Information Distribution Techniques in Sensor Networks via Satellite

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

Agatino Mursia

Selex Communication S.p.a.
Via Peragostini 80 - Pia 13, 16151, Genoa, Italy
Agatino.Mursia@selex-comms.com

Abstract— **The reference environment is composed of a sensor network that conveys information towards earth stations (called sinks) that give access to the satellite backbone and, through it, to the destination. The choice of the sink where to convey sensor information may affect the overall communication performance.**

After introducing the application environment, the paper introduces a method to select the sink that assures the improvement of network performance in terms of energy consumption, load, and total time spent by information packets in the network, considering the fading level measured by earth stations. After selecting the sink, the technique how to propagate information within the sensor network has a main role. The paper compares flooding-based techniques on the basis of the metrics mentioned above.

Keywords- Satellite channels, Sensor Network, Multi Attribute Programming.

I. INTRODUCTION

INTEGRATION of existing terrestrial sensor networks and satellite components is a key issue for systems that allow achieving ubiquitous information exchange between geographically separated sites at affordable cost [1]. In this view, a possible reference network may be composed of a widespread sensor network (where sensors have the capability to reveal and measure phenomenon variations; to process data; and to route the messages) and of a satellite backbone whose role is to transport the measures taken by the sensor up to a remote monitoring host, which represents the destination. The satellite backbone may have several access points remotely located each other. It improves the redundancy of the network improving the probability of message arrival in case of failure or outage of satellite earth stations due to fading.

The main problems to match are: the selection of the earth station (called sink) where sensor information must be addressed; the method to propagate information through the sensor network itself. Concerning the latter, flooding-based techniques are widely employed due to the high topology variability of the networks under study [1, 2]. Nevertheless, a direct information flooding may be very inefficient because redundant information is forwarded through the network and the satellite links causing bandwidth, memory, and power consumption.

The paper deals with the mentioned problems by:

- Introducing a Multi Attribute Decision Making (MADM) scheme to select the sink nodes aimed at improving network performance in terms of energy consumption, load, and total time spent by information packets in the network, considering also the fading level measured by earth stations;
- Comparing flooding-based information distribution methods aimed at reducing the number of redundant messages so enhancing the overall performance.

The paper is structured as follows: Section II introduce the considered satellite-based sensor network. The dynamic sink choice methods and the flooding techniques applied within the network are described in Section III and Section IV, respectively; Section V contains the performance evaluation. Section VI lists the conclusions.

II. SATELLITE SENSOR NETWORK ARCHITECTURE

The sink nodes collect all the information sent by sensors and transmit it to a monitoring host remotely located through a geostationary satellite channel. The network infrastructure shown in Fig. 1 and aimed at monitoring a wide geographical area, is composed of sink nodes and of sensor nodes, which compose the sensor field. Each sensor node may be both a traffic source (e.g. measures encapsulated in message packets) and an intermediate node. The paper supposes that a fixed quantity of energy is spent when a packet is transmitted either by a source node or by an intermediate node.

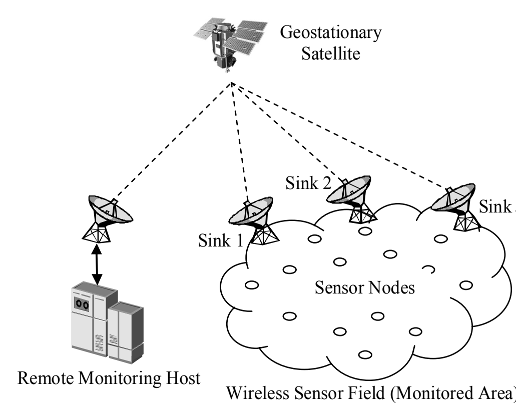

Fig. 1. Satellite Sensor Network Architecture.

1-4244-0355-3/06/$20.00 (c) 2006 IEEE

This full text paper was peer reviewed at the direction of IEEE Communications Society subject matter experts for publication in the IEEE ICC 2006 proceedings.

