Collaborative Relaying Strategies in Autonomic Management of Mobile Robotics

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Abstract- Mobile robotics is a field that presents a surprising set of challenges to communications. One concept that can result in radically different solutions in mobile robotics is that of collaborative and cooperative communications. Cooperative techniques in wireless networks can enhance the performance of communication especially in cases where a small number of robots can be used to aid the establishment of reliable and efficient communication links. In this paper, we present a scenario for hybrid mobile robotics, where a small number of carriers are able to reposition nodes according to communication needs. We developed a common information management layer in order to coordinate cooperation (including communication aspects) between all units (information nodes and robots) according to high level self-established policies. We select IEEE 802.11 technology as the technology for the communication infrastructure and explore its potential for cooperative mobile environments in terms of power and spectrum efficiency presenting the rules required to reconfigure such a mobile robotic environment.

Keywords- Cooperative communications, mobile robotics, policy, spectrum, power.

1. INTRODUCTION

Exploring modern communication techniques may lead to improved communication performance between mobile robots. Some interesting methods work based on the collaboration of several entities, employing cooperative techniques that can influence remarkably system performance. In order to implement a complete cooperative technique in an environment where several nodes can move, several issues should be taken in consideration: the role of each robot in the whole communication process, the requirements of the application handled by that role, the relative location and power available for each robot/node and the ability of neighbors to establish a cooperative communication scenario. Moreover, the specific wireless technology and the potential of existing protocols to coordinate cooperation are other issues which will the overall communication performance. Thus, for handling such scenarios, two sets of challenges are required to be tackled: the benefits of specific cooperative techniques have to be understood and formalized; and autonomic management rules need to be developed in such a way that the inherent mobility of some robots fully exploit the benefits of cooperative techniques in the communication process.

The main objective of our work is to provide an infrastructure that maps the roles and application services of fixed and mobile nodes to cooperative opportunities in wireless communications, and eventually lead to location changes of mobile nodes, aiming to enhance the efficiency of the network and optimize operations. Since IEEE 802.11 wireless networks appears as a common solution for communication of mobile robots, we try to employ the cooperative schemes of 802.11 MAC protocols in a practical scenario of mobile robotics where the mobility of the nodes can be controlled by both the policies and role of each node (even if not all information nodes are robots, we assume that most of them can be moved and relocated into new positions). We present a theoretical analysis on geographical areas where nodes can be located to improve communications efficiency (e.g. by reducing communication power) by exploring cooperative techniques. This analysis permits the system to form an optimum network topology by forcing movement for selected nodes aiming to adjust their relative locations for cooperation.

The rest if this paper is thus organized as follows. In Section II we describe related work in the field of autonomic management of robots and networked systems. Section III introduces basic concepts of cooperative relay communications in wireless networks. Section IV presents an analysis of the actual performance and power gain bounds which can be obtained when using IEEE 802.11 b/g/n, and which ultimately is mapped into control policies for mobile nodes. Section V describes the solution we propose to link low level link layer information, and high level policies in order to allow enhanced movement models for robotic systems. Section VI presents our conclusions regarding this work, as well as future prospects for research.

2. AUTONOMIC ROBOTIC SYSTEMS

Robotic systems have long been used for several ranging and remote sensing applications. While they are able to sense the environment and trigger actuators like traditional static sensing platforms, mobile robotic systems are given more computational capabilities and the possibility of moving in the environment they reside. Dependent on the specific application, it can be considered that robots are self-mobile, or that the mobility capabilities are assisted by other specialized devices, or even human operators (see other papers in this issue on the subject). A frequent scenario consists in operator-assisted mobility until near the area of actuation, followed be self-mobility in a geographically more reduced area. Independent of their mobility characteristics (self vs assisted), mobile robotics are computation platforms which are deployed in order to fulfil a set of tasks, frequently in cooperation. In many cases, this cooperation is established by carrier robots transporting repositionable information nodes, optimizing overall system cost: only some few robots are fully mobile, while most of the nodes are much simpler and with lower costs.

Methods for managing such networked devices in so complex distributed systems have since long been tackled by the research community. The research problem is simple: how to devise management mechanisms allowing systems to fulfil their purpose, while reacting to (unpredicted) changes in the environment.

Recently, multi-tenancy was also introduced as a relevant aspect for managed systems, and as a way to look at this problem. Distributed systems interact through interfaces, following clearly specified methods for exchanging information. In the domain of computational sciences, these interfaces, available over a great set of applications, are often implemented following Service-Oriented Architecture (SOA) solutions such as SOAP [1], REST [2], or CORBA [3]. Following this approach, most specifications being developed for the Internet of Things (IoT) by standardization bodies consider these more complex interfacing methodologies, in detriment of legacy, non-standardized description methods. In a SOA, the internal implementation of the "service" is not necessarily known, and the only requirement is that its interface is readily available and understood. Robotic systems, which result from the integration of both software and hardware components, possess an inherent level of isolation from their environment that makes techniques akin to SOA natural in these environments. Robotic systems have internal processes and will provide some service with other systems, managing instances, or even human operators (like in the case of remote controlled systems).

Solutions based on agents [4], actors [5], or bio inspired cooperating systems [6] are popular in the field of management of mobile robots. The difference between these approaches is how the internal control loops are organized, what inputs are considered, how information freshness decays with time, what adaptation mechanisms to novel situations are available, and how systems organize themselves together. The complexity of these different approaches have different orders of magnitude. This constrains the application of specific solutions and management models to specific scenarios, according to specific hardware/power/requirements compromises. Actor based solutions [5] are usually simpler and follow an approach where systems observe the world and report information regarding an event to a central point, while receiving instructions for acting in reaction to the event. The Agent model is slightly more complex as the environment is sensed, and some actions can be triggered locally. Local state and memory are frequently required for these systems, as well as coordination mechanisms between agents. Bio inspired systems try to apply concepts also used by biological organisms. The pheromone decay method used by ants [7] is frequently put to use, but also neural networks, that mimic neuronal structures in biological brains and try to use the capacity to adapt to initially unknown situations [8].

Although there is almost always some level of automaticity in these approaches, autonomic systems or (more importantly) knowledge based autonomic systems are considered a different, more complex, approach for the purpose of system management. Autonomic capabilities are frequently orthogonal to other approaches, e.g. an actor based system can have autonomous capabilities or not, even if mediated by a coordination point, or if the autonomous behaviour is available at the level of a set of systems (cluster) and not the individual system.

A basic structure of autonomic systems was first specified by IBM [9], and implement the now classical Monitor, Analysis, Planning and Execution architecture (MAPE), later improved to consider knowledge (MAPE-K) [10] (see Figure 1). Knowledge is sometimes distributed among system nodes, but not necessarily across all nodes, and not necessarily uniformly over all nodes.

