Performance analysis of low earth orbit satellites for power system communication

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Abstract

In this paper the main performances of communication services based on low earth orbit satellites (LEOs) have been analyzed in order to evaluate their suitability for a typical set of power system monitoring functionalities. As an experimental test bed, an intelligent electronic device (IED) for remote monitoring and protection of power components equipped with a bi-directional communication system based on the LEO satellites of the Globalstar® consortium has been prototyped. Thanks to the adoption of this facility the main parameters characterizing the performance of the satellite TCP/IP services have been evaluated. They comprise in particular the connection time, the degradation of service and data latency for both packet and asynchronous data services. The experimental results obtained show that the application of LEO satellites based communication technologies exhibits a set of intrinsic advantages that could be particularly useful in several fields of power system communication.

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1. Introduction

The increase in the growth of information and communication technology (ICT) could play a strategic role in the attainment of the new targets induced by the liberalized electricity market. In particular, amongst the possible solutions available, the employment of satellite based technologies appears to be particularly suitable since it could make possible the realization of advanced, high value communication services such as:

- sophisticated metering;
- remote control and supervision;
- interactive e-commerce and trading applications.

Without requiring the construction of complex and expensive infrastructure and assuring, at the same time, a set of intrinsic advantages such as wide area coverage, easy access to remote sites, cost independent of distance, low error rates and adaptable to changing network patterns.

Moreover, satellite based technologies are considered a key factor in lowering the degree of vulnerability of complex interactive networks and critical infrastructures as far as the electric power grids and transportation networks are concerned [1–3].

On the other hand, the main factors that in the past have limited the application of satellite based technologies in power system communication have been recurring leasing cost of services and intrinsic time delay.

Nowadays the large number of satellite service providers in conjunction with the continuous lowering of the cost driving factors characterizing the new technologies are driving satellite communications to become competitive with other wireless based services. At the same time the recent launch of low earth orbiting (LEO) satellites, characterized by an orbital period of much shorter than a day, permits large reduction of communication time delay. These technologies have been successfully applied to support a wide range of advanced telecommunication services such as wire-
less Internet [4] and high-speed terrestrial/satellite networks [5].

Nevertheless, to the best of our knowledge, the application of LEO satellites based telecommunication technology has not so far been explored in the literature on power system communication. With this paper, we intend to fill this gap.

The paper analyses the performance of LEO satellites based communication services in order to establish their suitability for a typical set of monitoring and supervision functionalities required by power system utilities.

In particular, after a comparative analysis of the latest data services offered by the main system providers, the LEO satellites based data services furnished by the Globalstar® consortium have been adopted as reference in our experimental activities.

The performance of these services have been tested by an experimental test bed consisting of a prototype IED that integrates advanced modeling methodologies and LEO satellites based TCP/IP communication services for the remote monitoring and protection of power components.

Thanks to the adoption of this facility the main parameters characterizing the data link performance have been considered. They comprise in particular the connection times, the degradation of services and the data latency. These experimental activities have been developed connecting the IED to the Internet by the Globalstar® satellite gateway and submitting multiple queries to the remote device by a web connected host server. As far as the connections modalities of the host server, several kinds of Internet connections, based on both Local Area Networks and private Internet Service Providers (ISP), have been explored. In the latter case both wired (analogue modem connected to a Public Switched Telephone Network (PSTN)) and wireless technologies (based on satellite and GPRS data links) have been considered for the Server/ISP connection. The analysis of the results obtained shows LEO satellites based communication systems, compared with geostationary satellite (GEO) based services, are characterized by a set of intrinsic advantages that could be particularly useful in power system communication such as rapid-connecting packet data, asynchronous dial-up data availability, reliable network services and reduced overall infrastructure support requirements.

The outline of the paper is as follows: an analysis of the existing literature on satellite based technologies applied to power system communication is given in Section 2. In Section 3, a comparative analysis between the main LEOs based communication services is presented. Section 4 describes the main features of the experimental test bed adopted to assess the performance of LEOs based data services and presents a discussion of the experimental results. Conclusions and future work are summarized in Section 5.

