On-Demand Beaconing: Periodic and Adaptive Policies for Effective Routing in Diverse Mobile Topologies

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Abstract

Locally aware routing protocols base their next-hop selection on information about their immediate neighborhood, gathered by means of a beaconing mechanism. In general, beacons may be proactively broadcasted from nodes to their neighbors ('receiver-initiated' beaconing) or may be solicited by the node carrying the routed message ('on-demand' beaconing). On-demand beaconing is of growing importance, mainly in more dynamic and sparse environments (e.g., Delay Tolerant Networks), and is addressed in this paper.

A generic analysis is provided for the case of periodically issued beacons, linking the beacon period to the trade-off between the quality of neighborhood perception (determining the routing effectiveness) and the required amount of signaling (related to energy expenditure at the nodes). The analysis leads to upper and lower bounds for the length of the beacon period, expressed in terms of mobility characteristics.

The paper also investigates policies where the inter-beacon intervals vary adapting to the environment, an approach most beneficial when routing is based on metrics bearing some relevance to time. This is the case with the MAD routing protocol, which incorporates the notion of 'retaining time', an estimate of the time that the carrying node will retain the message. It is shown that linking the beacon intervals to the each time applicable retaining time leads to an effective and efficient beacon policy.

The paper provides simulation-based evaluation results, validating the beacon period bounds and demonstrating that, for the case of MAD, adaptive beaconing is capable of providing even better performance.

Keywords: On-demand Beaconing, periodic/adaptive beaconing, diverse network conditions, routing protocols, Delay Tolerant Networks

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1. Introduction

In recent years there has been a growing interest in locally aware routing protocols, for use in mobile ad hoc networks and networks with even sparser topologies, e.g., Delay Tolerant Networks (DTNs). Such protocols can cope with the variability encountered in mobile environments by focusing only on information about the local area around the routed message, rather than trying to find or maintain an end-to-end path. Specifically, the node that carries a message collects relevant status from its neighbor nodes and then selects the most suitable neighbor for forwarding/routing the message. Typical suitability criteria include, among others, distance from the destination (to select the closest neighbor, which is suitable for routing in relatively dense topologies), or velocity (to select the best directed and/or fastest-moving node, which is suitable for routing in sparser topologies), or appropriate mixtures of both.

Regardless of the details associated with the particular suitability metric employed, there are two mechanisms that underlie the routing operation. The first is a mechanism to discover the position of the message destination, typically implemented through querying a location service [1]. The second is a signaling mechanism, referred to as beaconing, that enables the collection of neighbors-related status (position and/or velocity) by the node carrying a message.

There are two main approaches to beaconing. The first is 'receiver-initiated': the node possessing the message (also referred to as the "current node" in the following) waits for beacons issued proactively from its neighbors [2, 3]. The second approach is 'on-demand': the current node triggers itself the neighbors to send information, when it sees fit [4, 5]. Finally, there exist some schemes that attempt to eliminate beacons altogether, aiming at a reduced signaling overhead [6, 7, 8]. However, beacon-less schemes are associated with significantly higher end-to-end delays [9] and need to resort to local packet broadcasting, rather than next hop forwarding, something that leads to a higher collision probability and to a lower packet delivery ratio [10]. For a comprehensive taxonomy of the scheme categories just outlined see [11, 12].

In this work we focus on the 'on-demand' approach because it is better for routing in highly diverse topologies, which is our main target. Indeed, in dynamic and probably sparse topologies the routing information becomes frequently outdated and the current node deciding about the next hop should make sure that it has up-to-date information, in order to decide optimally and avoid forwarding failures. The 'on-demand' approach guarantees that an accurate depiction of the local topology is available, contrary to the 'receiver-initiated' approach, where it is necessary to incorporate additional mechanisms for validating the cached topology information [13, 14]. Another important characteristic of the 'on-demand' approach is the potential for energy savings at the nodes, something that contributes to a prolonged network lifetime. This is because in 'on-demand' schemes only nodes in the local area around the message need to be awake when triggered by a beacon from the current node. However, exploitation of this potential typically requires the usage of an additional interface, through which nodes are triggerred to wake up.

An important aspect of 'on-demand' beaconing is the pattern according to which the current node issues beacons to trigger its neighbors for information. An obvious possibility is to use a scheme of regularly issued beacons (referred to as 'periodic on-demand beaconing' in the sequel). Additionally, in many cases it is also possible to vary the inter-beacon intervals, in response to changes in the values of appropriate status parameters. This is called 'adaptive on-demand beaconing' in the following.

Periodic 'on-demand' beaconing has the merit of being generic, thus suitable for use with any existing routing protocol. Given the periodic nature of the beacons, the issue is to select an appropriate beacon period, as the value of this parameter has clear implications on the trade-off between performance and signaling overhead (and associated energy expenditure). Indeed, if the beacon period is very short, the local area around the routed message is burdened with unnecessarily heavy signaling (and the associated energy depletion and bandwidth consumption side-effects), without significant gains in status updates, as it is likely that almost nothing will have changed from the previous check of the neighborhood. On the other hand, if the beacon period is very long the signaling becomes negligible, but the current node now has only a poor perception of its neighborhood and may miss forwarding opportunities, so the routing becomes less effective.

Despite these important implications, to the best of the authors' knowledge the issue of determining appropriate values for the beacon period has not been studied yet. In an attempt to fill this gap, the paper contributes a generic analysis linking the beacon period to the quality of neighborhood perception. The analysis leads to upper and lower bounds for the length of the beacon period, expressed in terms of mobility characteristics. By employing a beacon period between the two boundary values, the current node can successfully balance the trade-off between routing effectiveness and signaling overhead. In accordance with the generic overall character of the periodic 'on-demand' beaconing, the analysis is applicable to any routing protocol that may make use of the beaconing scheme.

No matter how attractively simple and ubiquitously applicable the periodic 'on-demand' beaconing may be, there are cases where adaptive 'on-demand' beaconing schemes offer a greater potential, due to their intelligent adaptation of beacon intervals to status changes. Ideally, an adaptive 'on-demand' scheme should issue a beacon to trigger a neighborhood exploration only when the current node "senses" that some neighbor is likely to be a more suitable carrier than itself. Obviously, such functionality can be accomplished only if the routing protocol provides appropriate support, through relevant parameters and/or metrics.

The recent routing protocol MAD, developed in [15] and refined in [16], is particularly suitable for use with such adaptive 'on-demand' beaconing, as it incorporates a notion of time that can be naturally exploited for adaptivity. Specifically, MAD employs the, so called, 'retaining time', an estimate of the time that a node will keep the message once selected for carrying it. The retaining time encapsulates information relevant to the local environment around the routed message (nodal density and mobility) and to the current node (location and motion attributes).

In view of these remarks, the second contribution of the paper is an adaptive 'on-demand' beaconing scheme based on the current node's retaining time. As with periodic beaconing, to the best of the authors' knowledge this is the first attempt on beacon adaptation for the domain of 'on-demand' schemes. However, for completeness we now compare our approach with the recent works [17, 14], addressing the 'receiver-initiated' beaconing context.

[17] proposes two different adaptive schemes. In the first, called 'distance-based' beaconing, a node broadcasts a beacon whenever it has moved a given distance d. Also, a node removes from its neighborhood list a neighbor after moving for more than k times the distance d without hearing a beacon from this neighbor, or after a maximum time-out elapses. The main drawbacks of this scheme are that a slow node has outdated information and that such a node is not considered from a faster moving neighbor.

