Efficient Satellite-Based Sensor Networks for Information Retrieval

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***Abstract*—This paper considers a packet-based telecommunication network architecture suited to be used as an Environmental Monitoring System (EMS) over wide areas. It can be employed to retrieve the measures of physical quantities, such as temperature, humidity, and vibrations intensity (physical information) together with the geographical position where the measures are taken (position information). The telecommunication network supporting the EMS is composed of: a network of sensors, a group of earth stations called Sinks, a satellite backbone, and a destination. Each sensor collects physical and position information, encapsulates it into packets and conveys it towards the sinks which give access to the satellite backbone that connects the sinks to the destination. A single sensor transmits the information to all sinks but only one sink transmits it over the satellite channel. Even if the redundant transmission of the same data from more than one sink would increase the safety of the system, it would increase also the costs of it. The selection of the sink which forwards the information of a sensor to the destination is important to increase the performance of the EMS. This paper introduces specific performance metrics to evaluate the functionality of the whole EMS in terms of reliability, reactivity, and spent energy. The reference metrics are packet loss rate, average packet delay, and energy consumption. Then the paper presents an algorithm to select the transmitting sink for each sensor, which is aimed at maximizing the performance in terms of the mentioned metrics. The algorithm is tested through simulation.**

***Index Terms*—Monitoring system, multi-attribute programming, performance evaluation, satellite infrastructures, sensor networks and sink selection.**

I. Introduction

An ENVIRONMENTAL Monitoring System (EMS) employed in military and civil protection environment has three main objectives: 1) to measure physical quantities (temperature, pressure, vibrations) and to reveal possible changes of them; 2) to individuate the position where measures are taken as precisely as possible; 3) to provide the information quickly and reliably where it is needed. Due to the need of transmitting information remotely from possibly isolated areas, the integration of existing terrestrial sensor networks and satellite components is a key issue for systems that allow achieving ubiquitous information exchange at affordable cost [1]. In this view, modern EMSs may be composed of widespread fixed and mobile sensor networks collecting information and of a satellite backbone whose role is to transport the information taken by sensors to a destination Remote Monitoring Host (RMH). In this context, sensors should have the capability to get measures of physical quantities and information about their geographical location; to encapsulate this information within packets; to process data; and to forward messages. The access to the satellite channel is provided through earth stations that gather information from sensors. They are called Sinks for that. An example of EMS supporting telecommunication network is shown in Fig. 1. It is the telecommunication network used as a reference in this paper.

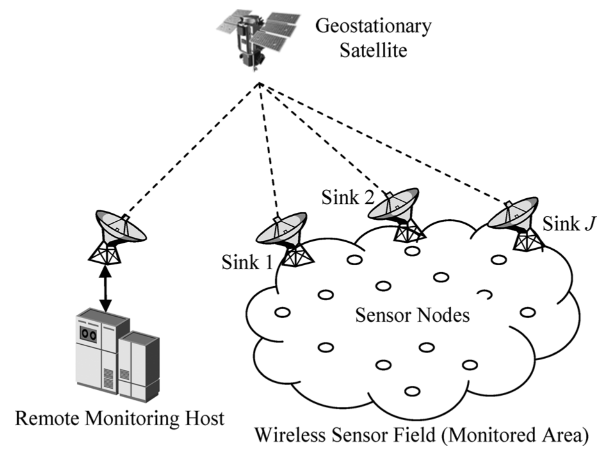

Fig. 1. EMS architecture.

A practical example of the use of the proposed architecture is a modern weather prediction system [2]. It is composed of different sensors, which measure precise quantities (temperature, humidity, wind speed, etc.), establish their position by proper localization techniques (e.g., GPS, Galileo) and transmit the overall information to specific destination by using a satellite network, as shown in Fig. 2. Received data are processed at destinations by special computers that use a weather model to provide fast and precise predictions of the meteorological evolution and of possible emergency conditions.

The need to guarantee the whole system reliability, to limit both the delay to transfer information from sensors to the destination and the energy consumption of the network, so increasing the lifetime of the system, is outstanding in this environment. The problem is that these aims are often in contrast with each other. Increasing the offered bandwidth to limit losses and delays often implies the use of more energy. Also dropping packets and increasing losses may also mean lower end-to-end delays. So there is the need of a formal approach that, after translating the general efficiency needs into objective performance metrics, defines the problem, introduces a choice criterion, and proposes a solution.

Manuscript received February 04, 2008; revised June 12, 2008. First published November 18, 2008; current version published December 31, 2008.

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Digital Object Identifier 10.1109/JSYST.2008.2004850

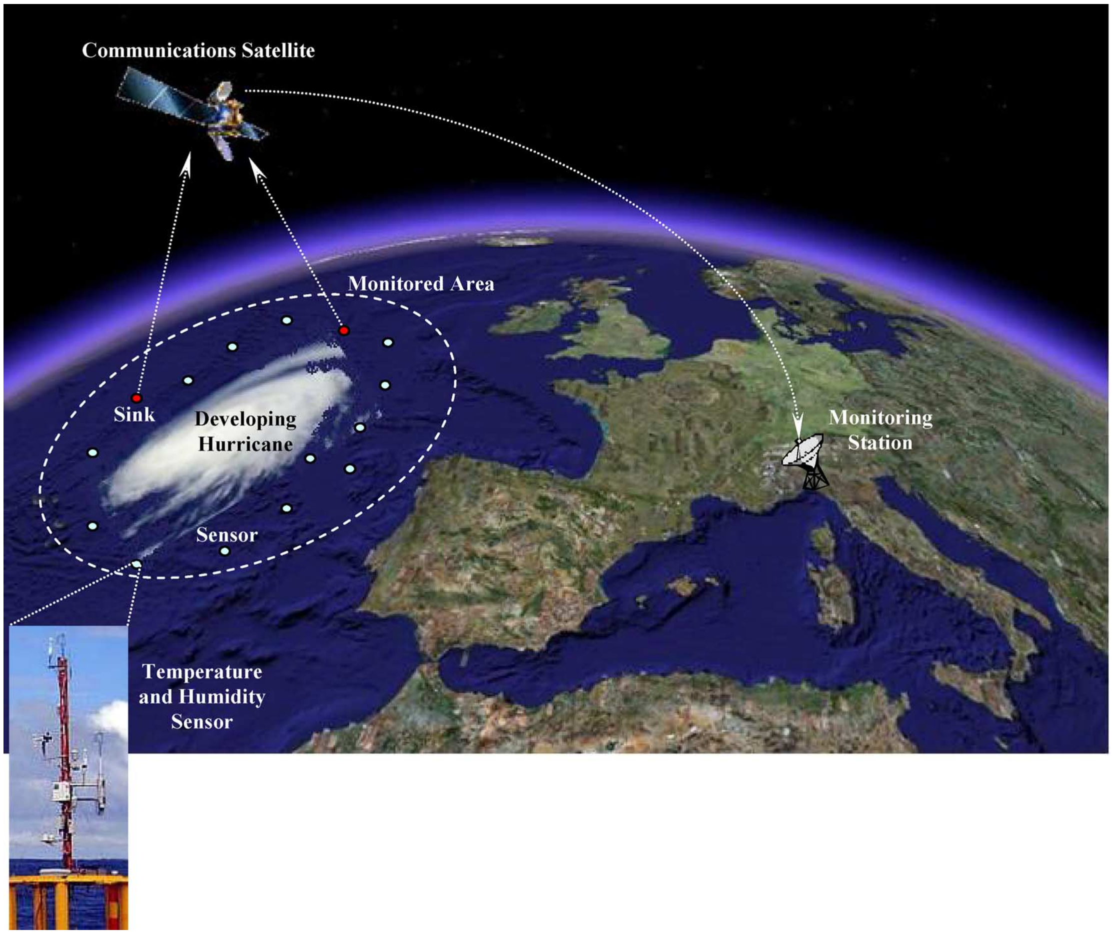

Fig. 2. Example of EMS for weather prediction.