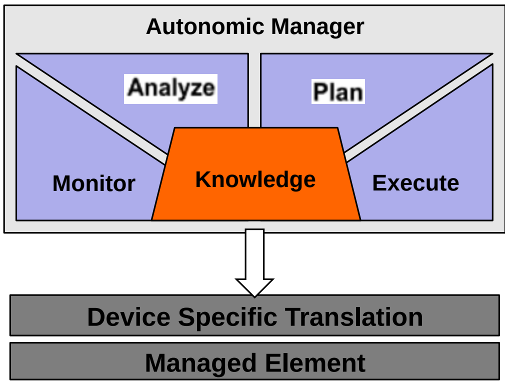


Figure 1 – Autonomic feedback loop with Knowledge

The MAPE-K control loop is a form of feedback loop, with the purpose of enabling (Autonomic) Managed Nodes to act autonomously according to a set of long-term goals. Under the scope of mobile robotics, MAPE-K involves both software components (such as vision processing software or services of the communication stack) and hardware resources (such as sensors and actuators, e.g. temperature sensors or step motors). A translation layer interfaces the management components with the remaining components of the robotic system, actually translating policies into effective commands. The component responsible for creating and keeping knowledge resides at each system, and is isolated from others. This component is vital in order to allow systems to avoid past errors and to discern if they are getting closer to the desired goals, or in opposition, are drifting from them.

Some approaches consider that knowledge can be distributed between members of a domain [11], and even propose the creation of new communication approaches for networked devices [12]. As with other distributed systems, keeping consistency of distributed information adds an increased burden but it is frequently required. Also, given that each system is an independent observer, and can act autonomously, the actions it derives may be different from those derived by other neighbours. This brings an extra problem, the need of consensus and knowledge convergence mechanisms in autonomous systems.

Under the scope of mobile robotic systems, autonomic control loops present the possibility of coordinating actions between the different robots, and to have a distributed, always updated policy available to all members of the same policy domain. Considering the case of communications between mobile robots, distributed knowledge also allows robots to take in consideration both the policies active locally, and the policies of their neighbours, making it possible for systems to act in coordination.

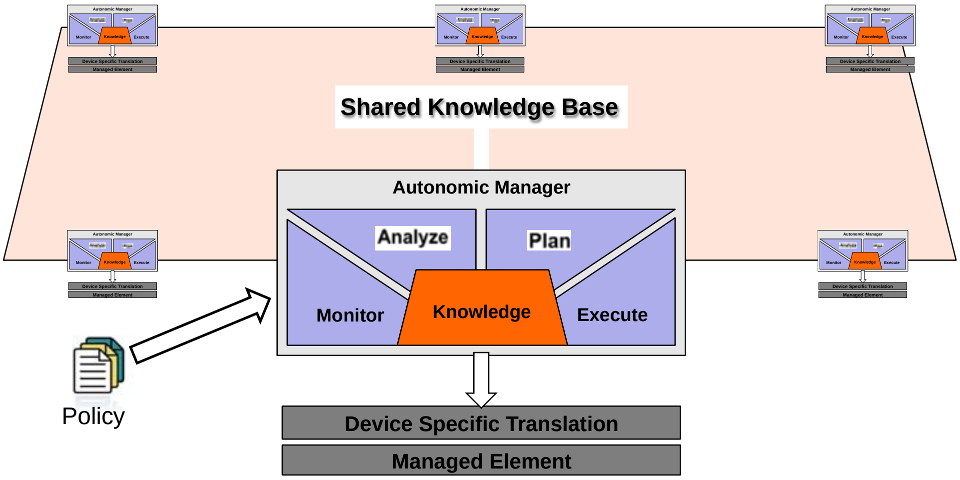


Figure 2 - MAPE-K loop with distributed knowledge and policies

In a previous work we explored the challenges brought by autonomic management tackling the creation of a management framework aiming at managing heterogeneous network resources, owned by multiple tenants [13]. The key concept on this management framework is the *Community*, the set of interoperating nodes. The system can grow organically in a distributed manner by means of role delegation. At its root, the management system deploys an Event Condition Action (ECA) control loop with dynamically pluggable policies and a shared knowledge repository. These concepts map easily into the case of mobile robots jointly exploring/surveying/analyzing a sparse area, and are especially useful for situations where some robots are responsible for providing reposition for other elements (either nodes or smaller, specialized robots, as discussed elsewhere in this issue). The Autonomic Manager instance running at each robot should both consider local information, as well as information (knowledge) from the collective. Our objective here is then deploying sensor networks with mobile nodes, able to monitor large surfaces with increased performance and reduced power consumption. In this work we show how our lightweight management system, taking in consideration simple network link information, location information, and device profiles, can be applied to environments where carrier robots reposition low power units in order to increase network reliability and longevity.

3. COOPERATIVE RELAYING TECHNIQUES

Our solution focus in the dynamic behavior of the communication medium, in particular 802.11, and in optimizing node location, so that applications running in mobile systems experience maximum performance with lowest energy consumption. In particular we focus in the use of cooperative relaying techniques as enablers of increased performance. Therefore, we will first describe the framework to analyse the performance figures resulting of a communication in mobile environments, when using cooperative communications. This communication model has emerged as a new approach beyond the point-to-point and point-to-multipoint paradigms of classical wireless communications, and more controlled than generalized, multi-hop routing present in ad-hoc networks. From a communicational point of view, cooperation techniques can be applied to take advantage of synergic operation of more than one system with sharing resources, aiming to improve the performance. Entities can be engaged in cooperation at different levels including signal and packets in every layer of OSI model, protocols and algorithms. In this approach, a new element (relay) is employed to improve the quality of communication between transmitter and receiver. While conventional research mainly considers the broadcast nature of wireless channel as the origin of interference and performance degradation, cooperative communication exploits this inherent feature to overhear traffic from other users. Exploring this technique in environments with mobile robots has the added advantage that units may be repositioned to optimally explore cooperation opportunities available.

Recently, the topic of cooperative techniques has received significant attention from researchers, in particular when considering the IEEE 802.11 standards [15][16][17]. Mobile robots can explore the concept as it brings clear benefits in terms of increased reliability, power savings and performance. The IEEE 802.11 family of protocols have appeared as the dominant industrial standard for the establishment of either infrastructure or ad-hoc networks. Nowadays it is commonly available, and hardware developed around it is of low cost and easy maintenance.

