Performance Evaluation of Sink Selection Techniques in Satellite Sensor Networks

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***Abstract*—Recent environmental monitoring systems are based on Satellite-based Sensor Networks (SSN) where earth stations (Sinks) gather messages from sensors and use the satellite channel to send sensible information to remote monitoring sites. In these systems, the Sink selection process may play a crucial role and needs to be investigated. The work includes: an introduction of the SSN scenario considered; a brief description of the Sink selection method aimed at guaranteeing the optimization of the energy consumption and, simultaneously, of the message transfer delay; a deep performance investigation, which represents the main contribution of this paper, carried out by simulation, of the studied technique.**

Keywords-Satellite Sensor Network, Multi Attribute Programming, Performance Evaluation.

I. Introduction

In Satellite-based Sensor Networks (SSN) [1], earth stations 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.

In more detail, the network considered consists of N sensor nodes, which compose the sensor field. The sensors send information towards J satellite earth stations (called sinks in the following) that transmit the received information to a Remote Monitoring Host through a geostationary satellite link. Each sensor node has a finite quantity of available energy (expressed in Joule [J]). It may be both a source of information typically measures of physic phenomena through *message packets* and an intermediate node [2], which forwards the messages received from other nodes. The sensor nodes are modeled as arrays of buffers aimed at temporarily storing received packets. The sensor network is wireless and its topology varies. A topological variation is a modification of the node visibility.

The satellite frequencies considered vary in the interval 20-30[GHz] (Ka-band) where the transmissions may be heavily corrupted by fading mainly due to meteorological precipitations. Fading is modeled as bandwidth reduction in this paper: the satellite channel bandwidth C_j (for the j-th sink) is reduced of a factor $\beta_j \in [0,1]$. Its technical interpretation may be the bandwidth reduction due to the presence of a FEC (Forward Error Correction) used to make the channel errors negligible. It reduces the available service capacity, due to the redundancy bit added by FECs, so increasing the time needed to transmit the packets to the monitoring host (transfer time).

In the described environment, the choice of the sink may play a crucial role and the aim is the selection of the best sink so to get the simultaneous optimization of different performance metrics such as energy consumption and message transfer delay.

The absence of a dynamic selection or a selection of a sink on the basis of the optimization of a single performance metric may be unfair and limited. For example, an optimal selection in terms of message transfer time might imply excessive energy consumption. To reach the aim, a sink selection technique, based on the *Multi Attribute Decision Making* (MADM) problem, (initially introduced in [1]) is thoroughly investigated in this work.

The paper is structured as follows: Section II presents the theoretical framework of the paper. Section III contains the performance investigation of MADM through simulations. Section IV lists the conclusions.

II. Theoretical Framework

A. Multi-Attribute Decision Making Algorithms.

The Sink Selection techniques, based on the *Multi Attribute Decision Making* (MADM) [3] theory, are quickly revised here for the sake of completeness. The *Decision Maker* (DM) is an entity that takes decisions about the sink choice. It is possible both to have just one DM for the overall sensor network (*single decision* (S) scheme) and one DM for each sensor node (*multiple decision* (M) scheme). 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 DM. For the sake of simplicity, the index referring to DM is dropped in the following. 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).

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

The term X_{jk} is the k-th attribute, 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:

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

The attributes contained in the matrix represent the sensor

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network status and their precise definitions are reported in sub-section *C*.