The assumption of this paper is that all sensors directly communicate with and send information to all sinks, but only one of them is selected to forward the information coming from a given sensor to the destination. The problem is to select the best sink for each single sensor so to approach an ideal situation in terms of a given set of metrics possibly contrasting with each other. The multi-attribute decision making theory [9] gives a great help for this.

In short, this paper:

- introduces the reference telecommunication network (Section II);
- defines the following metrics: loss rate, average packet delay, and energy consumption; formalizes the dynamic sink selection problem within the framework of the Multi-Attribute Decision Making (MADM) theory, which is briefly summarized; and proposes a selection solution for the simultaneous optimization of the given set of metrics (Section III);
- presents the performance evaluation through simulations (Section IV) and the conclusions (Section V).

II. Environmental Monitoring System

A. Network Functionalities

As previously said, the main aim of a distributed-sensor-based EMS is to measure physical quantities and to reveal possible changes of them [5]. This operation is called *Sensing*. In general, *Sensing* represents the ability to take inputs from the external world through proper devices and perform the translation of these inputs into electrical signals, which can be remotely transferred through a telecommunication network. Electrical signals are often digitalized and encapsulated into packets by using analogue-digital converter circuits and appropriate interfaces.

Typical environmental applications are habitat monitoring, precision agriculture, climate control, surveillance, and intelligent alarms. The aim of the EMS is more complex in these cases. It is necessary to define a high spatiotemporal resolution data collection in the monitored areas aimed at building accurate predictive models, as reported in [2], and at controlling complex systems in real time.

To increase the capability of the overall monitoring system, the operation of Sensing a quantity can be joined with the power of individuating the position where the quantity is measured. The operation is called *Positioning* and allows associating each measure with a geographical map [6]. It can be very important to provide specific services.

The Global Positioning System (GPS) may solve the *positioning* problem, when a GPS receiver is installed in each sensor. Actually, in several cases, GPS may not be used: the *Positioning* service is available if at least four satellites of the GPS constellation are simultaneously visible. In the case of indoor, under foliage, and obscured by buildings networks, GPS-based *Positioning* services may be compromised but other possible methodologies [6] may be used without affecting the general EMS architecture. An example of the *Positioning* approach may be the Collaborative Multi-Lateration (CM) Method [7], which consists of a set of mechanisms that enable the collaboration between nodes located several hops away from the designed beacon nodes, whose position is known *a priori*. This collaboration allows estimating the nodes location with accuracy. CM may be implemented both centralized and distributed. The latter has the advantage to distribute the computation cost among the network nodes but requires more complex hardware for sensors. Implementations are based on the internode physical distances, which are periodically measured by using ad hoc transmissions between beacon nodes and sensors and between sensors: the systems employed for measuring the internode distances are based either on ultrasonic devices or on the Received Signal Strength Indication (RSSI) approach, which is a measure of the received radio signal strength.

Sensing [2] and *Positioning* [7] operations are not the object of this work, which is focused on the structure and on the management of the telecommunication network aimed at guaranteeing the reliable and efficient delivery of *Positioning* and *Sensing* data independently of the techniques employed to get them. *Positioning* and *Sensing* information is supposed already measured, digitalized, and encapsulated into the packets that are the minimum data unit considered in this paper to analyze performances.

Network Management is strictly related with the third important EMS functionality: to provide the information quickly and reliably where it is needed. It mainly depends on the specific network characteristics and involves solutions for resource reservation, call admission control, traffic control, traffic shaping, scheduling, queue management, buffer management, flow control, power control, routing, and planning. The attention, in this paper, is focused on the optimal Sink Selection.

B. Requirements for EMS Telecommunication Networks

Applying the general performance requirements of a sensor network, which are contained in the survey [8], to the EMS environment considered in this paper, it is possible to structure what is expected from a telecommunication network supporting EMS into four performance macro areas. It is the first step towards the formal definition of objective performance metrics.

1) Information Loss: The importance of the Information Loss for EMSs is clear, for example, in the weather prediction system previously described (Fig. 2 and [2]). A limited Information Loss allows obtaining precise prediction of the meteorological condition. It is really useful in emergency situations for military and civil protection applications.

From the technical viewpoint, being wireless and possibly small, sensors and sinks may run out of energy or simply be damaged. It implies the loss of information. The problem is emphasized if the telecommunication network includes a satellite portion, as supposed in this paper, because of the particular nature of the satellite channel. Communication noise, rain fading, and transmission failures compromise the reliability of the whole system because may reduce the transmission capability of the satellite components and introduce information loss. The satellite portion of the telecommunication network is a very important component of the whole architecture because it is the connection element between the sensor field (where sensors are deployed) and the remote monitoring host (RMH). In consequence it is important that the robustness of the sink selection algorithm against fading, noise, and component failure is considered during the design phase. It means that the loss of information (i.e., the packet loss) needs to be measured by applying the sink selection scheme in different channel conditions so to check the algorithm tolerance to channel and element faults.

2) End-to-End Delay: The importance of small end-to-end delay for EMSs may be seen also in the weather prediction system of Fig. 2 (similarly to the case of the Information Loss), where a small delay may guarantee a more precise weather prediction because updated data reduce the computation errors of the prediction system. As well as for limited losses, small delays importance is outstanding in special cases such as emergency situations for military and civil protection applications.

Technically, end-to-end delay is a traditional metric for quality-of-service (QoS)-based networks. It comes from multimedia applications but may be useful also for EMS networks where applications require that message packets spend a limited time to go from the source sensor node to the destination RMH. End-to-end delay is composed of the propagation delay, both through the sensor network and the satellite link, and of the service and waiting time in each traversed network component.

Also in this case, as well as for the information loss, the peculiar features of the wireless and satellite communication (fading, noise, faults) have a great impact on this metric. The robustness of the sink selection concerning this metric against channel faults needs to be attentively considered. In more detail, the end-to-end delay may increase in consequence of fading countermeasures. Actually, when the satellite channel is corrupted by fading and noise, the trend is to protect the information with redundant bits by following a given forward error correction (FEC) code. Increasing the FEC correction power (i.e., the number of redundant bits) can help make negligible the errors due to fading, but reduces the available bandwidth (the packet service rate) and increases the time necessary to transmit the information to the RMH.

3) Lifetime: In sensor networks, nodes have a limited amount of energy provided by batteries. The replacement of batteries is usually not practicable when the energy limit is reached so any action and algorithm operating on a sensor network should consider that sensors must operate as long as possible. Considering again the EMS example in Fig. 2, all sensor nodes are deployed in the ocean. In this case, the replacement is not effectively practicable. Energy saving is essential.

The concept of lifetime, which, in this case, is the time when a network, or a sensor, is operative, is strictly related to the energy spent by sensors. Energy consumption is related only to communication components in this paper. A possible metric is the average quantity of energy spent to propagate each single packet from the source to the destination. It includes both the wireless sensor network and the satellite backbone. The sink selection

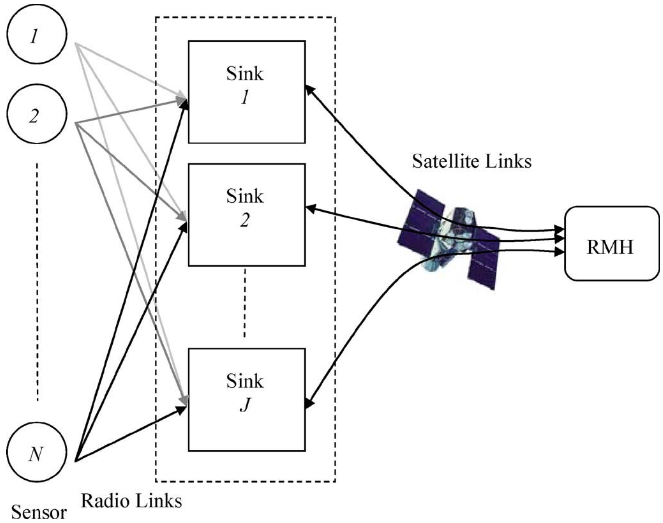

Fig. 3. EMS SSN.