One of the main features of IEEE 802.11 networks is to support multiple transmission data rates depending to instantaneous conditions of the wireless channel. This feature increases the coverage area of wireless communication, however it leads to the problem called performance anomaly [18]: equal transmission opportunity provided to all involved nodes in the same IEEE 802.11 network leads to high latency required to complete the transmission of low data rate nodes, thus degrading the performance of the remaining, higher rate nodes. For instance, the duration time for the transmission of a packet of fixed size at the minimum data rate (6Mbit/s), using the IEEE 802.11g protocol [16], makes the shared medium being occupied 9 times longer when compared to the transmission the same packet at highest data rate (54Mbit/s). This problem can be exacerbated in more recent amendments of the standard, such as IEEE 802.11n [17], which supports up to 300Mbit/s. Therefore overall system performance is constrained by the ratio of low data rate nodes to all nodes in the same collision domain. Furthermore, the nodes at the edge of coverage area suffer from high packet loss rate due to worse channel conditions and higher interference levels. Cooperative protocols provide promising solutions to overcome these challenges of IEEE 802.11 networks. The key idea is that devices can sense their environment, and decide to replace one channel with bad conditions by two good channels. The meaning of bad and good channels depends on the purpose of the cooperation. If the main concern of cooperation is to achieve higher capacity, one low data rate direct transmission link can be replaced by two faster transmission links by employing a relay node (see Figure 3). This key idea is the main objective of several cooperative MAC protocols [19][20][21][22][23][24] in context of IEEE 802.11 standards.

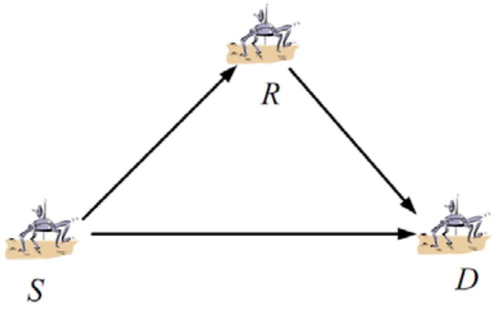


Figure 3 - Relay communications model

A well-known cooperative protocol following this approach is CoopMAC [20]. In CoopMAC protocol, every node opportunistically use passively collects information about channel conditions with its neighbors. With this information, it can measure their Signal to Noise Ratio (SNR) and estimate relative distances and modulation schemes to use. In the CoopMAC protocol, MAC addresses of potential relay nodes, as well as transmission rates to neighbors are stored in a table called CoopTable. When a packet is ready to be sent, source node (S) searches the CoopTable for a potential relay node. The best relay node is the joint neighbor of source and destination which has the highest data rates with them. If it succeeds to find a relay node, it sends a modified RTS packet including the MAC address of the relay (Figure 4). The relay responds with a new control packet called Helper To Send (HTS) to inform the sender that it can operate as a relay. Afterwards the receiver sends a CTS packet to complete the handshaking. Results obtained in [20] show that the CoopMAC protocol gives better performance in terms of capacity gain and access delay.

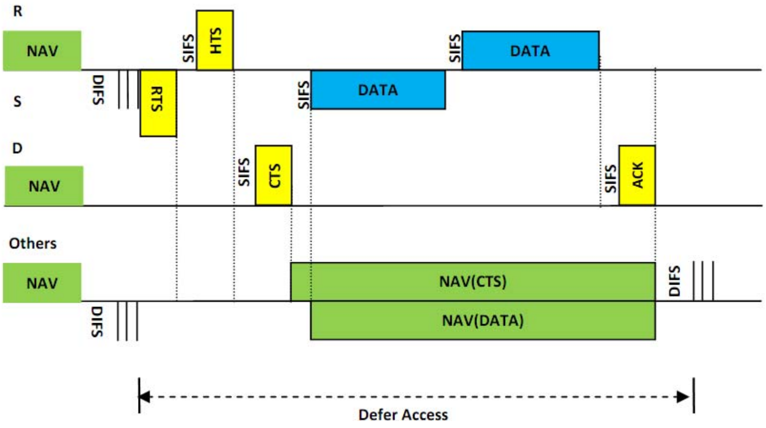


Figure 4 - CoopMAC enhanced 802.11 frames

The energy efficiency of the IEEE 802.11 MAC protocol is another important aspect of communications, especially for autonomous robots, where efficient utilization of energy is a main concern of MAC protocol designers. Similar to capacity gain provided by cooperative techniques, we can obtain the power gain by replacing two good channels instead of one bad channel. Obviously, in this context, good channels are provided by using of those relay nodes which reduce the energy consumption of cooperative scenario compared to non-cooperative one while the delay keeps constant. This power saving can be achieved by transmitting with lower power or equivalently with lower SNR when the equivalent data rate of cooperative path is the same as direct path. The impact of relay nodes on the energy efficiency in cooperative relay based IEEE 802.11 networks has been addressed in several works [25][26][27][28]. The authors of [25] demonstrated that cooperative relay schemes provides the power saving ranging from 7 to 20 dB over direct transmission and from 1 to 3 dB over multihop routes. It was observed in [20] that besides the network capacity gain by cooperative communications, energy efficiency gain is on the order of 20%-40%. The energy efficiency of MIMO and cooperative MIMO systems were also investigated in [26] in which the authors address the issues such as energy cost and reduction of transmitter power in cooperative relay schemes. In addition, the authors in [27] demonstrate the energy efficiency of single relay cooperative MAC protocol while the results of [28] indicate the energy saving mechanism and energy performance improvement of multiple relay protocol when compared to normal IEEE 802.11 MAC protocol. Nevertheless, none of these works is able to provide a practical view to determine the time of cooperation when the main objective is power saving or bandwidth efficiency.

In [29], we provide an analysis to demonstrate the existing potential of capacity gain and power gain of cooperation in IEEE 802.11 standards. We introduce the *delay ratio* as the metric to indicate the suitable relay node providing capacity gain. Furthermore, we presented a metric for energy consumption to select appropriate relay node with power gain. One of the important issues which was addressed in [29] is the location area of relay nodes which provide the benefits of cooperation in term of power and spectrum. The mobility characteristics of the nodes (and relay nodes) including speed of mobile nodes and direction of movements are random parameters and they have a crucial impact on the performance of the cooperative techniques. Nonetheless, the mobility features are in the key concern of the cooperative scenarios when the movement of the relay nodes can be governed by order of a given pair of transmitter and receiver nodes seeking a relay node to improve the performance of the communication for application services required the bandwidth efficiency or power saving.

In this paper we apply this previous work and extend it, in order to propose a new policy based model for coordination of autonomous robots. In particular we focus in how location of robots and their repositioning are importance to maximize network performance, and completion of the goals assigned to each robot.