The satellite channel behaviour, considered in the sink (Section III), is strictly dependent on the fading, which, in this paper, is considered as a mere bandwidth reduction coherently with the state-of-the-art in the field (see [3], for example). 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 β_j, which is a parameter distributed in the real numbers interval [0, 1]. A specific value β_j corresponds to a fixed fading level. A technical interpretation of the quantity β_j may be the bandwidth reduction due to the presence of a FEC (Forward Error Correction) scheme.

III. Dynamic Choice of Sinks

A. *Multi-Attribute Decision Making Algorithms.*

The selection of a sink on the basis of the optimization of a single metric (energy consumption or time spent in the network for example) may be limited. Novel network management techniques should perform decisions representative of a simultaneous trade-off among different metrics. In this direction, the *Multi Attribute Decision Making* (MADM) [4] theory is used in this paper.

Some definitions are necessary: a *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. The index referring to DM is dropped in the following for the sake of simplicity. 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. Four attributes ($K = 4$) are considered in this paper. Their formal definition for each of them changes in dependence of the number of used decision makers because, if one DM is used, the metrics should be representative of the overall network status to go from a generic node to a specific sink, while, if there is a DM for each sensor node, the metrics will represent the network status to go from a peculiar node, where the DM is located, to a specific sinks. The precise definitions are reported in sub-section C. The preliminary introduction reported below should help fix ideas about the used metrics.

- Average Energy Consumption (AEC): it 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 [Joule]. AEC metric is identified as $k = 1$ (e.g. X_{j1} defines the energy to go to j-th sink).
- Delivered Load (DL): it is the packets delivered to the j-th sink per time unit [packets/s]; $k = 2$ (X_{j2}).
- Fading level measured by an earth station (F): it represents the satellite channel status through the factor β_j, as said in section II. j is the sink index; $k = 3$ and $X_{j3} = \beta_j$.
- Average Transfer Time (ATT): it 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 components traversed. $k = 4$ and X_{j4}, if the intermediate earth station to reach the destination remote host is j.

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

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

The problem defined above needs an optimization criterion to be solved. Two different optimization approaches are introduced and applied in this paper: MINMAX and LINear Programming techniques for Multidimensional Analysis of Preferences (LINMAP).

Concerning the former: $j^{opt}(t) = j_{MINMAX}(t)$ and

$$j_{MINMAX}(t) = \left\{ j = \arg\min_{j \in [1,J]} \left[\max_{k \in [1,K]} X_{jk} \right] \right\} \tag{4}$$

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 (5), at each time t, whose components are defined as in (6).

$$A^{id}(t) = \left[X_1^{id}, ..., X_k^{id}, ...X_K^{id}\right] \tag{5}$$

$$X_k^{id} = \left\{ X_{jk} : j = \arg\min_{j \in [1,J]} X_{jk} \right\}, \forall k \in [1, ..., K] \tag{6}$$

The solution of the decision problem is the alternative minimizing the distance, in term of Euclidean Norm, with the ideal alternative: $j^{opt}(t) = j_{LINMAP}(t)$ and

$$j_{LINMAP}(t) = \left\{ j = \arg\min_{j \in [1,J]} \left\| A_j(t) - A^{id}(t) \right\|^2 \right\} \tag{7}$$

This full text paper was peer reviewed at the direction of IEEE Communications Society subject matter experts for publication in the IEEE ICC 2006 proceedings.

B. Probing Procedure of the Decision Method.

To collect the values of the attributes necessary to take the mentioned decisions at the DM, it is possible to use a probing procedure (as in [5]): 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 considered negligible in this paper.

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. That is the motivation because the probing action is not performed continuously but at fixed time instants of period T_D and for limited time length T_P. Decisions periods are reported in Fig. 2 for two consecutive T_D periods.