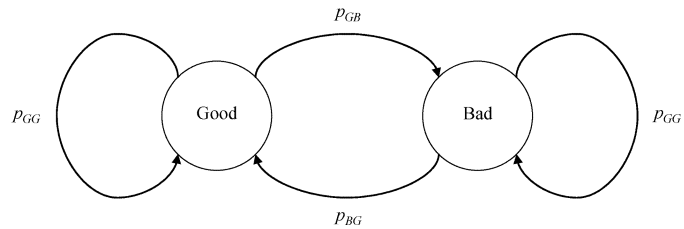

Fig. 4. Gilbert–Elliot two-state Markov chain.

scheme must consider also the energy as a metric, together with loss and delay.

4) Scalability: Due to the large number of sensor nodes included within a SSN EMS, the complexity of employed algorithms, protocols, and solutions, should be independent of the number of network nodes.

C. Network Structure

The network infrastructure considered in this work is shown in Fig. 3. It is identified as satellite-based sensor network (SSN) in the reminder of this paper. The set of satellite earth stations (called Sinks) is composed of J stations. N sensors are directly connected to all J sinks through wireless channels. Sinks communicate with the destination RMH through satellite links. The wireless terrestrial portion of the network has been supposed error free in the performed simulations. Each sink is modeled through a buffer of given dimension. Data packet contained in the buffer access the satellite channel by a server.

D. Satellite Channel Model

The model used for wireless and satellite channels does not impact on the sink selection algorithm which is only based on measures. Nevertheless, to define a reference environment and, in particular, to simulate it and allow the reproduction of results, it is important to model the behavior of the satellite channel.

The satellite channel model used in the simulations of this paper is based on the Gilbert–Elliot model [3], which is a bit level one, extended to packet level here coherently with [4]. It is quite simple. More complex alternatives for satellite and, more generally, for radio channels can be found in the literature, but it is worth noting that the Gilbert–Elliot model does not limit the validity of the proposed sink selection algorithm being responsive to channel errors both due to noise and fading.

The Gilbert–Elliot model follows the evolution of a two-states Discrete Time Markov Chain (DTMC). One state is identified as "Good" ("G"). The bit error probability $p^G_{\rm err}$ of the "Good" state may be considered negligible. It typically ranges from 0 to 10^{-9}. This channel condition is called quasi error free condition in the performance evaluation section of this paper. The other state is identified as "Bad" ("B"). The satellite channel experiences a significant bit error probability $p^B_{\rm err}$ (e.g., typically ranging from 10^{-3} to 1) in "Bad" state. This channel condition is called error prone in the remainder of the paper. The Gilbert–Elliot two-states DTMC is shown in Fig. 4. The probability to stay in the Good state is p_{GG}, while the probability to change the state from Good to Bad is p_{GB} ($p_{GB} = 1 - p_{GG}$). The probability to stay in the Bad state is p_{BB} and the probability to go from Bad to Good is p_{BG} ($p_{BG} = 1 - p_{BB}$). The channel is slotted and each slot contains one packet. Each state change can happen at the beginning of each slot. Slot duration is constant and set to T_s. Given the transition probabilities, the average permanence times in the Good and Bad states are stochastic variable exponentially distributed. The average permanence time is T_s/p_{GB}, for the Good state and T_s/p_{BG}, for the Bad state. The Appendix contains detailed computations. To perform the mapping operation from the Gilbert–Elliot bit level model to the packet level model, the bit error probabilities of Good and Bad states have been used to compute the packet loss probabilities in the same states. Taking one single bit, the probability that it is incorrect is $p^G_{\rm err}$, in the Good state, and $p^B_{\rm err}$, in the Bad state. The probability that an entire packet is incorrect is $p^G_{\rm loss} = 1 - (1 - p^G_{\rm err})^l$, in the Good state, and $p^B_{\rm loss} = 1 - (1 - p^B_{\rm err})^l$, in the Bad one. l is the packet length in bit and it is supposed fixed for each packet.

III. Dynamic Sink Selection Algorithm

A. Sink Selection Criterion

Fig. 3 is the reference. All sinks receive the information but only one of them must be selected to forward the information coming from a specific sensor. The selection is based on the simultaneous optimization of a set of metrics possibly contrasting with each other. The choice of a sink on the basis of the optimization of a single metric (e.g., either energy consumption or delay or loss) may bring to practical unsatisfying results. For example, if only the Information Loss is optimized and a specific earth station experiences deep fading and "sees" a severely corrupted satellite channel, all packets will be directed to and queued in the other sinks so increasing the traffic load and, as a consequence, the time needed to traverse the sinks' buffers and the overall end-to-end delay. Novel *Network Management* techniques should perform decisions representative of a simultaneous tradeoff among different metrics. In this direction, the MADM [9] theory is of great help. It is used in this paper, as well as in [10], where the basic theory of the sink selection process has been introduced.

Fixed the general idea, the practical approach is to minimize the performance vector composed of the distance between a set of measured metrics, called attributes, and the corresponding references where the metrics assume an ideal minimum value not reachable in practice. The choice is performed for each packet when it arrives at sinks on the basis of a decision taken by virtual entities, called decision makers (DMs).

DMs are supposed located at the destination but physical location may change without affecting the algorithm. The number of DMs corresponds to the number of sensors N. $DM^{(n)}$ is the decision maker for the nth sensor. It takes decisions at fixed instants $t_{D,h}^{(n)}, n \in [1,N], h \in \mathbb{N}$. $T_{D,h}^{(n)} = \left[t_{D,h+1}^{(n)} - t_{D,h}^{(n)}\right], n \in [1,N], h \in \mathbb{N}$ is the length of the hth decision period for sensor n. It is kept fixed $\forall h, \forall n$, in this paper. After taking the decision, DMs transmit it to sinks which apply the decided strategy. The strategy is kept the same for the overall length of the decision periods $T_{D,h}^{(n)}, n \in [1,N], h \in \mathbb{N}$.

The attributes composing the set may be in contrast with each other, so the selection algorithm is based on the MADM [9]. Formally speaking: the index $k \in [1,K]$ identifies the attribute; $j \in [1,J]$ identifies each sink within the available set. There is one decision matrix for each $DM^{(n)}$. $X_{jk}^{n}(t)$ is the value of the kth attribute measured at time t for the nth sensor when the jth sink is chosen. For $DM^{(n)}, \forall n \in [1,N]$, the vector containing the attributes related to the jth alternative, at time t, is

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

The attribute matrix $J \times K$ for $DM^{(n)}$ at time t, for all possible J choices, is

$$\mathbf{A}^n(t) = \begin{bmatrix} X_{11}^n, \ldots, X_{1k}^n, \ldots, X_{1K}^n \\ \cdots\cdots\cdots\cdots \\ X_{j1}^n, \ldots, X_{jk}^n, \ldots, X_{jK}^n \\ \cdots\cdots\cdots\cdots \\ X_{J1}^n, \ldots, X_{Jk}^n, \ldots, X_{JK}^n \end{bmatrix}. \quad (2)$$

The selection algorithm is based on the knowledge of the ideal reference, called utopia point, characterized by the ideal vector of attributes ${}^{id}A^n(t)$, defined in (3), at time t

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

Each component of the vector is

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

In practice, ${}^{id}A^n(t)$ is a utopia vector selecting the best (minimum) value for each single attribute among all alternatives. In other words, it is the minimum value in the rows fixing the column in matrix (2).

