Multi Attribute Based Algorithm for Reliable Satellite-based Sensor Networks

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***Abstract*—Modern environmental monitoring systems are based on Satellite-based Sensor Networks (SSN) where earth stations (Sinks) gather information from sensors and use the satellite channel to send it to remote sites. For the sake of efficiency of a whole monitoring system, the SSN has to be managed by following two main aims: to guarantee the reliability, in particular in case of failure of the satellite portion of the network, and to limit both delay, which is representative of a very important Quality of Service (QoS) metric, and energy consumption. The dynamic sink selection process may allow reaching both aims of the system. In more detail, the paper proposes: the description of the SSN architecture taken as reference, the quality requirements of the system, a revision of the Sink selection method called LINMAP, and an introductive simulative study of its performance in case of failure of the satellite portion of the system.**

Keywords-Monitoring Systems, Satellite Sensor Networks, Efficiency Requirements, Multi Attribute Programming.

I. Introduction

Ambient Intelligence is the new vision of the modern monitoring systems (MSs), where many different devices gather and process information from many different sources both to control physical processes and to interact with human users [1]. To realize this vision, three crucial elements are needed: computation, control and communications capacities.

The typical instrument designed to implement the requirements mentioned is a new class of networks appeared in the last few years: the Wireless Sensor Networks (WSN) that consist of individual nodes, which are entities able to interact with their environment by sensing or controlling physical parameters. Recent evolution of WSNs are the Satellite-based Sensor Networks (SSNs) [2] where all the characteristic of classical WSN are maintained but earth stations, which communicate through a satellite system, represent the sink nodes of the sensor field and they may be simultaneously used to send messages from the sensors to remote monitoring hosts where data are stored and managed. An applicative example of the usage of SSNs may be modern weather prediction systems (for hurricanes, storms, floods) [3], which are composed of different sensors, for example deployed in the sea, that detect and send precise measures (temperature, humidity, wind speed etc.), by using a satellite architecture. Received data are used by specific computers that elaborate a weather model used to provide precise prediction.

In these architectures, computation, control and communication requirements may be compromised due to the dynamic of the satellite channel (e.g., it may be failed or faded). A possible solution may be to consider a multiple sink structure because the redundancy of sinks allows limiting the possible information loss due to the failure of the satellite channel. In practice, the use of multiple sink may help mitigate the problem because it increases the probability that the information arrives at the destination but if redundant information is entirely transmitted through the satellite link, the cost in energy and overload would be unacceptable. As a consequence, it is necessary the selection of the best sink, for each sensor, so to get the network reliable (e.g., all the measures detected by sensors reach the RMH) and to simultaneously optimize different performance requirements such as energy consumption and message transfer delay.

The paper is structured as follows: Section II proposes an overview of the specific requirements of a SSN. Section III revises the LINMAP method. Section IV contains the performance investigation of the proposed techniques through simulations. Section IV lists the conclusions.

II. SSN Requirements

Typical important requirements of the SSN are [1]:

A. *Fault Tolerance.*

Sensors and sinks may run out of energy or be damaged. This problem is emphasized in the SSN case due to the particular nature of the satellite channel. In more detail, communication noise, rain fading and transmission system failures compromise the reliability of the SSN because some message packets may be lost due to earth stations (sinks) failure. The *Packet Delivery Ratio* (PDR) is the metric representative of the Fault Tolerance capability. PDR is the ratio between the number of message packets received by the RMH and the overall number of message packets generated by sensors. A robust sensor network should guarantee PDR=1.

B. *Quality of Service.*

Traditional concept of Quality of Service (QoS), usually coming from multimedia applications, may be useful in a SSN. In applications such as the MS, the *Measure Detection Delay* (MDD), defined as the time needed for a message packet to reach the destination (RMH) from a sensor node, is very important: considering the example of the weather prediction system, lower MDDs may guarantee a more precise weather prediction because data provided to the computers that calculate the weather model rapidly arrive, so reducing computation errors of the prediction.

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C. *Lifetime.*

The concept of lifetime, which is the time for which the network is operational, is strictly related to the energy consumed by sensors when used. In practice, for lower level of consumed energy the network lifetime is longer. In this paper, the energy consumption concept concerns the communication components of the sensors. In more details, the overall quantity of energy spent to propagate each message packet by sensors to reach the RMH has been considered. It is termed *Energy per Measure* (EM) and it is expressed in [mJ]. Each packet transmitted by a sensor is assumed to spend 1 [mJ].