4. ANALYSIS OF CAPACITY AND POWER GAIN

Since power and spectrum are main resources for mobile robots communicating through a wireless medium, analysis of capacity and power gain obtained by cooperative techniques is very important. By having a correct characterization of the transmission medium, and its boundaries, it is possible to better fit location to the actual role of each robot, as well as minimize power consumption. In this section, we present an analysis of the performance bounds achieved for power and bandwidth when using IEEE 802.11 b/g/n, when associated with different locations of a source, destination and relay robot.

a. Capacity gain

In order to improve the throughput in cooperative IEEE 802.11 network using relay nodes, the total transmission delay should often considered as the main concern to initiate the cooperation process. Transmission delay is the time a data packet takes to be transmitted over the medium. So we should have a practical sensing method to obtain the transmission delay of direct and relay paths. As shown in Figure 3, node R as a candidate relay can explicitly obtain the actual data rate between Source (S) and destination (D) from overhearing data frames exchanged between them. The 802.11 MAC header (or in more detail, the PLCP sub-header), contains a field named SIGNAL, which denotes the bit rate of every data packet sent to the network. R can also estimate the potential data rate between itself and pair of source-destination. Node R can measure the RSSI of RTS and CTS and ACK frames issued by nodes S and D, and compute the corresponding data rates of obtained RSSI(s). After obtaining the three data rates between these three nodes, we can define a metric such as Delay Ratio (DR) [30]. Delay ratio is the ratio between the transmission delay of relay path, and that of the direct path. When the relay node supports data rates of B_{SR} Mbps and B_{RD} Mbps to S and D, respectively, and the direct transmission data rate between S and D is B_{SD} Mbps, the delay ratio estimated by R in Figure 3 can be expressed as:

$$DR_i = \frac{(B_{SR})^{-1} + (B_{RD})^{-1}}{(B_{SD})^{-1}} \qquad (1)$$

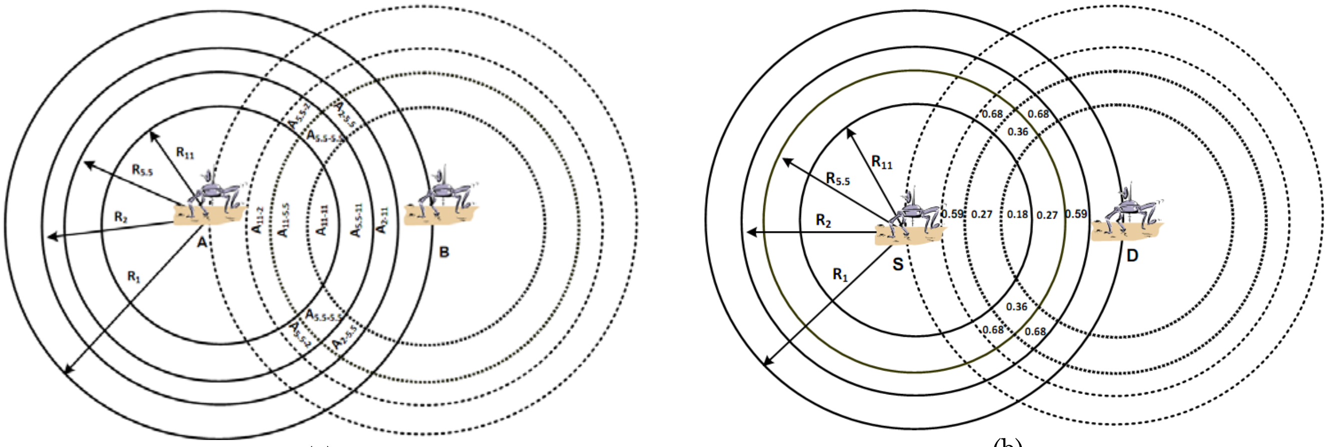
Clearly, if the value of the calculated delay ratio is less than 1, the relay channel may provide better transmission characteristics than the direct channel, due to the resulting effective higher bandwidth and lower transmission delay for end-to-end communication. It is noted that source and destination nodes can obtain the same delay ratio estimation of using *R* as the relay, if they do the same sensing and computation. Therefore, the decision to participate in cooperation or not can be taken by source, destination and relay nodes. Due to multi rate capability of IEEE 802.11 and according to the location of the relay node, various delay ratios and cooperative throughput can be obtained. Thus, the respective distances of relay node to source and destination nodes can determine the corresponding delay ratio. A relay can change its location within an area called relay area while its delay ratio does not change. To obtain the relay area versus delay ratio, we consider the geometric model of cooperation. In order to calculate the relay area, we need to obtain the overlap area between two circles. The overlap area of two circles with radii of r_1 and r_2 and distance *l* between the centers can be written as (12).

$$S_{r_1 r_2} = r_1^2 \sin^{-1}(h/r_1) + r_2^2 \sin^{-1}(h/r_2) - hl \qquad (12)$$

where, $h = \frac{\sqrt{2r_1^2 r_2^2 + 2(r_1^2 + r_2^2)l^2 - (r_1^4 + r_2^4) - l^4}}{2l}$. As depicted in Figure 5, we can compute different relay area versus the overlap area of circles made by transmission ranges. The relay area of Figure 5.a can be computed as (13):

$$\begin{cases} A_{11-11} = S_{R_{11}-R_{11}} \\ A_{11-5.5} = A_{5.5-11} = S_{R_{11}-R_{5.5}} - S_{R_{11}-R_{11}} \\ A_{11-2} = A_{2-11} = S_{R_{11}-R_2} - S_{R_{11}-R_{5.5}} \\ A_{5.5-5.5} = (S_{R_{5.5}-R_{5.5}} - S_{R_{11}-R_{5.5}} - A_{11-5.5})/2 \\ A_{5.5-2} = A_{2-5.5} = (S_{R_{5.5}-R_2} - S_{R_{5.5}-R_{5.5}} - A_{2-11})/2 \end{cases} \qquad (13)$$

Where A_{i-j} is relay area in which a relay node can change its position while the data rates to source and destination are *i* Mbps and *j* Mbps respectively, and S_{Ri-Rj} is overlap area of two circles with transmission ranges of R_i and R_j.



(a)

(b)

Figure 5 - Relay area in IEEE 802.11b (a), and the corresponding Delay Ratio (b)

As can be seen in Fig. 5, direct data rate of source and destination is 1 Mbps. By applying the similar recursive calculations in (13), we can obtain the relay area for every direct transmission data rates supported by 802.11 standards. The total area estimated in the previous theoretical analysis can be obtained by adding the area of the geometrical approximation for all possible delay ratios. Figure 5.b shows the corresponding delay ratio when cooperation occurs in IEEE 802.11b standard.

In order to compute the relay area corresponding to delay ratio, we need the specification of transmission range for each data rate. We focus our evaluation in indoor environment for three amendments: 802.11b [15], 802.11g [16] and 802.11n [17].