Among the J alternatives, the sink selection algorithm chooses the sink called $j_{\mathrm{opt}}^n(t)$ which minimizes the distance, in term of Euclidean Norm, with the ideal alternative

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

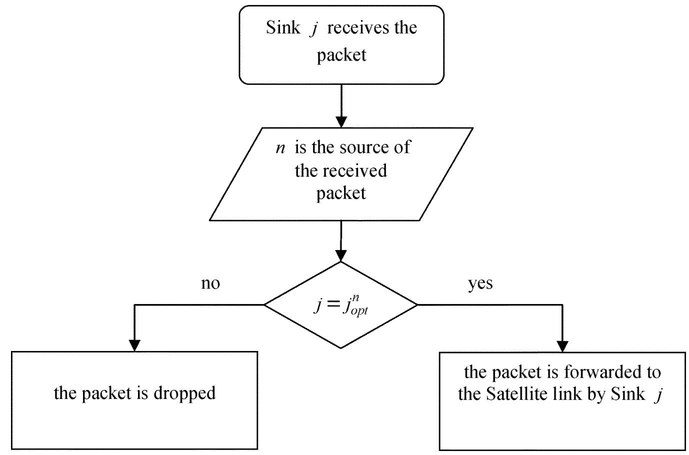

Fig. 5. Algorithm used after a DMs' decision.

The minimization criterion reported in (5) is called linear programming technique for multidimensional analysis of preferences [9] (LINMAP) and is applied dynamically in this paper (from here the used acronym DLINMAP). It allows getting the selection vector (SV) in (6)

$$SV(t) = \left[j_{\mathrm{opt}}^1(t), \ldots, j_{\mathrm{opt}}^n(t), \ldots, j_{\mathrm{opt}}^N(t)\right]. \quad (6)$$

From the operative viewpoint, after performing the computation in (5) at time $t = \left\{t_{D,h}^{(n)}, h \in \mathbb{N}\right\}$, the generic $DM^{(n)}$ communicates the decisions to each sink. For example, it can transmit the vector $SV(t)$ from which each sink can read the source sensor whose information must be forwarded or not. The source sensor is recognized in each sink by using a specific field in the packet header. Considering the jth sink, the algorithm works as reported in the flow chart in Fig. 5, for the period of time when $SV(t)$ is valid.

The computation of the attributes for the decision is a topical point. It constitutes the theoretical novelty of this paper with respect to [10], where the sink selection method has been introduced. The sink selection approach, based on MADM theory, has been defined in [10] together with a simple method to compute the metrics, which was not the focus of the paper. This paper concentrates on the metrics computation through the introduction of specific control fields in the packets' headers which allow a computation method really applicable in the field and feasible measures of the attributes. Attribute computation will be explained in Section III-C. The metric measures are taken at the RMH, where also the DMs are located for the sake of simplicity, so to fill the matrix (2) and the vector (3). Attribute values are collected through periodic measure phases $T_{M,h}^{(n)}, n \in [1,N], h \in \mathbb{N}$ for each sensor during which the packets coming from sensor n are forwarded through all J sinks. In short, during the measure phase for sensor n, the algorithm reported in Fig. 6 is applied for each sink j.

Time relation between measure phases and decision instants is shown in Fig. 7.

Measure phases are kept separate for each single sensor n. This is a design choice. Measure phases for different sensors may be also overlapped, paying attention to limit the interference with regular traffic, which is introduced by the algorithm

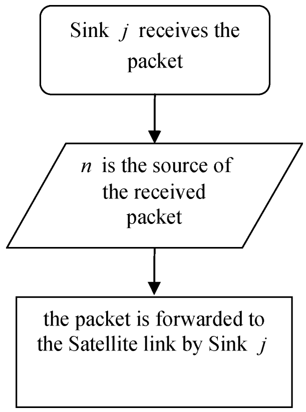

Fig. 6. Algorithm applied during the measure phase.

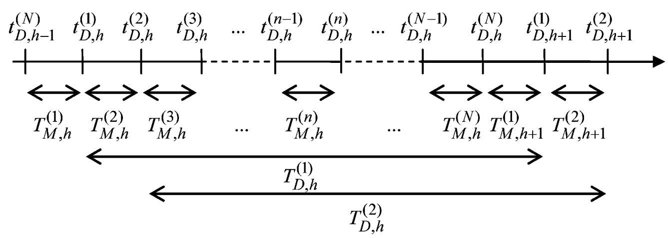

Fig. 7. Decision instants.

described in Fig. 6. Consecutive measures for single sensors followed by related decisions, as in Fig. 7, guarantees to limit the traffic interference during measure phases to a minimum. The drawback may be the length of the period $T_{D,h}^{(n)}, n \in [1, N]$, where the decision taken in $t_{D,h}^{(n)}$ is valid. It may impact on the algorithm reaction to sudden traffic changes. On the other hand, single $T_{M,h}^{(n)}$ must be long enough to assume reliable measures. Tradeoff between measure reliability and fast reaction to traffic changes will be the object of future performance evaluation.

B. Attribute Definitions

Even if the formal approach presented above is not linked to a specific choice of attributes, the set of selected metrics for this paper, as introduced previously, is as follows.

- Packet loss rate (PLR), which is the ratio between lost and sent packets in the nth node. $PLR_j^{(n)}(t)$ is the value of this attribute, valid at time t, for sensor n, having chosen sink j. In short, $PLR_j^{(n)}(t) = X_{j1}^{(n)}$. This attribute is a measure, for the nth node, of the aforementioned information loss quality index.
- Average packet delay (APD), which is the average time that a packet needs to go from the source sensor to the RMH at destination. Similarly, as done for the previous case, $APD_j^{(n)}(t) = X_{j2}^{(n)}$. In this case, the attribute is aimed at measuring the end-to-end delay performance index.
- Energy consumption (EC), which is the energy spent by sinks to propagate the packets from the source to the destination when the network works. $EC_j^{(n)}(t) = X_{j3}^{(n)}$. Broadcasting for each hop is assumed to use 1 mJ. The attribute is the measure of the aforementioned global quality index concerning lifetime. It is worth noting that this attribute is not specifically related to the nth node but it is strictly linked to the employed sink. In the network in Fig. 3, only the satellite backbone has been considered for the energy issue because the energy spent by the source nodes is the same independently of the used sink. EC of each single sink has been simultaneously minimized and, as side effect, the equalization of the energy spent by sinks has been reached. For this motivation, also the standard deviation of the EC (EC Std. Dev.) among the sinks is shown in the results. It allows showing the balance of EC among the sinks and, in consequence, having an idea of the lifetime of the sinks and of the entire network. A big unbalance of EC among the sinks would imply a shorter lifetime for some of them so reducing the topology of the network over time.

C. Attribute Computations

From the practical viewpoint, the following information must be contained in the generic ith packet header to allow the collection of measures: *Source Identifier* (identified by the index n); *Sink Identifier* (j), which is a field filled by the sink itself when employed; *Sequence Number* (${}^i\sigma_j^{(n)}$) and *Time Stamp* (${}^i\tau_j^{(n)}$), both set by sources to measure PLR and APD, respectively; *Energy* ${}^i\varepsilon_j$, independent of the source node n, which is the number of transmissions for the jth sink and it is used to measure EC. A global clock to align *Time Stamps*, which allows monitoring the temporal evolution of the system t, is supposed available throughout the network. All the information contained in the header except for the *Source Identifier* concerns time functions: sequence number is sequential over time and time stamp is time itself. The defined metrics PLR, APD, and EC are measured as follows. Some definitions are necessary. The set of all received packets from a specific source n through the jth sink within a generic measure interval $T_{M,h}^{(n)}, n \in [1, N], h \in \mathbb{N}$ is

$$\mathrm{N}_j^{(n)} : \big[\text{set of packets sent from the node } n \text{ arrived in } T_{M,h}^{(n)} \text{ through Sink } j.\ n \in [1, N], j \in [1, J]\ h \in \mathbb{N}\big]. \quad (7)$$