The second scheme is called 'speed-based' beaconing. According to it, both the beacon interval and the neighbor time-out interval are correlated with the node's speed. Also, a node determines the time-out applicable to a neighbor as the minimum between its own time-out and the time-out of the considered neighbor. With this enhancement, a slow node has a short time-out interval for its fast neighbors, therefore the first drawback of the previous scheme is eliminated. However, the drawback that a fast node may not detect slow nodes remains. Moreover, another drawback relevant to both schemes is that in sparse networks a node may fail to be detected from its neighbors.

Finally, the same work [17] also presents a reactive beaconing scheme, where a node having a message to transmit broadcasts locally a beacon request and waits for the beacons from its neighbors. Obviously, this last scheme belongs to the 'on-demand' category and the authors of [17] note that it outperforms the two other 'receiver-initiated' adaptive schemes. The scheme lacks a periodic or adaptive pattern for the beacons and relies on the assumption that the current node has at least one neighbor at all times. However, this is not true for the sparse topologies of DTNs. To combat this shortcoming, a pattern for issuing the beacons would be required (periodic or adaptive), as discussed here.

Work [14] proposes another 'receiver-initiated' adaptive beacon strategy, based on two rules for maintaining updated neighborhood lists. Towards the first rule, the neighbors of a node track this node's motion using simple linear equations. In parallel to this, the beacon generation rate at the node adapts to the frequency with which this node's velocity changes. Through these mechanisms, the neighbors of the node can accurately forecast the node's position. However, if the node moves in a steady linear pattern for a long time, e.g., as in highways [18], the beacon generation is very infrequent and new neighbors are unaware of the existence of that node in their vicinity. To combat this shortcoming, the second rule is incorporated, according to which, nodes overhearing a data transmission broadcast a beacon in response, towards maintaining a 'rich' neighbor list along the forwarding path. However, this mechanism presupposes the existence of at least one neighbor that would transmit a message and trigger the process of revealing more neighbors. As already mentioned, the existence of a neighbor at all times is not always a valid assumption, not only in very sparse networks, but also in more dense networks with uneven topological characteristics.

Recapitulating, the adaptive schemes in the works just reviewed are suitable only for dense environments, where a node always has at least one neighbor. By contrast, it will be seen that the 'on-demand' adaptive beaconing for the MAD protocol, as proposed here, has the potential of adapting to the whole range of topologies, from very sparse to dense. Moreover, by belonging to the 'on demand' category, the proposed scheme is capable of capturing and beneficially exploiting information relevant to the current node. Such a capability is inherently limited in 'receiver-initiated' schemes.

The remainder of this paper is organized as follows: Section 2 reviews principles and characteristics related to the MAD routing protocol and the retaining time concept and how this is impacted by the nodes' environment. Besides the background review, this section also provides comments on how the retaining time (and the routing decision metric that employs it) can capture the network environment and the current node's status. These remarks provide the basis for explaining the effectiveness of the adaptive beaconing scheme and facilitate its comparison with periodic beaconing later on in the paper. Section 3 presents the analysis for periodic 'on demand' beaconing, culminating in the development of the upper and lower bounds for the beacon period. The subsequent Section 4 develops the adaptive beaconing scheme based on the notion of the retaining time, for use with the MAD routing protocol. Section 5 evaluates and compares the performance of the paper's proposals, by means of simulation results. Finally Section 6 provides conclusions and some directions for future work.

2. Dynamically Optimized Routing for Networks with Diverse Density and Mobility Characteristics

2.1. General Overview of MAD and the Advance Metric

We consider a mobile ad hoc setting, where each mobile node can communicate directly with all other nodes within some given range r, defining the node's neighborhood. By means of the beaconing process, the current node checks its neighborhood and evaluates the appropriateness of the neighbor nodes as a next hop for the message, according to the advance metric to be discussed shortly. When this evaluation process indicates that there exist neighbor nodes more suitable than the current node, the latter forwards the message

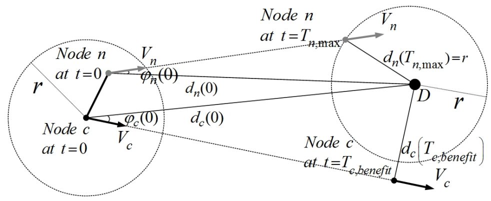

Figure 1: Packet forwarding and carry actions, and associated quantities.

to the most suitable such neighbor. Complementarily to the evaluation just mentioned, if the current node encounters within its neighborhood the destination node, it immediately delivers the message to it, thus terminating the routing process. When evaluating a neighbor, the current node employs information about the position and velocity of that neighbor.

The advance metric is intended to assess the rate at which the message will approach its destination, if the node associated with the metric is selected as the message's next hop. High rates of approach contribute to a smaller end-to-end delay. As we will see, the metric can capture the combined effect of important characteristics, including the nodal density in the surrounding area. The potential of the advance metric for expressing the impact of such factors is instrumental in making MAD capable to dynamically adapt its routing actions in diverse environments. In the following we refer to the reduction of a message's distance (actually, the carrier node's distance) from its destination as *progress* (measured in units of length) and the rate of progress as *advance* (measured in units of speed).

To proceed further, we need to describe concretely the degree by which the message approaches its destination node (labeled D in Figure 1) as a function of time, if the current node (c in Figure 1) forwards the message to a neighbor node (n in Figure 1). Conventionally, this forwarding is assumed to occur at time $t = 0$. Let $d_n(t)$ stand for the distance of node n from the destination D at time t and use V_n and $\phi_n(t)$ to denote the magnitude of node n's velocity and the angle between this velocity and the line segment from node n to the destination D at time t, respectively (see Figure 1).

When node n keeps on moving on a straight line trajectory at constant speed, its distance from the destination as a function of time is simply

$$d_n(t) = \sqrt{(V_n t)^2 + d_n(0)^2 - 2V_n t d_n(0) \cos\phi_n}, \quad \forall t \geq 0. \tag{1}$$

When the current node c considers its neighbor n as a next hop candidate, it takes into account the progress due to both the forward and carry actions. The first of these occurs instantaneously when passing the message from c to n at time $t = 0$, so

$$\mathrm{prog}_{cn,\mathrm{fwd}} = d_c(0) - d_n(0). \tag{2}$$

The effect of the carry action depends on the time T_n that node n will retain the message if it is selected as the next hop node. Given an estimate of this retaining time, the progress due to the carry action is equal to

$$\text{prog}_{n,\text{car}}(T_n) = d_n(0) - d_n(T_n). \tag{3}$$

Note that $\text{prog}_{cn,\text{fwd}}$ and $\text{prog}_{n,\text{car}}(T_n)$ may take negative values, the first when the distance of neighbor n from the destination at $t = 0$ is greater than that of the current node, the second when $\cos\phi_n(0) < 0$, i.e., when node n moves away from the destination.

