Methodologies for Effective Self-adaptive Decisions in Routing, Signaling, Cooperation, and Other Operations in Diverse Mobile Networks

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Abstract. In this PhD dissertation we provide methodologies for effective decision making in the fundamental networking functions in diverse network topologies. This provision becomes a difficult task, because the nodes belonging in such networks must take decisions based on several sources of context, related to the local environmental and nodal characteristics. The thesis fills this gap, by introducing quantities expressed in terms of time, which are the *'retaining time'* and the more general notion of *'Decision-Related Event Occurrence Time'* (DREOT). These novel notions are able to appropriately "translate" the environmental conditions and nodal characteristics (which may be adjusted, to also reflect social aspects through the novel notion of *'subjective density'*) in a form suitable for taking the decision in question. Furthermore, the notion of the retaining time has been successfully exploited towards dynamically self-adjustable routing in diverse mobile topologies by the proposed MAD (Maximum Advance Decision) protocol. The thesis studies also on-demand beaconing techniques (required for a realistic implementation of the routing protocol), suggesting a generic analysis and policies for information exchange between the involved nodes. A rich set of numerical and simulation results demonstrate the efficient and effective nature of the proposed techniques and notions.

Keywords: context aware decisions, network mobility, routing, beacon scheduling mechanisms, cooperation.

1 Introduction

Modern deployments of Mobile Ad Hoc Networks (MANETs) frequently exhibit topologies with highly variable characteristics, for example in terms of the nodal density and mobility. This is particularly true for Delay Tolerant Networks (DTNs), Wireless Sensor Networks (WSNs) and vehicular networks (VANETs) where the density and mobility vary through time and by location. These variable

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characteristics are highlighted even more in many emerging wireless applications with a need for network inter-operability. Moreover, the need for energy saving techniques, lead also to a further variability of the nodal density with time. Finally, higher layer aspects (e.g., social relations) might introduce additional nodal dependencies that can increase the variability of conditions even further.

For networks exhibiting the variable environmental conditions just mentioned, the provision of fundamental networking functions (such as self-organization or routing) becomes a difficult task, because the network nodes must take decisions based on several sources of context, related to the local environment and to the characteristics of individual neighbor nodes. The issue is typical in routing applications, where a node carrying a message is called to decide whether or not to forward the message to a neighbor node when an opportunity arises.

Because of the problem's complexity, most of the current routing protocols address only a subset of the possible conditions. For example, the forward-based multihop routing protocols [11] are usually employed for networks with a relatively high nodal density. On the contrary, in sparse topologies carry-based multihop protocols [3] fit better. However, none of the approaches just mentioned are capable of addressing the entirety of conditions that may be encountered. To combat this lack of adaptivity, other approaches try to take advantage of the multiple copies of the same message. However, the multicopy approaches achieve low delay and improve the reliability of message delivery [9], they are inappropriate for settings with scarce networking and device resources, due to their inherent redundancy.

The thesis targets the amelioration of single copy approaches. It introduces a routing protocol, called *Maximum Advance Decision* (MAD), based on the novel notion of the *'retaining time'*, which is capable of automatically adjusting for best performance under the conditions applicable each time [6, 7]. Along the process, the thesis develops techniques that are useful for studying more general times between events governing a decision-driven system, called *'Decision-Related Event Occurrence Time'* (DREOT). Besides being useful on their own right, these results enable an in depth study of how the retaining time is affected by relevant network and nodal parameters and lead to an even grater improvement of the routing protocol [5].

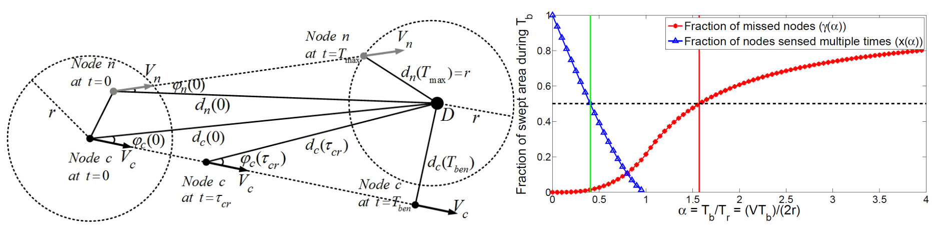
It is noted that the significance of taking the right routing decision becomes more important in networks where social ties of varying strength are built between nodes. Proposals for forwarding strategies in such environments introduce the social tie as an additional parameter multiplying or adding to a purely contact-based metric [4] and failing to capture that these attributes largely shape, in turn, the topological characteristics of the network environment. The results in this thesis suggest a simple, yet non-arbitrary and robust, way of capturing the effect of social ties, through an appropriate adjustment to the notion of nodal density, called *'subjective density'* [7].