Within the set $\mathrm{N}_j^{(n)}$ it is necessary to extract the packets that are really arrived during $T_{M,h}^{(n)}$ and to ignore the packets that are already within the buffer of the sink that had been chosen to forward the packet of the sensor n at the end of the previous measure period $T_{M,h-1}^{(n)}$ for the same sensor. The situation is shown in Fig. 8. Sink 1 is supposed to be the sink selected to forward the packets of sensor n at the instant $t_{D,h-1}^{(n)}$ after the measure phase $T_{M,h-1}^{(n)}$. It means that the packets of the sensor n have been stored in the Sink 1 buffer and forwarded through Sink 1 to the satellite channel for the entire period $T_{D,h-1}^{(n)}$. The striped packets are already in the buffer of Sink 1 when the measure phase $T_{M,h}^{(n)}$ begins. They are the residual packets left in the Sink 1 buffer during $T_{D,h-1}^{(n)}$, which arrive at the destination during $T_{M,h}^{(n)}$ because of the satellite channel delay. They have to be forwarded to the RMH but they do not have to be considered by it for the measure phase $T_{M,h}^{(n)}$. So it is important to find out the first packet in the sets $\mathrm{N}_j^{(n)}, \forall j$, which must be considered at RMH for the measure phase. In short, it is the first packet arrived in any of the sink queues after the beginning of the measure phase $T_{M,h}^{(n)}$. This packet may be individuated through the

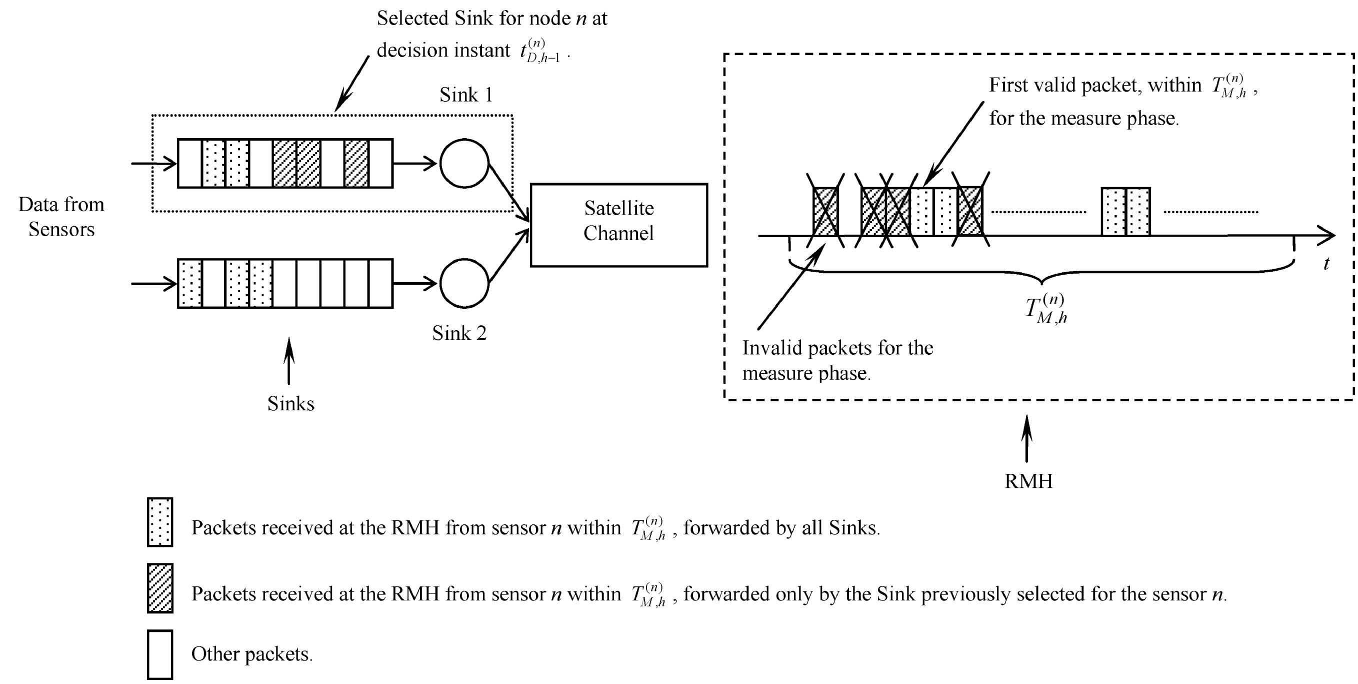

Fig. 8. Packets in sinks during the measure phase.

sequence number ${}^i\sigma_j^{(n)}$ and through the consideration that the packets from sensor n can be only in the buffer of the sink selected in $t_{D,h-1}^{(n)}$ at the beginning of phase $T_{M,h}^{(n)}$. Referring to Fig. 8, it means that the packets of sensor n can be only in the buffer of Sink 1 at the instant $t_{D,h}^{(n-1)}$. Operatively, at the RMH, it is necessary to select the minimum sequence number (the first arrived packet) among all sets $\mathrm{N}_j^{(n)}, \forall j$, ignoring the packets that were already in the buffer (of Sink 1, in Fig. 8) at the beginning of the measure phase, and to consider only the packets with a sequence number higher than the selected minimum.

From the formal viewpoint it means to define the following subset of packets belonging to $\mathrm{N}_j^{(n)}$:

$$\nu_j^{(n)} : \left[\nu_j^{(n)} \subset \mathrm{N}_j^{(n)} : {}^i\sigma_j^{(n)} \geq \cdots \geq \min_{j\in[1,J], j\neq j_{\mathrm{opt}}^{(n)}\left(t_{D,h-1}^{(n)}\right)} \left\{ \min_{i\in \mathrm{N}_j^{(n)}} {}^i\sigma_j^{(n)} \right\} \right]. \quad (8)$$

$\nu_j^{(n)}$ is the set of the packets received at the RMH after the reception of the packet with the minimum *Sequence Number* forwarded through a sink that has not been selected at the previous decision instant related to the nth node. This action solves the possible inconvenience linked to the validity of the received packets within the measure phase: as said before, during the hth measure period for the sensor n ($T_{M,h}^{(n)}$), the buffer of the sink designated by the previous decisional phase, $j_{\mathrm{opt}}^{(n)}\left(t_{D,h-1}^{(n)}\right)$, contains sensor n packets. They are forwarded to the RMH, but their *Sequence Number* is not valid for the current measure phase and would alter it, if considered. An alteration due to the presence of invalid packets during the measure may concern the possible privilege reserved to the previously selected sink $j_{\mathrm{opt}}^{(n)}\left(t_{D,h-1}^{(n)}\right)$: within the set $\mathrm{N}_j^{(n)}$ that contains all received packets from the nth sensor, the number of packets forwarded by the sink $j_{\mathrm{opt}}^{(n)}\left(t_{D,h-1}^{(n)}\right)$ may be larger than the number the packets forwarded by the other sinks, because of the residual presence of traffic conveyed from n into the $j_{\mathrm{opt}}^{(n)}\left(t_{D,h-1}^{(n)}\right)$ queue before the measure phase $T_{M,h}^{(n)}$. It can introduce an underestimation of the packet loss in $T_{M,h}^{(n)}$ and a consequent sink selection mistake.

Fixed the sets of packets that have to be considered in the measure phase for the computation of the attributes, the following quantities need to be also defined

$$\left|\mathrm{N}_j^{(n)}\right| : \text{cardinality of the set } \mathrm{N}_j^{(n)} \quad (9)$$

and

$$\left|\nu_j^{(n)}\right| : \text{cardinality of the set } \nu_j^{(n)}. \quad (10)$$

1) Packet Loss Rate: The PLR, as said in Section III-B, is the metric representative of the Information Loss. It is computed through the *Sequence Number* field of the received packets. $X_{j1}^{(n)}$ is the corresponding attribute computed as in (11)

$$X_{j1}^{(n)} = 1 - \frac{\left|\nu_j^{(n)}\right|}{\delta^{(n)}} \quad (11)$$

where

$$\delta^{(n)} = \max_{j\in[1,J]} \left\{ \max_{i\in \mathrm{N}_j^{(n)}} {}^i\sigma_j^{(n)} \right\} + - \min_{j\in[1,J], j\neq j_{opt}^{(n)}\left(t_{D,h-1}^{(n)}\right)} \left\{ \min_{i\in \mathrm{N}_j^{(n)}} {}^i\sigma_j^{(n)} \right\}. \quad (12)$$

$\delta^{(n)}$ is the number of generated packets by the nth sensor in the measure phase $T_{M,h}^{(n)}$. It is computed as the difference between the highest and the lowest *Sequence Number* received by RMH among the packets that belong to $\nu_j^{(n)}$. Equation (11) corresponds to the PLR because the ratio $\left|\nu_j^{(n)}\right|/\delta^{(n)}$ is the probability of the correct reception of a sent packet. Being the packet loss the only alternative event to the correct reception, (11) is the Packet Loss probability. The computation method for this metric has been chosen because the only information available is the number of received packets.