D. *Scalability.*

A satellite MS typically covers a wide area of interest (sensor field). In this environment, the SSN architecture may be composed of a large number of sensor nodes. The employed architectures, protocols and, in particular the network control algorithms, should guarantee scalable performance of the whole system.

III. MADM MANAGEMENT

The network considered consists of N sensor nodes, which compose the sensor field. Sensors send information towards J satellite earth stations (also called sinks) that transmit the received information to a Remote Monitoring Host (RMH) through a geostationary satellite link. Sensors are sources of information (measures) sent through message packets and intermediate nodes [4]. Sensor nodes are modeled as buffers aimed at temporarily storing received packets. As reported in [1], this scenario represents one of the most challenging cases because the management of the network presents several difficulties.

The Sink Selection algorithms proposed in the following are aimed at managing the SSN so obtaining the robustness of the system (PDR close to 1) by reacting to possible sink failure(s) and, simultaneously, the optimization of the other performance metric (e.g., MDD and EM).

The considered Sink Selection technique, based on the *Multi Attribute Decision Making* (MADM) [5] theory, has been proposed in [2] and here quickly revised, for the sake of completeness. The *Decision Maker* (DM) is an entity that takes decisions about the sink choice. It is supposed to have one DM for each sensor node (*multiple decision* (M) scheme [2]). The *decision matrix* contains the *attributes* (i.e. the metrics of interest) related to the choice of specific sinks (i.e. the possible *alternatives*). There is one decision matrix for each n-th DM ($n \in [1, N]$). For each DM, the vector containing the attributes (identified by index $k \in [1, K]$) related to the j-th alternative, at the time t, is expressed in (1).

$$A_j^n(t) = \left[X_{j1}^n, ..., X_{jk}^n, ..., X_{jK}^n \right] \quad (1)$$

The term X_{jk}^n is the k-th attribute of the n-th node, at time t, if the j-th possible alternative is chosen. K is the number of attributes. Directly from (1), the decision matrix of the DM entity is:

$$\mathbf{A}^n(t) = \left[A_1^n(t), ..., A_j^n(t), ..., A_J^n(t) \right]^T \quad (2)$$

The attributes contained in the matrix represent the sensor network status seen by the n-th node.

The sink selection problem is aimed at obtaining the best alternative. In this work, the LINMAP method [2] is the operative approach used. It is based on the knowledge of the ideal alternative, also called *utopia point*, characterized by the ideal vector of attributes ${}^{id}A^n(t)$, in (3), at each time t, whose components are defined as in (4).

$${}^{id}A^n(t) = \left[{}^{id}X_1^n, ..., {}^{id}X_k^n, ..., {}^{id}X_K^n \right] \quad (3)$$

$${}^{id}X_k^n = \left\{ X_{jk}^n : j = \underset{j \in [1,J]}{\arg\min}\, X_{jk}^n \right\}, \forall k \in [1, ..., K] \quad (4)$$

The solution of the decision problem is the alternative minimizing the distance, in term of Euclidean Norm, with the ideal alternative:

$$j_{opt}^n(t) = \left\{ j^n = \underset{j \in [1,J]}{\arg\min} \left\| A_j^n(t) - {}^{id}A^n(t) \right\|_2 \right\} \quad (5)$$

A. *Effect of the Sink Selection Algorithm.*

The effect of the selection is to apply, in a specific Sink, a policy that allows dropping the message packet transmitted by nodes (sources) that have not selected that Sink. From the operative viewpoint, the source of a message packet has been recognized by using a specific field *source* in the header of the packet itself and, if the j-th sink is considered, the policy is (the time t has been omitted for the sake of simplicity):

$$\begin{cases} \text{Being } n \text{ the source of the received packet} \\ \textit{if } \left(j == j_{opt}^n \right) \textit{ then } \text{forward the packet} \\ \textit{else } \text{drop the packet} \end{cases} \quad (6)$$

Where n is the (*source*) index of the sensor that sends a message packet (shortly "packet" in (6)). In practice, only if the j-th sink is designed for node n, it will queue the packet and then will transmit it through the satellite link. Vice versa, the packet will be dropped so allowing a lower level of congestion in the sink j and, simultaneously, energy saving.

B. *Information Forwarding Method.*

Due to the necessity of a robust propagation of packets in the sensor network (the aim is to obtain the PDR close to 1), the flooding techniques are widely employed. Also in this paper, the propagation (also called forwarding) of the message packet to the sinks is performed by using a flooding strategy [1]. Actually, the classical flooding, also termed blind (BF),

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has not been used because all the sensor nodes forward all the source and transit packets to all the neighbor nodes performing no selection at all among them. In this work, the Selective Flooding (SF) is used: it allows reducing multiple copies of the same packets, typical of the BF approach, because it broadcasts only when a new message packet, identified by its *source* and by its *identifier*, arrived at a specific node, has a *source-identifier* pair never forwarded before. Both the *source* and the *identifier* field are contained in the header of the packet sent within the SSN. The former, as previously mentioned, is used to recognize the node that generates the measures; the latter allows identifying a specific measure (message packet) provided by a sensor.