The sink selection problem is aimed at obtaining the best alternative (i.e. the sink called $j^{opt}(t)$) so that :

$$j^{opt}(t) = \min_{j \in [1,J]} A_j(t) \tag{3}$$

As stated in [1], the problem needs of an optimization criterion to be solved. In this paper, the LINear Programming techniques for Multidimensional Analysis of Preferences (LINMAP) is taken as main reference and compared, in the performance evaluation section, with other possible approaches. The LINMAP method is based on the knowledge of the ideal alternative, also called *utopia point*, characterized by the ideal vector of attributes $A^{id}(t)$, in (4), at each time t, whose components are defined as in (5).

$$A^{id}(t) = \left[X_1^{id}, ..., X_k^{id}, ... X_K^{id} \right] \tag{4}$$

$$X_k^{id} = \left\{ X_{jk} : j = \arg\min_{j \in [1,J]} X_{jk} \right\}, \forall k \in [1,...,K] \tag{5}$$

The solution of the decision problem is the alternative minimizing the Euclidean distance from the ideal alternative:

$$j^{opt}(t) = j_{LINMAP}(t) = \left\{ j = \arg\min_{j \in [1,J]} \left\| A_j(t) - A^{id}(t) \right\|^2 \right\} \tag{6}$$

B. Probing Procedure of the Decision Method.

To complete the decision matrix of the DM, sensor nodes probe the network by using *probing* packets. Sinks collect information about the attributes and sent it to the Decisions Maker(s). After solving the optimization problem, in the *single decision* case (S) (when there is just one DM for the overall network), the DM takes decisions for all the sensor nodes within the network and transmit it directly to them. In the *multiple decision* (M) case, when each sensor node has its own DM, the sink selection is transmitted from the DM to its own controlled sensor node (in case they are located remotely). In both cases, each DM provides the sink selection to the sensor nodes at discrete intervals. In more detail: attribute measures are collected during the probing phase whose length is T_P (called *probing time*). Each DM solves the optimization problem in a time, which is considered negligible. The probing procedure acts in parallel with the message distribution because the regular network functions cannot be stopped. It implies that probing introduce a temporary network overload, which should be as limited as possible. The probing action is not performed continuously but at fixed time instants of period T_D and for limited time length T_P. The DMs are supposed located in the sinks (one specific in case of *single decision* case). It allows reducing the amount of exchanged messages useful to provide the DM(s) of its decision matrix.

C. Decision Modalities.

As previously specified, the LINMAP may be implemented both over a *single decision* scheme, where the attributes are global (independent of the sensor source node), or over a *multiple decision* scheme, where the attributes are specialized for each node (in practice, each node has its specific attributes set). The formal definition of the attributes are reported in [1] and here briefly described for the sake of completeness.

The considered metrics are the Average Energy Consumption (AEC), the Average Transfer Time (ATT), the Delivered Load (DL) and the Fading level seen by an earth station (F). In more detail:

- AEC is the overall quantity of energy spent to propagate the packets from the sensors to the sinks. Each packet broadcasting is assumed to spend 1 [mJ].
- ATT is the average time spent by a packet to reach the destination from a sensor node. It is an end-to-end measure composed of the propagation delay both through the sensor network and through the satellite link, of the service and waiting time and of each network component traversed.
- The DL metric is aimed at weighting the overall load of each sink. The same metric for the single and multiple decision is used. It is the overall number of probing packets and message packets delivered to sink j within the measure period T_P.
- F is strictly linked to the satellite channel status at the sinks. It follows the fading model mentioned in the introduction of the paper.

The value of each attribute is normalized to smooth the negative effect of the different scale of each single attribute.

D. Information Distribution Techniques.

The flooding schemes allow robust propagation of packets (both *message* and *probing*). To evaluate the Sink Selection methods performance, they have been tested jointly with four flooding strategies [1, 4]: 1) the classical flooding, also termed blind (BF), the heuristic flooding (HF), the Multipoint Relay (MPR) and an advanced version of flooding (AF). In the BF case, all the sensor nodes forward all the source and transit packets to all the neighbor nodes performing no selection at all among them. It may introduce excessive power consumption and a redundant number of sent packets, caused by the multiple arrival of the same packet copies from nodes. It may also generate possible congestion of satellite links. Being BF inefficient, possible heuristics are proposed to reduce the number of re-broadcasts of the same packet. 2) the heuristic method (HF) considered in this paper is the probabilistic: packets are re-transmitted to all neighbor nodes with a fixed probability p_b. 3) with the MPR technique, nodes collect the list of neighbor nodes reachable through two hops (called two-hops nodes). Received packets are transmitted only to a subset of neighbors that, together, can guarantee the reaching of all two-hops nodes. 4) the AF allows reducing multiple copies of the same packets because it broadcasts only when a new packet, identified by its *source* and by its *identifier*, arrived at a specific node, is broadcasted only if its cost is lower than the cost of the previous packets received and characterized by the same *source-identifier* pair. The AF cost, in this paper, is the energy consumed by a packet to reach a specific node.