Another important complementary issue is the operational aspect of the signaling required for a realistic implementation of the routing protocol. The 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) [10] or may be solicited by the node carrying the routed message ('on-demand' beaconing) [2]. On-demand beaconing is of growing importance, mainly in more dynamic and sparse environments, or in mobile environments with variable conditions, which is the main target of the thesis. The major question that arises in this context is: How frequent should beacons be? The thesis explores quantitatively the trade-off between beacon intervals (periodic and adaptive) and routing effectiveness [8].

2 Dynamically Optimized Routing for Networks with Diverse Density and Mobility Characteristics: the Retaining Time and the MAD Protocol

2.1 MAD: A Dynamically Adjustable Hybrid Location and Motion-based Routing Protocol

The Maximum Advance Decision-MAD protocol [6, 7] addresses 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 a beaconing process, the node possessing a message (called 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.



(a) (b)

Fig. 1: (a) Quantities relevant to the MAD policy checks. (b) Fractions of nodes missed and sensed multiple times vs the α parameter, and corresponding bounds.

When the current node c considers its neighbor n as a next hop candidate, it takes into account the anticipated progress due to both the forward and carry actions. The overall anticipated progress occurs over a time interval of length T_n, called 'retaining time' and is the time that this node would retain the message if it is selected as the next hop node. The advance metric is defined as the overall progress per unit of time due to receiving and holding of the message by node n and is given by

$$\mathrm{ADV}_{cn}(T_n) = \frac{d_c(0) - d_n(T_n)}{T_n},$$

where $d_i(t)$ stand for the distance of node i from the destination D at time t (see Fig. 1a).

This metric expresses the anticipated 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 $\text{ADV}_{cc}(T)$ over a common value of retaining time denoted as T, whose value is related with T_n and T_c. The relative merit of the neighbor node n over the current node c is expressed by the difference of the corresponding advance metrics

$$\Delta_n(T) = \text{ADV}_{cn}(T) - \text{ADV}_{cc}(T) = \frac{d_c(T) - d_n(T)}{T}.$$

The same procedure is repeated for all neighbors of the current node and ultimately the message is forwarded to the node with index $j = \arg\max_n \Delta_n(T)$, justifying the name of the protocol.

2.2 The Retaining Time Estimation and its Dependence from Topological and Node-oriented Characteristics

In order to compute the advance metric, the current node collects (by means of a beaconing process) information about the positions and velocities of its neighbor nodes. Given a neighbor's distance and velocity at time $t = 0$, the current node estimates the corresponding retaining times for all nodes n, as well as the node's distance at future time instants. In the absence of information about the future pattern of motion, MAD assumes that the neighbor will maintain straight line motion at constant speed equal to $V_n = V$, up to that future time instant. Also, let 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, respectively, at time t (see Fig. 1a).

It is clear that the notion of the retaining time should reflect the potential of the node as a message carrier, for the given nodal and environmental attributes. The original heuristic approach, has been presented in [6]. It follows an approach based on the fundamental notion that when node n moves towards the destination, i.e., $V > 0$ and $\cos\phi_n(0) > 0$, 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 $T_{\text{ben}}(d_n(0), \phi_n(0))$ (see the lower right part of Fig. 1a). The node shouldn't keep the message further, because after this time it will start moving away and its distance from the destination will keep increasing. In the complementary case, i.e., $V = 0$ or $\cos\phi_n(0) \leq 0$, node n should 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 network's nodal density ρ in the local environment of the node. In view of these comments, the retaining time value is chosen so that the highest expected node density corresponds to the smallest possible value of the retaining time, equal to T_d. Putting together these observations, the original MAD estimates the retaining time as $T_n = T(d_n(0), \phi_n(0))$ where

$$T(d,\phi) = \begin{cases} T_{\text{ben}}(d,\phi), & \cos\phi > 0, \\ T_d\, \rho_{\max}/\rho, & \text{otherwise.} \end{cases} \tag{1}$$

