A Local Information Based Protocol for Networks Data Exchange with Application to Mobile Sensor Networks

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Abstract: The paper presents a new protocol for multi hop data transmission between nodes in a mobile sensor network. The only requirement for the network is to be connected. The routing is handled locally on the basis of informations contained in the data transmitted. Global (time dependent) routing table as well as knowledge on the position of the nodes are not required, since the protocol itself contains an Hand-Shake phase for the neighbour detection. This allow to have high mobility for the nodes and, moreover, it is dynamically reconfigurable once the number of the nodes varies. A innovative data structure called "the Postman Bag" is introduced to spread data collected by sensor quickly and simply. Some considerations about the computational complexity and the performances of the proposed approach are reported on the basis of some simulations and some initial tests on small dimension networks.

Key–Words: Mobile sensor network, Data transmission, Protocol, Wireless communications, Local management, Dynamic reconfiguration.

1 Introduction

Communication infrastructures represent a relevant part in the modern human life. They are usually constituted by complex networks whose nodes are the end-users, mainly humans (for example phones, mobiles, TV, radios) or computers (for example Internet). Their operations and management requires sophisticated protocols for connections, communications, routing, billing and so on.

On the other hand, sometimes small networks are set up for particular specific applications. In this case the problem of making the nodes communicate each other can be approached and solved in different ways, depending on the information that has to be routed on the net and on the characteristics of the net itself. It has to be taken into account the communication channel adopted, the type and the amount of informations and then the bandwidth required, the directions of the communication among nodes, the structure of the network, the position of the nodes. A further element of complexity can be represented by mobile networks, where each node has a time varying position.

In the present work the case of mobile sensor networks is considered, meaning a set of sensors moving over a large area and cooperating for getting measures.

Distributed sensors systems and networks are gaining a relevant interest in larger and larger fields of research and applications. For example, sensor networks can be involved in monitoring or surveillance tasks for large areas or in hazardous structures as well as in detection and localization of persons in particular areas or buildings during critical events, and so on.

Taking into account the limited range of measurement for a sensor, the problem of maximizing, for a given set of sensors, the number of detectable events or in general the field of measure of the sensor network is known in literature as the *area coverage* problem (for example [1, 2]). Using fixed positions for the sensors, the coverage problem can be faced in terms of collocation of sensors in the area under measurement. Thanks to the different aspects involved, there is a large literature on the theme (for example [3, 4, 5, 2] and references therein).

More recently, the idea of using mobile sensors has been proposed where the mobility is used for the first sensors allocation and for occasional reconfiguration tasks (for example [6, 7, 8]).

Increasing the motion capabilities, the so called *dynamic sensors networks* or *mobile sensors networks* have been proposed, with sensors that take measures while moving continuously. This approach increases the flexibility of the sensor network and reduces the number of sensors but, on the other hand, pointwise continuous measurement is no longer possible: only a maximum time interval T_{MAX} between two consecutive measures at the same coordinates can be guaranteed.

The coverage area problem in this case is not posed in terms of collocation of sensors but as suitable trajectories for the moving sensors in presence of some constraints. Some results are in [9, 10, 11, 12, 13, 14]. The problem of communications between nodes in a mobile sensor network involves different data having to be transmitted all over the network. In fact, together with the measurement data that each sensor acquires, also informations about the status of the nodes, at least in terms of position, neighborhood radio and sensing connections, energy status, operative conditions and so on, must be notified to all the nodes that can require these for planning their behavior, or to a central unit that operates in a centralized way to plan the motion of all the network. Then, both for centralized and for distributed control of mobile sensor networks, one of the main aspect to be carefully taken into account is represented by the connectivity conditions between nodes. This problem has been specifically addressed in [15, 16, 17].

A common characteristic, both in case of centralized planning and in case of local one, is that the motion of each node is based also on some informations that other nodes own because directly acquired and that must be communicated to all the nodes in the net.