Table 1 indicates the data rates supported and maximum transmission ranges of these amendments when BER=10^{-5}.

Table 1 - Data rates and approximated transmission ranges of 802.11b/g/n

802.11n	Data rate (Mbps)	7.2	14.4	21.7	28.9	43.3	57.8	65	72.2
	Typical Range (meter)	115	91	78	62	46	34	31	29
	Min-SNR (dB)	11	14	16	19	23	27	28	29
802.11g	Data rate (Mbps)	6	9	12	18	24	36	48	54
	Typical Range (meter)	122	107	96	85	75	61	42	31
	Min-SNR (dB)	8	9	11	13	16	20	24	25
802.11b	Data rate (Mbps)	1	2	5.5	11				
	Typical Range (meter)	180	150	130	100				
	Min-SNR (dB)	2	2.9	5.4	10				

Table 2 - Delay ratio and relay area of 802.11b/g/n

	S to D Data rate (Mbps)	*S to R Data rate (Mbps)*	*R to D Data rate (Mbps)*	Delay ratio	(Relay area/ Coverage area)%	
802.11b	1	11	11	0.18	1.2~4.5	19~22.3%
		11	5.5	0.27	7.2	
		5.5	5.5	0.36	1.8	

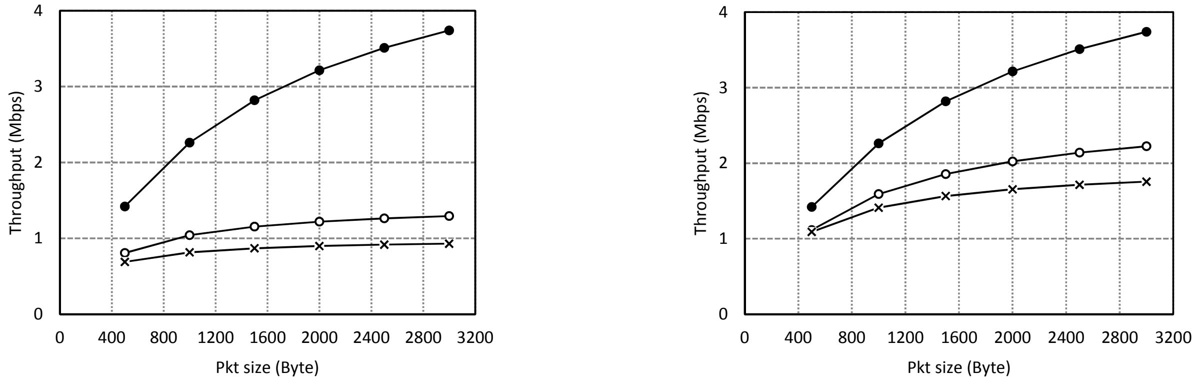
		2	11	0.59	6.4	
		2	5.5	0.68	2.4	
	2	11	11	0.36	4.5~7.3	11.2~14%
		11	5.5	0.54	4.9	
		5.5	5.5	0.72	1.8	
802.11g	6	24	36	min:0.42	13~16%	
		12	18	max:0.83		
	9	36	36	min:0.5	7.4~13%	
		18	24	max:0.88		
	12	36	54	min:0.55	3.3 ~4.6%	
		24	36	max:0.83		
	18	48	54	min:0.7	1.2~4.3%	
		36	48	max:0.88		
	24	54	54	min:0.89	2~3.6%	
		48	54	max:0.94		
802.11n	7.2	43.3	86.7	min:0.5	15.8~24.5%	
		28.9	43.3	max:0.83		
	14.4	57.8	144.4	min:0.7	8.6~12%	
		43.3	115.6	max:0.92		
	21.7	86.7	115.6, 130	0.87	0.1~1.5%	
	28.9	115.6	144.4	min:0.9	0.1~1.5%	
		115.6	130	max:0.94		

According to the computation discussed for relay area and based on the data rate and considering the approximated maximum transmission range of Table 1, we can calculate the delay ratio and corresponding useful relay area percentage (Table 2). For 802.11b, we calculate all possible delay ratio values less than one and their corresponding relay area. For 802.11g and 802.11n, due to the many possibilities for delay ratio less than one, we only present the delay ratio bounds and corresponding relay area bounds. Table II indicates that in 802.11g, which supports data rate from 6 Mbps to 54 Mbps, the cooperation is beneficial for direct data rates between 6 Mbps to 24 Mbps. As the direct data rate increases, the probability to find a useful relay node will decrease. Similarly, the delay ratio less than one is possible for direct data rate in range of 7.2 Mbps and 28.9 Mbps in 802.11n while 802.11n can support data rates from 7.2 Mbps to 72.2 Mbps in one spatial data stream. It is noted that for 802.11n with two, three and four spatial streams, we have the same delay ratio and relay area, while the data rates are multiplied respectively by two, three and four. The performance gain provided by each delay ratio at every 802.11 amendment is another main issue to justify the cooperation. We consider the throughput performance of the CoopMAC protocol when delay ratio changes. Minimum and maximum of delay ratios lead to upper and lower bounds of throughput performance respectively.

As depicted in Figure 6, the performance bounds of CoopMAC protocol are also dependent to the application packet size and direct data rate (R) between source and destination nodes. Since small packets impose higher overhead per bit of application data compared to larger packets, the relay performance is increased with high data packet size. Furthermore, cooperative communications with the purpose of low latency and high throughput can be obtained when the direct data rate between source and destination is low and there are more possibilities for relay nodes to have higher data rates to source and destination.