One direction for improvement over (1) 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. Specifically, when $\cos\phi_n(0) \geq \sqrt{1-[r/d_n(0)]^2}$, the destination will enter the node's range and receive the message at time $T_{\max}(d_n(0), \phi_n(0))$ (see upper right part of Fig. 1a). This is the greatest possible value for the retaining time in this case. A refinement along these lines was presented in [7]. Putting together the above observations, the improved MAD estimates the retaining time as $T_n = T(d_n(0), \phi_n(0))$ where

$$T(d,\phi) = \begin{cases} T_{\text{ben}}(d,\phi)\frac{\rho_{\min}}{\rho} + \frac{r}{V}\frac{\rho_{max}}{\rho}, & 0 < \cos\phi < \sqrt{1-[\frac{r}{d}]^2}, \\ T_{\max}(d,\phi)\frac{\rho_{\min}}{\rho}, & \cos\phi \geq \sqrt{1-[\frac{r}{d}]^2}, \\ \frac{r}{V}\frac{\rho_{\max}}{\rho}, & \cos\phi \leq\ 0. \end{cases} \tag{2}$$

Both of the approaches for the determination of the retaining time have desirable properties and they can help MAD achieve self-adaptation in a considerable range of density and mobility conditions (see Section 3.1).

3 Methodologies for Calculating Decision-Related Event Occurrence Times

The notion of the retaining time appropriately "translate" the environmental conditions and nodal characteristics in a form suitable for taking the decision in question. Clearly, the retaining time is a particular instance of the more general notion of *'Decision-Related Event Occurrence Time'* (DREOT) [5], which refers to the time duration up to the occurrence of an event linked to the decision, e.g., the time that an entity will sustain a property, or the time during which some conditions remain in effect, or the time until a node reaches a battery depletion level, etc.

Determining the value of a DREOT metric is challenging, especially in network environments with variable conditions. For a specific example, consider routing and the use of the retaining time for determining when (and to which node) to forward the message. In this setting, the node currently holding the message employs the retaining time pertaining to itself and to the other nodes in contact with it, to take the forwarding decision. At the same time, a message forwarding decision marks the end of the retaining time for the current node.

Towards addressing these difficulties, the thesis contributes techniques for enabling DREOT-related calculations. The proposed methodology introduces "bounding" events, $R_{\pm,n,t}$, that are either broader or stricter than the events triggering the decision and are more amenable to analysis. Probabilistic reasoning about these more general events leads to bounds for the probability distribution and for the mean value of the DREOT. By employing some further, very mild, uniformity assumptions about the local environment, the results take a more concrete form that explicitly captures the nodal density and the degree of mobility and given by

$$T_{-}(0,\infty) \leq \mathrm{E}\,[T] \leq T_{+}(0,\infty),$$

with

$$T_j(t_1,t_2) \triangleq e^{-\rho\pi r^2 h_j(0)} \int_{t_1}^{t_2} \mathrm{e}^{-\rho 2Vr \int_0^t h_j(\xi)\, d\xi}\, dt,\ j=\pm$$

and

$$h_j(t) \triangleq \begin{cases} 1-\hat{\omega}_{-}(t), & j=-, \\ \hat{\omega}_{+}(t), & j=+. \end{cases} \tag{3}$$

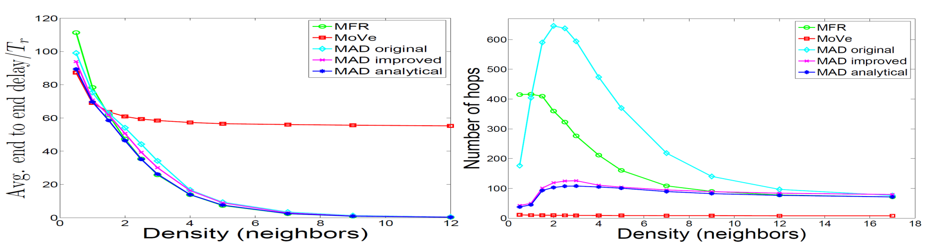
It is noted that it is always possible to use any lower bounding functions $\hat{\omega}_{\pm}(\cdot) \leq \omega_{\pm}(\cdot)$ in place of $\omega_{\pm}(\cdot)$, and thus (3) has been written so as to indicate this possibility. The actual policy descriptor probability bounds $\omega_{\pm}(\cdot)$ given by $\omega_{-}(t_A,t_B) \triangleq \min\limits_{n\in N(t_A,t_B)} \Pr\{R_{-,n,t_A}\}$ and $\omega_{+}(t_A,t_B) \triangleq \min\limits_{n\in N(t_A,t_B)} \Pr\{R^C_{+,n,t_A}\}$, where $N(t_A,t_B)$ is the set of nodes checked in $(t_A,t_B]$. The methodology and results just outlined are generally applicable, not being tied to a particular protocol or mobility model.