Clearly, the overall progress is the sum of the forward and carry components in (2) and (3), respectively, and occurs over a time interval of length T_n, thus corresponding to an overall advance equal to

$$\text{ADV}_{cn,\text{tot}}(T_n) = \frac{d_c(0) - d_n(T_n)}{T_n}. \tag{4}$$

This overall advance metric is the sum of two terms, namely the advance component $\text{ADV}_{cn,\text{fwd}}(T_n) = \text{prog}_{cn,\text{fwd}}/T_n$, corresponding to (2), and the carry component $\text{ADV}_{n,\text{car}}(T_n) = \text{prog}_{n,\text{car}}(T_n)/T_n$, corresponding to (3). They represent the message's spatial transposition towards the final destination, over the entire retaining time, due to node's n forward and carry action respectively. In particular, the function $\text{ADV}_{n,\text{car}}(t)$ reflects the velocity of node n. Indeed, it is easy to see that $\text{ADV}_{n,\text{car}}(t) \approx V_n \cos\phi_n(0)$ for small values of t (and is a constant function equal to V_n for all t, when $|\cos\phi_n(0)| = 1$). When T_n is small (i.e., $T_n \to 0$), $\text{ADV}_{cn,\text{fwd}}(T_n)$ tends to $+\infty$ for positive forward progress and to $-\infty$ for negative forward progress. In both cases, its magnitude becomes much bigger than the $\text{ADV}_{n,\text{car}}(T_n)$, signifying that, for small retaining times the location factor is more important than motion. On the contrary, for large retaining times T_n, $\text{ADV}_{cn,\text{fwd}}(T_n)$ diminishes and $\text{ADV}_{n,\text{car}}(T_n)$ dominates, so the value of the metric is predominantly due to the carry action. In that way, the estimated retaining time T_n acts as a parameter for tuning the relative importance of the forward and carry actions.

As mentioned in the beginning of this section, the value of the metric $\text{ADV}_{cn,\text{tot}}(T_n)$ expresses the rate at which the message will approach its destination if node n is selected as the next hop. Such a selection will be reasonable only if this rate is higher than the one achieved when the current node retains the message. In order to determine this, the current node also calculates its own advance metric $\text{ADV}_{cc,\text{tot}}(T_n)$, setting $n = c$ in (4), but maintaining the same value of the retaining time T_n used when calculating $\text{ADV}_{cn,\text{tot}}(T_n)$ (the reason being that the advance of both nodes should be determined over the same time interval). Clearly, the value of $\text{ADV}_{cc,\text{tot}}(T_n)$ is only due to the carry effect. (This can be seen by (2), applied with $n = c$.) The relative merit of the neighbor node n over the current node c is expressed by the difference of the corresponding advance metrics

$$\begin{aligned}\Delta_n(T_n) &= \mathrm{ADV}_{cn,\mathrm{tot}}(T_n) - \mathrm{ADV}_{cc,\mathrm{tot}}(T_n) \\ &= \frac{d_c(T_n) - d_n(T_n)}{T_n}.\end{aligned} \tag{5}$$

If $\Delta_n(T_n) > 0$, node n is more beneficial than the current node and becomes a next hop candidate.

The same procedure is repeated for all neighbors of the current node and ultimately the message is forwarded to the node with index $j = \arg\max_n \Delta_n(T_n)$, justifying the name of the protocol (as Maximum Advance Decision or, alternatively, Maximum Advance Difference). Note that the selection works correctly even if $\Delta_j < 0$ for all neighbor indices j, since, by definition, $\Delta_c = 0$ and the current node will retain the message. (Ties with other nodes featuring also a zero Δ-value are resolved in favor of the current node.)

It is noted that the estimated retaining time T_n is used only for the purpose of calculating the advance metric of the respective node. If this node is chosen as the message's next hop node, it will not wait until the retaining time used for its selection expires, but will rather initiate a check for subsequent next hop nodes whenever the next beacon is issued.

2.2. Estimation of the Retaining Time and Associated Properties

The previous discussion made clear that the value of the Advance metric relies critically on the value of the associated retaining time, so a proper estimation of the latter is key to the effectiveness of the protocol. The original MAD protocol [15] followed an approach based on the fundamental notion that when node n moves towards the destination, it remains a beneficial carrier for the message's routing until it reaches the point closest to the destination along its straight-line trajectory. The time required for node n to reach that point is equal to

$$T_{n,\mathrm{ben}} = d_n(0)\cos\phi_n(0)/V_n \tag{6}$$

(see the lower right part of Fig. 1).

The node shouldn't keep the message further, because after time $T_{n,\mathrm{ben}}$ it will start moving away and its distance from the destination will keep increasing. Therefore, in this case the retaining time estimation is set equal to $T_{n,\mathrm{ben}}$. In the complementary case where node n moves away from the destination, the objective is to find a better next hop to forward the message as soon as possible, because the motion is harmful for the message's routing. The more neighbors around node n, the easier it becomes to find a next hop, thus the time required for that is a decreasing function of the nodal density ρ in the local environment (i.e., the number of neighbor nodes divided by the area of the coverage region πr^2). For the highest expected node density, the retaining time assumes its smallest possible value, equal to a protocol specified parameter T_d.

Putting together these observations, the original MAD estimates the retaining time as

$$\hat{T}_n = \begin{cases} T_{n,\mathrm{ben}} = d_n(0)\cos\phi_n(0)/V_n, & \cos\phi_n(0) > 0, \\ T_d\,\rho_{\max}/\rho, & \text{otherwise.} \end{cases} \tag{7}$$

Despite the fact that this estimation method is somewhat primitive, it can help MAD achieve self-adaptation in a considerable range of density and mobility conditions. Nevertheless, (7) fails to fully reflect the fact that, regardless of the direction of motion, as the forwarding opportunities (neighbors) observed by the node per unit of time increase, due to either an increased density ρ and/or an increased speed V_n, the retaining time of this node will tend to become smaller. Indeed, (7) involves the speed parameter only in its first branch (through (6)) and the density parameter only in its second branch.

Therefore, one direction for improvement over (7) is to involve both of the density and speed parameters in the retaining times relevant to all directions of motion. Additionally, a node moving towards the destination can be treated in a more refined way, by distinguishing between directions enabling the node to approach the destination close enough for delivering the message itself and directions for which such delivery is not possible. A refinement along these lines was presented in [16]. We now briefly review the main elements of this approach and comment on its potential to capture topological and node-oriented characteristics.

For the case of moving away from the destination ($\cos\phi_n(0) \le 0$) the reasoning behind the derivation of the retaining time remains much the same as before. The motion is counterproductive and the node should find a next hop to forward the message as soon as possible. The time required for that is still proportional to $\rho_{\max}/\rho$. The refinement is achieved by setting the smallest possible retaining time (corresponding to $\rho = \rho_{\max}$) equal to the time required by the node for renewing its neighborhood, namely equal to r/V_n. With this change, the retaining time when moving away from the destination takes the form of the third branch in (9) below.

When the node moves towards the destination ($\cos\phi_n(0) > 0$), it will eventually become capable of delivering the message to it exactly when the closest distance between node and destination is no greater than the node's range, i.e., when $d_n(0)\sin\phi_n(0) \le r$, or, equivalently, $\cos\phi_n(0) \ge \sqrt{1 - [r/d_n(0)]^2}$. The destination will enter the node's range and receive the message at time

$$T_{n,\max} = (d_n(0)\cos\phi_n(0) - \sqrt{r^2 - [d_n(0)\sin\phi_n(0)]^2})/V_n \tag{8}$$

(see upper right part of Fig. 1).

This is the greatest possible value for the retaining time in this case. It is assumed to occur in environments with the smallest expected density $\rho_{\min}$, in reflection of the fact that in such sparse topologies the node is not likely to encounter any forwarding opportunities better than itself until it reaches the destination. Higher densities result in a reduction of the retaining time in an inversely proportional fashion, as when the node moves away from the destination, and give rise to the expression in the middle branch of (9).