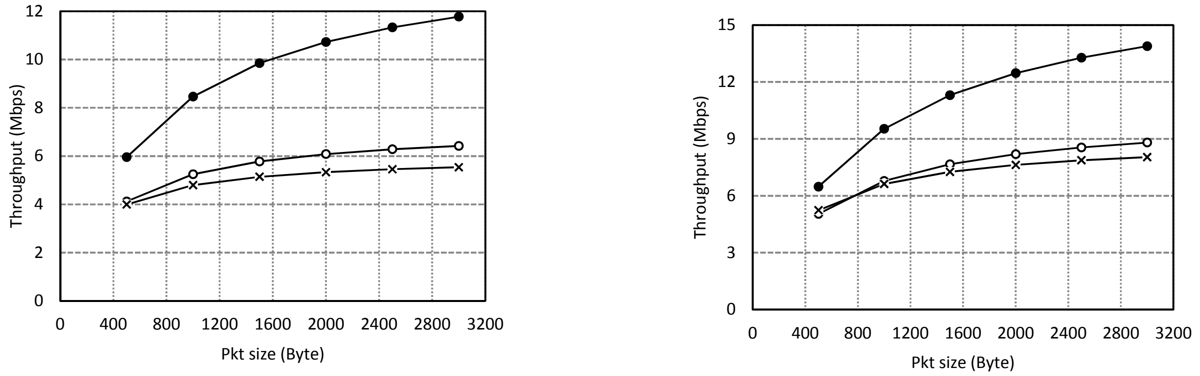
b. Power gain

Energy efficiency in networks using IEEE 802.11 is affected by several factors such as the transmit power and the processing power required for forwarding packets by nodes. In a non-cooperative direct transmission, the power allocation is carried out only by the source node, while in a cooperative scenario both source and relay nodes should allocate power to complete the transmission. Due to the multi-rate nature of IEEE 802.11 and minimum SNR required for each data rate (Table 1), we can consider the scenarios with reduce the power consumed while the delay of direct and cooperative path are the same. We exploit this idea and provide a mathematical analysis in [28] to demonstrate the performance bounds of power gain by using relay node. The power gain is defined as the transmitted power allocated by source in non-cooperative case to total transmitted power consumed by source and relay in cooperative scenario. Since the path loss is directly proportional to distance and in order to obtain the maximum power saving, we assume that the relay node is located between source and destination and $d_{SR} \approx d_{RD} \approx d_{SD}/2$.



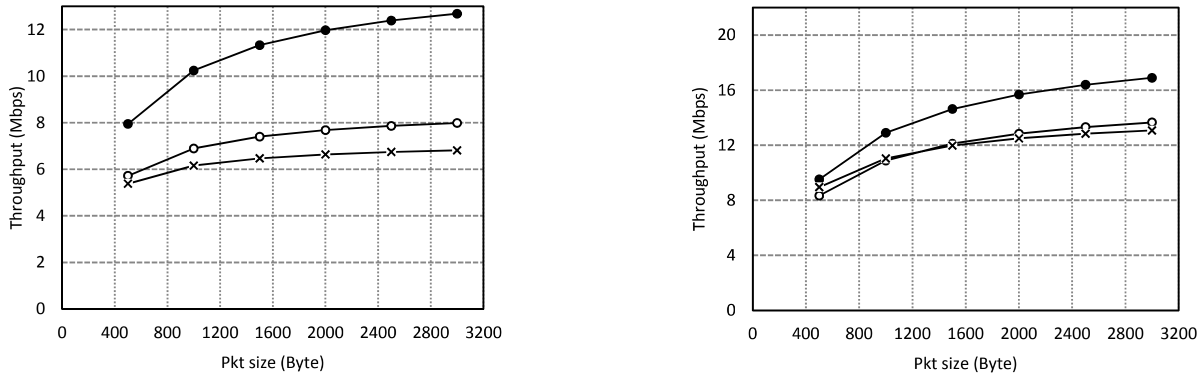
a. 802.11b, R=1 Mbps

b. 802.11b, R=2 Mbps



c. 802.11g, R=6 Mbps

d. 802.11g, R=9 Mbps



e. 802.11n, R= 7.2 Mbps

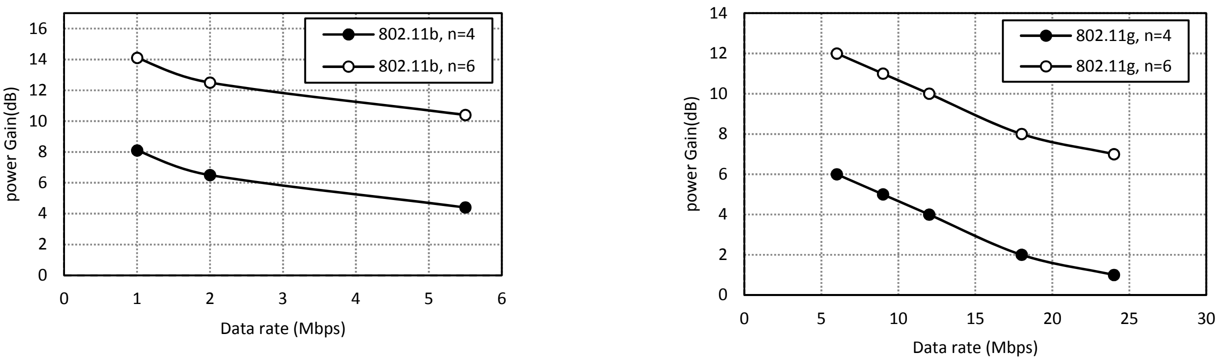
f. 802.11n, R=14.4 Mbps

Figure 6 - Throughput performance bounds of CoopMAC and normal 802.11 b/g/n

Table 3 shows the scenarios of cooperation with the purpose of power gain when the delay ratio is close to one. To achieve this delay ratio, the data rates of source-relay ($R_{S\to R}$) and relay-destination ($R_{R\to D}$) are double of direct data rate ($R_{S\to D}$). According to the mathematical analysis in [28], the power gain (PG) can be obtained based on the SNR of received packet at destination in direct and cooperative modes ($SNR_{S\to D}$ and $SNR_{R\to D}$) and path loss coefficient (n). The power gain obtained by these scenarios is depicted in Figure 7. As can be seen in cooperative scenarios and for communicating with a lower data rate, we can achieve higher energy efficiency, when compared to the higher data rate. The energy efficiency of 802.11b in a cooperative scenario outperforms 802.11g/n when the main purpose of cooperation is energy saving with no improvement over throughput.

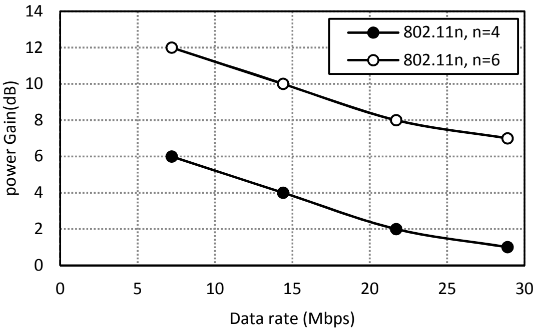
Table 3 - Data rate set and power gain in 802.11/b/g/n

	Data rate (Mbps)	Min(SNR) (dB)	Data rate set (Delay ratio≈1)			PG(dB) $PG(dB) = SNR_{S\to D} - SNR_{R\to D} + 3(n-1)$	
			$R_{S\to D}$	$R_{S\to R}$	$R_{R\to D}$	n= 4	n=6
802.11n	7.2	11	-	-	-	-	-
	14.4	14	7.2	14.4	14.4	6	12
	21.7	16	-	-	-	-	-
	28.9	19	14.4	28.9	28.9	4	10
	43.3	23	21.7	43.3	43.3	2	8
	57.8	27	28.9	57.8	57.8	1	7
802.11g	6	8	-	-	-	-	-
	9	9	-	-	-	-	-
	12	11	6	12	12	6	12
	18	13	9	18	18	5	11
	24	16	12	24	24	4	10
	36	20	18	36	36	2	8
	48	24	24	48	48	1	7
802.11b	1	2	-	-	-	-	-
	2	2.9	1	2	2	8.1	14.1
	5.5	5.4	2	5.5	5.5	6.5	12.5
	11	10	5.5	11	11	4.4	10.4



a. 802.11b

b. 802.11g



c. 802.11n

Figure 7 - Power gain versus data rate and path loss coefficient (n) in 802.11b/g/n