Some more words are necessary concerning the Decision Makers location. Being each DM a virtual entity, its location not necessarily corresponds with a sink (where the measures are collected) and/or with sensor (where the probing action is generated). It may be also located elsewhere, in a separate machine. It is the motivation because the paper specifies the decision sending action from DM to sensor. Actually, if, in the multiple decision scheme, each DM were located together with each sensor, the sending concept may be dropped because there is no remote communication between DM and sensor but only information transmission between functional entities. But the basic concept is the same. The decisions about the sink choice are taken at fixed instants and, between two consecutive decision instants (e.g. between $(i-1)\cdot T_D + T_p$ and $i \cdot T_D + T_p$, referring to Fig. 2), the messages from a specific sensor will be routed towards the same sink (i.e. the sink decided at $(i-1)\cdot T_D + T_p$, following the example above). Obviously it implies that choices may taken having information not updated coherently with the network status. It highlights the role of the quantities T_P and T_D and the importance of establishing a trade-off between the frequency of the probing action, the length of it and the noise introduced in the network by it. These important points will be the object of future research. For the sake of simplicity, as should be clear from the formal definitions of the metrics, DMs are supposed located by the sinks (one specific in case of single case). For the control scheme proposed here, it allows reducing the amount of exchanged messages.

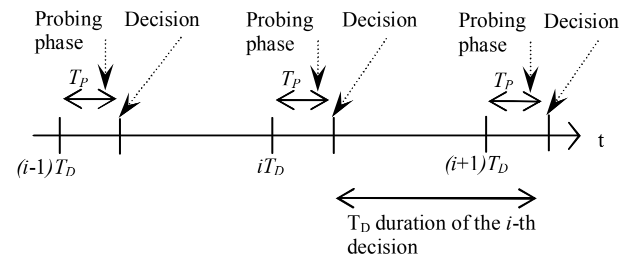

Fig. 2. Decision instants.

C. Decision Modalities.

The sink choice methods (MINMAX and LINMAP) may be implemented both over a *single decision* (S) scheme or over a *multiple decision* (M) scheme. As said in sub-section A., the formal definition of the attributes, specified in detail below, is different in the two cases. The value of each attribute $k \in [1, K]$ is averaged over the maximum value $X_k^{\max}$, defined in (8), to smooth the negative effect of the different scale of each single attribute.

$$X_k^{\max} = \max_j X_{jk}, \ \forall k \in [1, K] \tag{8}$$

- AEC (Average Energy Consumption)

Single Decision

$$X_{j1} = \frac{1}{X_1^{\max}} \cdot \frac{1}{N_j} \cdot \sum_{h=1}^{N_j} e_j^h, \ \forall j \in [1, J] \tag{9}$$

The quantity N_j is the number of total energy measures referred to sink j (i.e. the overall number of probing packets delivered to sink j, independently of the sensor source node) and e_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 Joule for each hop).

Multiple Decision

Having one DM for sensor, n is the identifier both of the DM and of the sensor.

$$X_{j1}^n = \frac{1}{X_1^{\max}} \cdot \frac{1}{N_j^n} \cdot \sum_{h=1}^{N_j^n} e_j^{h,n}, \ \forall j \in [1, J] \tag{10}$$

N_j^n is the number of energy measures (e.g., of probing packets) 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 probing packet originated by the n-th sensor node and delivered to sink j).

- DL (Delivered Load)

The metric is aimed at weighting the overall load of each sink. So, even if it would still make sense to differentiate the measure depending on the origin of the load, it appears more efficient to have just one metric independently of the source sensor node. It means the same metric for the single and multiple decision is used.

$$X_{j2} = \frac{N_j + M_j}{T_P} \tag{11}$$

N_j, as above, is the overall number of probing packets delivered to sink j within the measure 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. Following the fading model presented in Section II:

$$X_{j3} = \frac{1}{X_3^{\max}} \cdot \frac{1}{\beta_j} \tag{12}$$

- ATT (Average Transfer Time)

<u>Single Decision</u>

$$X_{j4} = \frac{1}{X_4^{\max}} \cdot \frac{1}{N_j} \cdot \sum_{h=1}^{N_j} T_j^h, \ \forall j \in [1, J] \tag{13}$$

T_j^h is the overall time spent by the h-th probing packet to go from the source to the destination remote host through sink j.