C. Probing Procedure of the Decision Method.

To complete the decision matrix of the DMs, sensor nodes probe the network by using a *probing* phase. Sinks collect information about the attributes and sent it to the Decision Makers. In more detail, the attribute measures are collected during a periodic probing phase whose length is T_P (called *probing time*) and each DM provides the sink selection at discrete intervals of period T_D.

A decision provided at the beginning of T_D is valid and used for the overall T_D duration. The probing phase acts during the regular network working phase that it is not stopped. Each sink gathers information about attributes related to network nodes and sends it, through the satellite channel, to the RMH where DMs are supposed located. The DMs compute the selections and then transmit them to the sink nodes that became able to apply the policy (6) illustrated in Section III.

In the implementation proposed in this paper, realized within a simulation framework, the described control process needs of about 600 [ms] to exchange attributes and decisions. Nevertheless the results proposed in the following have been carried out by dedicating 1 [s] to the operations mentioned above. In more detail, the last second of T_D is dedicated to them. The first part of T_D is employed to collect the attributes: it represents the probing phase of T_P [s]. In practice T_P has been set equal to $T_D - 1$ [s].

The proposed probing procedure of the network, which is currently object of ongoing research, is a delicate problem and it needs to be deeply investigated.

IV. PERFORMANCE EVALUATION

In this work, two main metrics have been evaluated through an "ad hoc" C++ based simulator:

i) the reliability level of the network by measuring the Packet Delivering Ratio (PDR). A completely reliable sensor network should have PDR equal to 1;

ii) the Measure Detection Delay (MDD) defined as the time elapsed by a packet between its transmission and its delivering to the monitoring host, averaged over the number of received packet by the RMH.

These metrics give an idea of the overall performance of the network used to monitor a wide area environment: they represent the reliability level of the system and the time spent to communicate possible critical conditions perceived by sensors.

In the comparison proposed in the following, also two static methods have been taken into account: Heavy Static (HS) – this method uses simultaneously all the sinks in the network. It represents a brute force approach that surely guarantees the maximum PDR but, as shown below, it penalizes the MDD performance; Static (S) – the network is virtually split in a number of portions equal to the number of sink employed. It is, in practice, a single decision provided at the beginning of the network usage. The packets generated by a node of a specific portion are sent by using always the same sink. It reduces the duplication implied by the HS approach, which forward indistinctly all packets comprehensive of multiple copies of the same messages, but is less reliable. HS and S represent two extreme cases: HS is the most reliable but it implies the highest end to end delay, S is not reliable but, due to the fair distribution of the traffic among the sink, it implies lowest delay. Both have been compared with the LINMAP approach which represents a compromise among them.

A. LINMAP Setup.

The LINMAP method, quickly revised in the previous Section, needs of specific attributes' definition. The metrics implemented in this paper are synthetically described in the following. It is worth noting that the specific attributes chosen may be changed coherently with the application scenario without loss of generality of the LINMAP optimization method.

The considered metrics are the EM, the MDD, coherently with the network requirements (Section II), the Delivered Load (DL) and the Fading level (F) "seen" by an earth station (Sink), which are both causes of failure: in the former case due a heavy overload of the earth station, in the latter due to a high fading level.

In more practical words, to smooth the negative effect of the different scale of each k-th , $k \in [1, K]$ attribute they have been normalized over their maximum value $X_k^{\max}$:

$$X_k^{\max} = \max_j X_{jk}, \ \forall k \in [1, K] \tag{7}$$

and, specifically, they have been defined as:

- EM (Energy per Measure, described in Section II):

$$X_{j1}^n = \frac{1}{X_1^{\max}} \cdot \frac{1}{N_j^n} \cdot \sum_{h=1}^{N_j^n} e_j^{h,n}, \ \forall j \in [1, J] \tag{8}$$

Having one DM each sensor n is the identifier both of the specific DM and of the sensor. N_j^n is the number of measures (obtained by packets flooded during the probing phase) originated by sensor nodes n and delivered to sink j. $e_j^{h,n}$ is the value of the h-th measure (i.e., the energy spent to deliver the h-th packet originated by the n-th sensor node and delivered to sink j).