3.1 Decision-Related Event Occurrence Times in the Context of Routing: The Retaining Time

The precise nature and effect of the decision, at the abstract DREOT-related results presented in Section 3, is abstracted away to, so called, *'policy descriptor probability bounds'*. Expressions for these quantities can be derived by employing further properties of the specific policy and mobility model in hand. This is demonstrated by applying the general results to the particular case of routing according to the MAD protocol. The nodes are assumed to move according to the Random Direction Mobility model, which is particularly challenging with respect to the routing effectiveness. As already mentioned in Section 2, MAD bases its decision policy on the notion of the retaining time, so it can be readily addressed within the scope of the general DREOT framework. The calculation of the retaining times by means of the general DREOT-related results [5], as pursued here, not only leads to much more refined expressions, compared with the two variants of the heuristic expressions mentioned in Section 2.2, but also provides formal justification for certain functional relationships and a reinforced insight, without the need for resorting to heuristics. Numerical and simulation results illustrate that the refined expressions for the retaining time make the protocol even more effective in adapting to a very wide range of mobility and density conditions encountered in real-world environments.

The simulations addressed a network topology where the mobile nodes moved within a rectangular open area of size 10km $\times$ 10km. The source and destination were static nodes at diagonally opposite corners of the rectangle; the destination's position was globally known. Mobile nodes could communicate with other nodes in a range $r = 250m$. These network parameters are also obtained for the set of simulation in the other sections.

The value of T_{check} and T_d was set equal to 1s and 0.2s respectively. The corresponding values reported here were obtained as averages over 1000 messages and the mobile nodes moved according to the random direction mobility model with zero pause time and constant speed [1]. In this set of results, we compare the performance of the MAD routing protocol where all the nodes take decisions using the minimum between the lower bounds of the retaining time for the current and the checked neighbor, with four other protocols. From the forward-based routing protocols we choose the greedy MFR protocol [11], which selects the candidate node maximizing the distance between the current node and the candidate node's projection point on the line connecting the current and destination nodes. A typical representative of the protocols focusing on the carry action is the MoVe protocol [3], which uses a metric based on the direction of the nodes' motion. The third is the MAD protocol with the original expressions for the retaining time [6] (labeled 'original MAD'). The last is the MAD protocol with the improved retaining time estimation [7] (labeled 'improved MAD'). A wide range of node density values were examined, ranging from 0.5 neighbors to 17 neighbors. For each value of nodal density, the speed value was examined corresponds to a very slow-changed topology with 10 km/h for each node.



(a) (b)

Fig. 2: Average (a) end-to-end delay and (b) number of hops vs nodal density for slow-changed topology (nodes' speed 2.8 m/s).

From the total results in Figs. 2a–2b, it can be directly evidenced that both of the average end-to-end delay and the number of hops to delivery (for all examined routing protocols) decrease as the nodal density increases. This happens because a more dense topology results in an increased number of forwarding opportunities observed by the current node per unit of time. By comparing the end-to-end delay of the MFR and MoVe, the results indicate that the MoVe protocol outperforms in the sparse topologies and the MFR outperforms in the more dense topologies. The results indicate that all versions of MAD are capable of adjustment as the density increases. Also, for all the three versions of MAD protocols, the number of hops is lower in sparse topologies compared to that in dense topologies, because in sparse (resp. dense) topologies they tend to carry-based (resp. forward-based) protocols. The 'analytical MAD' achieves better efficiency regarding to the end-to-end delay and the number of hops than that of the 'original MAD' and the 'improved MAD'. Specifically, the efficiency of the 'analytical MAD' is equivalent or better than that of the MoVe and the MFR protocols in sparse and dense topologies, respectively. This is because MAD simultaneously takes advantage of both the forward and carry actions.