<u>Multiple Decision</u>

$$X_{j4}^n = \frac{1}{X_4^{\max}} \cdot \frac{1}{N_j^n} \cdot \sum_{h=1}^{N_j^n} T_j^{h,n}, \ \forall j \in [1, J] \tag{14}$$

N_j^n has been defined for AEC. $T_j^{h,n}$ corresponds to T_j^h but is related only to probing packets originated by n-th sensor node.

In both cases, the time measure up to the sink j ($\forall j \in [1, J]$) is really performed. Time to cover the satellite link up to the destination is estimated by using the knowledge of the earth station transmission buffer status and the satellite propagation time.

IV. INFORMATION DISTRIBUTION TECHNIQUES

The method how messages (probing and information) are distributed through the network heavily impacts on the metrics and, as a consequence, on the sink choice. Coherently with the literature [1, 6], information distribution is based on flooding schemes in this paper. They allow robust propagation of packets (both *message* and *probing*) through the sensor network, also considering the high variability of the topology. Four flooding strategies are considered: classical flooding, also termed blind (BF); heuristic flooding (HF); Multipoint Relay (MPR, exhaustively described in [7]); advanced flooding (AF).

Fixing node n, neighbour nodes of it, are defined as the nodes that are reachable via radio from node n.

A. Blind Flooding (BF).

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 redundant power consumption and number of sent packets, caused by the multiple arrival of the same packet neighbour from nodes, also generating possible congestion of satellite links.

B. Heuristic Flooding (HF).

Being BF inefficient, heuristics are proposed to reduce the number of re-broadcasts (e.g., [6] and references therein). Forwarding of received packets is not automatic. It may depend on:

1. Given probability.
2. Number of duplicates below a given threshold.
3. Relative distance among sensors.

The heuristic method considered in this paper is the probabilistic one. A packet is re-transmitted to all neighbour nodes with a fixed probability p_b.

C. Multipoint Relay (MPR) [7].

Nodes collect the list of neighbour nodes reachable through two hops (called two-hops nodes). Received packets are transmitted only to a subset of neighbours that, together, can guarantee the reaching of all two-hops nodes. Obviously being wireless transmitted, the messages reach also the other neighbour nodes but they are not authorized to read and to re-broadcast them, so reducing network load.

D. Advanced Flooding (AF).

It is currently used in industrial applications as control message exchange mechanism for heterogeneous networks. AF allows reducing packet multiple copies because it broadcasts only a portion of the them. Each node keeps an information register related to the cost of arrived packets. The cost used in this paper is the energy spent by a single packet to reach a node, defined as for the metrics. 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.

V. COMPARATIVE PERFORMANCE EVALUATION

- Metrics AEC and ATT (not normalized now) are used to evaluate the performance.

The topology is randomly generated and is kept the same in each test. The duration of the observation network time is

This full text paper was peer reviewed at the direction of IEEE Communications Society subject matter experts for publication in the IEEE ICC 2006 proceedings.

set to 220 [s]. The following parameter values are used: $T_p = 5\,s$, $T_D = 50\,s$. The bandwidth available for nodes (assumed not conflicting each other for now) is 2 Mb/s; the propagation delay between two nodes to 1 ms. The probing packet size is 1500 bytes. The total number of nodes N is 25. The generation of both message and probing packets follows a Poisson probability distribution with average 0.1 packets/s, for each single node. The number J of sinks is set to 4 and the bandwidth available for them is 2 Mb/s. The satellite propagation delay is 260 ms. The satellite channel status is "clear sky" for each earth station in Figures 3 and 4.