Finally, for motion towards the destination without the possibility of direct delivery (i.e., when $0 < \cos\phi_n(0) < \sqrt{1-[r/d_n(0)]^2}$), the node will keep approaching the destination up to time $T_{n,\mathrm{ben}}$; subsequently, it will move away. By a reasoning similar to the previous case, it is assumed that for sparse topologies corresponding to $\rho = \rho_{\min}$ the node reaches the point closest to the destination at time $T_{n,\mathrm{ben}}$ without having forwarded the message to another node and then moves away for an additional time equal to the value resulting from the third branch of (9) for $\rho = \rho_{\min}$, viz. $(r\rho_{\max})/(V_n\rho_{\min})$, after which it forwards the message. The total retaining time is $T_{n,\mathrm{ben}} + (r\rho_{\max})/(V_n\rho_{\min})$. Again, for higher densities, this maximal retaining time is reduced by the factor $\rho_{\min}/\rho$, leading to the first branch in (9).

$$\hat{T}_n = \begin{cases} T_{n,\mathrm{ben}}\frac{\rho_{\min}}{\rho} + \frac{r}{V_n}\frac{\rho_{max}}{\rho}, & 0 < \cos\phi_n(0) < \sqrt{1-[r/d_n(0)]^2}, \\ T_{n,\max}\frac{\rho_{\min}}{\rho}, & \cos\phi_n(0) \geq \sqrt{1-[r/d_n(0)]^2}, \\ \frac{r}{V_n}\frac{\rho_{\max}}{\rho}, & \cos\phi_n(0) \leq 0. \end{cases} \tag{9}$$

It may be observed that the retaining time in the third branch (node moving away from the destination) is always smaller than that in the first branch (node moving towards the destination, but without reaching it). This is not coincidental and reflects the fact that nodes moving away are not beneficial and should forward the message as soon as possible. On the contrary, nodes moving towards the destination without reaching it move in a more or less 'right' direction and are allowed to carry the message longer. Finally, nodes governed by the middle branch of (9) head towards the destination 'right on'.

Note also that, by virtue of (6) and (8), the 'threshold angle' $\phi_{n,\mathrm{thr}} = \cos^{-1}\sqrt{1-[r/d_n(0)]^2}$ yields $T_{n,\mathrm{ben}} = T_{n,\max}$. Thus, when the angle of approach to the destination increases crossing $\phi_{n,\mathrm{thr}}$ the value of $\hat{T}_n$ experiences a discontinuity (from the value in the second branch of (9) to the higher value in the first branch). Again, this is not coincidental and expresses the additional time required for forwarding the message once direct delivery to the destination cannot be achieved. There is no such discontinuity when the angle ϕ_n increases further, crossing $\pi/2$ (i.e., in the transition from moving 'loosely' towards the destination to moving away from it), as for this value (6) yields $T_{n,\mathrm{ben}} = 0$ and the values in the first and third branches of (9) coincide.

It is remarked that, once the estimation of the retaining time has been obtained, there is one further issue that must be taken into account: As explained in Subsection 2.1, the difference of the advance metrics for the neighbor node n and the current node c has to be calculated, through (5), and both metrics in the difference must refer to the same retaining time, during which both nodes should be capable of carrying the message.

In view of this, the estimate $\hat{T}_c$ is also calculated, by applying (9) with $n = c$, and the value $T_n = \min\{\hat{T}_c, \hat{T}_n\}$ is employed in the calculations associated with the metrics. Obviously, a single computation of $\hat{T}_c$ suffices for the calculation of the retaining times of all current node's neighbors.

The retaining time in (9) possesses additional desirable properties: For any given values of the local density ρ and the speed V_n, when the message is far from its destination and the examined node n heads towards the destination, both $T_{n,\text{ben}}$ in (6) and $T_{n,\max}$ in (8) will be relatively big, so $\hat{T}_n$, as obtained from (9) will also be big and the advance metric will emphasize the carry action. This is appropriate behavior, because when the message is far from the destination the carry action is more effective than the forward action for enabling a rapid approach. By a similar reasoning, as the message gets closer to the destination, $T_{n,\text{ben}}$ and $T_{n,\max}$ become smaller and the forward action now prevails. Furthermore, for all three directions of motion, when the density is high, the retaining time will be small and the advance metric will emphasize the forwarding action (which is effective in such conditions). Low densities will result in a big retaining time and the carry action will prevail. Lastly, when the speed V_n increases by a factor, the retaining time $\hat{T}_n$ is reduced by the same factor (see (9) and also (6) and (8) when node n approaches to the destination), expressing the fact that node n will encounter its forwarding opportunities, it will process them and, in general, it will perform whatever functions it would otherwise do at an increased rate. A corresponding remark applies when the speed V_n is reduced by a factor.

These remarks will be put in use towards explaining the effectiveness of the adaptive beaconing scheme to be presented in Section 4.

3. Beacon Periods and their Impact to the Perception of a Node's Neighborhood

We now explore the trade-off between periodic beacon intervals and routing effectiveness. As a general comment, very frequent beacons (the limiting case being continuous beaconing) result in best routing performance due to optimal neighborhood perception, but also to heavy signaling, leading to energy depletion at the nodes, waste of bandwidth and potentially increased message collisions. On the other hand, infrequent beaconing saves on signaling but reduces routing performance. Therefore the question arises: How frequent should beacons be? This section concentrates in periodic beacons providing an analysis linking beacon periods with the resulting neighborhood perception. As already mentioned, the analysis for the periodic case is generic and applies to other routing protocols beyond MAD. Before embarking on that, we describe how the beacons can be employed in the context of a duty-cycling approach which targets to reduce the energy consumption. For a comprehensive taxonomy of the energy conservation schemes and specifically of duty cycling mechanisms see [11, 12].

It is assumed that all the nodes in the network are normally in sleeping mode. Every node that carries a message wakes up at appropriate points in time (periodically in this section, adaptively determined in the next section) in order to explore its neighborhood. For that, the current node transmits a beacon message to all of its one hop neighbors. Such schemes typically use different radios for the wake up signal (low-rate and low-power for signaling) and the data packet transmission (high-rate and high-power for data communication) [4, 19]. When a neighbor receives a beacon, it sends back to the current node a message with its position and motion information. Afterwards, it turns on its data radio for a brief time before the current node decides either to forward the message, or to continue retaining it until the next neighborhood exploration. Then, all the nodes go back to the sleeping mode. Such on-demand sleep/wakeup schemes aim at a very low percentage of the time where the data radio is active and therefore reduce energy consumption (low duty cycle). In connection with this, a desirable characteristic of the MAD routing protocol is that only the one hop nodes around the routing message are involved in the routing procedure, thus only these nodes need to wake up for a while. In particular, beaconed nodes need not forward beacons further.

We now proceed to analyze the impact of beacon periods to the depiction of the surrounding environment scanned by the current node c, as this node sweeps an area due to its motion in the time interval $[0, t]$. An implication of the node's motion is that the size of the scanned area depends on the length t of the time interval and on the speed of the node. The transmission range is a third parameter affecting the swept area; in this paper it is assumed to be a constant system parameter, whose value is governed by the radio technology in use. Given this framework, we consider a carrier node c exploring its surrounding environment by means of periodic beacons of period T_b and focus on the area scanned by the node within time T_b, from the occurrence of a beacon until just before the next one.

With respect to the time, say $\Delta\tau$, elapsing between the instant a beacon is issued by node c and the instant by which the responses from all neighbors have been collected at node c, it is assumed that $\Delta\tau \ll T_b$ and that the locations of node c at the beginning and end of $\Delta\tau$ are not appreciably different. In view of the typical values of the bandwidth offered by the radio links, of the low signaling payload involved and of the speeds with which nodes move in practice, these assumptions are reasonable. Therefore the analysis assumes that all beacon-related information exchange occurs at the time when the beacon is issued and then the node travels for T_b, unaware of further changes in its environment.

