

Attributes Definitions and Measurement Methods for MADM based Sink Selection Controls in Satellite Sensor Networks

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Abstract— The framework of the work is an Environmental Monitoring System (EMS) realized by a Satellite based Sensor Network (SSN). The paper introduces and formalizes specific performance metrics needed to implement an efficient Sink selection process (where Sink represents a Satellite channel access node) based on a Multi-Attribute Decision Making algorithm. It is aimed at enhancing 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. The algorithm is tested through simulation.

Keywords- *Satellite Sensor Networks, Sink Selection, Multi Attribute Programming and Performance Evaluation.*

I. INTRODUCTION

The 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) together with the geographical position where the measures are taken. The former operation is termed *Sensing* [1], while the latter is termed *Positioning* [2]. 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 called Remote Monitoring Host (RMH). 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 one sink which forwards the information of a sensor to the RMH is important to increase the performance of the EMS. The paper introduces specific performance metrics to implement an efficient Sink selection process based on the Multi-Attribute Decision Making (MADM) algorithm aimed at enhancing the functionality of the whole EMS in terms of reliability, reactivity and spent energy. The reference metrics, whose formalization in the MADM optimization framework constitutes the main contribution of this work, are the packet loss rate, the average packet delay, and the energy consumption.

In short, the paper introduces the reference telecommunication network (Section II); summarizes the dynamic MADM based Sink Selection approach (Section III); formally defines the previously listed metrics (Section IV); presents the performance evaluation through simulation (Section V) and the conclusions (Section VI).

II. NETWORK STRUCTURE AND CHANNEL MODEL

The network considered infrastructure is identified as Satellite-based Sensor Network (SSN, [3] and reference therein). Its topology is composed of a set of J Satellite Earth Stations (called Sinks). 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.

The model used for wireless and satellite channels does not impact on the sink selection algorithm, object of this paper, which is only based on measures. Nevertheless, to define a reference environment and, in particular to simulate it, it is important to model the behavior of the satellite channel. The simulated satellite channel behavior is based on the Gilbert-Elliot model, which is a bit level model, extended to packet level coherently with [4]. The Gilbert-Elliot model follows the evolution of a 2-states Discrete Time Markov Chain (DTMC). One state is identified as “Good”. The bit error probability p_{err}^G of the “Good” state may be considered negligible. It typically ranges from 0 to 10^{-9} . The other state is identified as “Bad”. The satellite channel experiences a significant bit error probability p_{err}^B (e.g., typically ranging from 10^{-3} to 1) in “Bad” state. 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 . The average permanence times in the Good and Bad states are stochastic variable exponentially distributed. Given the transition probabilities, the average permanence time is T_s/p_{GG} , for the Good state and T_s/p_{BG} , for the Bad state. To perform the mapping operation from the Gilbert-Elliot bit level model to the packet level one, 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 bit error probability is p_{err}^G , in the Good state, and p_{err}^B , in the Bad state. The probability that an entire packet is lost is $p_{loss}^G = 1 - (1 - p_{err}^G)^l$, in the Good state, and $p_{loss}^B = 1 - (1 - p_{err}^B)^l$, in the Bad one. l is the packet length in [bit] and it is supposed fixed for each packet.

III. DYNAMIC SINK SELECTION ALGORITHM

As previously introduced, 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. 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) theory is of great help. It is used in this paper as well as in [3] where the basic theory of the sink selection process has been introduced. In the remainder of this section, the method has been quickly revised for the sake of completeness.

The sink choice is 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 n -th sensor. It takes decisions at fixed instants $t_{D,h}^{(n)}, n \in [1, N], h \in \mathbb{N}$ and the choice is valid for $T_{D,h}^{(n)} = [t_{D,h+1}^{(n)} - t_{D,h}^{(n)}], n \in [1, N], h \in \mathbb{N}$, which is the length of the h -th 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. It is kept the same for the overall length of the decision periods $T_{D,h}^{(n)}, n \in [1, N], h \in \mathbb{N}$.

Concerning the decision criterion: the index $k \in [1, K]$ identifies the attribute, which is a specific measured metric formally defined in Section IV; $j \in [1, J]$ identifies each sink within the available set also said alternative. $X_{jk}^n(t)$ is the value of the k -th attribute measured at time t for the n -th sensor when the j -th sink is chosen. For $DM^{(n)}$, the vector containing the attributes related to the j -th alternative, at time t , is:

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

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 (2), at time t .

$$^{id}A^n(t) = [^{id}X_1^n, \dots, ^{id}X_k^n, \dots, ^{id}X_K^n] \quad (2)$$

Each component of the vector is:

$$^{id}X_k^n = \left\{ X_{jk}^n : j = \arg \min_{j \in [1, J]} X_{jk}^n \right\}, \forall k \in [1, \dots, K] \quad (3)$$

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

$$j_{opt}^n(t) = \left\{ j^n = \arg \min_{j \in [1, J]} \|A_j^n(t) - ^{id}A^n(t)\|_2 \right\} \quad (4)$$

The minimization criterion reported in equation (4) has been originally proposed in [3] and it is called in this paper Dynamic LINMAP (DLINMAP). From the operative viewpoint, after performing the computation in (4) at time $t = \{t_{D,h}^{(n)}, h \in \mathbb{N}\}$, the generic $DM^{(n)}$ communicates the decisions to each sink.