4 Exploiting Topology and Behavioural Attributes for Effective Routing in Mobile Networks

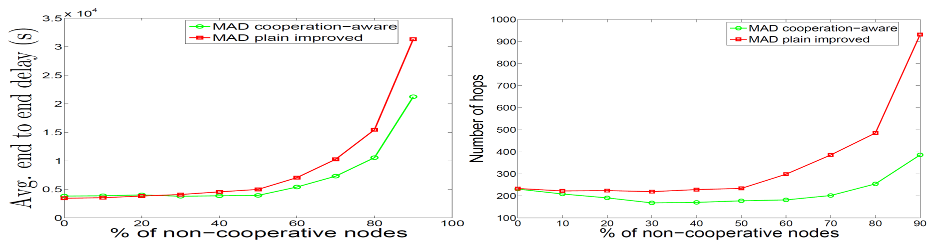
The number of forwarding opportunities observed by a node at each point in time is a key parameter influencing the node's retaining time and, through it, the efficiency of the routing protocol. Up until now the forwarding opportunities have been quantified through the topological density. However, the forwarding opportunities observed by different nodes in an area may not be the same, due to different individual characteristics of the nodes inherited from higher layers. In doing so, the thesis introduces the novel notion of *'subjective density'* [7]. This notion is defined as

$$sd_i = c_i \rho,$$

which adjusts the topological density according to higher layer properties relevant to individual nodes, such as cooperation attributes. The cooperation level, denoted as c, is a real number in the interval $[0, 1]$, where 1 indicates complete co-operation and 0 indicates complete lack of cooperation. Once these aspects have been captured, they can be incorporated in the decision policy of the routing protocol, in a simple yet robust way.

We compare two versions of improved MAD. In the first version (labeled "plain improved MAD"), the protocol uses the topological density (ρ), while in the second version the protocol employs the subjective density (sd) instead (this version is labeled "cooperation-aware MAD"). We also use a topology of moderate density (with 500 nodes in the rectangular area) and intense mobility (each node moves with speed 120 km/h). Mobile nodes moved according to the random way-point mobility model with zero pause time and constant speed [1]. Various environments of widely varying degrees of cooperation were examined, from completely cooperative to 90% of the nodes non-cooperative, varying the percentage of the total nodes that are non-cooperative in incremental steps of 10%. A node is characterized as cooperative if the value of its cooperation level

(c) ranges between 0.8 to 1, the actual value being sampled uniformly in this range. Similarly, a node is characterized as non-cooperative, if the value of its cooperation level (c) ranges between 0 to 0.2, the actual value again being sampled uniformly.



(a) (b)

Fig. 3: Average (a) end-to-end delay and (b) number of hops vs non-cooperative environment (500 nodes and 120 km/h).

The results in Figs. 3a–3b provide direct evidence that both of the average end-to-end delay and the number of hops to delivery increase as the environment becomes more hostile. This happens for completely different reasons in the two versions of the protocol: The "plain" improved MAD takes the forwarding decision ignoring the notion of cooperation and the message may be "trapped" in non-cooperative nodes that handle its further routing inefficiently. On the other hand, cooperative-aware MAD encapsulates the notion of cooperation in the subjective density and thus the cooperative nodes are preferred as next hops.

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

The already described contribution of the thesis, addresses issues regarded the context-aware routing policy including cooperation. Another important issue is the operational aspect of the signaling required for a realistic implementation of the routing protocol. In addressing this aspect, the thesis studies relevant on-demand beaconing techniques. 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 [8].

For the balance between energy efficiency (and reduced beacon signaling) and the protocol efficiency, 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, and from the analysis yields

$$T_b \leq 3.142r/V_c, \tag{4}$$

where T_b is the beacon period and V_c is the speed of the carrier node c.