Like in other local ad-hoc networks as in military field operation, disaster control, etc., one of the most sensible topics is the medium access control (MAC) protocols, which coordinate the efficient use of the limited shared wireless resources. However, in these wireless networks, the limited wireless spectrum, low sophistication, and the high mobility together impose significant challenges for MAC protocol design to provide reliable wireless communications with high data rates. MAC protocols represent an active research topic for the last 30 years, and there exists a huge body of literature on it (some recent examples are [18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35]).

One of the most commonly used approach is the fixed assignment one: the available resources are divided between the nodes such that the resource assignment is long term and each node can use its resources exclusively without the risk of collisions.

Typical protocols of this class are TDMA, FDMA, CDMA, and SDMA.

The Time Division Multiple Access (TDMA) scheme subdivides the time axis into fixed-length super frames and each super frame is subdivided into a fixed number of time slots. These time slots are assigned to the nodes exclusively and hence each node can transmit in its time slot periodically for every super frame. TDMA requires tight time synchronization between nodes in order to avoid overlapping of signals in adjacent time slots.

In Frequency Division Multiple Access (FDMA), the available frequency band is subdivided into a number of sub channels that are assigned to nodes so that each node can transmit exclusively on its own channel. This scheme requires frequency synchronization, a relatively narrow band filters, and the ability of the receiver to tune the channel used by the transmitter. As a consequence, an FDMA transceiver tends to be more complex than a TDMA transceiver.

In Code Division Multiple Access (CDMA) schemes, the nodes spread their signals over a bandwidth much larger than needed, using different codes to separate their transmissions. The receiver has to know the code used by the transmitter; all parallel transmissions using other codes appear as noise.

Finally, in Space Division Multiple Access (SDMA), the spatial separation of nodes is used to separate their transmissions. SDMA requires arrays of antennas and sophisticated signal processing techniques and cannot be considered a good candidate technology for WSN.

More recently, new kinds of protocols, developed especially for WSN, has appeared; examples are the Direct Diffusion protocol ([36, 37]), the Low-Energy Cluster Hierarchy (LEACH) protocol ([38, 39]) and the Sensor Protocols for Information via Negotiation (SPIN) ([40]).

The Direct Diffusion protocol is data-centric and highly adaptive, since it selects empirically low delay paths based on local interactions. This also implies that the non end-to-end approach is adopted and that there is no need for global IDs throughout the net.

LEACH organizes the network into clusters. Each node can decide whether to become a cluster head according to a certain probability specified a priori. LEACH differs from the other protocols cited here since it adopts direct instead of multi-hop transmission.

The last protocol, SPIN, is designed to address three deficiencies of flooding: implosion, overlap and resource blindness. Implosion refers to the waste of resources arising when a node forwards a message to a neighbour although the latter may have already received it from another source; overlap occurs when two nodes sense the same region, produce the same data and push into the network the same results; resource blindness denotes the protocol incapability of adapting the nodes behavior according to the power status.

In this paper, a novel Dynamic Light-Weight protocol is proposed, able to efficiently manage the MAC side problem and at the same time the routing problem in a mobile senor network. The proposed protocol works like a postman who has to collect mails and, at the same time, deliver them to a certain number of locations without passing through a central post office. The protocol makes use of a unique data structure that, on the analogy of what just said, will be denoted the *Postman Bag*. The Bag is used to spread sensors informations in a fast and simply way, without the necessity of using any routing table or hierarchical structure into the net, using a policy similar to a token passing scheme. The algorithm is based on local informations only in the sense that the nodes are not required to have global informations on the net status, so reducing the amount of data to be transmitted.

In Section 2 the protocol is described and all the phases (initialization, transmission, updating, reading and so on) are presented and discussed in its Subsections. Some critical cases are presented and solutions are illustrated. Section 3 is devoted to present some considerations about the performances related to the protocol and the transmission complexity on the basis of theoretical estimation, numerical simulations and a first implementation. Some conclusions are reported in Section 4, so ending the paper.

2 Protocol Description

The structure of the protocol is strongly dependent on the specific data that are assumed to be shared between nodes.