Performance evaluation concerns MINMAX and LINMAP associated with each flooding scheme introduced (AF, BF, HF and MPR). Fig. 3 shows AEC in presence of *multiple decision* modality (M in the following figures). The performance of the *single decision* follows the same trend and it is not shown here. Fixed each information distribution method, LINMAP and MINMAX offer equivalent performance. AEC performance heavily depends on the information distribution method. AF performance is very good. Concerning ATT (Fig. 4), the best performance is achieved again with AF because it introduces a lower level of congestion in the network. In this case, also the sink choice procedure has a role and LINMAP offers the best results.

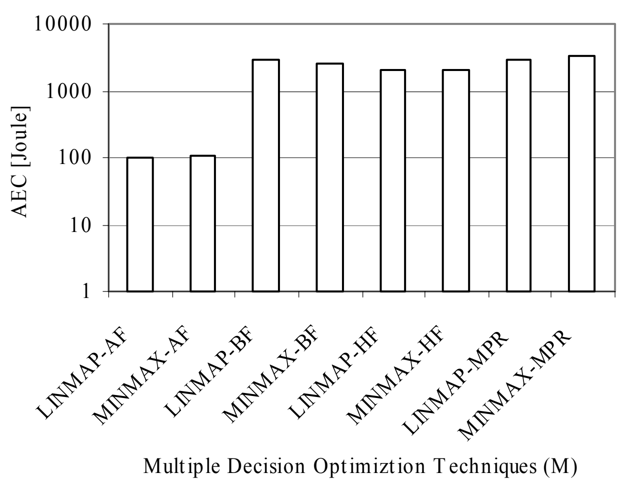

Fig. 3. Average Energy Consumption of Multiple Decision Techniques.

LINMAP-AF-M is now compared with mono-attribute optimization techniques to highlight the advantage offered by the simultaneous minimization of different attributes. In more detail, each metric considered in the MADM approach is used as a single cost function of the problem (3). To carry out a fair comparison, AF distribution method has been implemented also in the mono-attribute cases together with *multiple decision*. Strategies are identified as Metric-M, where "Metric" assumes the following meaning: AEC, DL, F, and ATT, depending on the attribute minimized; "M" stands for multiple decision. Two fading levels are considered: *No fading*, where all sinks are in clear sky and *Deep fading*, where sink 4 is highly faded (the real bandwidth availability is reduced to the 15% of the nominal value) and the other sinks are in clear sky.

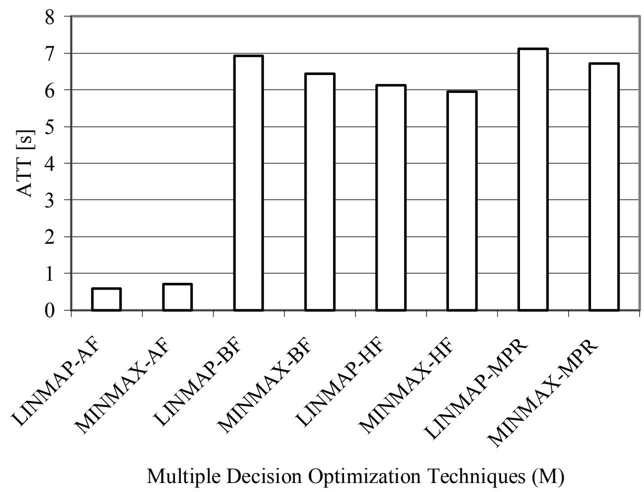

Fig. 4. Average Transfer Time of Multiple Decision Techniques.