- MDD (Measure Detection Delay, described in Section II):

$$X_{j2}^{n} = \frac{1}{X_2^{\max}} \cdot \frac{1}{N_j^n} \cdot \sum_{h=1}^{N_j^n} T_j^{h,n}, \ \forall j \in [1, J] \qquad (9)$$

N_j^n has been defined for EM. $T_j^{h,n}$ is the end to end delay experienced by the h-th packet, reaching the sink j, sent by the n-th sensor node.

- DL (Delivered Load):

$$X_{j3} = \frac{1}{X_3^{\max}} \cdot \frac{N_j}{T_P} \qquad (10)$$

it is a metric aimed at weighting the overall load of each sink. N_j, as above, is the overall number of packets delivered to sink j within the measure period T_P.

- F (Fading Level):

$$X_{j4} = \frac{1}{X_4^{\max}} \cdot \frac{1}{\beta_j} \qquad (11)$$

this attribute is strictly linked to the satellite channel status at the sinks. The metric depends on a simple fading model widely used in the literature ([2] and references therein). In practice, it is used a parameter $\beta_j \in [0,1]$, which represents the fading level seen by the j-th sink. It is defined as the bandwidth reduction factor due to the usage of a specific fading countermeasure such as Forward Error Correction (FEC) codes: a clear sky condition means $\beta_j = 1$, while in failure conditions $\beta_j = 0$.

B. Simulation Setup.

The network considered in the simulations is composed of 25 nodes. Four of them are Sinks that can transmit packets towards the RMH. The topology of the sensor network, which is, in practice, the radio visibility among nodes, has been randomly changed during the simulation runs so considering possible effects of the mobility of nodes, the presence of obstacles and possible problems of the radio channel between sensors. Each node of the network has been implemented as a single buffer served with a capacity C that has been varied in the following tests from a Wideband case ($C = 2$ [Mb/s]) to a Narrowband case ($C = 20$ [Kb/s]). Also Sinks have been implemented as simple buffer with a fixed service capacity of 200 [Kb/s]. The propagation delay among sensors is considered fixed and equal to 30 [μs] and the propagation delay of the satellite link between sinks and RMH is 260 [ms]. Buffers' size is considered, for all nodes of the network, equal to 100 [packets]. Each simulation run has a length of 600 [s].

The practical aim of this performance study is to evaluate PDR (fault tolerant index) and MDD (traditional QoS index) in presence of possible sink failures. T_D has been fixed equal to 60 [s] and, as a consequence, T_P is 59 [s]. The packet size is 1000 [b] and each sensor transmits, in average, 1 [packet/s]. In the results proposed, the EM (lifetime index), which is a sensitive parameter for a sensor network, has not been reported because, in the scenario here considered, its behaviour is partially influenced by the Sink Selection process. Its performance depends on the joint effect of the forward techniques (flooding-based) and the Sink Selection control as shown in [1]. In this work, the information forward method is always fixed (Selective Flooding) and, as a consequence, no particular variation of the EM has been measured. The average EM in all the test proposed is around 75 [mJ].

C. PDR Analysis.

Fig. 1 shows the PDR when the Wideband case ($C = 2$ [Mb/s]) is taken into account. HS approach guarantees the maximum reliability of the Satellite Sensor Network because PDR=1. S method has a linear decreasing behaviour of the PDR: when the number of sink failures increases, the S approach, obviously, becomes less reliable. LINMAP, which is a dynamic approach, is completely fault tolerant (PDR=1). In practice, it changes dynamically the Sink used to forward packets to RMH by applying the buffer management policy in (6) and, as a consequence, all the packets of the network can reach the remote monitoring station. In terms of PDR, when the wideband case is considered, HS and LINMAP are equivalent. When the Narrowband case ($C = 20$ [Kb/s]) is considered, as shown in Fig. 2, HS is the most reliable: its PDR is close to 1. S method has always a decreasing PDR. LINMAP is not equivalent to HS: it has a PDR around 0.8 and slightly decreasing with the number of Sink failures. This result depends on the congestion of the network nodes, which is due to the low available capacity. In practice, some packets are lost in the sensor nodes but, in HS case, copies of them, generated by the flooding-based forwarding method, can reach however the RMH. It is not possible with LINMAP because it applies the policy (6) to the sink nodes' buffers and, as a consequence, drops some messages.