5. POLICY BASED COOPERATIVE RELAYING

The discussion of capacity gain and power gain in cooperative 802.11 wireless networks presents the clear conclusion that the relative node location, as well as traffic characteristics, can influence relay performance. Based on distance, location, and traffic characteristics, cooperative communications can either be a source of great performance increase, or of great performance penalty and increased power drain. Local feedback loops can make systems to fulfill their goals, but if communication between elements, or with a central anchor is required, typical, self-centered, MAPE-K loops may be insufficient. This is a special problem if systems are unable to keep permanent communication with central anchors (e.g. through UMTS or other cellular technology), and must rely on multi-hop relay. Local operation requires coordination with neighbors so that, if required, communication is not severed, or at least degraded below the required levels of performance. In our vision of autonomous mobile robots cooperating for their tasks, we aim to have a solution, which allows communication through multi-hop relay cooperative links, exploiting relay based cooperative techniques. To do this we make use of the notion of common knowledge layer, as well as a clear set of policy management concepts enclosed in a policy domain that we first proposed in [13]. By domain we consider all robots that are jointly operating in and geographically disperse area. Systems may be owned by multiple entities and action is ultimately tied to both user roles and system capabilities. Examples of such scenarios are distant monitoring situations. In both cases it may make sense to have a group of mobile devices that can be moved an area, reporting back information in a multi-hop fashion. In some cases, devices may interact with the environment by enabling actuators.

The common knowledge layer consists of a repository of information that is publicly available to all members of the same domain, and to which sensed data can be published and queried for further correlation. Information in this layer consists of both policy objects stating the tasks to be developed, a manifest token which associates each node with an existing role, and other information produced by the applications enabled. Roles are composed of information elements (policies) which can be grouped in both obligations and authorizations. Obligations state the actions that must be taken by the autonomous robot, as well as how to react to events occurring in the environment or internally. Examples of such events are structural damage, tampering (in urban scenarios), or simply hardware malfunction. By authorizations we consider the need for constraining location (thus implementing virtual fences), or limiting the action of systems in some pre-determined way. Especially if robots are leased or rented between tenants in the same domain, or to another administrative domain (e.g. to the local municipality). A key aspect to a lightweight implementation of this layer is the adoption of concepts from distributed hash tables such as Chord, CAN, or Pastry [32][33][34]. In our case, the system makes use of a custom designed persistent storage based on Kademlia [35]. These concepts allow the definition of a load balanced, redundant, persistent communication channel based on, keyed *set* and *get* primitives. Adding information to the knowledge based makes use of a *set* operation, while *get* is used to retrieve information. The Distributed Hash Table (DHT) provides operations with low delay, and allows the exchange of information between different instances. The requirement for using this efficient system is that all information objects should have an identifier (e.g. 256bit SHA digest) that is unique in the management domain.

Applied to the case of user communities of interest, the solution we presented in [13] follows these guidelines, by providing a cross layer management system where policies can be disseminated to what is called a *Community* (management domain). Systems are considered to be owned by one entity (user, corporation, group, etc...) and act according to strict policies. Multiple layers of authorization may be in place, and by using the common distributed storage, it forms a full featured distributed Role Based Access Control (DRBAC) system.

The main advantage of this common communication layer is to enable enhanced cooperation, both in terms of high level polices, but as well as to keep communication requirements. For this purpose we adopt the use of *ApplicationManifests* (AM) by applying concepts evolved from [14], together with the dissemination of network structure and performance into the common distribution layer. Later, these objects can be used by the policy engined in order to better fulfill a nodes role.

ApplicationManifest are XML blocks, composed by a *Traffic Description* and *Performance Targets*, describing the communication and operational characteristics of an application, in a particular system. Therefore, *ApplicationManifests (AM)* are related to systems in the sense that systems have zero or more active applications. Each robot may have one or more *AM* active at a single time, in correlation to the actual set of applications (tasks) which is running at any given moment. Several other manifests may be available but inactive, and are not published to others. The purpose of the *AM* is, to define the characteristic of the traffic produced, and computational requirements of a task executed by a system. They are related to the capabilities of a given robot, and are added during setup time. Over the air update can also be considered, but this is out of focus of the current work. Listing 1 describes the manifest of a video stream application and the respective system (autonomous robot).

```
<System owner=”EntityA” name=”RoboA”>
       <Locators>
               <NetworkAddress>10.0.0.1</NetworkAddress>
               <GeoLocation>
      <Latitude>40.0231</Latitude><Longitude>-8.4345</Longitude>
    </GeoLocation>
</Locators>
<Devices /> <!--Sensors and actuators -->
<NetworkInterfaces /> <!—Network Communication Devices -->
<Services /> <!-- Services provides to others -->
</System>

<ApplicationManifest name=”VideoSurveilance”  system=”RobotA” status=”active” >
       <TrafficDescription protocol=”UDP” port=”5060” Src=”10.0.0.1”, Dst=”10.0.0.10/>
  <PerformanceTargets>
       <Target name=”PacketLoss” priority=”10”> 0</Target>
       <Target name=”Bandwidth” priority=”5”> 512k</Target>
       <Target name=”MinPowerAvailable” priority=”1”> 10% </Target>
       <Target name=”PowerConsumption”> 105mA </Target>
       <Target name=”AvgPacketSize”> 1400 </Target>
  </PerformanceTargets>
  <Relays>
       <Relay>RobotB</Relay>
  </Relays>
</ApplicationManifest>
```

Listing 1 – System description and ApplicationManifest for a VideoSurveilance application

Internally, this information can be used mainly for two aspects: selecting the best communication strategy, or to trigger the process of moving the autonomous robot to a more appropriate location. In autonomous networks, the relay performance can improve when roles and common knowledge are employed. Figure 8 depicts a scenario with several nodes with various level of battery power and application services to be handled. For instance, when node *B* with low battery tries to send an image to anchor node, node *A* can be moved in order to cooperate with the relaying process and hence minimize the power consumption. When node *C* has an application service which needs high bit rate link to anchor node, node *D* can operate as a relay to provide capacity gain for forwarding the packets. In this case, relative movement of source, destination and relay node would change the throughput performance. Thus, node *D* should be placed in areas corresponding to lower delay ratio. However, there may be some nodes such as node *E* that will make use of direct transmission, since it has enough battery power and its application service needs a low bit rate link.