2) Average Packet Delay: The attribute related to the end-to-end delay is the average packet delay. It is computed by using the *Timestamp* field through (13).

$$X_{j2}^{(n)} = \frac{1}{\left|\nu_j^{(n)}\right|} \cdot \sum_{i \in \nu_j^{(n)}} \left({}^i t_j^{(n)} - {}^i \tau_j^{(n)}\right). \qquad (13)$$

${}^i t_j^{(n)}$ is the reception instant at the RMH of the ith packet sent from node n through the Sink j. Also, in this case, the reference set of packets is $\nu_j^{(n)}$.

3) Energy Consumption: The attribute related to the lifetime of the SSN is the Energy Consumption. It is computed by considering the specific *Energy* field of the received packets as

$$X_{j3}^{(n)} = \max_{i \in \nu_j^{(n)}} {}^i \varepsilon_j^{(n)}. \qquad (14)$$

In practice, among the received packets in the set $\nu_j^{(n)}$, being the energy field increasing over time, the highest energy consumption has been considered for the computation of this attribute.

D. Computational Complexity

Algorithms computation complexity is always a topical point to be evaluated because the real employment of algorithms often depends on it. It impacts on the time needed to compute the solution of a given problem and depends on the dimension of the data structures (vectors and matrixes) used to implement algorithms.

Concerning the Sink Selection scheme in this paper: the final step of the Sink Selection process is implemented by (5) whose elements are the components of the Utopia Vector defined in (3) and (4) and, as said in Section III-A, each component of the Utopia Vector is the minimum value in the rows fixing the column in matrix (2). In practice, it is computed through three simple "*for*" loops. The first loop (the most internal one) is used to run along each row of the matrix (2) and acts over the variable j (for $j = 1$ to J). It selects the ideal value for a specific attribute k. The second loop is used to change the column in matrix (2) so fixing a specific attribute. It acts on the variable k (for $k = 1$ to K). The last loop (the most external one) is used to compose the Utopia Vector for each sensor node and acts on the variable n (for $n = 1$ to N). In pseudo code, the mentioned "*for*" loops are so nested

```
for n = 1 to N {
    for k = 1 to K [
        for n = 1 to N (
        )
    ]
}.
```

Employed attribute matrixes have size $J \times K$. K is the number of attributes and J is the number of sinks. Both quantities have necessarily limited size. Size $J \times K$ should be small. The critical quantity for the computational complexity of the sink selection algorithm is the number of sensor nodes N whose size may be very large. Its order of magnitude may be twice or more the order of magnitude of J and K. While J and K may range between 1 and 10, N may be 100, 1000, and more.

More formally, the computational complexity of the proposed Sink Selection procedure is $O(J \times K \times N)$. Considering the different order of magnitude between the quantities J, K and N, $O(J \times K \times N)$ may be approximated through $O(N)$. Complexity linearly grows with the number of sensor nodes of the SSN. It makes the proposed solution tractable from the computation viewpoint and possibly feasible with the time dynamics of the whole system. Even if the complexity linearly growing with N is quite reassuring for the real applicability of the schemes, real measures need to be taken before going towards a prototype. It will be object of future research.

IV. Performance Evaluation

A. Parameters Setting

The metrics evaluated, through an *ad hoc* event driven simulator, are: 1) PLR; 2) APD; 3) EC expressed in millijoules; and 4) EC Std. Dev. As said in Section III-B, EC Std. Dev. is not the object of the optimization algorithm but its analysis is important to evaluate the lifetime of the overall monitoring system.

The duration of the simulations is 300 s. The network topology is reported in Fig. 3. The bandwidth capacity and the propagation delay between sensors and sinks in the sensor network are 100 Kb/s and 30 μs, respectively. The packet size l is 1000 bit and the buffer size of each sink is 20 packets. The maximum number of sensors N is 20. The average packet generation rate (PGR) of each sensor is 20 packets/s and follows a Poisson probability distribution. There are $J = 4$ sinks (Sink 1, 2, 3, and 4) characterized by an overall satellite channel capacity $C_{\rm sat}$ of 250 Kb/s and by a propagation delay of 260 ms (geostationary environment). The decision period, for each sensor, is 20 s. Each single measure phase lasts 1 s.

The algorithm DLINMAP is compared with two alternatives: "Static" and "Mono Attribute" sink selection. Static distributes the sensor packets among all sinks uniformly. It is completely insensitive to traffic load changes and to satellite and radio channel variations. Mono attribute approaches work exactly as reported in Section III-A, but the optimization criterion is applied to each single attribute. All mono attribute versions have been included in the comparison: mono attribute the optimization of PLR (MA-PLR), of APD (MA-APD) and of EC (MA-EC). Each of them optimizes the sink choice by considering just one of the performance metrics. All techniques are compared in the four channel corruption conditions described in the following Section IV-B and the five network congestion conditions presented in Section IV-C. The results are reported in Sections IV-D and IV-E, respectively.

B. Satellite Channel Corruption

The satellite channel between Sink 4 and RMH is supposed corrupted by noise and fading. The other satellite links and the terrestrial connections are supposed error free. The satellite channel model employed in the simulation is a Gilbert-Elliot Two State Markov Chain described in Section II-B. The following four conditions are simulated.

- *Error Prone*: The satellite channel is always in Bad state ($p_{BB} = 1$) and $p_{\mathrm{err}}^{B} = 10^{-3}$.
- *Slowly Variable Channel*: The satellite channel switches from Bad ($p_{\mathrm{err}}^{B} = 10^{-3}$) to Good state ($p_{\mathrm{err}}^{G} = 10^{-9}$), and vice versa; variations are quite slow: $T_s/p_{GB} = T_s/p_{BG} = 30$ s $p_{GB} = p_{BG} = 0.000133$ and $T_s = l/C_{\mathrm{sat}} = 0.004$ s.
- *Fast Variable Channel*: The satellite channel switches from Bad ($p_{\mathrm{err}}^{B} = 10^{-3}$) to Good state ($p_{\mathrm{err}}^{G} = 10^{-9}$), and vice versa; variations are quite quick: $T_s/p_{GB} = T_s/p_{BG} = 4$ s $p_{GB} = p_{BG} = 0.001$ and being $T_s = l/C_{\mathrm{sat}} = 0.004$ s.
- *Quasi Error Free*: The satellite channel is always in Good state ($p_{GG} = 1$) and $p_{\mathrm{err}}^{G} = 10^{-9}$.

C. Network Congestion

Congestion is forced only in Sink 3, where the capacity available for transmission is reduced, so creating a bottleneck that causes increasing packet loss, due to buffer overflow, or packet delay. The following five conditions have been considered.

- *Regular Congestion Level*: Sink 3 "sees" the same capacity of the other sinks.
- *Low Congestion Level*: Sink 3 is provided with the 75% of the capacity used by the other sinks (187.5 Kb/s).
- *Medium Congestion Level*: Sink 3 has got the 50% of the capacity used by the other sinks (125 Kb/s).
- *High Congestion Level*: Sink 3 uses only the 25% of the capacity used by the other sinks (62.5 Kb/s).
- *Failure Level*: Sink 3 is in failure and has no capacity available. It cannot be used and it is considered failed.

