Comparative Performance Evaluation for Information Distribution Methods in Satellite-based Sensor Networks

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Abstract— **The advances in satellite networking and material science enabled the deployment of low cost and low power small sized sensors that can transmit information through satellite channel to remotely located host. Earth stations represent sink nodes of the sensor network and often, for safety reasons, they are redounded. In this environment, controlled information distribution methods may play a crucial role and represent a sensible field of investigation. In particular, distribution methods proposed in the paper are aimed at guaranteeing the lower energy consumption and the lower level of congestion in the network. The paper includes: the presentation of the application environment composed of sensor networks and sink earth stations; the introduction of the sinks management functions and the description of the flooding-based techniques used to propagate information through the network; an introductive comparison of the performance in terms of energy consumption and total time spent in the sensor network.**

Index Terms — *Satellite channels, Sensor Network, Multi Attribute Programming, Signalling, Flooding Schemes, Performance Evaluation.*

I. Introduction

Recently the advances in material science enabled the deployment of low cost and low power small sensors that can transmit information over a limited area [1]. Satellite links are an essential element of long distance telecommunications and they will have a major role within the future global information distribution infrastructure. So, the integration of existing terrestrial sensor networks and satellite components is a key issue for monitoring systems that allow achieving ubiquitous information exchange between geographically separated sites at affordable cost. The sensor nodes are densely deployed in large numbers and the wireless network topology, as well as the satellite link availability, changes frequently. Moreover sensor nodes may be randomly deployed over inaccessible terrains (e.g., near a volcano) and over disaster relief operation environments. Reliability and, possibly, efficacy of the communication should be assured over these environments with limited energy, bandwidth and computing capacity, implementing in the same time, self-organizing and cooperative behaviour.

In the environment considered, the sensors have the capability to reveal and measure phenomenon variations; to process data; to manage alarm messages; to communicate and route the messages through the sensor network and the satellite link to reach a monitoring host remotely located. To robustly propagate the messages sent from the sensors to the remote monitoring station, flooding-based techniques are widely employed due to the high topology variability of the networks under study. Nevertheless, a direct information flooding may be very inefficient because redundant information is forwarded through the network and the satellite links causing bandwidth, resource and, in particular, power consumption. In more details the paper deals with a Satellite based sensors network in which sensors may send information to more than one sink node. Multiple sinks approach is useful in dynamic environments where satellite sink nodes must be redounded for security and robustness reasons. The techniques introduced and evaluated in the paper are:

- dynamic management techniques, based on the Multi Attribute Programming, of the sink nodes aimed at obtaining a more efficient information distribution process;
- intelligent information distribution methods flooding-based (also called signalling methods in the reminder of the paper) aimed at reducing the number of redundant messages so enhancing the overall performance.

The paper is structured as follows: Section II introduce the satellite-based sensors network architecture considered; the dynamic management methods proposed and the flooding techniques applied within the network are described in Section III and Section IV respectively; Section V proposes an introductive comparative study of the performance obtained by using the proposed methodologies; Section VI lists the conclusions.

II. Satellite Sensor Network Architecture

A sensors network consists of many nodes, each with multiple links connected to other nodes, which allows information exchanges from the point where a sensor has received a stimulus, or has made a measure, to the sink node where information is collected [2]. In a wired network, each router is connected with other routers forming a graph. In sensor network each node has a radio that provides a set of transmission links to nearby nodes. The Sink node collects all the information sent by sensors and transmits it to a monitoring host remotely located through a geostationary satellite channel. For the sake of network robustness, a sensor infrastructure, aimed at monitoring a wide geographical area, is composed of several sink nodes (Fig. 1).