As shortly discussed in the Introduction, once a network with several nodes is considered, the problem of making the nodes communicate is usually faced assigning, statically or dynamically, a resource (time, bandwidth, slot, channel, and so on) in order to avoid possible conflicts between transmitters.

Hierarchies among the nodes in the networks are usually introduced for simplifying communication between nodes not directly connected, for which a multi hop (involving more nodes) link is required.

Finally, in order to manage efficiently the channels, the resources and the communications, a centralized approach to the connections establishment and the data routing is adopted: one central unit receives all the informations and distribute them to the net.

For the present case of a mobile sensor network, communications between nodes too far to establish a direct connection is very common; moreover, the structure is known at each time instant but it changes dynamically: the positions of the nodes changes as they move, but also the number of the nodes can vary due to faults or new additions for increasing the area coverage. This means that solutions aiming to give a structure to the network cannot work efficiently unless they make use of high computation efforts. At the same time, multi hop communications are quite frequent.

The solution proposed does not introduce any constraint on the network, except its connection. The idea is to use a more sophisticated data structure for reducing the connections requests. In some sense it is a sort of time division access regulated as a token ring, where the token is represented by the transmitted data itself.

The protocol works like a postman who at the same time collects and delivers mails each time it reaches each address. And in its tour no house is excluded.

Then, in the same way, the proposed protocol is a light-weight dynamic protocol based on a unique data structure: the Postman Bag. The Bag is organized to store, sort and forward the information collected by the sensors network, in a simple, fast way. Among all nodes in the network, only the node holding the Bag is responsible for sending it to the successor. When a node receives the Bag, it checks the presence of messages addressed to itself and can insert a message for another one. A successors list is also created analyzing the counter fields on the Bag following a special policy and after an hand-shake phase the real successor is detected.

In the present form, the proposed protocol works effectively and properly if some assumptions are verified. The first one is quite general and does not restrict the field of applications: the network must be represented by a connected graph. It is clear that, if this hypothesis is not fulfilled, there exist couples of nodes that cannot communicate each other neither directly nor using a multiple hop path through nodes. A second hypothesis, strongly related to the present version of the implemented protocol, is on the knowledge of the number of nodes in the network. This is necessary since the record transmitted must contain as many counters as agents of the network and a field that contains such a number. Notice that such a number can vary, so allowing removal or adjoint of nodes: the constraint is that such a number must be known as it varies.

The protocol is called *dynamic* because it is possible to change on the run the Bag structure, according to the increasing or the decreasing of the node population. It is also light-weight because the routing is managed locally, without routing table, and using a limited computing power. A half-duplex transmission antennas is used to overcome the hidden terminal problem and the exposed terminal problem.

An initialization phase is performed at the beginning of the process. Then, each node that receives the Bag performs two ordered distinct phases

- Hand-Shake
- Bag update and forward.

the first one devoted to the local planning of data transfer while the second one concerns the extraction/insertion of the messages and data transmission.

2.1 Protocol Description

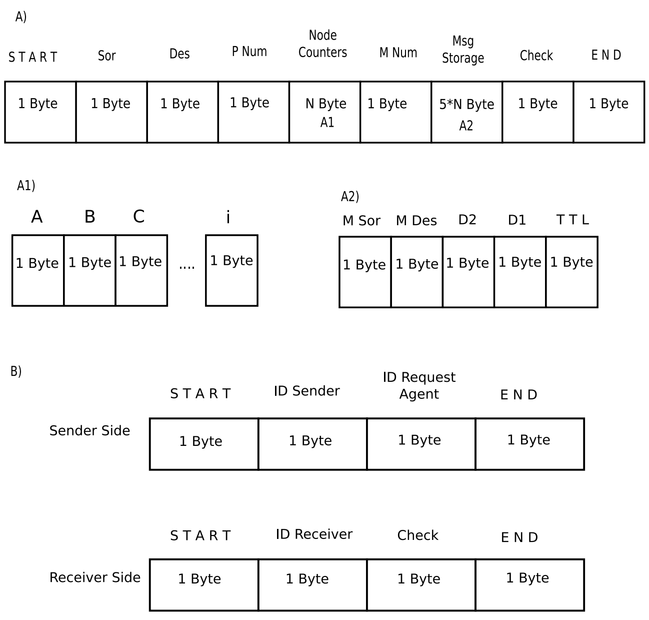

Figure 1: Postman Bag structure

2.1.1 The Bag initialization

At the very beginning of the process, the data structure "Bag" has to be created by one node.