2. Related works

The use of satellites by electric utilities has been investigated for a number of years.

In particular in [6] the employment of an Immarsat-C based satellite system is proposed as a communication unit for the remote management of the rural distributions networks. In [7], the integration of geo-stationary (GEO) satellite based technologies and terrestrial communication systems is proposed in order to develop hybrid communication networks supporting dedicated functionalities for power utilities. In [8], the interconnection of distributed networks over satellite links employing asynchronous transfer mode (ATM) cell based transmission is proposed as a sound basis to develop high-speed networks supporting advanced telecommunications services. In these hybrid networks, the satellite component is expected to operate alongside that of terrestrial components providing a complementary rather than a competitive service.

In [1–3], the development of satellite telecommunication systems is considered as a key factor in lowering the vulnerability degree of complex interactive networks such as the electric power grids. In the same papers architectures that integrate machine learning based methodologies and advanced communication services are proposed for the reliable management of critical infrastructures.

In [9] a critical review on the employment of geostationary satellite based systems for communication in EMS/SCADA and Distribution Dispatching Centre Projects is presented.

The studies reported reveal that although the application of satellite based technologies in power system communication could lead to sensible technical benefits, many critical aspects should be overcome in order to assure a wide and useful application of such technologies.

These comprise in particular:

- problematic link feasibility due to the long satellite–user distance (on-board antennas that are very large could be required if low power terminals are considered);
- high propagation delays;
- low minimum elevation angles at high latitudes (i.e. polar regions, cannot be covered);
- leasing cost.

In this regard the employment of LEO satellites based technology could represent a key factor in overcoming most of such limiting factors.

This technology, compared to medium-earth-orbit or geostationary-earth-orbit satellites, offers several intrinsic advantages such as minimum delay, multi-satellite handoff, extremely small antenna, lower power consumption, and lower cost. It appears therefore particularly suitable to support TCP/IP-based services [4] that are emerging as an essential tool in the remote management of large-scale systems.

The profitable extension of these benefits in power system communication requires a preliminary testing of the true functionalities of LEOs based communication systems in order to evaluate their potential integration with the specific power system applications.
In agreement to the discussions in the next sections, after a comparative analysis on the main performances of LEOs based data services, the main figures of merit characterizing a LEOs based data link employed to support a typical set of monitoring and supervision power system functionalities are experimentally evaluated.

3. LEO satellites based communication systems

3.1. Satellite service performances comparison

In the frame of the technologic assessment, several telecommunication subsystems have been considered for the reference scenario. The items considered for the analysis were the following:

- minimum delay,
- continuous availability of service,
- end-user performance (real throughput, BER, FER, etc.),
- compact and low cost terminals and antennas,
- low power consumption,
- support for Internet-based services,
- coverage,
- availability of a commercial solution, flexible and cost effective.

In this regard several commercial services have been considered: Iridium, Emsat, Globalstar® and Thuraya.

The nominal performance characterizing these telecommunication systems in terms of data exchange services and coverage area have been analyzed with reference to the considered application. The comparative analysis has shown LEO satellites based services are characterized by a nominal data rate potentially suitable to support the remote monitoring and protective functionalities considered.

As far as the LEO satellites services providers are concerned, a white paper [10] reports the results of a rigorous testing of the true functionality of the latest equipment and services offered for the Iridium and Globalstar® satellite data exchange systems. Many variables were evaluated and taken into account in this testing and the results demonstrate that there are a number of statistically significant differences between the two systems.

In particular, in order to enable quantitative measures to be made, the satellite communication systems were tested determining the actual data rates on multiple downloads using the file transfer protocol (ftp) from a server located on a high-speed connection to the Internet. Table 1 summarizes the results obtained, relative to 80 downloads, in both packet and dial-up scenarios [10].

The results obtained show the Globalstar® system exhibits some technical advantages in terms of data exchange speed and reliability. In particular, Globalstar® achieved a 100% success rate in the download attempts compared to 79% for Iridium. In agreement with these results the adoption of Globalstar based services has been considered in our experimental activity.