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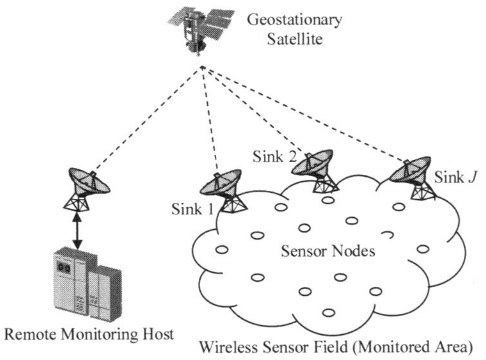

Fig 1. Satellite Sensor Network Architecture.

In more details, the network is composed of N sensor nodes, which compose the sensor field. Each node may be both a source of measures, thus of traffic, and an intermediate node. The network is wireless and its topology varies. A topological variation is a modification of the node visibility (i.e., working connection between nodes). The earth stations are J and represent the available sink nodes. Each of them may be statically or dynamically managed as sink node of the sensor network. The satellite used to transmit information from sensors to the Monitoring Host is geostationary with constant sink-to-Monitoring Host propagation delay and a fixed bandwidth capacity. The satellite bandwidth, considered as technological reference, is the Ka-band (20-30GHz) where the information exchange may be corrupted by fading mainly due to meteorological precipitations. The Remote Monitoring Host receives information from the satellite channel, stores it and manages possible alarms. In the network proposed, each sensor node has a finite quantity of available energy (expressed in [Joule]). In the paper is supposed that when a packet is transmitted by a source node, or by an intermediate node a fixed quantity of energy is spent.

A. *Satellite Channel Model.*

The geostationary satellite channel behaviour, considered in the dynamic sinks management schemes (Section III), is strictly dependent on fading compensations; due to its main role, it is very important to get a method to describe the effect of fading: a simple way is to consider it as a mere bandwidth reduction coherently with the state-of-the-art in the field (see [3] as example). Mathematically, it means that the nominal bandwidth $C^{(j)}$ (available for the j-th, $\forall j \in [1, J]$ earth station) is reduced of a factor $\beta^{(j)}$, which is a parameter distributed in the real numbers interval [0,1]. A specific value $\beta^{(j)}$ corresponds to a fixed fading level. A technical interpretation of the factor $\beta^{(j)}$ may be the bandwidth reduction due to the presence of a FEC (Forward Error Correction) scheme widely use in satellite systems. The FEC strategies make the channel errors negligible but reduce the available service capacity so creating congestion and increasing the time needed to transmit the packets to the monitoring host. The work explicitly considers the reduction through the factor $\beta^{(j)}$.

III. Dynamic Management of Sinks

Typically, the sinks redundancy allows to substitute a sink, which is an earth station, with another one if it fails so guaranteeing a continue monitoring service (Static approach). Actually, the presence of several sinks allows a dynamic management of them by selecting an earth station as sink on the basis of the network status. In particular, if a sink is overloaded of signalling packets or the global energy consumption spent by nodes to reach it is high or the satellite channel, seen by it, is severely corrupted by fading it might be dynamically changed with another sink.

A. *Decision Making Definitions.*

The management techniques proposed are based on the *Multi Attribute Decision Making* methods (MADM) [5]. The *Decision Maker* (DM), which is the entity making decisions, is provided of a *decision matrix* in which are contained the *attributes* of all the possible decision also termed *alternatives*. In practice a single alternative, at the time t, may expressed as:

$$A_j(t) = \left[X_{j1}, \ldots, X_{jk}, \ldots, X_{jK} \right] \tag{1}$$

where the term X_{jk} is the k-th attribute, at time t, of the j-th possible alternative. In the environment above described a possible alternative may be represented by a sink while the attributes may be a measure of the status network at time t. From the definition contained in (1), the decision matrix owned by the DM entity is:

$$\mathbf{A}(t) = \left[A_1(t), \ldots, A_j(t), \ldots, A_J(t) \right]^T = \begin{bmatrix} X_{11} & \ldots & X_{1K} \\ & & \\ X_{J1} & \ldots & X_{JK} \end{bmatrix} \tag{2}$$

where K is the number of attributes considered by the DM.