Each node is identified by a (integer) number, so a natural order is induced by the order of the labels. Sometimes this natural order can be used to differentiate nodes that result indistinguishable otherwise. This happens in the initialization phase, in which there is not any reason to prefer one node to another. Then, the Number One, or the node with the lower identification number, is the node that has to perform the initialization task.

In order to set up the Bag, a list containing all the specified fields has to be produced.

Figure 1 illustrates the data structures of the Bag (A) and of the hand-shaking string (B).

2.1.2 The Bag structure

In Figure 1-A, Start and End identify the begin and the end of the Bag, Sor and Des the source and destination nodes ID, Check the checksum for the Bag. The total number N of the nodes in the network is stored in P Num. This number is increased or decreased each time an element joins in or parts from the network respectively. A different transmission frequency is used for changing this field dynamically. The N node counters Ai, one for each node of the network and ordered in a ring-like way, are modified every forward step of the Bag (Figure 1-A1). The values in these fields and the order in the Bag are the keys to create the list for the Hand-Shake phase. The message number M Num is the total number of messages present in the Bag. Any time a node wishes to transmit a data from sensors or a status information or anything else, a message is generated and when the Bag reaches it, the message is stored in. All the messages have the same structure (Figure 1-A2). M Sor and M Dest identify the source and the destination node ID of the message, D 1 and D 2 are the data fields and TTL (time to live) represent the number of times the message has been forwarded.

When the Bag is created at the beginning of the procedure, all the counters are set to zero.

2.1.3 Hand-Shake Phase

Every node holding the Bag contacts one of his neighbor through an hand-shake message. To reduce the transmission overhead, the hand-shake frame should be as small as possible, ensuring sender/receiver side a simple two way hand-shake. As illustrated in Figure 1-B, the fields in hand-shakes frames successfully perform this operation.

A. List Creation

When a node initializes or receives the Bag, it creates a list to perform the hand-shake phase. Each agent follows a check sequence to generate it. First of all the Bag sender is excluded and then the remaining