The measure of the attributes for the decision is a topical point analyzed in Section IV. The metric measures are taken at the RMH, where also the DMs are located for the sake of simplicity, so filling the vectors (1) and (2). Attributes 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. Time relation between measure phases and decision instants is shown in Fig. 1.

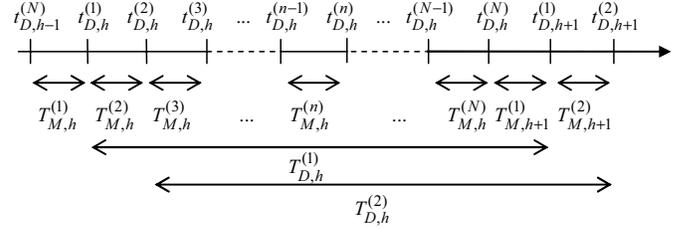


Fig. 1. Decision instants.

Measure phases are kept separate for each single sensor n . This is a design choice coherently with [3]. Measure phases for different sensors may be also overlapped, paying attention to limit the interference with regular traffic. Consecutive measures for single sensors followed by related decisions, as in Fig. 1, 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. Trade-off between measure reliability and fast reaction to traffic changes will be the object of future performance evaluation.

IV. ATTRIBUTES DEFINITIONS AND MEASUREMENT

The first attribute considered in the decisional process is the Packet Loss Rate (PLR). It is the ratio between lost and sent packets of the n -th node. $PLR_j^{(n)}(t)$ is the value of this attribute, valid at time t , for sensor n , having chosen sink j . In short, $PLR_j^{(n)}(t) = X_{j1}^{(n)}$.

The second attribute is the 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, $APD_j^{(n)}(t) = X_{j2}^{(n)}$.

The third metric formalized is the Energy Consumption (EC), which is the energy spent by sinks to propagate the packets to the destination when the network works. $EC_j^{(n)}(t) = X_{j3}^{(n)}$. Broadcasting from each sink is assumed to use 1 [mJ]. It is worth noting that this attribute is not specifically related to the n -th node but it is strictly linked to the employed sink. In the network considered, 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 a consequence, the equalization of the energy spent by sinks has been reached. For this motivation only the standard deviation of the Energy Consumption (EC Std. Dev.) among the sinks is shown in the results. It allows showing the balance of EC among the sinks and, as a 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.

To measure the above defined metrics, from the practical viewpoint, the following information must be contained in the generic i -th 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 j -th 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* is 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.

The set of all received packets from a specific source n through the j -th sink within a generic measure interval $T_{M,h}^{(n)}, n \in [1, N], h \in \mathbb{N}$ is

$$N_j^{(n)} : \left[\begin{array}{l} \text{set of packets sent from the node } n \text{ arrived in} \\ T_{M,h}^{(n)} \text{ through Sink } j. \quad n \in [1, N], j \in [1, J] h \in \mathbb{N} \end{array} \right] \quad (5)$$

Within the set $N_j^{(n)}$ it is necessary to extract the packets that are really arrived at the j -th sink 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. This situation can be clarified by considering a simple situation where two sinks are considered: Sink 1 and Sink 2. 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 $T_{D,h-1}^{(n)}$. Some other 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 $N_j^{(n)}, \forall j$, 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 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 $T_{M,h}^{(n)}$. Operatively, at the RMH, it is necessary to select the minimum

sequence number (the first arrived packet) among all sets $N_j^{(n)}, \forall j$, ignoring the packets that were already in the buffer 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 $N_j^{(n)}$:

$$v_j^{(n)} : \left[v_j^{(n)} \subset N_j^{(n)} : i\sigma_j^{(n)} \geq \min_{j \in [1, J], j \neq J_{opt}^{(n)}(t_{D,h-1}^{(n)})} \left\{ \min_{i \in N_j^{(n)}} i\sigma_j^{(n)} \right\} \right] \quad (6)$$