The attributes contained in the matrix play the most important role in the decisional process. As mentioned above, the attributes should represent the sensor network status. In particular, for a sensor network based on a satellite infrastructure aimed at monitoring a waste geographic area the following attributes seem to be the more significant of the system:

- Energy Consumption (X_{j1}), is the overall quantity of Energy, expressed in [Joule], spent to propagate packets sent by sensors to the j-th sink. Each broadcasting, performed by the information distribution method (Section IV), is assumed to spend 1 [Joule].
- Offered load (X_{j2}), is the quantity of packets delivered to the j-th sink per time unit, expressed in [packets/s], at time t. In practice, it represents the ratio between the number of packets received by the j-th sink at time t and t itself.
- The reciprocal of the number of nodes reachable in 1 hop from the j-th sink at time t (X_{j3}). The reciprocal of the number of nodes reachable in 2 hops from the j-th sink at

time t (X_{j4}). The last attributes are useful to select the sink with the maximum number of sensor nodes reachable in only two hops.

- Average signalling time (X_{j5}), is the average time spent by a packet through the network to reach the remote host from a sensor node. It is composed of the propagation time in the sensor network and in the satellite link and of the service and waiting time of each buffer traversed. In particular, that metric considers the effect of the fading, seen by a earth station, as a reduction $\beta^{(j)}$ of the service capacity of the satellite channel thus an increase of its service and waiting time.

The overall number of attributes considered in this work is $K=5$ and all the metrics considered may vary between a minimum and a maximum value. Nevertheless in the decision matrix (equation (2)) the attributes must be homogeneous, thus they should be normalized:

$$X_{jk}=\frac{X_{jk}}{X_k^{max}},\forall k\in[1,5] \quad (3)$$

where

$$X_k^{max}=\max_j X_{jk},\forall k\in[1,5] \quad (4)$$

Given attributes, which represent the network resources employment $X_k, k\in[1,K]$ the functional vector of them is

$$\underline{F}[A(t)]=\{X_1(A(t)),...,X_k(A(t)),...,X_K(A(t))\} \quad (5)$$

where $A(t)$ is the current decision, which is the current sink (or earth station) used to convey information sent by sensors. The problem aimed at obtaining a fair resource employment and a dynamic management of the sinks is:

$$A^{opt}(t)=\min_{A(t)\in\mathbf{A}(t)}\underline{F}[A(t)] \quad (6)$$

where $A^{opt}(t)$ is the optimal selection in dependence on the optimization criterion, which allows the minimization of the resource employment.

B. Decision Methods.

Starting from the definition above reported the DM entity may dynamically select the sink of the sensor network by solving the problem defined in (6). To reach this aim an optimization criterion is needed. In this paper, the DM will be based on two different optimization approaches: the MINMAX method and the LINear Programming techniques for Multidimensional Analysis of Preferences method (LINMAP).

In the MINMAX approach, a classical MADM method, each alternative is represented by the worst attribute and the sink selected is the earth station with the better of them.

$$A^{*}(t)=\left\{A_j : j=\arg\min_j\left[\max_k X_{jk}\right], j\in[1,J]; k\in[1,K]\right\} \quad (7)$$

The LINMAP method bases its functionality on the knowledge of the ideal alternative. In practice, given the decision matrix $\mathbf{A}(t)$ the DM entity selects the ideal alternative as:

$$A^{id}(t)=\left[X_1^{id},...,X_k^{id},...X_K^{id}\right] \quad (8)$$

where

$$X_k^{id}=\left\{X_{jk} : j=\arg\min_j X_{jk}\right\},\forall k\in[1,...,K] \quad (9)$$

and then gives the solution of the decision problem as the alternative minimizing the distance, in term of Euclidean Norm, between the ideal alternative and itself.