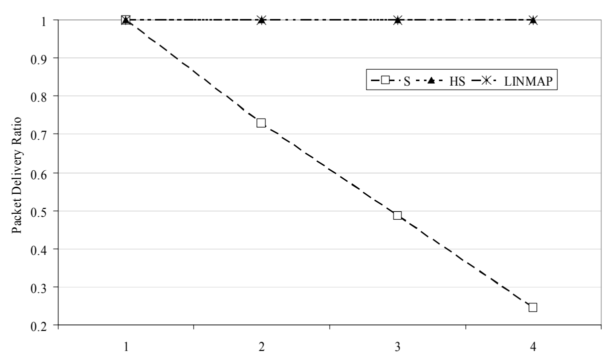

Fig 1. Packet Delivery Ratio – Wideband Case.

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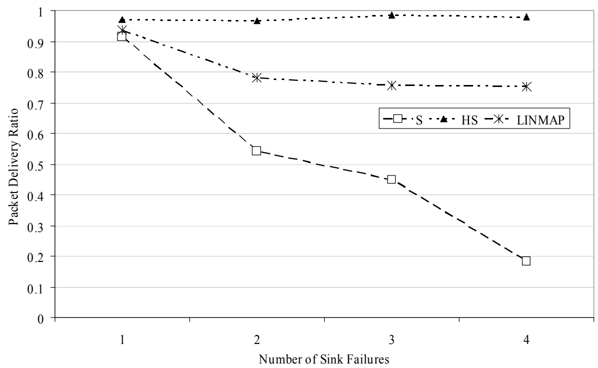

Fig. 2. Packet Delivery Ratio – Narrowband Case.

D. MDD Analysis.

The performance study of this paper is completed with the MDD (in [s]) analysis reported in Figs. 3 and 4. In both cases evaluated (Wideband and Narrowband), S has the best MDD and HS the worst, as previously introduced. LINMAP acts in the middle. In the wideband case ($C = 2$ [Mb/s], in Fig. 3) there is not practical difference among the method evaluated: the MDD from the best case (S) to the worst case (HS) varies of about 2 [ms]. When the Narrowband condition ($C = 20$ [Kb/s], in Fig. 4), typical of civil protection or tactical environment, is considered the situation changes: the employment of S implies an MDD of about 5 [s] while HS usage allows performing MDD of about 11 [s]. LINMAP is a compromise: its MDD is increasing and tends to be equal to the behaviour obtained with the S approach, when the number of Sink failures is low. It tends to the HS behaviour if the number of failed sinks grows.

From the results, both in terms of PDR and MDD may be concluded that LINMAP is representative of the better compromise among the techniques evaluated. It allows sufficiently reliable and fast communications between the sensors and the RMH, in particular when the sensor network operates in narrowband condition.

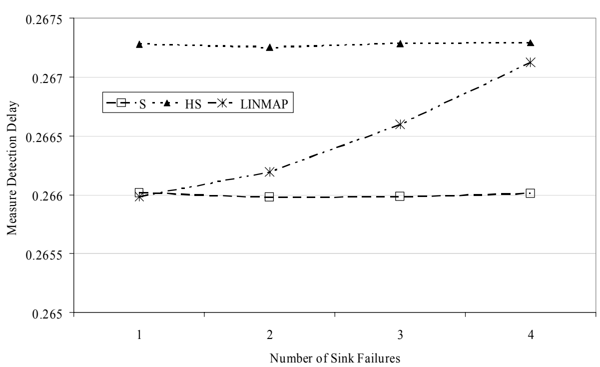

Fig. 3. Measure Detection Delay – Wideband Case.

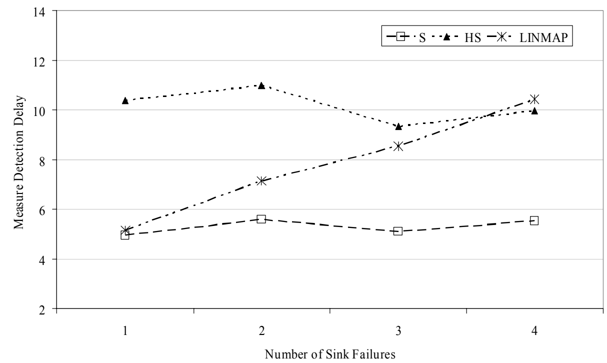

Fig. 4. Measure Detection Delay – Narrowband Case.

V. CONCLUSIONS

The paper revises the concept of Satellite Sensor Network architecture, typically used as monitoring system of wide geographical areas. The work moreover individuates some important metrics that should be considered to make efficient the overall network and proposes sinks management functions aimed at optimizing these metrics.

The performance, studied in failure conditions of the satellite link, is investigated in terms of reliability and delay. The main indication of the results is that the absence of a dynamic sink selection technique, in the proposed environment, may cause performance detriment and, in particular, reduce the reliability of the whole monitoring system.

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