$v_j^{(n)}$ 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 n -th node. This action solves the possible inconvenience linked to the validity of the received packets within the measure phase: as said before, during the h -th measure period for the sensor n ($T_{M,h}^{(n)}$), the buffer of the sink designated by the previous decisional phase, $J_{opt}^{(n)}(t_{D,h-1}^{(n)})$, contains the packets of sensor n . They are forwarded to the RMH, but their *Sequence Numbers* are not valid for the current measure phase and 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 $J_{opt}^{(n)}(t_{D,h-1}^{(n)})$: within the set $N_j^{(n)}$ that contains all received packets from the n -th sensor, the number of packets forwarded by the sink $J_{opt}^{(n)}(t_{D,h-1}^{(n)})$ 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 $J_{opt}^{(n)}(t_{D,h-1}^{(n)})$ 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: $|N_j^{(n)}|$: cardinality of the set $N_j^{(n)}$ and $|v_j^{(n)}|$: cardinality of the set $v_j^{(n)}$.

The Packet Loss Rate (PLR) is computed through the *Sequence Number* field of the received packets. $X_{j1}^{(n)}$ is the corresponding attribute computed as in (7).

$$X_{j1}^{(n)} = 1 - \frac{|v_j^{(n)}|}{\delta^{(n)}} \quad (7)$$

where

$$\delta^{(n)} = \max_{j \in [1, J]} \left\{ \max_{i \in N_j^{(n)}} i\sigma_j^{(n)} \right\} - \min_{j \in [1, J], j \neq J_{opt}^{(n)}(t_{D,h-1}^{(n)})} \left\{ \min_{i \in N_j^{(n)}} i\sigma_j^{(n)} \right\} \quad (8)$$

$\delta^{(n)}$ is the number of generated packets by the n -th 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 $v_j^{(n)}$. The attribute related to the Average Packet Delay is computed by using the *Timestamp* field through (9).

$$X_{j2}^{(n)} = \frac{1}{|v_j^{(n)}|} \cdot \sum_{i \in v_j^{(n)}} (i_{t_j}^{(n)} - i_{\tau_j}^{(n)}) \quad (9)$$

$i_{t_j}^{(n)}$ is the reception instant at the RMH of the i -th packet sent from node n through the Sink j . Also in this case the reference set of packets is $v_j^{(n)}$.

The attribute related to the Energy Consumption is computed by considering the specific *Energy* field of the received packets as:

$$X_{j3}^{(n)} = \max_{i \in v_j^{(n)}} i_{\mathcal{E}_j}^{(n)} \quad (10)$$

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

V. PERFORMANCE EVALUATION

The metrics evaluated, through an “ad hoc” event driven simulator, are: i) Packet Loss Rate (PLR); ii) Average Packet Delay (APD); iii) Energy Consumption Standard Deviation (EC Std. Dev.) in [mJ]. As said in Section IV, EC Std. Dev. is not the object of the optimization algorithm (actually Energy Consumption (EC) is the object of the minimization) but its analysis is important to evaluate the lifetime of the overall EMS. The results of EC are not so meaningful because the effect of a simultaneous minimization of each single sink EC implies a uniform distribution of the energy consumption. In consequence the real metric of interest is the distance of each EC from the average EC computed over all sinks. In other words, it is the EC Std. Dev. The duration of the simulations is 300 [s]. The network topology has been described in Section II. The bandwidth capacity and the propagation delay between sensors and sinks in the sensor network are 100 [Kb/s] and 30 [μ s], 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_{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 for 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 four channel corruption conditions described in the following together with the results. Only the satellite channel between Sink 4 and RMH is supposed corrupted by noise and fading. The satellite channel model employed in the simulation is a Gilbert-Elliot Two State Markov Chain described in Section II. The following four conditions are simulated: *Error Prone*: the satellite channel is always in Bad state ($p_{BB}=1$) and $p_{err}^B=10^{-3}$; *Slowly Variable Channel*: the satellite channel switches from Bad ($p_{err}^B=10^{-3}$) to Good state ($p_{err}^G=10^{-9}$) and vice versa; variations are quite slow: $T_s/p_{GB}=T_s/p_{BG}=30$ [s] $p_{GB}=p_{BG}=0.000133$ and $T_s=l/C_{sat}=0.004$ [s]; *Fast Variable Channel*: the satellite channel switches from Bad ($p_{err}^B=10^{-3}$) to Good state ($p_{err}^G=10^{-9}$) and vice versa; variations are quite quick: $T_s/p_{GB}=T_s/p_{BG}=4$ [s] $p_{GB}=p_{BG}=0.001$ and $T_s=l/C_{sat}=0.004$ [s]; *Quasi Error Free*: the satellite channel is always in Good state ($p_{GG}=1$) and $p_{err}^G=10^{-9}$.

Fig. 2 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 values 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. The slight drawback in terms of APD, which is about 15 [ms] in the worst case (Error Prone condition of Fig. 2) is fully compensated by the performance for the other metrics.