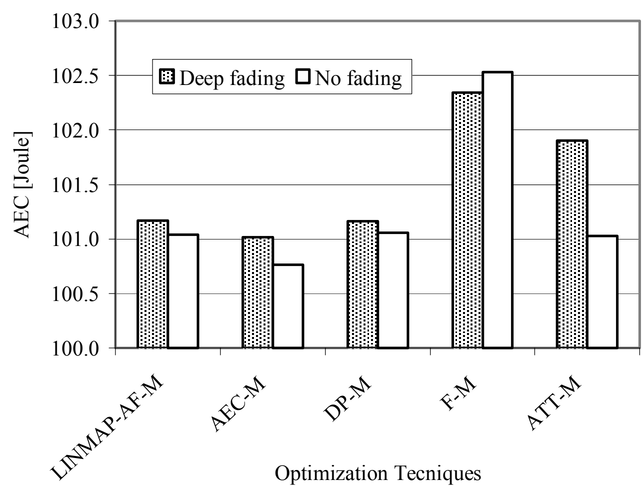

Fig. 5. Multiple Attribute versus Mono Attribute Techniques (AEC).

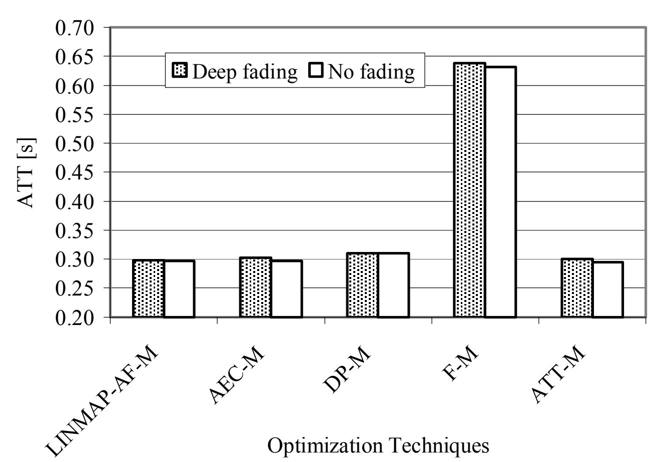

Fig. 6. Multiple Attribute versus Mono Attribute Techniques (ATT).

This full text paper was peer reviewed at the direction of IEEE Communications Society subject matter experts for publication in the IEEE ICC 2006 proceedings.

Fig. 5 shows AEC: LINMAP-AF-M technique has performance close to AEC-M, where just and only the average energy consumption is minimized and that is a very good result. When the other attributes are minimized the AEC values are higher, in particular for "deep fading" tests.

Concerning ATT (Fig. 6), the performance of LINMAP-AF-M is, in practice, the same of ATT-M, which minimizes just ATT ignoring the other attributes, as clear by the performance of ATT-M for "Deep fading", in Fig. 6.

VI. CONCLUSIONS

The paper introduces an architecture for satellite-based sensor networks and control mechanisms for the sink choice associated with flooding-based techniques used to propagate information through the network. The proposals are compared in terms of energy consumption and average time spent in the sensor network by packets.

REFERENCES

[1] 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.

[2] http://www.argo.ucsd.edu/index.html.

[3] N. Celandroni, F. Davoli and E. Ferro, "Static and Dynamic Resource Allocation in a Multiservice Satellite Network with Fading," *International Journal of Satellite Communications*, vol. 21, no. 4-5, July-October 2003, pp. 469-488.

[4] R.L. Keeney, H. Raiffa, "Decisions with Multiple Objectives: Preferences and Value Trade-offs," Wiley, New York, 1976. Reprinted, Cambridge University Press, 1993.

[5] P. Key, L. Massoulié, "Probing Strategies for Distributed Admission Control in Large and Small Scale Systems," In Proc. *IEEE Conference on Computer Communications*, San Francisco, California, USA, March 2003, pp. 608 – 618.

[6] Y. Yi, M. Gerla, T. J. Kwon, "Efficient Flooding in ad hoc Networks: A Comparative Performance Study," *IEEE International Conference on Communications*, Anchorage, Alaska, USA, May 2003, pp. 1059 – 1063.

[7] A. Qayyum, L. Viennot and A. Laouiti, "Multipoint Relaying: An Efficient Technique for Flooding in Mobile Wireless Networks," INRIA, *report no. 3898*, March 2000.

This full text paper was peer reviewed at the direction of IEEE Communications Society subject matter experts for publication in the IEEE ICC 2006 proceedings.