D. Numerical Results Concerning Satellite Channel Corruption

Fig. 9 reports the APD value for DLINMAP, Static, and MA-APD, by varying the channel conditions. The Static method is the best. The result is due to the fair distribution, obtained statically, of the packets among sinks, so reducing the average delay. MA-APD provides also very good results but it has a slightly higher APD than Static because of the overhead packets used during the measure phases necessary to implement both the mono and multi-attribute versions of the proposed optimization control. DLINMAP provides, concerning the delay metric, the worst result. Even if the optimization of a single metric is not the aim of DLINMAP, and the objective numerical value of APD are really low also for DLINMAP, some more comments may help understand the algorithm better. The behavior is due to the reactivity of the DLINMAP approach to channel corruption of Sink 4. The algorithm tends to assign packets to uncorrupted Sinks so increasing their congestion levels and, as a consequence, the APD.

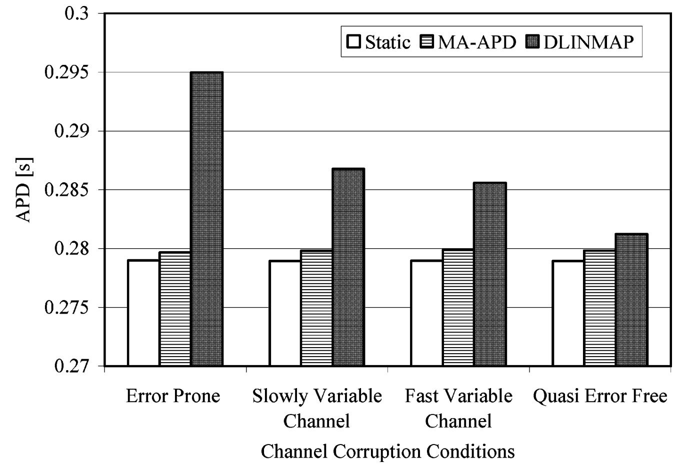

Fig. 9. APD comparison in satellite channel corruption condition.

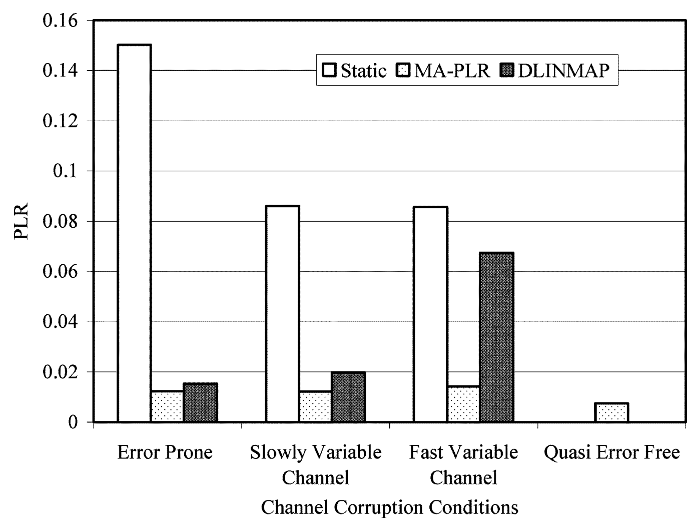

Fig. 10. PLR comparison in satellite channel corruption condition.

The slight drawback in terms of APD, which is of about 15 ms in the worst case (error prone condition of Fig. 9), is fully compensated by the performance for the other metrics.

Fig. 10 shows the performance of the PLR for the same algorithms. Static use implies a significant quantity of lost packets in all the considered Satellite channel conditions except for the *Nearly* error free case. MA-PLR behavior is excellent. DLINMAP offers a very good performance. Two situations, reported in Fig. 10, need to be clarified: the first one concerns the high PLR value measured for DLINMAP in the fast variable channel case and the second one concerns the PLR, which is not zero, obtained by MA-PLR, in the *Nearly* error free condition. The former, is due to the nature of the algorithm: too fast channel variations do not allow the convergence of the DLINMAP control technique to a stable decision. The algorithm continuously switches from one decision to another without reaching convergence. The latter is justified as follows: MA-PLR approach needs to experience packet losses different from zero to react and, as a consequence, it assigns all packets

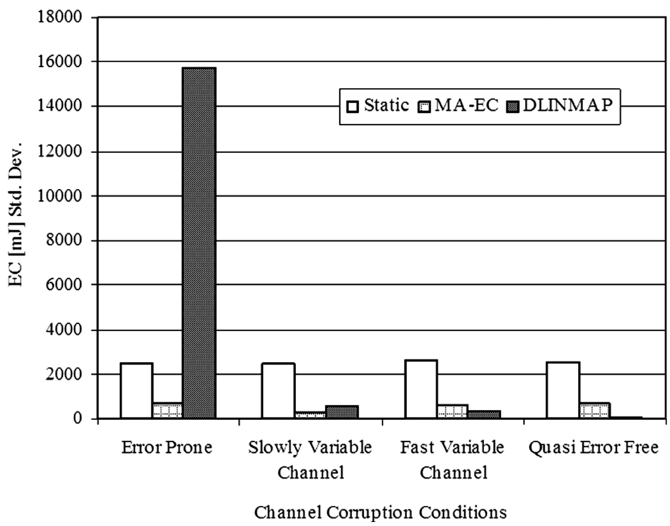

Fig. 11. EC Std. Dev. comparison in satellite channel corruption condition.

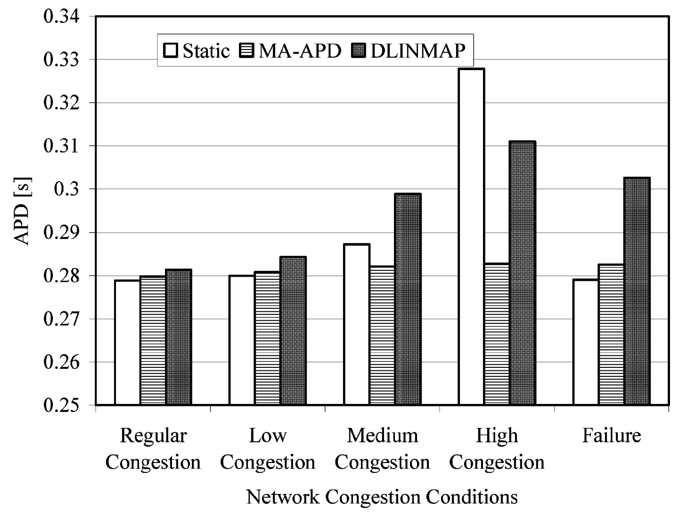

Fig. 12. APD comparison in network congestion condition.

to one sink until some packets are lost, only due to congestion in the *Quasi* error free situation, are measured.

Concerning the energy consumption, Fig. 11 shows the standard deviation of EC metric. This result is aimed at evaluating if the Sink selection method distributes the overall energy consumption among sinks fairly. This may appear as a side effect of the proposed Sink selection method because EC standard deviation is not an attribute but it is a quite direct consequence of the EC metric [in (14)] minimization. Actually, the simultaneous minimization of the EC of each earth station implies the equalization of EC among earth stations. Additionally, it gives clear indication about the overall SSN Lifetime. Large EC Std. Dev. values imply unfair distribution of the energy spent among the sinks (e.g., the earth stations) and, probably, rapid fail of the energetically overloaded ones. Small values of EC Std. Dev. imply fair distribution of the energy and, as a consequence, higher life of the entire network.

Static provides a constant and low value. It is an expected behavior because the method uniformly distributes the packets among the sinks and, as a consequence, also the "energetic load" is distributed in the same way. MA-EC provides the best performance being specifically aimed at optimizing this metric. DLINMAP provides very good performance, similar to MA-EC, except for the Error Prone case where it does not allow forwarding the packets through Sink 4, due to the channel corruption. It increases the EC Std. Dev. In practice, this is the "cost" of the higher reliability (in terms of PLR) of DLINMAP.