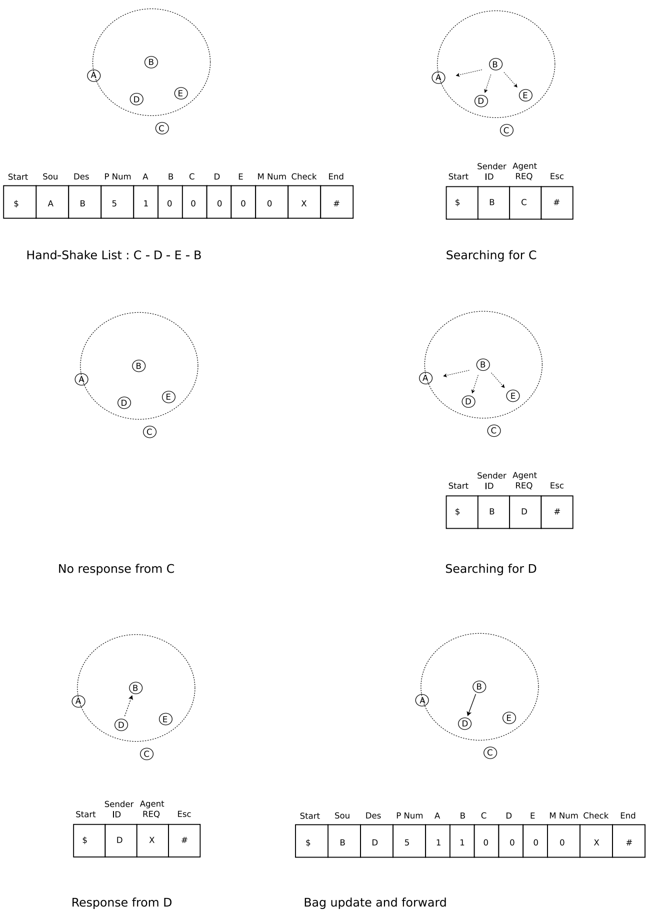

Figure 2: Hand-Shake List Creation and Hand-Shake Phase

agents are sorted in ascending counter order. If multiple nodes have the same counter value, a priority is associated according to the counters order. The node holding the Bag is always the last on the list. Figure 2 shows an empty bag at node B. B creates the list following the criteria explained above: C-D-E-B. In the present example the priority order is the alphabetical order related to the letters associated to the nodes.

B. Determination of the successor

After the list creation, the Bag holder tries to reach the node in first position using a hand-shake message. If it cannot receive a reply message in a reasonable prefixed time, it will try to contact the next node in the list. According to Figure 2, using the list C-D-E-B defined in the previous phase, the handshake with C fails, because C is not in B connection area, i.e. it is out of communication range. B discards C and tries with D. D accepts the hand-shake message and sends a response to B. At this point, B can update the Bag and, then, forward it to D.

2.1.4 Bag Updating

When a successor becomes available in the handshake phase, the Bag holder updates the Bag fields. First of all Sor and Des fields are updated and then the sender counter is increased by one. Before sending the Bag, the node checks its cache searching for messages. The node will continue adding messages in the Bag and increasing the M count of one unit for each message. When all the messages have been added, the Bag is forwarded. After the arrival of the Bag, the node performs a control for the messages present in the Bag, searching for its ID in each of the M Dest field. If a message directed to the Bag holder is found, the information inside are acquired, the message is deleted and the M count field is decreased by one.

Figure 3 shows these controls excluding the handshake phase already discussed. First of all C adds a message for A in the Bag, increasing its size. Then the Bag is passed to E, then B and, finally, A. Each of such nodes checks for messages addressed to it and then performs a control of M Dest field in order to pass over the Bag. In this scenario, only A acquires the message and decreases the size of the Bag.

2.2 Critical situations

The above illustrated protocol works in all the regular situations for the nodes and the network configurations.

It can fail if during the hand shake and data transfer phases one of the following two situations occur. The first one is represented by the presence of *sink nodes*, i.e. nodes in the network that are characterized by one connection edge only, so that the data cannot *pass through*. The second one is related to the possibility of a loop over a subnet of the whole network. Such situations can be easily faced in the present context by an efficient construction of the Bag and of the list of successors.

2.2.1 Solution for Sink Nodes

Using the method illustrated in the previous Subsection to generate the hand-shake list, if the network contains a sink node the Bag stops on it. This problem is avoided improving the protocol adding also the Bag-holder in the hand-shake list as the last node. This addiction does not changes the protocol behaviour in the regular cases, while assures the escape from the sink nodes in this singular case.

In fact, as illustrated in Figure 4, the node B receives the Bag from A, and then creates the list, excluding, by construction, the Bag sender from it. B is a sink node and can reach A only. The simple policy

