{3}$. That represents a gain of 50% and 33%, respectively, over the single path case.

It is presented which kind of alternative path is able to bypass the interference problem. Since finding an appropriate alternative path depends on the knowledge of the position of the nodes, we suggested the use of the geographic routing paradigm. The process is easier accomplished for networks composed by static nodes, such as rooftop networks, or slow moving nodes, such as sensor networks. For networks composed by rather faster nodes, we suggested the use of an anchored path, as it is done by the Terminodes routing.

It is shown that the use of more than one alternative path does not increase the maximum utilization. Nevertheless, its use can be considered if the goal is load or energy balancing, which might be necessary since both bandwidth and energy are scarce resources in wireless networks.

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