Multi Attribute Sink Selection Techniques in Satellite Sensor Networks: Study and Performance Evaluation

Igor Bisio, *Student Member, IEEE,* Mario Marchese, *Senior Member, IEEE,* Giancarlo Portomauro
CNIT – Italian National Consortium for Telecommunications
University of Genoa Research Unit
Via Opera Pia 13, 16145, Genoa, Italy
{igor.bisio, mario.marchese, giancarlo.portomauro}@cnit.it

Abstract—**In Satellite-based Sensor Networks (SSN), earth stations represent the sink nodes of the sensor field and they may be simultaneously used to sent messages from the sensors to the remote monitoring hosts where data are stored and managed. In this environment, the choice of the sink may play a crucial role and represent a interesting field of investigation. The work includes: an introduction of the network scenario considered; a brief description of the Sink selection methods aimed at guaranteeing the optimization of the energy consumption and, simultaneously, of the message transfer delay; a performance investigation of the proposals, which represents the main contribution of this paper, carried out by simulation.**

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

I. INTRODUCTION

A Satellite-based Sensor Network (SSN) [1] 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 forward the messages received from other nodes. The sensor nodes are modelled as arrays of buffers aimed at temporarily storing received packets. Each buffer can be congested, because it has limited memory capacity (i.e., buffer size Q), so causing packet losses. 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 modelled 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). The FEC strategies make the channel errors negligible but reduce the available service capacity so increasing the time needed to transmit the packets to the monitoring host (transfer time).

In the described environment, 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 dynamic selection of a sink on the basis of the optimization of a single 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 MADM technique. Section III contains the performance investigation of MADM through simulations. Section IV lists the conclusions.

II. DYNAMIC CHOICE OF SINKS

A. Multi-Attribute Decision Making Algorithms

The mentioned definitions, 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 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)

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

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:

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

The attributes contained in the matrix represent the sensor 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 :

1-4244-0119-4/06/$20.00 ©2006 IEEE

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

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).

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

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

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, 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 (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 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 by the sinks (one specific in case of *single* case). It allows reducing the amount of exchanged messages useful to provide the DM(s) of its decision matrix.

C. Decision Modalities.

The LINMAP may be implemented both over a *single decision* (S) scheme or over a *multiple decision* (M) scheme and the formal definition of the attributes, summarized below, is different in the two cases. Four attributes ($K = 4$) are considered in this paper. The value of each attribute $k \in [1,K]$ is averaged over the maximum value $X_k^{\max}$, defined in (7), to smooth the negative effect of the different scale of each single attribute.

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

- AEC (Average Energy Consumption) and ATT (Average Transfer Time): AEC is the overall quantity of energy, expressed in Joule, spent to propagate the packets from the sensors to the sinks. Each packet broadcasting (in practice each step) 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 though the sensor network and through the satellite link; of the service and waiting time of each network component traversed. Their definitions are similar and may generalized as follows.

Single Decision

$$X_{j\hat{k}} = \frac{1}{X_{\hat{k}}^{\max}} \cdot \frac{1}{N_j} \cdot \sum_{h=1}^{N_j} m_j^h,\ \forall j \in [1,J] \tag{8}$$

The quantity N_j is the number of total measures referred to sink j (i.e. the overall number of probing packets delivered to sink j, independently of the sensor source node) and m_j^h is the value of the h-th measure (i.e. the energy spent to deliver the h-th probing packet to sink j, considering 1 [mJ] for each hop ($m_j^h = e_j^h$) or the overall time spent by the h-th probing packet to go from the source to the destination remote host through sink j, ($m_j^h = T_j^h$)). $\hat{k} = 1$ if the AEC is considered, $\hat{k} = 2$ in the ATT case.

Multiple Decision: having one DM for sensor, n is the identifier both of the DM and of the sensor.

$$X_{j\hat{k}}^n = \frac{1}{X_{\hat{k}}^{\max}} \cdot \frac{1}{N_j^n} \cdot \sum_{h=1}^{N_j^n} m_j^{h,n},\ \forall j \in [1,J] \tag{9}$$

N_j^n is the number of measures (e.g., of probing packets) originated by sensor nodes n and delivered to sink j. $m_j^{h,n}$ is the value of the h-th measure (i.e., the energy spent to deliver the h-th probing packet originated by the n-th sensor node and delivered to sink j ($m_j^{h,n} = e_j^{h,n}$) or the T_j^h but is related only to probing packets originated by n-th sensor node ($m_j^{h,n} = T_j^{h,n}$)). $\hat{k} = 1$ if the AEC is considered, $\hat{k} = 2$ in the ATT case.

- DL (Delivered Load): the metric is aimed at weighting the overall load of each sink. The same metric for the single and multiple decision is used.

$$X_{j3}=\frac{N_j+M_j}{T_P} \quad (10)$$

N_j, as above, is the overall number of probing packets delivered to sink j within the period T_P and M_j is the overall number of message packets delivered to sink j in the same time.