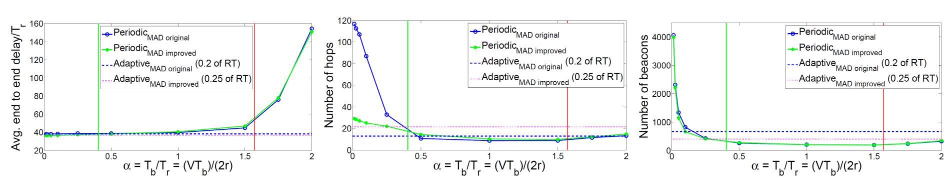
On the other hand, it is not necessary to insist on very small values of T_b. Although the refresh of information is good for maintaining an updated status of these nodes, a too frequent such update is excessive, wastes energy and increases signaling. One can set an empirical lower bound, by requiring that the fraction of nodes repeatedly checked among those nodes sensed should not be greater than the complementary fraction of nodes checked once. The analysis leads to

$$T_b \geq 0.808r/V_c. \tag{5}$$

For a visual representation of the aforementioned concepts, Fig. 1b displays the fraction of missed nodes and nodes checked multiple times, as a function of α. 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.

Also, the thesis 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, and also a potential application for other instances of DREOT. Linking the beacon intervals to each time applicable retaining time leads to an effective and efficient beacon policy [8].

The performance of the proposed periodic and adaptive beaconing schemes is considered in the context of the MAD routing protocol. In the set of results to be presented in Fig. 4, we investigate the impact of parameter α on the performance of the periodic beaconing scheme (the relevant results labeled 'periodic'). At the same time, the results illustrate the relevance of the upper (4) and lower (5) bounds on parameter α. Also, we compare the performance of the periodic with the adaptive beaconing scheme (the relevant results labeled 'adaptive'). Each beaconing scheme is tested with two versions of MAD employing different expressions for the retaining time, the original simpler (1) (labeled 'original MAD') and the more accurate/refined (2) (labeled 'improved MAD'). Mobile nodes move according to the random direction mobility model with zero pause time and constant speed. In order to compare the performance of the periodic and adaptive schemes, we present a topological scenario that corresponds to sparse density but high mobility, where the speed of the nodes is 50 km/h.



(a) (b) (c)

Fig. 4: Results for sparse and high mobility environments: (a) end-to-end delay; (b) number of hops; (c) total number of beacons.

By comparing the average end-to-end delay of the two periodic versions of MAD, the results indicate an increase as parameter α increases. This is because a greater value of α implies more neighbor nodes not detected as such from the current node. With respect to the average number of hops required for the message delivery from source to destination, the results show that the number of hops decreases with α, until α_{upp} is reached and then starts to increase. The initial decreasing trend is explainable if one recalls that higher values of α correspond to routing in sparser environments. The increasing trend of the number of hops beyond some value of α is due to the fact that overly long beacon periods result in the message being "lost" in the network. The number of beacons exhibits similar trends. Also, it can be said that the values of α between α_{low} and α_{upp} constitute an appropriate zone for beacon period selection.

To compare 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 comparing in terms of the number of hops. By studying the figures, it can be seen that the adaptive scheme provides a better trade-off between performance and beacon messages than the periodic scheme.

6 Conclusions

In this PhD dissertation we provide methodologies for effective decision making in the fundamental networking functions in diverse network topologies, which is a cooperative problem solving. Towards contributing to the routing problem, the thesis introduces a routing protocol, called *Maximum Advance Decision* (MAD), based on the novel notion of the *'retaining time'*, which is capable of automatically adjusting for best performance under the conditions applicable each time. Along the process, the thesis develops techniques that are useful for studying more general times between events governing a decision-driven system, called *'Decision-Related Event Occurrence Time'* (DREOT). Besides being useful on their own right, these results enable an in depth study of how the retaining time is affected by relevant network and nodal parameters and lead to an even grater improvement of the routing protocol. The ability of the retaining time to capture at the same time both routing environmental conditions and nodes' characteristics, motivates an appropriate adjustment of the topological density to also reflect cooperation or other social aspects, through the novel notion of *'subjective density'*. Another important complementary issue is the operational aspect of the signaling required for a realistic implementation of the routing protocol. In addressing this aspect, the thesis proposes and examines two different 'on-demand' beaconing schemes, one with periodic beacons and the other with adaptively adjusted beacon intervals based on the notion of the retaining time. Finally, all these aspects are compared and verified through a rich set of numerical and simulation results. The efficient and effective nature of the proposed techniques and notions reveals useful insights and provides guidelines as to how the decision policy of different operations is able to be self-adapted in diverse mobile environments.

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