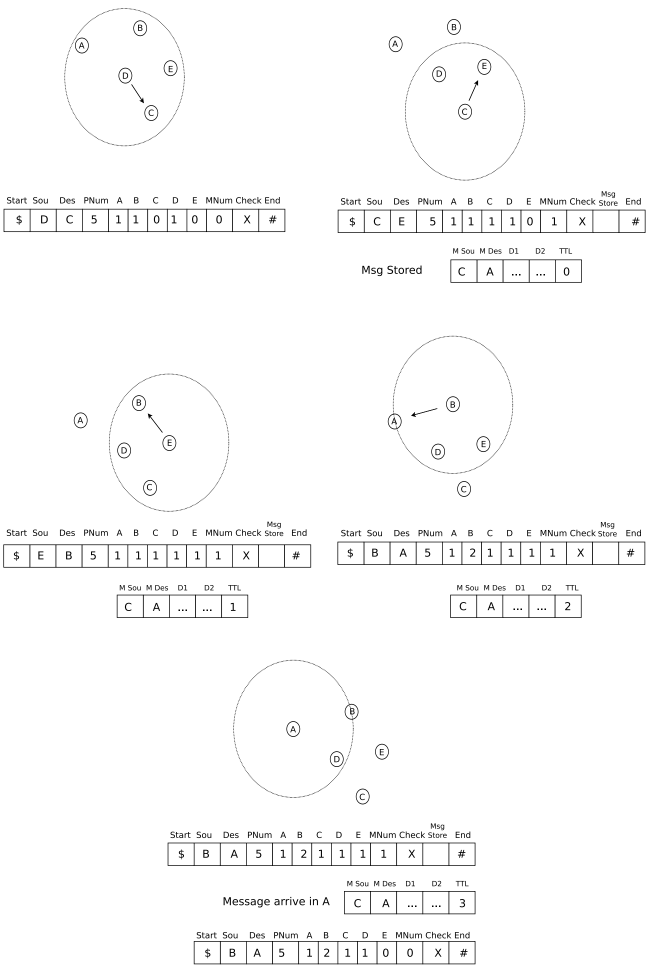

Figure 3: Bag Filling and Emptying

excludes the forwarding to A since it is the sender, so the Bag is blocked on B. The improved policy just illustrated requires that B is added on the hand-shake list, so the Bag is forwarded on the same node. The forwarding is performed only changing the B counter of one unit. A new list is then created, excluding B, as sender, but now including A and the Bag is sent out of the sink.

2.2.2 Solution for Bag Looping

This problem can be generated by the list creation policy.

The list is created following the node counters values, giving higher priority to nodes with lower counter number. If two or more agents join the network after a while, they can create a cycle in the network since each of them attracts the Bag due to its very low counter value. Then, the Bag will be forwarded between the nodes belonging to the loop until all their counters are increased enough to reach the counter values of the other nodes. This fact is illustrated in the left side of Figure 5.

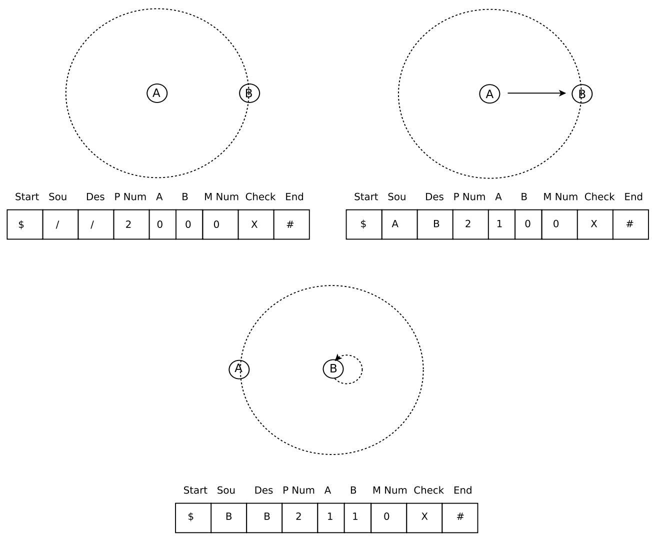

Figure 4: Sink node solution

This fact does not represent a real loop, in the sense that the data are transmitted in a cyclic way over a subnet only for a certain number of cycles. The drawback is represented by the time wasted to perform the possibly high number of loops before restarting to operate regularly.

The solution adopted is based on the control of the gap between the max value of counter fields and the counter fields of the newcomer nodes. It is checked if the gap is greater than two; if it is, the counter fields are updated to a value equal to the maximum value minus one.

Right hand side of Figure 5 shows the steps and the effects of the corrective action.