III. PERFORMANCE EVALUATION

In this work, two main metrics have been evaluated:

i) the Average Energy Consumption (AEC), it is the measure of the average energy consumed (expressed in [mJ]) by all packets reaching the designed sink node. Each packet broadcasted, by a generic node, is supposed to consume 1 [mJ];

ii) ii) the Average Transfer Time (ATT) [s], it is 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 designed sink. 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 duration of the simulations is fixed and equal to 220 [s]. The decision period is 55[s], composed of the probing period of 5[s]. The bandwidth capacity and the propagation delay between nodes in the sensor network are always fixed and equal to 2 [Mb/s] and 1 [ms], respectively. The signaling packet size is 1500 [byte]. The maximum number of nodes N is 25. In these cases the number of stimuli perceived from sensors, thus the average number of packets (both probing packets and messages) generated in one second (Packet Generation Rate, PGR) from nodes is 0.1 [packets/s]. The generation of the stimuli follows a Poisson probability distribution. The satellite accesses are $J = 4$ stations (Station 1, Station 2, Station 3 and Station 4) with a fixed bandwidth of 2 [Mb/s] and propagation delay of 260 [ms].

The first step of this performance evaluation is aimed at highlighting the main functionality of the proposed algorithm. In this case, the topology is fixed as reported in Fig. 1. In more detail, in the scenario described above, the LINMAP method, together the AF flooding with *multiple* decision scheme M, has been simulated in presence of different fading conditions: *Deep Fading* ($\beta_j = 0.156$), *Medium Fading* ($\beta_j = 0.625$) and *No Fading* ($\beta_j = 1$). The sink nodes are located at the corner point of the topology.

In Fig. 1 (a), all the earth stations are not corrupted by fading (*No* fading level) and the Sink selection method (the LINMAP-AF-M) distributes the *messages* fairly among the sinks. As a consequence, the network is split in four similar groups, in which the sensors send their packets to the nearest earth station. Nodes of the same group are marked by the same filling of their selected sink. If the fading condition over the station 4 (the circled sink node depicted in the figures) changes from *No* fading to *Medium* (Fig. 1(b)), the number of sensors sending packets to the faded station decreases because the DMs of some nodes select other possible sinks. It is due to the increase of the transmission time of the corrupted station, which is larger than the time spent to reach sink nodes physically further from sensors than the circled earth station. In fig. 1 (c) the simulation has been carried out by fixing *Deep* the fading level of station 4. In this case, the faded sink is not used: all the sensors send their *messages* to the other sinks. It means that DMs select the earth stations in clear-sky condition because the Average Transfer Time ATT is lower than the ATT obtained by using the faded station. In these cases, the proposed strategy reacts to the fading variation by a redirection of the messages to the clear sky earth station.

The energy consumption in the simulation does not play any role because the changes of the fading level impact only on the Transfer Time, which includes the transmission time of the packet from the earth stations to the remote monitoring host.