Formally the decision problem is solved with:

$$A^{\bullet}(t)=\left\{A_j : j=\arg\min_j\left\|A_j(t)-A^{id}(t)\right\|^2, j\in[1,J]\right\} \quad (10)$$

Both the decision methods allow to switch dynamically the sink by following the rules expressed from equation (7) to equation (10). The sink selected will have performance similar to the attribute measured at time t for the alternative expressed in equation (7), (in practice, it is set $A^{opt}(t)=A^{*}(t)$) if MINMAX method is used, or expressed in equation (10) (it is set $A^{opt}(t)=A^{\bullet}(t)$) if LINMAP is applied. The techniques have been implemented and compared in term of performance in Section V.

C. Probing Procedure of the Decision Method.

In the definitions of the decision methods above reported the DM makes its selection at the generic time t. At this time, which is the decision instant, the values of attributes are measured because a closed form expression of the attributes as functions of the alternatives (and, as a consequence of time) do not exist. Moreover, the DM should operate its decision after fixed length interval or after a detected changing of the network status. The former approach is choice to probe the DM.

In more details, the DM selects the sink after a interval of length T_D called *decision time* composed of two element: T_P that is the *probing time*; T_W that is the *working time*; in particular the decision time is: $T_D=T_P+T_W$.

The former element, the probing time, is a period where a special signalling (*probing signalling*) is sent by nodes into the network to each possible sink. The probing signalling is added to the traffic generated by sensors and it creates a network overloaded condition in which are collect the attributes useful at completing the decision matrix of the DM. The probing is useful to test periodically all the possible alternatives which may change over the time mainly due to network topology variations. After T_P, the probing signalling is stopped, the DM operates the decision, in a time considered negligible to respect the overall length of T_D, and then the network works regularly for a time T_W.

Finished the working time, thus the decision time, a new probing phase begins aimed at collecting new attributes for a new decision. A decision is valid from the end of a T_P to the end of the successive T_P. A graphical interpretation of the probing procedure is reported in Fig. 2.

The probing procedure approach guarantees a collection of attributes, provided to the decision matrix, in a condition in which the regular traffic load sent from sensors is added of the probing signalling. This mean that the network status "seen" by the DM is an overestimation of the regular status in which the sensor network operates. In other words, a decision that provides the better performance in overloaded conditions guarantees better performance during the working phase. It worth nothing that the tuning of T_P and T_W in real environment may be a delicate operation and it depends on the specific application of the sensor network. In the introductive performance study provided in this paper they will be always fixed.

The decisions happen by following the temporization above proposed thus is fixed:

$$A^{opt}\left((i-1)T_D+T_P\right)=\begin{cases} A^{*}\left((i-1)T_D+T_P\right) & \text{with MINMAX} \\ A^{\bullet}\left((i-1)T_D+T_P\right) & \text{with LINMAP} \end{cases} \quad (11)$$

where $i \in \aleph,\ 0 < i < \infty$ is the number of the decision. In the instants $(i-1)T_D+T_P$ the DM solves the problem (6) with the techniques above reported.

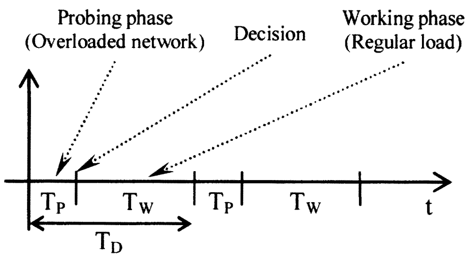

Fig 2. Probing procedure.