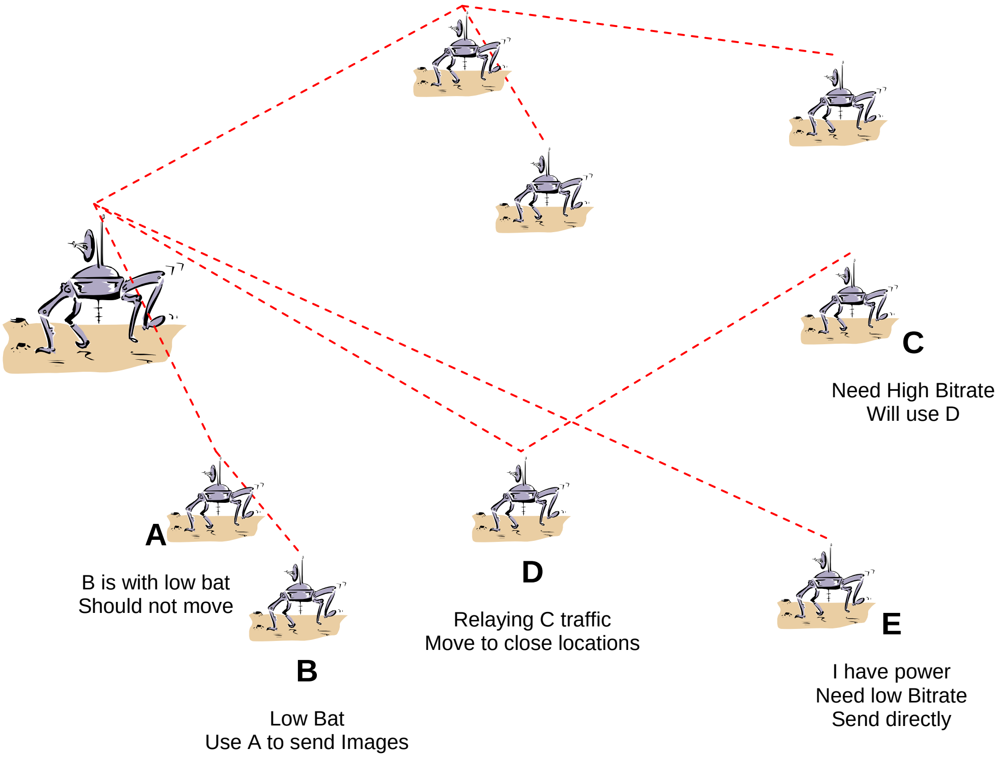


Figure 8 - Policy based multi-relay scenario

The *ApplicationManifest* plays an essential role in the selection of the best relay, from the list of candidates. Systems could simply use the best communication path (lowest *DR*). However, this could both limit robot movement, as well as result in sub-optimal spatial diversity of multi-hop communications. Therefore, systems try to match the candidate relays to the requirements of the current active *Application Manifests*, and select one that fits the characteristics required. It should be noticed that the candidate relay with best *DR* may be or not be chosen. Nevertheless, the selected relay will be one that demonstrated to support the required rates and matches the required power constrains for communication. The *priority* field allows sorting relays and selecting a particular one, even if some target is not achieved. As implied, different applications should be routed through different relays, or eventually be sent directly to the anchor point.

Active application manifests are published to all other systems, and if a relay is used, that information will be available to others. If node *A* uses *B* as a relay for the *VideoSurveillance* application, *B* will be bound to let *A* fulfill his task. Because this mechanism alone would imply a strict limitation on movement from the autonomous systems, we also introduce the concept of a *NeighborManifest* (NM). This manifest is created by each system, and provides information to others, and to system administrators, about current neighbors in reach and the performance metrics observed for them. This object is also available to all systems and allows for bound relays to be moved, as long as the source node has alternative relays providing the required performance targets.

As presented in Listing 2, the *NeighborManifest* provides information to neighbors about candidate relays from the perspective of the current system. The number of performance targets available varies with each system. The *lastUpdate* field denotes the last time the information was updated in seconds. The higher it is, the oldest is the information. Nodes will stop including neighbors in their *NeighborManifest* when the information becomes too old.

```
<NeighborManifest system=”RobotA”>
  <Neighbor MAC=”00:01:01:01:01” lastUpdate=”14”>
    <Target name=”PacketLoss” > 0</Target>
               <Target name=”Rate”> 54M</Target>
               <Target name=”RSSI”> 45</Target>
  </Neighbor>
  ...
</NeighborManifest>
```

Listing 2 - Example *NeighborManifest* of system RobotA

Taking in consideration the information present in both the application and neighbor manifests, together with policies, systems can propose the optimization of their location in order to tweak performance targets, and better fulfill the tasks there are entitled to perform. Although reflections of radio signals are a problem to solve, as then may suggest a different direction from the real one, the current solution allows systems to select the best relay taking in consideration power and performance constrains, know if a given node is being a relay, and more importantly by taking in consideration geographical location, and optimize forwarding capabilities.

6. CONCLUSIONS

In this work we presented a system for complex mobile robot environments, able to consider both fully mobile, semi-mobile, and fixed robots. The reference case assumes a set of low cost information nodes that are potentially repositioned by robots, in order to optimize communication (both in terms of performance and energy) by exploring cooperative communications.

For this, we present a formal analysis of the expected bounds found when transmitting information through cooperative relay channels in IEEE 802.11, when considering multi-rate MAC. As we show, if location, traffic characteristics and low level link information are not taken in consideration, the use of relay channels may result in sub-optimal performance. In fact, we show that the percentage of area around a robot, where a relay may be placed in order to provide better than direct capacity, is of reduced dimension. Moreover, only for packet sizes near the limit MTU of IEEE 802.11 there is an advantage for the use of cooperative relay techniques in mobile robotics. Regarding power efficiency (a very important aspect for autonomous mobile systems) we show that assuming cooperative relaying as the default method is not always beneficial. Relay selection, and even the use of relay cooperation techniques, must take in consideration aspects such as location, application traffic characteristics, candidate relays and number of neighbors, which may have an impact in how the tasks of each autonomous system is implemented. Thus positioning of nodes in a mobile robotics environment is a critical and complex action.

For handling this task in autonomous systems, we show how the evolution of concepts developed for policy based management of lightweight network resources, and by means of role based access control concepts, can be tied with low level link information in order to provide increase system performance. Such an autonomous distributed system can be used to explore optimum communications in the diversity of scenarios posed by mobile robotics.

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