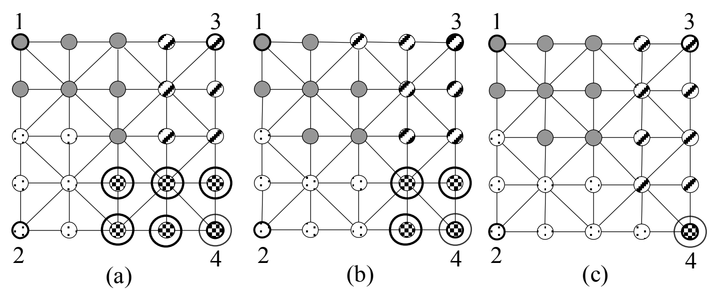

Fig. 1. Simulated Network Topology with a corrupted earth station [*No* fading (a), *Medium* fading (b) and *Deep* fading (c)].

In practice the simulations performed allow concluding that the algorithm proposed is sensitive to network status changes and reacts by performing different sink selections. To give an idea of the advantages of the LINMAP-AF-M technique, Table I reports the ATT measured by using the techniques, indicated as *No* and *Deep* fading conditions compared with two static sink selection approaches called FD and FC.

TABLE I.
ATT [s] OF DIFFERENT DISTRIBUTION TECHNIQUES

	FD	FC	LINMAP-AF-M
***No* Fading**	0.295	0.313	0.297
***Deep* Fading**	0.314	0.387	0.298

The Fully Distributed (FD) technique splits the network in 4 similar portions and chosen the sink closer to the sensor, independently of the network status. In clear-sky condition it is representative of the ideal condition and the LINMAP-AF-M follows its behaviour. When the fading level is *Deep* the Fully Distributed solution increases the ATT while the proposed algorithm maintains its performance similar to the clear-sky case. It is worth noting that the difference between the ATT of the FD strategy and the LINMAP-AF-M is limited because, as reported in Fig. 1 (c), the sensors, originally linked with station 4, send packets to the other stations and the advantage of the exclusion of the heavily faded station is reduced by the increase of the number of hops needed to reach the selected sink nodes. Nevertheless, LINMAP-AF-M allows maintaining the performance in *Deep* fading condition similar

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to the *No* fading case. The Fully Centralized (FC) Technique allows selecting statically the only sink node of the whole network (there is just one sink): the presence of a single earth station (or the selection of a single sink for all the sensors) implies a deterioration of the performance, with respect to the other considered schemes. It means that a single selection for each node is detrimental: this result justifies the presence of multiple sinks in the SSN architecture introduced in [1].

In table II, the satellite channel seen by each earth station is in clear-sky condition. From here, the network topology is always randomly generated and kept equal in each observation. In these cases the technique evaluated is the LINMAP associating them each flooding scheme previously described. Together with LINMAP minimization approach also the MINMAX criteria [1, 3] is considered for comparison. In the MINMAX approach each alternative is represented by the worst attribute and the sink selected is the earth station with the better of them. Both the single decision (S) and in multiple decision (M) modalities have been applied. Concerning single decision modality, fixed each information distribution method, LINMAP and MINMAX optimization are equivalent. This means that the AEC performance is enhanced, in particular, by using efficient packet distribution schemes. The performance is really outstanding if AF is used. Concerning ATT, the better performance is achieved if AF signaling method is used because it implies a lower level of congestion in the network. In this case, the performance enhancement is due to both the signaling scheme and the presence of the decision control. The LINMAP performance, which minimizes the distance from the performance utopia point, is equivalent in terms of AEC and slightly better in terms of ATT than the MINMAX performance. Concerning the multiple decision modality, the considerations are analogous. It is worth noting that the multiple decision modality achieves a slight better performance to respect the single decision approach. It allows to conclude that the multiple decision approach associated with the LINMAP minimization and the advanced flooding techniques is preferable (LINMAP-AF-M) in both flexibility and performance senses.