The entire area swept by the node between two beacons can be regarded as the sum of two areas. The first is the area $A_{\text{sense}} = \pi r^2$, including neighbor nodes sensed by the current node and the area $A_{\text{miss}}(T_b)$, including nodes not sensed (i.e., missed) during the current node's movement until the next beacon occurs. The area $A_{\text{miss}}(T_b)$ is a function of the beacon period. It does not include any area overlapping with the area A_{sense} covered by other beacons. Note that A_{sense} is independent from the beacon period T_b, always

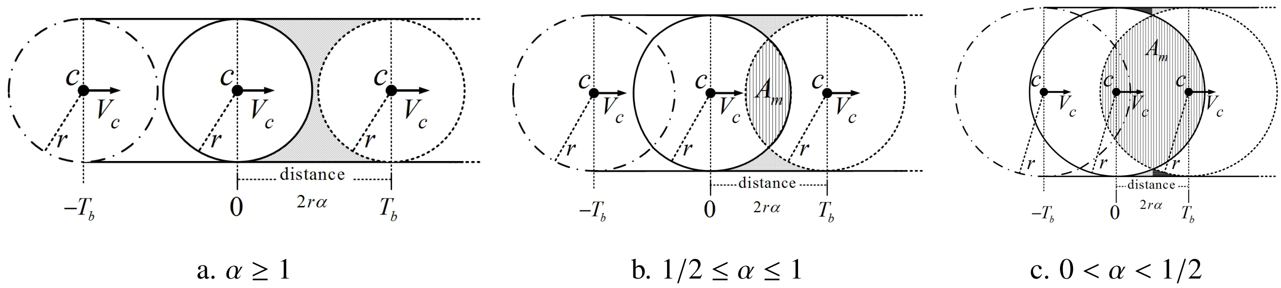

Figure 2: Periodic beacons with: a) non-overlapping areas sensed at successive beacons b) overlapping areas sensed at successive beacons c) overlapping areas for very low motion between two successive beacons.

being equal to the circular area covered at the time the beacon occurs. Assuming a uniform nodal density ρ throughout the area spanned during a beacon period (which is the case with all conditions encountered in practice) the number of nodes included in the areas just discussed are proportional to the areas. Therefore one obtains

$$N_{\text{tot}}(T_b) = \rho(\pi r^2 + A_{\text{miss}}(T_b)), \quad \text{and} \quad N_{\text{sense}} = \rho\pi r^2. \tag{10}$$

One can define the loss factor $\gamma(T_b)$ as the fraction of swept nodes that are missed (i.e., not sensed as neighbors). By (10),

$$\gamma(T_b) = \frac{\delta(T_b)}{1+\delta(T_b)}, \qquad \text{with} \quad \delta(T_b) = \frac{A_{\text{miss}}(T_b)}{\pi r^2}. \tag{11}$$

Although the absolute number of nodes swept depends on the nodal density (see (10)), the fraction $\gamma(T_b)$ is invariant to it. Note also that, by definition of $\gamma(T_b)$, the fraction of the nodes sensed as neighbors, among all nodes swept, is simply equal to $1 - \gamma(T_b)$.

In the following, we characterize the dependence of $\gamma(T_b)$ on T_b. It will be convenient to work through the dimensionless quantity

$$\alpha \triangleq T_b/T_r, \qquad \text{where} \quad T_r \triangleq 2r/V_c. \tag{12}$$

In other words, α expresses T_b in multiples of the generic time constant T_r, which is the minimum time that must elapse before the area covered by the node at the beginning of the time duration is completely non-overlapping with the area covered at the end. The introduction of α enables a characterization that is invariant to the range of coverage r and the speed of the node V_c.

We start from the case $\alpha \geq 1$, for which the areas sensed by two successive beacons do not have any common overlap. Within T_b, the diameter of the node's circular area of coverage perpendicular to the direction of motion sweeps a rectangular area equal to $2rV_cT_b = 4r^2\alpha$. In order to calculate $A_{\text{miss}}(\alpha)$ (shaded area in Figure 2a) one must exclude from this rectangular area the two semicircular areas sensed by the node at this and the next beacon. Thus,

$$A_{\text{miss}}(\alpha) = r^2(4\alpha - \pi). \tag{13}$$

For $\alpha \le 1$, the areas sensed by the two successive beacons have a common overlap (marked with slanted lines in Figure 2b). By means of simple geometrical arguments this overlap area can be seen equal to $A_m(\alpha)$, where

$$\frac{A_m(\alpha)}{\pi r^2} \triangleq \chi(\alpha) = \frac{2}{\pi}(\cos^{-1}\alpha - \alpha\sqrt{1-\alpha^2}), \quad \alpha \le 1. \tag{14}$$

$A_m(\alpha)$ must not be included twice when calculating $A_{\text{miss}}(\alpha)$. Thus, one now has

$$A_{\text{miss}}(\alpha) = 4r^2\alpha - (\frac{\pi r^2}{2} - A_m(\alpha)) - \frac{\pi r^2}{2} = r^2(4\alpha - \pi) + A_m(\alpha). \tag{15}$$

The method of calculating $A_{\text{miss}}(\alpha)$ must be revised when $\alpha \le 1/2$, because in this case $A_m(\alpha)$ extends beyond the borders of the rectangular area, as shown in Figure 2c. In this case, $A_{\text{miss}}(\alpha)$ is the sum of four equal sub-areas (two of which are marked by dark shading in Figure 2c). By calculation through direct integration, one obtains

$$A_{\text{miss}}(\alpha) = 4\int_0^{r\alpha}[r - \sqrt{r^2 - x^2}]\,dx = 4r^2\int_0^{\alpha}[1 - \sqrt{1-u^2}]\,du,$$

which can be readily seen to yield the same result (15). Therefore, (15) applies for all $0 \le \alpha \le 1$.

By combining (13) and (15) with (11), one may express the fraction of missed nodes as

$$\gamma(\alpha) = \frac{4\alpha/\pi - 1 + q(\alpha)}{4\alpha/\pi + q(\alpha)}, \qquad \text{with} \quad q(\alpha) = \begin{cases} \chi(\alpha), & \alpha \le 1, \\ 0, & \alpha > 1, \end{cases} \tag{16}$$

and with $\chi(\alpha)$ as in the right hand of (14). It is noted that $q(\alpha)$ is the fraction of nodes sensed multiple times across successive beacons, among all the nodes sensed. Note that $\gamma(\alpha)$ in (16) is strictly increasing and continuous, as expected.

3.1. Trade-offs Between Accurate Neighborhood Exploration and Energy Efficiency

Now we discuss about the balance between energy efficiency (and reduced beacon signaling) and the protocol efficiency. For the latter, α should not be overly big. An empirical upper bound can be established by requiring that the fraction of nodes sensed is greater than or equal to the fraction of nodes missed. In other words, one must have $\gamma(\alpha) \le 1/2$. The threshold value is governed by the second branch in (16), yielding

$$\alpha_{\text{upp}} \le \pi/2 \simeq 1.571, \quad \text{equivalently} \quad T_b \le 3.142 r/V_c. \tag{17}$$

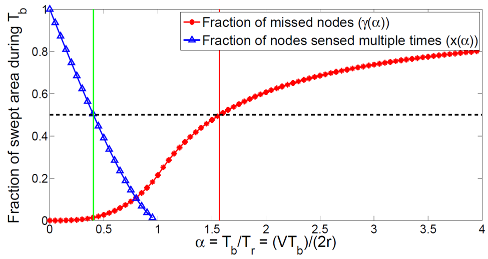

Figure 3: Fractions of nodes missed and sensed multiple times vs the α parameter, and corresponding bounds.