Concerning MA-EC two more peculiarities need to be explained: it has, also in the *Quasi* error free situation, EC Std. Dev. which different from zero and, in two cases, it provides higher EC Std. Dev. values than DLINMAP. It is due to the MA-EC assignation that, at the beginning of the tests, allows forwarding packets to just one or two Sinks. The others do not forward any packets. The choice allows obtaining low energy consumption levels because some sinks do not transmit any packet. The problem is that when the sinks originally excluded from the forwarding process are involved, the others stop their transmission. This alternation between subsets of sinks allows minimizing the energy consumption but causes the behavior evidenced above. It does not happen if DLINMAP is employed because, as previously said, it does not consider uniquely the energy attribute, but also different joint metrics.

It is important to evidence the compromise performed by DLINMAP by observing the presented results. Operatively, it allows balancing the performance of all metrics together and getting global satisfactory results for all the evaluated conditions.

E. Numerical Results Concerning Network Congestion

Fig. 12 reports the APD. APD values for Static grow if the congestion level increases. It is due to the insensitivity of the Static method to any metrics. When Sink 3 is in failure, Static provides low APD values because the metric measured at the RMH and, as a consequence, the packets reaching Sink 3 are not counted being lost. MA-APD maintains the APD value constantly around 280 ms. DLINMAP provides growing APD when the level of congestion increases. In the case of Sink 3 failure, DLINMAP does not select the sink in failure, so performing a slightly higher APD. As in previous set of results, it is important to note that, even if a little bit larger the results provided the MA-APD; the APD values provided by DLINMAP are really low from the operative viewpoint.

Fig. 13 reports the PLR. DLINMAP provides very good results always in line with real operative requirements. Its behavior is not so far from MA-PLR's one, also in failure case. Static performance is not compatible with operative requirements in case of high congestion and failure.

The EC Std. Dev. behavior is reported in Fig. 14. EC Std. Dev. has satisfying performance for all the considered techniques in regular, low, and medium congestion: MA-EC obviously has outstanding performance and DLINMAP has satisfactory EC Std. Dev. levels. When the Sink 3 congestion level is High, DLINMAP provides increasing EC Std. Dev. because the sink selection depends on Sink 3 congestion and tends to optimize also delay (APD) and packet loss (PLR). A completely different consideration should be done in case of failure: no packets are forwarded by the sink in failure and, as a consequence, the EC

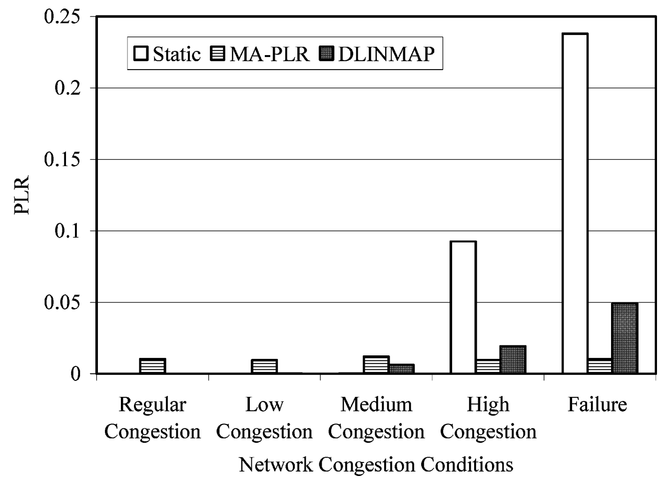

Fig. 13. PLR comparison in network congestion condition.

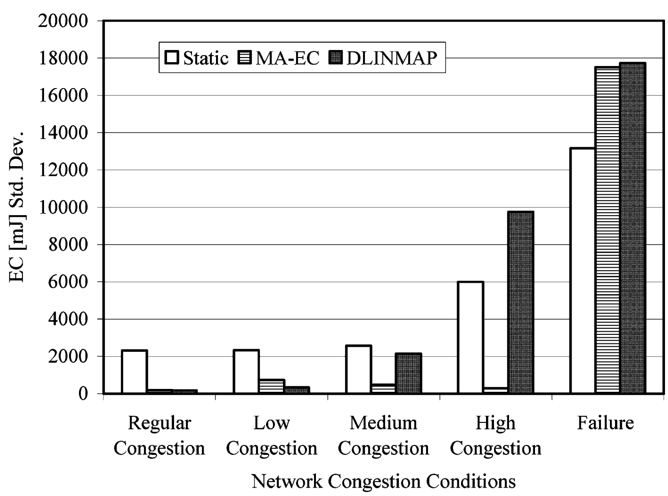

Fig. 14. EC Std. Dev. comparison in network congestion condition.

Std. Dev. computed among all sinks, included Sink 3 in failure which has zero energy consumption, increases. In this specific case, EC Std. Dev. does not give operative information about the energy performance of the considered methods. It is worth noting that if the sink in failure is not considered in the EC Std. Dev. computation, DLINMAP and, of course, MA-EC offer EC Std. Dev. values close to zero because, in practice, a new regular congestion condition is considered.

Static deserves an additional consideration. In all studied cases (see Figs. 9 and 14), in terms of EC Std. Dev. the values reported in the figures are never zero. It is expected value because the packets are distributed uniformly among the sink through a (pseudo) random packet generation process, which is totally convergent. In practice each sink does not receive the same quantity of packets. Again, it is important to evidence that the sink choice performed by DLINMAP is always a good and operative compromise among the need of more than one metric.

V. Conclusion

This paper presents an architecture for satellite-based sensor networks useful to be employed for EMSs, where *Sensing* and *Positioning* information is collected and transmitted.

The choice of sink where the information from sensor is conveyed to the destination RMH is very important in this environment. This paper proposes a group of metrics to evaluate the performance of an EMS and an algorithm for the sink selection, which considers, for the choice, all metrics together. This algorithm is called DLINMAP.

DLINMAP is compared with a static selection and with schemes that are optimized for one single metric. It shows a satisfying behavior. The most important thing to evidence is that DLINMAP, even if provided, for a specific metric, worst results if compared with the schemes which are optimized just for that metric, always gets numerical results compatible with most real applications. It happens both testing the system by corrupting the channel and congesting the buffer of a sink and allows regarding DLINMAP as a promising solution for real system in future.

Appendix

The aim is to compute the average permanence time in Good and Bad states having the two-state Markov chain in Fig. 4 as a reference. Concerning Good state: the probability that the permanence time is T_s is $(1-p_{GG})$, that the permanence time is $2\cdot T_s$ is $p_{GG}\cdot(1-p_{GG})$, that is $3\cdot T_s$ is ${p_{GG}}^2\cdot(1-p_{GG})$, and so on. The average permanence time in Good state $\overline{T}_G$ is given by (A.1)

$$\overline{T}_G=\sum_{n=1}^{\infty} n\cdot T_S\cdot {p_{GG}}^{n-1}\cdot(1-p_{GG}). \tag{A.1}$$

Developing simple computations and considering that $\sum_{n=1}^{\infty} n\cdot {p_{GG}}^{n-1}=1/(1-p_{GG})^2$

$$\sum_{n=1}^{\infty} n\cdot T_S\cdot {p_{GG}}^{n-1}\cdot(1-p_{GG})=\sum_{n=1}^{\infty} n\cdot T_S\cdot {p_{GG}}^{n-1}+ \\ -\sum_{n=1}^{\infty} n\cdot T_S\cdot {p_{GG}}^{n}=\frac{T_S}{(1-p_{GG})^2}-\frac{p_{GG}\cdot T_S}{(1-p_{GG})^2}. \tag{A.2}$$

So

$$\overline{T}_G=\frac{T_S}{(1-p_{GG})^2}-\frac{p_{GG}\cdot T_S}{(1-p_{GG})^2}=\frac{T_S}{1-p_{GG}}=\frac{T_S}{p_{GB}}. \tag{A.3}$$

Performing similar computations, the average permanence time in Bad state $\overline{T}_B$ is

$$\overline{T}_G=\frac{T_S}{1-p_{BB}}=\frac{T_S}{p_{BG}}. \tag{A.4}$$

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