- F (Fading Level): this attribute is strictly linked to the satellite channel status at the sinks. Differentiating the metrics on the sources appears meaningless. So, the choice is to have the same metric for both single and multiple decision. It follows the fading model mentioned in the introduction of the paper:

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

B. *Information Distribution Techniques.*

The flooding schemes allow robust propagation of packets (both *message* and *probing*), the information exchanging and the *probing* procedure of the network. An efficient flooding strategy has been considered coherently with reference [1]: the advanced flooding (AF). In the classical flooding case, all the sensor nodes forward all the source and transit packets to all the neighbour 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 neighbour from nodes, also generating possible congestion of satellite links. The AF allows reducing packet multiple copies because it broadcasts because 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

This section is aimed at completing the performance evaluation of the LINMAP technique originally presented in [1]. In the mentioned reference, the impact of the flooding version used together with the decision criterion applied has been highlighted. Here, the three main aspects will be evaluated, in particular:

a) the behaviour of the DM in presence of a faded earth station;

b) the impact of the probing procedure on the DM behaviour;

c) the effect of a variable number of sensor nodes deployed in the monitored area and the effect of the load offered to the network by sensors, which are, obviously, the traffic sources of the system.

In more detail, two main metrics have been evaluated via simulation: i) the AEC, which is, as previously reported, 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) the ATT [s], which is, coherently with the definition previously provided, 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 observations is fixed and equal to 220 [s]. The decision period (T_D) is 55[s], composed of the probing period (T_P) 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 signalling 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 from nodes, called Packet Generation Rate (PGR), 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].

A. *Behaviour of the Sink Selection Techniques in presence of Faded Sink.*

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 (shortly LINMAP-AF-M in the following), 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 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 Fading* (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 Fading* 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 station in clear-sky condition because the 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.

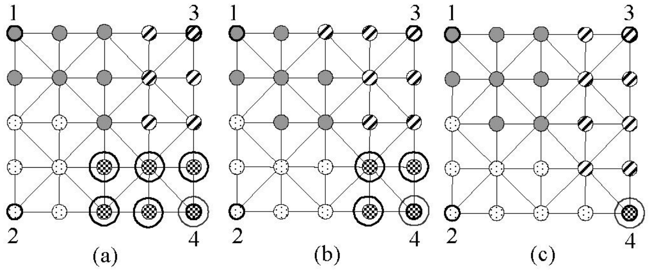

Fig. 1. Simulated Network Topology with a corrupted earth station [*No* fading (a), *Medium* fading (b) and *Deep* fading (c)].

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 LINMAP-AF-M, Table I reports the ATT measured by using the techniques, compared with two static sink selection approaches called Fully Distributed (FD) and Fully Centralized (FC). The fading levels considered are *No* and *Deep*.

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 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 FD 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 to the *No Fading* case. The 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 justify the presence of multiple sinks in the SSN architecture introduced in [1].

B. The impact of the Probing Procedure.

From the description of the proposed techniques (Section 2.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 subject 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 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 the 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.

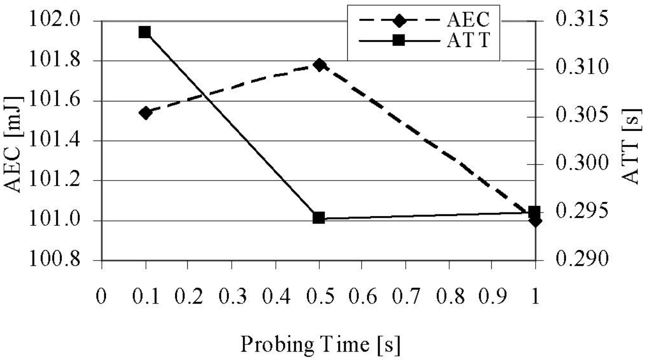

Fig. 2. AEC and ATT measured by varying the Probing Time duration lower than 1[s].

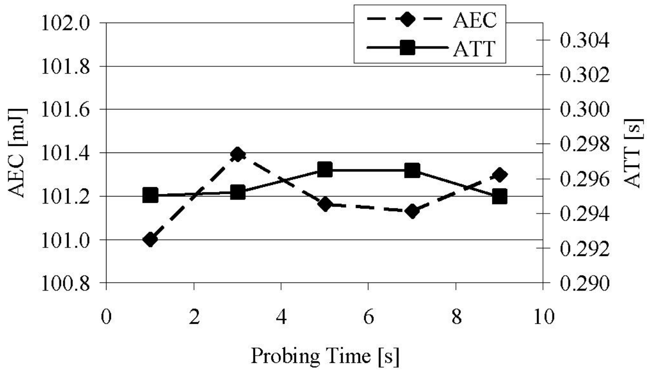

Fig. 3. AEC and ATT measured by varying the Probing Time duration larger than 1[s].

C. Performance with Variable Number of Sensors and Different Packet Generation Rates.

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 II, where the Gain, in terms of ATT (eq. (12)), obtained with the usage of the LINMAP-AF-M with respect to the employment of other generic techniques ($(\cdot)$ in the equation) is indicated.

$$G_{\%} = \left[\left| ATT(\text{LINMAP-AF-M}) - ATT(\cdot) \right| / ATT(\cdot) \right] \cdot 100 \quad (12)$$

TABLE II.
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 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 technique has 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 in which PGR has been fixed as reported in Table III. 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 references for the comparison. AEC is considered in the first part of Table III. 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, 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 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 III.
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 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.

REFERENCES

[1] I. Bisio, M. Marchese, A. Mursia, G. Portomauro, "Information Distribution Techniques in Sensor Network via Satellite," *IEEE International Conference on Communications*, Istanbul, Turkey, June 2006, to appear.

[2] I. F. Akyldiz, W. Su, Y. Sankarasubramaniam and E. Cayirci, "A Survey on Sensor Networks," *IEEE Communication Magazine*, vol. 40, no. 8, August 2002, pp. 102 – 114.

[3] K.P. Yoon, C. Hwang, "Multiple Attribute Decision Making – An Introduction," Sage Publications, Thousand Oaks, CA, 1995.