D. DM Localization.

The decision method (MINMAX and LINMAP) may be implemented in both the centralized and the distributed mode. The centralized approach is based on the presence of a master station (or master sink) in which all the information related to the attributes, collected in the earth station after T_P, are conveyed through a exchange procedure among sinks and a single DM selects the sink at the time $(i-1)T_D+T_P$. After the decision, from the master station a backward signalling communicates to each sensor node the designed sink. In the distributed approach, there exist a DM for each sensor node. During T_P each earth station collects the values of attributes, transported by packets, and it communicates them, to the sensors, through a backward propagation from all the possible sinks. Then each node individually select its sink. The main differences between the approach are the flexibility offered by the distributed mode to respect the centralized and the energy consumed by the sinks: the centralized approach allow a non simultaneous working of each earth station. The localization of the decision is object of ongoing research and it will be widely investigated in future extension of this work.

IV. Information Distribution Techniques

To exchange information messages, nodes have to discover their neighbours and to distribute information. The techniques below described allow both the information exchanging and the probing procedure of the DM. Coherently with the literature in the field [1, 4], the information distribution techniques are based on flooding schemes. Two kind of flooding are considered: the classical flooding (also termed blind) and an advanced version of it (advanced flooding). Others schemes are widely considered in the literature such as the heuristic approaches, the Multipoint Relay (MPR), exhaustively described in [6], and the Clustering Techniques [4]. The information is propagated with packets, by using the techniques above mentioned, containing the measures of sensors and other important information.

A. Packet Structure.

The packets containing the measures and the probing packet are sent periodically from sensors and they are propagated through the network. Each packet may be identified by the fields *source* and *identifier*, which allow its univocal identification. They transport also the cost information that is the cost spent to reach a specific node (in the case considered in the paper will be expressed in term of energy consumption). Packets, moreover, transport information about attributes, refreshed each broadcasting.

B. Blind Flooding.

The blind flooding protocol allows to the nodes the broadcasting of all the received packets [1]. Receiving nodes retransmit the packets so that more distant nodes can receive it. The blind flooding technique (shortly BF in the reminder of the paper) may cause network inefficiencies in terms of power consumption and packets redundancy, which may congest the satellite channel because each sensor can receive different versions of the same message from several neighbour nodes and re-forward the same information so transmitting multiple copies of the same message to the sink.

C. Advanced Flooding.

To countermeasure the BF inefficiencies, an efficient flooding technique is taken in account. This scheme is called Advanced Flooding (AF in the following) and it is currently used in industrial applications as control messages exchange mechanism for heterogeneous networks. The AF signalling method allows to reduce the multiple copies of the packets propagated through the network because it implements only the broadcasting of the information "potentially useful". Each node of the network maintains a register with information related to arrived packets. When a new packet, sent from a specific sensor with a specific identifier, reaches a node, it is broadcasted only if it transports useful information not already registered into the node or its broadcasting does not imply an excessive consumption of resources. A possible approach is to propagate the packets with lower cost, which is a "measure" of an important metric (i.e., the energy consumed), to respect the previously received packets. The cost is an information contained within the signalling packet and it is updated when a packet is broadcasted.

V. Comparative Performance Evaluation

The simulative analysis is aimed at evaluating the performance of the control mechanisms proposed and the signalling methods. The signalling packets, if heavily duplicated, can create an high level of congestion in the satellite network, implying a reduction of the power availability in the sensor nodes and deteriorating the overall performance of the network. Two main metrics have been evaluated:

- the Average Energy Consumption (AEC) [Joule], Fig. 3. This metric is the measure of the average energy consumed (expressed in [Joule]) by all packets reaching the designed sink node. Each packet broadcasted is supposed to consume 1 [Joule].
- The Average Signalling Time (AST) [s], Fig. 4. It is defined as the average time elapsed by a packet between its transmission and its delivering to the monitoring host.