2.3 Network changing on the run

The proposed protocol allows nodes to join in or to part from the network dynamically. Before one or more elements enter or leave the graph, all the nodes have to be informed, using a different transmitting device or protocol or technique. Once the information reaches the node holding the Bag, it modifies the P num field and the Bag structure adding or deleting counter fields.

It is clear that the present protocol does not allow to inform the nodes about the addition of some other nodes, since the only nodes that knows the situation are the new ones, but they cannot be reached because excluded from the hand-shake phase. A different case is represented by nodes reduction (as in case of failures). In fact, in this case the protocol does not fail: in the hand-shake list the expired nodes should be present but not reachable, then skipped. The

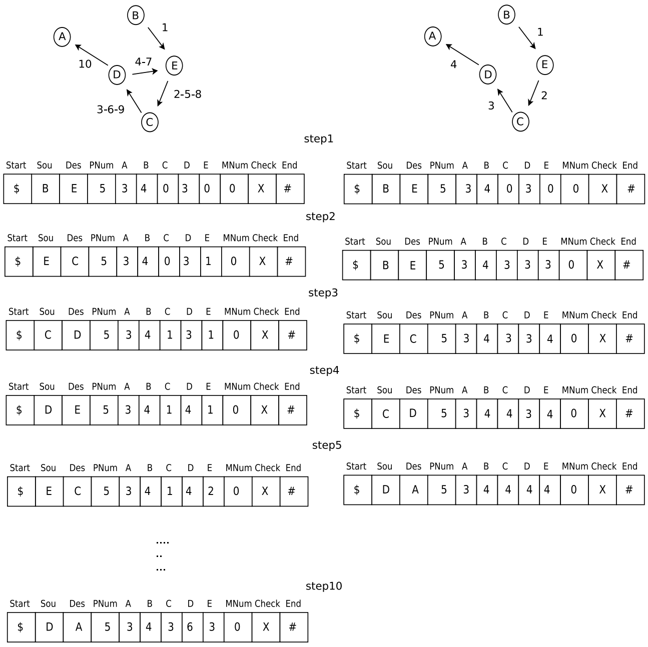

Figure 5: Bag Loop Solution

only drawback is represented by the fact that since the counter fields for such nodes do not increase, they should be always in the first positions of the hand-shaking list, so introducing a delay in the communications.

In order to both avoid this delay and manage the nodes addictions, the presence of a second channel for this communications only is supposed to be available.

3 Performances and Complexity Evaluations

From a theoretical point of view, it can be interesting to analyze the computational complexity of the proposed algorithm.

Let us denote by N the number of nodes in the network and let us refer to a single jump, i.e. a connection between two adjacent nodes for an unidirectional transfer of one string, for both cases of Hand-Shake and Bag delivery.

Then, from a computational point of view, the complexity for the protocol is evaluated in $O(N^2$.

In fact, for the analysis, the worst scenario in Bag forwarding phase is represented by N^2 jumps to deliver the Bag to every node at least one time. In fact, the problem of delivering the Bag to an arbitrary node in the net is equivalent to the problem of finding a path in a connected graph, once the visit of a node in the search algorithm is associated to the Bag transfer. Since no particular approaches are followed, the $O(N^2)$ complexity order comes.

The Hand-Shake phase also has the same complexity order, since each of the N node has $N-1$ as the maximum number of attempts before reaching one successor and the list is composed by all the nodes except the one who sent the Bag.

In the proposed protocol, the time T_{H-S} devoted to the hand-shake phase is always the same, thanks to the constant length of the messages in this phase. On the contrary, the Bag has variable length, depending on the number of messages contained, and its transmission time T_{Bag} is always greater than T_{H-S}. Then, an estimation of the maximum time required for the Bag to be delivered from a node to an arbitrary one, is represented by $T_{max} = N^2 * T_{Bag} + (N^2-1) * T_{H-S}$.

Since $T_{Bag} > T_{H-S}$ (depending on the network dimensions it often can be $T_{Bag} \gg T_{H-S}$), the approximation

$$T_{max} \simeq N^2 * T_{bag}$$

can be performed.