TABLE II.
SINGLE DECISION VS. MULTIPLE DECISION TECHNIQUES

	Single Decision		Multiple Decision	
Sink Selection Technique	**AEC [mJ]**	**ATT [s]**	**AEC [mJ]**	**ATT [s]**
LINMAP-AF	102.05	0.62	101.90	0.58
MINMAX-AF	102.20	0.63	106.43	0.70
LINMAP-BF	2218.76	6.47	2870.77	6.92
MINMAX-BF	2900.33	6.85	2487.49	6.44
LINMAP-HF	1974.53	5.77	2078.14	6.13
MINMAX-HF	2544.73	6.24	2080.42	5.94
LINMAP-MPR	3552.88	6.75	2805.33	7.12
MINMAX-MPR	2627.22	7.09	3249.01	6.71

From the introduction of the proposed techniques (Section II.B) it is possible to note that the setting of the duration of the probing procedure, when required, may be a delicate problem. In mode detail, a random setting of the T_P may imply worse sink selection than other possible alternatives. In this case an opportune setting of the T_P, dependent on the network and satellite channel status is surely needed to obtain an efficient behaviour of the Sink selection schemes. The problem is currently object of ongoing research, but for the sake of completeness, the empirical evaluation, carried out by simulations, has been introduced to validate the T_P value used in this paper. To reach the aim, the AEC and the ATT performed by the LINMAP-AF-M scheme, obtained by varying the T_P, have been measured and reported in Figures 2 and 3. It allows individuating the sensitivity of the algorithm with respect to the duration of the probing time. If the T_P is low, the DM(s) does not collect sufficient measures of the attributes from the sinks. In practice, the decision is excessively rough. When the Probing Time grows, the performance both in terms of AEC and ATT enhances. After $T_P = 1$ [s], the measures do not change. In facts: AEC and ATT have variations limited to 0.1 [mJ] and 3[µs], respectively, as reported in Fig 3. It means that the Probing time setting fixed in all the tests performed ($T_P = 5$ [s]) is reliable. A too long Probing duration, coherently with the behaviour depicted in Fig. 3, is useless and implies an excessive waiting time of a sink decision for network nodes. It is worth noting that precise setting of T_P depends on the network status, hence the empirical validation proposed here is strictly valid for the network considered in the simulations.

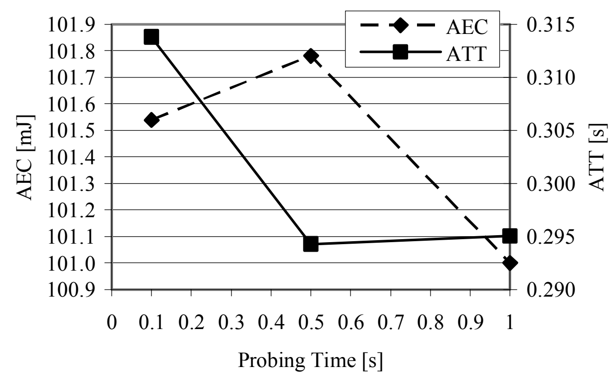

Fig. 2. AEC and ATT measured by varying the Probing Time duration lower than 1[s].

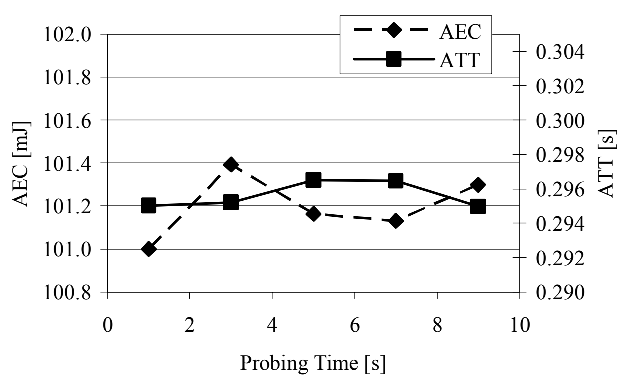

Fig. 3. AEC and ATT measured by varying the Probing Time duration larger than 1[s].