On the other hand, it is not necessary to insist on very small values of α and T_b. Such smaller values improve the routing efficiency further, by providing frequently updated information about the neighbors' status. However, as α becomes small, an increasing fraction of the nodes checked in successive beacons will coincide. Although the refresh of information is good for maintaining the status of these nodes, a too frequent such update is excessive, wastes energy and increases signaling. One can put an empirical lower bound, by requiring that the fraction of nodes repeatedly checked among those nodes sensed should not be greater than the complementary fraction of nodes checked once. By the comments after equation (16), this translates to the requirement that $q(\alpha) = \chi(\alpha) \leq 1/2$. The function $\chi(\alpha)$ to the right hand side of (14) is strictly decreasing, so the condition just mentioned translates to

$$\alpha_{\text{low}} \geq \chi^{-1}(1/2) \simeq 0.404, \quad \text{equivalently} \quad T_b \geq 0.808 r/V_c \tag{18}$$

For a visual representation of the aforementioned concepts, Figure 3 displays the fraction of missed nodes and nodes checked multiple times, as a function of α. It is clear from the figure that at a T_b value equal to the upper bound in (17) (resp., the lower bound in (18)) the fraction of missed nodes (resp., the fraction of nodes checked multiple times) takes value equal to $1/2$.

As an overall comment, the upper and lower bounds, (17) and (18) indicate that beacons should occur every $O(r/V)$ time units. The presence of the node's speed reflects the fact that a fast-moving node changes its environment quickly, so it needs quick information updates to properly exploit information about its environment. Analogously, for slowly moving nodes, the information updates (and the associated beacons) can be more infrequent. At the limit of $V \to 0$ where nodes become static, $T_b \to \infty$, indicating that once the information about the neighborhood has been gathered, no further updates are required.

4. Adaptive Neighborhood Exploration based on the Retaining Time

Periodic beaconing is a universal technique that can be applied unchanged over any routing protocol, without regard to its details. Moreover, the periodic scheme can be parameterized to ensure that a target fraction of encountered neighbor nodes will be detected and checked, but does not take into account the appropriateness of the neighbors. If the carrier is very suitable, most neighbors will not be preferable over it, so the carrier should be less persistent in checking for connectivity opportunities, because these will be less likely to be useful. On the other hand, in case the current node is not a very good carrier, the node should check frequently its environment, in order to discover a more suitable carrier as soon as possible. In both cases, a periodic beaconing scheme might be either overly frequent or overly sparse, leading to energy inefficiency in the first case and to routing inefficiency in the second case.

However, there are protocols that somehow quantify the appropriateness of the carrier node. For such protocols it is possible to devise adaptive beaconing schemes, making explicit use of the specific logic encapsulated in the protocol. The MAD protocol, in particular, calculates and uses the retaining time, which is a measure of the duration that the node is likely to retain the message. The nature of this quantity and the fact that its calculation requires information gathered by the current node only during the last beacon-initiated check make the retaining time a particularly suitable basis for determining the next inter-beacon interval.

As commented in Section 2, the retaining time has several appealing features, including its capability of capturing:

- the impact of nodal density and speed (mobility);
- the impact of a node's location (relative position) and direction of motion, relative to the destination.

Towards appreciating the significance of the first item, it is reminded that, as discussed in Subsection 2.2, the retaining time is a decreasing function of the nodal density ρ. By definition, a dense topology implies the existence of many nodes in a given area. Therefore, a frequent neighborhood exploration leads to small area patches not scanned by the current node, equivalently to a small fraction of nodes that are not perceived as neighbors by the current node. Furthermore, as also discussed in Subsection 2.2, in dense topologies the routing process operates mainly by exploiting the relative positions, instead of motion-related information. The frequent neighborhood exploration guarantees that accurate position information is gathered.

By an analogous reasoning, if the density is low the retaining time is big, emphasizing the carry action instead of the forwarding action. In such conditions only the nodes best directed towards the final destination should be selected and this matches well with an infrequent neighborhood exploration, because while the current node is in sleeping mode, the message is directed well towards its destination.

Looking at the sparse topology case from another point of view, the probability with which the current node finds a better carrier in a very short time is very low. This is because a) the current node is selected due to its beneficial motion towards the message destination and b) because very few forwarding opportunities exist per unit of time, as the low density leads to a small number of potential neighbors missed, despite the fact that the unscanned area may be quite large (see (10)). This alternative consideration leads to the same conclusion, namely that a frequent neighborhood exploration does not contribute to the improvement of the protocol's efficiency.

The second network-wide parameter to consider is mobility, reflected in the magnitude of the nodes' speed. When the speed increases by a factor, the retaining time is reduced by the same factor. This happens because the current node covers the same distance in a reduced time. Therefore, if the current node is to avoid missing forwarding opportunities, the neighborhood exploration should occur at an increased rate. An analogous argument applies when the speed is reduced by a factor. Again, it is seen that the appropriate interval between beacons grows or shrinks in the same fashion as the retaining time does.

We now address the second of the bullets previously mentioned, i.e., individual node characteristics: When the current node is better directed towards the message's destination, the node contributes more to the message routing and this is reflected to an increased retaining time. At the same time, the more beneficial the direction of the current node becomes, the rarer the neighborhood exploration should be. This is in accordance with the fact that in a network environment with given characteristics (density and mobility), a better directed current node will be less likely to find a carrier better than itself to forward the message. In consequence, a well directed current node has the opportunity to sleep a longer time interval (i.e., tolerate a longer time until the next beacon without missing significant next hop candidates), because the message is routed well due to the node's suitable motion towards the destination. Overall, both benefits, namely good routing progress and energy savings, can be achieved.

An additional observation in support of the claim that the retaining time captures properly the node's motion is that, when the current node moves along a straight-line trajectory towards the destination, its angle of motion increases with time, signifying that the current node becomes a worse carrier. The increasing angle of motion leads to a decreasing retaining time (indirectly, by a change to the applicable branch in (9), or to a reduced value from (6) or (8), as appropriate) and therefore to a more frequent beaconing.

The second node characteristic to consider is the node's proximity to the message destination. The existence of an end-to-end multi-hop path from the current node to the destination is more probable as the distance between them becomes shorter. Therefore, when the current node comes closer to the destination, it needs more accurate position information and should check its neighborhood more frequently. Again, the retaining time behaves properly, becoming smaller in locations closer to the destination (due to the form of (9) and (6) or (8)).

One might think that the behavior just mentioned may contribute to a funneling effect [20, 21], where nodes located closer to the destination/sink are loaded more than nodes located further apart, due to the delivery of traffic flows from remote locations, resulting in a premature energy depletion for the closer nodes. However, this is not so, because the retaining time (and the adaptive beaconing scheme based on the retaining time) also captures motion characteristics (responsible for changes in the nodes' locations), as well as the nodal density. With respect to the latter, by considering two different locations equally far from the destination but featuring a different topological density, it can be seen that, even in a completely static environment, the adaptive beaconing scheme based on the retaining time will load more the denser location. This phenomenon can be regarded as a form of load balancing [22], where the sparser locations (which might have emerged due to energy-exhausted local nodes) are protected more from further energy depletion.