Clearly, the analysis of the worst case is an interesting parameter, but it does not take into account the particular conditions or net structures that can sensibly reduce the times.

Then, some real implementations have been performed in order to evaluate the time required for the Bag delivering. In order to put in evidence the dependency of the time on the network topology, being usually far from the worst case, the Bag has been structured in a simplified way in order to neglect the effects of its variable length to the transmission time.

In this context, two different ways to managed the Bag are considered. In the first scenario the Bag can store only one message and a node can use the Bag only after the message of the predecessor is delivered. In the second situation, the Bag stores a single message for each node of the net.

A 16 Kbit/sec radio data rate is assumed and a node population between 0 and 30 has been considered.

In addition, also the case of a well-known topology structure like chain is considered for both the scenarios, for putting in evidence the dependency on the topology.

Figure 6 plots the diffusion time vs. the number of nodes for the four cases. The results are as expected; the Bag length in the scenario 2 is approximatively 10 times the one in scenario 1. This motivates the higher diffusion time depicted in the figure in case of not structured network.

The performances are sensibly improved in case of chain structures. This depends on the fact that in presence of particular structures the Hand-Shake duration time can be sensibly reduced, since only few (sometimes one) attempts has to be performed.

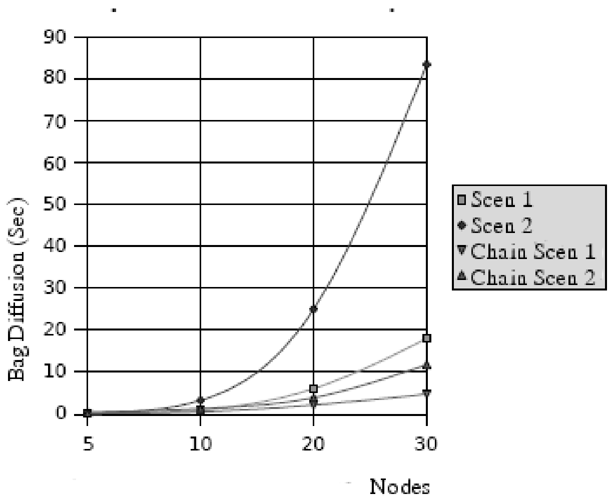

Figure 6: Diffusion Time Analysis

Clearly, the difference between the two scenarios remains, even if strongly reduced.

4 Conclusion

In the paper a routing protocol for data and command transmission between nodes in a mobile sensor network has been presented. The network is assumed homogeneous (all the nodes are equivalent from the transmission point of view) and no supervision is present. In this conditions, the approach allows to send a message from any node to any other one. It does not require a priori time or bandwidth division for communication as well as dynamic resources allocations. It is robust with respect to dynamic change in the node number. moreover, the protocol does not require any knowledge (real, measured or modeled) of the motion strategy and of the node position: the only obvious assumption of full connectivity, i.e. the existence of at least one path between any couple of nodes at any time, is required.

The proposed approach does not make use of any type of routing table or any other kind of global informations. Only the local information contained in the Bag and collected by each node simply analyzing the Bag are used for forwarding the data. This means that The possibility of local management with a low computational requirements means that this solution can be adopted also in case of decentralized (local) control of the nodes motion.

Some simulations show the effectiveness of the proposed strategy. Some implementation on small networks confirms such results. Implementations on large networks are under study.

It is also under investigation the possibility of adding some informations for reducing the Hand-Shake phase, for example letting each node store a list of the last nodes used as successors for a possible change in the list of successors.

In this case, as well as for any other change in the procedure based on the management of a larger amount of information, what is to be evaluated is the trade off between the (nondeterministic and not guaranteed) reduction of time for routing with respect to the higher complexity in the procedure that each node has to apply. At the moment, the solution proposed is the most light from the point of view of the nodes. In fact, in our experimental setup, simple units as the PICs of Microchip can easily manage both the sensors in the node and the communications.

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