The maximum advantage of the decision techniques proposed is more evident when the number of sensors composing the network significantly grows. The advantage is clear if the ATT metric is considered. Concerning the AEC, the performance enhancement is reached mainly due to the flooding technique employed. The joint usage of the LINMAP decision algorithm and of the AF scheme allows obtaining a satisfactory performance in presence of SSN densely deployed. It is clear from Table III, which contains the Gain, defined in equation (7), in terms of ATT. Table III, in practice, shows the Gain obtained with the usage of the LINMAP-AF-M with respect to the employment of other generic techniques ($(\cdot)$ in the equation).

$$G_{\%} = \left[\left| ATT\left(\text{LINMAP-AF-M}\right) - ATT\left(\cdot\right) \right| / ATT\left(\cdot\right) \right] \cdot 100 \quad (7)$$

TABLE III.
ATT GAIN OF THE LINMAP-AF-M

Sensors Number	FD	FC	LINMAP-AF-S
10	4%	20%	1.5%
25	4%	23%	4%
80	4%	26%	19%

The results have been carried out in *Deep* fading condition of station 4 with the following techniques: FD, FC and the LINMAP-AF-S (single decision version of the LINMAP-AF technique). The proposed LINMAP-AF-M scheme allows obtaining always a gain if station 4 is faded. The gain is limited (4%) if the FD is considered because it surely guarantees a good performance for the 75% of the network nodes. The ATT detriment is suffered by a limited portion of sensors. Concerning centralized static decisions, the advantage of the LINMAP-AF-M is obvious.

A centralized solution suffers of both network congestion, because all nodes convey their *messages* in a single sink, and fading condition. The usage of the single decision version of the algorithm provides satisfying ATT performance, in practice comparable with the multiple decision version (the gain is only 1.5%), if the number of sensor is small. If the number of nodes grows, the gain increases because the presence of a single sink, dynamically selected, allows obtaining the same performance of the FC.

The introduced techniques have been tested also in presence of variable packet generation rate. N is fixed and equal to 25. In practice, AEC and ATT have been measured in three different simulations where PGR has been fixed as reported in Table IV. The station 4 is supposed in *Deep* fading condition. In this case LINMAP-AF-M is compared with the previously mentioned methods FD, FC and LINMAP-AF-S, taken as reference for the comparison. AEC is considered in the first part of Table IV. The average energy consumed is substantially the same for each method. It means that the main role, in terms of AEC is played by the information distribution technique, which is the AF in all cases. It is worth noting that the LINMAP based methods have a slightly worse AEC performance due to the presence of the probing phase, not used in the FD and FC cases. The probing impacts of about the 2% compared with regular situation (in absence of probing). Concerning ATT (Table IV, second part), it is possible to note that the LINMAP-AF-M technique allows setting better performance and maintaining the ATT level constant also with PGR variations. Also the LINMAP-AF-S allows constant performance but it has higher ATT values than LINMAP-AF-M because the centralization of the sink choice implies the congestion of the chosen sink. FD and FC has increasing ATT versus the PGR. FC has, as expected, the worst ATT performance.

TABLE IV.
AEC AND ATT WITH VARIABLE PACKET GENERATION RATE

	AEC [mJ]			
PGR	**FD**	**FC**	**LINMAP-AF-S**	**LINMAP-AF-M**
0.1	99	99	101.863	101.781
0.5	99	99	100.573	100.46
1	99	99	100.074	100.157
	ATT [s]			
0.1	0.309	0.385	0.312	0.298
0.5	0.311	0.397	0.314	0.298
1	0.316	0.417	0.314	0.299

IV. CONCLUSIONS

The paper quickly revises the Satellite Sensor Network architecture where a monitoring host is remotely located, and a novel sinks management function introduced by the authors in a previous work. In this paper, the performance of this proposal is deeply investigated in terms of energy consumption and average time spent in the network by a message sent from the sensors to the remote host through the satellite channel. The main indication of the results is that the absence of sink selection techniques, in the proposed environment, may cause performance detriment in particular when the number of sensors deployed in sensor field grows significantly.

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