A collective consideration of all the remarks in this section leads to the conclusion that the retaining time is a quantity that captures effectively all the parameters associated with the network environment and the nodes' characteristics and that grows or shrinks in the same fashion as the inter-beacon interval that would be appropriate for use with any given set of these parameters. Therefore, it is natural to consider using a multiple of the each time applicable retaining time to adaptively adjust the time up to the next beacon. The multiplication factor employed should be less than 1, so that the neighborhood will be checked again before the estimated retaining time expires. This becomes even more important when considering that until the next beacon the current node will be in low-power (sleeping) mode, hence unable of sensing its environment.

Moreover, it is clear that a more accurate estimate of the retaining time provides the capability for issuing the next beacon closer to that estimate (i.e., for using a larger multiple of the estimated retaining time) without ill effects. Contrapositively, looser estimates of the retaining time may require the use of smaller multiplicative factors.

In the next section we undertake an extensive validation of the ideas presented in this section and we find that the proposed adaptive scheme is quite effective under diverse environmental and nodal characteristics.

5. Evaluation Results

We now evaluate the performance of the periodic and the adaptive beaconing schemes proposed in the paper, on the basis of results from an extensive set of simulations using the OPNET Modeler network simulator. The performance of the two schemes is considered in the context of the MAD routing protocol. This is natural for the adaptive scheme, as it is specifically intended for use with MAD. Moreover, it is also natural to employ the same routing protocol for the periodic beaconing, as this facilitates comparative performance evaluation of the periodic and the adaptive scheme over a common ground. However, there is an additional reason for considering the generic periodic beaconing with the specific MAD protocol, this reason being that MAD makes intelligent use of network- and node-related parameters, so it provides a good basis for studying to which extent longer beacon periods (hence more infrequently collected status updates) degrade the effectiveness of routing decisions.

In the set of results to be presented, we investigate the influence of the parameter α to the performance of the periodic beaconing scheme (the relevant results labeled 'periodic'), illustrating at the same time the relevance of the upper (17) and lower (18) bounds for that parameter to the trade-off between efficiency and energy/signaling cost. Also, we compare the performance of the periodic scheme with the adaptive beaconing scheme (the relevant results labeled 'adaptive'), exhibiting the significance of the retaining time factor in the decision making for adaptive neighborhood exploration. Each beaconing scheme is tested with two versions of MAD employing different expressions for the retaining time, the original simpler (7) (labeled 'original MAD') and the more accurate/refined (9) (labeled 'improved MAD').

The simulations addressed a network topology, where the mobile nodes moved within a square open area of size 10km $\times$ 10km. The source and destination were static nodes at diagonally opposite corners of the square; the destination's position was globally known. The mobile nodes were used to deliver data between the fixed source and destination, which were otherwise disconnected from each other. Mobile nodes could communicate with other nodes in a range r = 250m and move according to the random direction mobility model with zero pause time and constant speed [23]. At each beacon, all carrier nodes had knowledge of both their own position and velocity vector and of the positions and velocity vectors of their one hop neighbors.

In order to compare the performance of the periodic and adaptive schemes, three different topological scenarios were used, aiming to cover the various combinations of density and mobility conditions that may emerge in a network. The first scenario corresponds to a sparse and low mobility topology with 500 nodes in the rectangular area, with nodes moving at a speed equal to 2.8 m/s (10 km/h). The second corresponds to the same sparse density but high mobility, where the speed of the nodes is 13.9 m/s (50 km/h). The third scenario corresponds to a dense and high mobility network environment, with 2550 nodes in the rectangular area and a speed equal to 13.9 m/s (50 km/h).

The performance metrics produced by the simulation were the end-to-end delay for the packet delivery from source to destination, the total number of hops involved and also the total number of beacons required for delivery (used as a proxy for the energy/signaling cost). The metric values reported here were obtained as averages over 1000 packets. The time between the packet generation events was chosen sufficiently large, to ensure that the topologies "seen" by any two consecutive packets were completely different.

Figures 4, 5 and 6 display end-to-end delays, hop counts and number of beacons, as a function of the

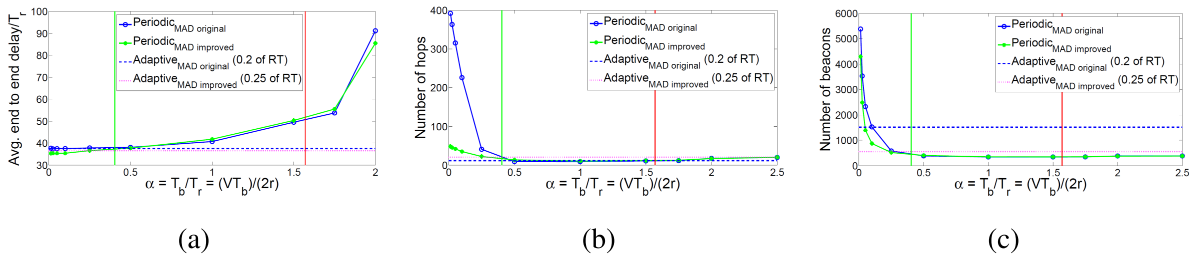

Figure 4: Results for sparse and low mobility environments: a) end-to-end delay; b) # hops; c) total # of beacons

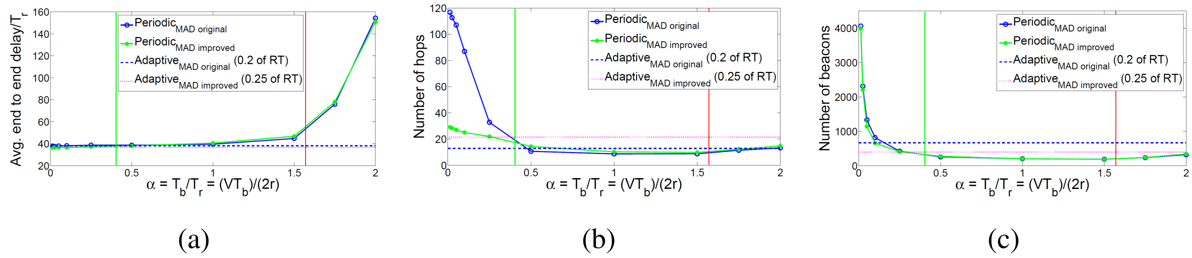

Figure 5: Results for sparse and high mobility environments: a) end-to-end delay; b) # hops; c) total # of beacons

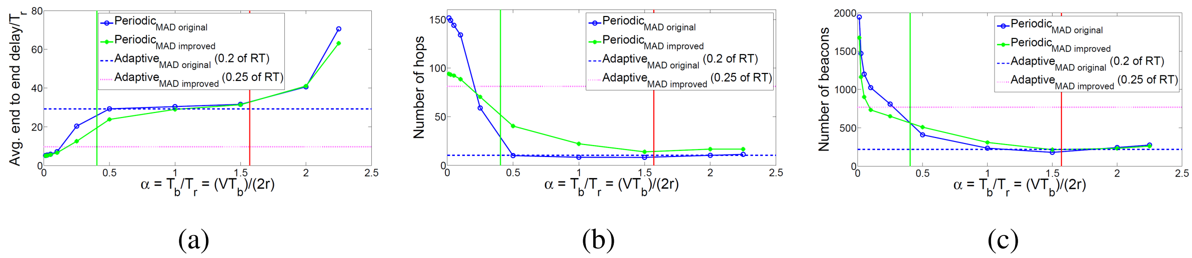

Figure 6: Results for dense and high mobility environments: a) end-to-end delay; b) # hops; c) total # of beacons

beacon period, expressed as the dimensionless parameter α (which factors away local mobility characteristics), for the three topological scenarios. Before examining the impact of α, two remarks are in order:

- For small values of $\alpha \to 0$, the protocol has immediate perception of new information. Therefore, the performance of the protocol is optimal, in the sense of being the best possible that the protocol can provide. This fact is reflected in the minimum values of the end-to-end delay achieved as $\alpha \to 0$. Naturally, the number of beacons increases unboundedly as $\alpha \to 0$. Finally, in this regime small changes in the value of α have negligible impact to the routing performance, serving only to change the beaconing rate in a reciprocal manner. However, apart from their intuitive appeal, these remarks are of no practical consequence, because in periodic beaconing applications the objective is to employ a value of α well above 0. (The lower bound (18) is equal to about 0.4).