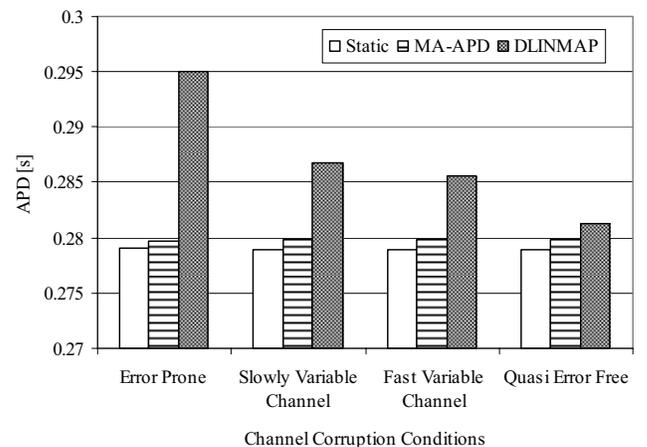


Fig. 2. APD Comparison in Satellite Channel Corruption Condition.

Fig. 3 shows the performance of the PLR for the same algorithms. Static use implies a significant quantity of lost packets in all considered satellite channel conditions except for the *Quasi Error*

Free case. MA-PLR behavior is excellent. DLINMAP offers a very good performance. Two situations, reported in Fig. 3, 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 *Quasi 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 to one sink until some packets are lost, only due to congestion in the *Quasi Error Free* situation, are measured.

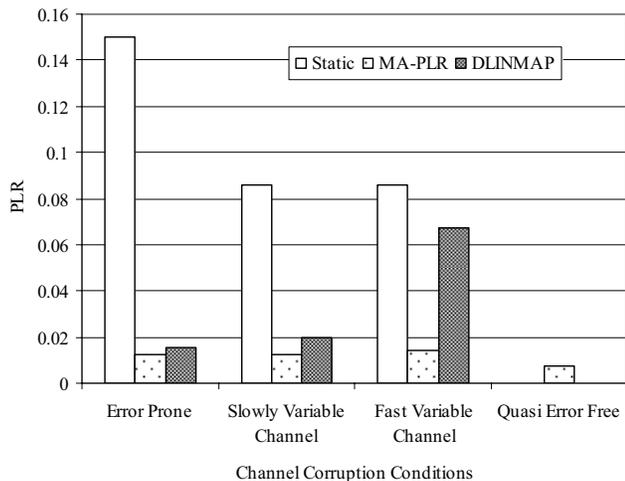


Fig. 3. PLR Comparison in Satellite Channel Corruption Condition.

Concerning the energy consumption, Fig. 4 shows the Standard Deviation of EC metric. 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. 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: MA-EC provides, also in the *Quasi Error Free* situation, EC Std. Dev. values different from zero and, in two cases, it provides higher EC Std. Dev. values than DLINMAP. It is due to the MA-EC assignment 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 in Fig. 4. It does not happen if DLINMAP is employed because, as previously said, it does not consider uniquely the energy attribute, but a group of joint metrics.

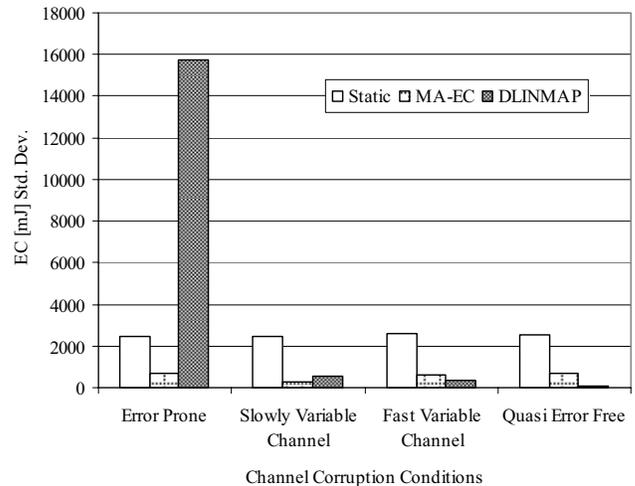


Fig. 4. EC Std. Dev. Comparison in Satellite Channel Corruption Condition.

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 evaluated conditions.

VI. CONCLUSIONS

The paper presents an architecture for satellite-based sensor networks useful to be employed for Environmental Monitoring Systems (EMSs) where Sensing and Positioning information is collected and transmitted. The choice of the sink from where the information from sensors is conveyed to the destination RMH is very important in this environment. The paper proposes a group of metrics to evaluate the performance of an EMS and their employment in 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 provides, 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 allows regarding DLINMAP as a promising solution for real systems in future.

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