This metric gives an idea of the overall performance of the network used to monitor a wide area environment: it represents the time employed to communicate possible critical conditions perceived by sensors. The scenario considered is aimed at verifying the metrics above introduced by varying randomly the network topology. The duration of the observations is fixed and equal to 600 [s]. The bandwidth capacity dedicated to the signalling and the propagation delay between nodes in the sensor network are always fixed and equal to 2 [Mb/s] and 1 [ms] respectively. The signalling packet size is 1500 [byte]. The maximum number of nodes N is 10. In these cases the number of stimuli perceived from sensors, thus the average number of signalling packets generated in a second from nodes is 0.1 [packets/s]. The generation of the stimuli follows a Poisson probability distribution. The satellite accesses are 2 stations (Station 1 and Station 2) with a fixed bandwidth of 2 [Mb/s] and propagation delay of 260 [ms]. The fading status of the channel is modelled with 3 possible level [3]: *Absent*, the earth station (a possible sink) is in clear sky $\beta^{(j)} = 1$; *Medium*, the satellite channel seen by a station is partially faded $\beta^{(j)} = 0.625$; *High*, the satellite channel is highly faded $\beta^{(j)} = 0.156$. In the results, only the station 2 varies its condition while $\beta^{(1)}$ is always equal to 1. The techniques evaluated are both the MINMAX and LINMAP associating them each flooding scheme (BF and AF).

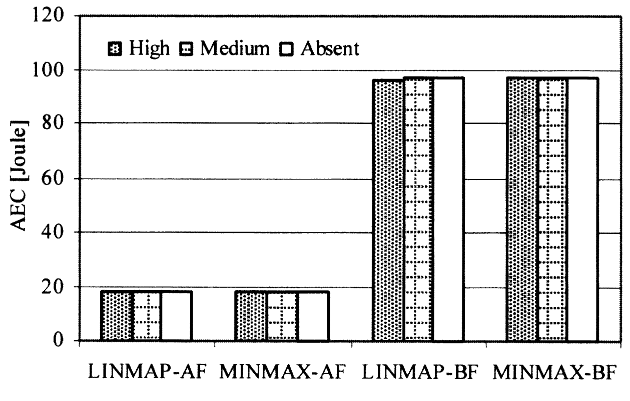

Fig 3. Average Energy Consumption.

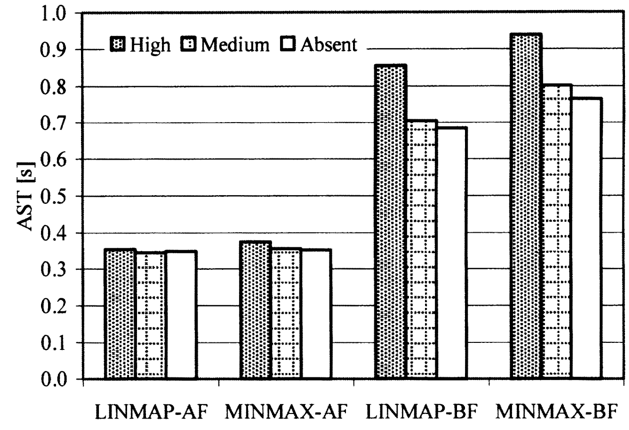

Fig 4. Average Signalling Time.

The results shown allow two main observation: the methods based on the AF signalling have outstanding performance; the LINMAP-based management allows equivalent performance in terms of AEC and better performance in the case of AST to respect the MINMAX criterion. In particular, LINMMAP-AF is advantageous when Station 2 is heavily faded. This advantage is mainly due to the use of the AF signalling scheme to respect the BF: it creates less congestion and a lower number of broadcasting in the network so limiting also the average energy consumption. LINMAP approach results more efficient to respect MINMAX. It means that a DM based on the ideal alternative finds a better solution for all the attributes to respect a decision based on one of them. The results proposed "open the doors" to further investigations aimed at highlighting the advantages of the proposals.

VI. CONCLUSIONS

The paper introduces an application environment for sensor networks satellite-based where a monitoring host is remotely located. In that framework, the introduction of the sinks management functions and of the flooding-based techniques used to efficiently propagate information through the network are proposed. The proposals are compared in terms of energy consumption and total time spent in the sensor network highlighting their advantages.

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