- Comparing between the two estimates of the retaining time, we see that for this best possible performance at $\alpha \to 0$ the refined estimate of the retaining time (9) provides better results than the cruder estimate (7), for both the end-to-end delay and the number of hops in the whole range of network conditions (density and mobility). For further details, the reader is referred to [16].

By comparing the average end-to-end delay of the two periodic versions of MAD (curves marked with circle and asterisk for the simpler and more refined versions of MAD, respectively) in all the three different topologies, the results indicate an increase as the α parameter increases. This is because a greater value of α implies more neighbor nodes not detected as such from the current node. A more detailed observation reveals that, as α increases, the performance remains close to the 'ideal' performance corresponding to $\alpha = 0$ up to a value of α beyond the theoretically predicted lower bound α_{low} in (18) (left vertical line). Then, the performance gradually worsens for values of α up to some value past the upper bound α_{upp} in (17) (right vertical line). Beyond this second threshold, the performance worsens rapidly. Clearly, α_{upp} and α_{low} bear a direct relevance to routing performance. The effects just mentioned are directly observable for the two sparse topologies. This is less so for scenarios featuring a dense topology, regardless of mobility. In such cases, values of α below the lower threshold may still discard many forwarding opportunities and worsen the performance over the optimal one, corresponding to $\alpha = 0$. This behavior is expected, because the bounds account only for the mobility parameter (see the second form of the bounds (17) and (18)), not for the nodal density parameter. Nevertheless, the degradation of performance at $\alpha = \alpha_{\text{low}}$ is far smaller than the degradation beyond α_{upp}. So, it can be said that, for every possible scenario, the same trends apply and the selection of a beacon period between α_{upp} and α_{low} is effective.

With respect to the average number of hops required for the message delivery from source to destination for all three topologies, the results show that the number of hops decreases with α, until α_{upp} is reached and then starts to increase. In fact, the number of hops increases intensely for values of α past the right edge of the corresponding figures. (Hop counts for larger values of α have been kept out of the figures intentionally, to avoid a "compressed" view of the results for lower α values.) The initial decreasing trend is explainable if one recalls that more infrequent beacons are necessarily associated with more infrequent message forwardings. It may also be explained by recalling that higher values of α correspond to routing in sparser environments (since the current node misses forwarding opportunities). The increasing trend of the number of hops beyond some value of α is due to the fact that overly long beacon periods deprive the current node from the necessary status information and result in the message being "lost" in the network, requiring an additional number of, in principle unnecessary, hops before delivery. In connection with the role of the two bounds for the α parameter, remarks similar to those for the end-to-end delay apply.

The number of beacons exhibits similar trends. In general, as α increases up to α_{upp}, the number of beacons decreases, reflecting the trade-off between performance (end-to-end delay) and the number of beacons required. However, beyond α_{upp} the number of beacons increases for the same reason that the number of hops does.

Recapitulating, the values of α between α_{low} and α_{upp} constitute an appropriate zone for beacon period selection, attaining a close to minimum number of hops (which is an important metric quantifying energy savings) and a very good end-to-end delay, without an unnecessarily excessive amount of beaconing.

We now compare with the adaptive scheme. As previously, we have tested the scheme with the two versions of MAD, one employing the simpler estimate of the retaining time (7) (dashed horizontal line), the other employing the more refined estimate (9) (dotted horizontal line). For determining the time up to the next beacon we use a value equal to 20% of the retaining time in the first case, and a value equal to 25% of the retaining time in the second case. These factors are in line with the observation, made in Section 4, that more accurate estimates of the retaining time allow the use of higher fractions of this quantity for determining the time until the next beacon. The particular fractions employed here have been found to be most appropriate for dealing with a a diverse set of network- and node-related characteristics, after checking (by means of simulations) a large set of potential values.

It is mentioned that the results for the adaptive scheme are invariant to α, so one value (per MAD variant) of the each time relevant metric applies to each figure. However, for an easy comparison with the performance of the periodic scheme, this single value is depicted a a constant function of α. To compare between the adaptive and periodic beaconing scheme, one starts from the figure for the end-to-end delay, finding the value of α for periodic beaconing that matches the end-to-end delay obtained by the adaptive scheme. Then, one turns to the corresponding figure for the number of required beacons, and compares the number of beacons in the periodic scheme employing the said value of α with the number of beacons required for the adaptive scheme. A similar procedure is involved when linking the number of hops to the number of beacons. By studying the figures, it can be seen that the adaptive scheme provides a trade-off between performance and beacon messages better than the periodic scheme, for all scenarios. Also, it can be seen that the adaptive scheme using the more refined retaining time estimate is more capable of adjustment and tracks better the near-optimal performance with respect to the end-to-end delay in dense topologies, overcoming the weakness of the lower bound of the periodic scheme in such settings. This happens because the refined retaining time captures better the nodal density and mobility information, but also node-related characteristics, which are completely neglected by the periodic scheme.

In conclusion, it is obvious from the results that choosing a value for the beacon period between the α_{upp} and α_{low} leads to a near-optimal trade-offs among all possible periodic beaconing schemes. Furthermore, the MAD-specific adaptive scheme performs even better, even compared to the best periodic scheme. Lastly, better retaining time estimates lead to better resultss, for all possible network conditions.

6. Conclusions

In this paper we have studied the 'on-demand' beaconing approach, with the aim of investigating the influence of the inter-beacon intervals on the routing effectiveness. We have proposed and examined two different schemes, one with periodic beacons and the other with adaptively adjusted beacon intervals. For the periodic case, we provided an analysis linking the beacon period with the accuracy of neighborhood perception and we determined upper and lower bounds for the beacon period that balance the trade-off between routing efficiency and low signaling overhead for energy efficiency. These bounds encapsulate local mobility characteristics. The analysis is generic and applies to every routing protocol with periodic 'on-demand' beaconing.

Furthermore, it was realized that, for routing protocols that somehow quantify the appropriateness of the carrier node, it is possible to devise adaptive beaconing schemes, making explicit use of the specific logic encapsulated in the protocol. This idea was exploited in connection with the MAD protocol, which calculates and uses the retaining time, a measure of the duration that the node is likely to retain the message. An adaptive beaconing scheme was proposed for use with MAD, putting a fraction of the each time applicable retaining time in place of time up to the next beacon. Since the retaining time captures effectively all the parameters associated with the topology and the nodes' characteristics, this beaconing scheme is capable of adapting to a diverse set of conditions.

An extensive evaluation through simulations led to the conclusion that, for the periodic case, selection of a beacon period between the upper and lower bounds can attain a reasonable trade-off between the protocol's efficiency and the number of beacons required. It was also seen that the adaptive scheme outperforms the periodic scheme in the whole range of topological conditions. Additionally, it was seen that more accurate estimates of the retaining time allow for placing the next beacon closer to the expiration of the retaining time without ill effects.

The significance of the retaining time and its ability to capture at the same time both routing environment conditions and nodes' characteristics motivate future work towards a more extensive and deeper investigation of this quantity.

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