3.2. Analysis of the Globalstar® based data services

Globalstar® communications services, whose main features are summarized in Table 2, handles two kinds of data connections:

- Packet—over the Internet or other TCP/IP packet-switched networks;
- Asynchronous—routed through the Public Switched Telephone Network (PSTN) to a modem destination.

In packet data mode, the communication unit lets the application device (DTE) originate or receive a “packet data call” via standard AT commands. It establishes a PPP session, connects to the Internet, and then establishes a session with a host server.

In asynchronous data mode, the communication unit lets the DTE originate or receive an asynchronous data call. It can dial or be dialled to a modem with a host server, connect-

<table>
<thead>
<tr>
<th>Globalstar®</th>
<th>Iridium</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average data rate for highly compressible files (kbps)</td>
<td>7.62</td>
</tr>
<tr>
<td>Average data rate for minimally compressible files (kbps)</td>
<td>6.88</td>
</tr>
<tr>
<td>Percentage of successful download attempts (%)</td>
<td>100</td>
</tr>
</tbody>
</table>

Table 2

Main features of the Globalstar® satellite communication systems

<table>
<thead>
<tr>
<th>Service</th>
<th>Asynchronous</th>
<th>Packet</th>
<th>Voice</th>
</tr>
</thead>
<tbody>
<tr>
<td>Architecture</td>
<td>Satellite architecture</td>
<td>Bent pipe</td>
<td>Variable rate up to 9.6 kbps</td>
</tr>
<tr>
<td>Satellites number</td>
<td>48 (plus 2 in orbit spares)</td>
<td>463 ms</td>
<td></td>
</tr>
<tr>
<td>Minimum propagation delay</td>
<td>11.5 ms</td>
<td>25 operational</td>
<td></td>
</tr>
<tr>
<td>Gatesways number</td>
<td>2500</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Voice circuit capacity/Sat</td>
<td>2000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>System</td>
<td>PSTN</td>
<td>Fully integrated</td>
<td></td>
</tr>
<tr>
<td>Access method</td>
<td>CDMA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Modulation</td>
<td>QPSK</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Multiplying satellite visibility</td>
<td>Significant (latitude dependent)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frequency usage</td>
<td>Feeder up link</td>
<td>5.981–5.250 GHz (C band)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Feeder downlink</td>
<td>6.875–7.055 GHz (C band)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Forward link</td>
<td>2483.5–2300.0 MHz (S band)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Reverse link</td>
<td>1410.0–1626.5 MHz (L band)</td>
<td></td>
</tr>
<tr>
<td>Cover</td>
<td>Highest latitude</td>
<td>70° (North/South)</td>
<td></td>
</tr>
<tr>
<td>Restriction</td>
<td>Limited by GW capacity</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 3

<table>
<thead>
<tr>
<th>Packet data</th>
<th>Asynchronous data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Connects through a gateway to the Internet</td>
<td>Connects through a gateway and the PSTN to a remote host modem</td>
</tr>
<tr>
<td>Packet data is transmitted over the Internet to a host server</td>
<td>Asynchronous data is transmitted to a dial-up modem or modem bank, which must be supplied by the host</td>
</tr>
<tr>
<td>Typically establishes connection within 2–3 s</td>
<td>Typically establishes connection in approximately 30–60 s, due to modem negotiation and training time</td>
</tr>
<tr>
<td>No long distance charges apply, because a connection is made directly to the Internet</td>
<td>PSTN long distance charges may apply</td>
</tr>
<tr>
<td>May require a VPN and software to get past firewalls</td>
<td>May be able to directly connect inside a firewall</td>
</tr>
</tbody>
</table>

A comparison between the main advantages/disadvantages characterizing these two satellite data connections is summarized in Table 3.

Both data connections provide real-time, low cost, bi-directional data exchange solutions for power system communication. In particular they could support several tasks of SCADA applications for electric utility industry use such as:

- capture polled, scheduled, and event driven data;
- report on power outages;
- monitor or remotely control the following:
  - capacitor bank monitors,
  - voltage regulators,
  - power components;
- load management.

Obviously the full accomplishment of these functionalities requires a preliminary performance analysis of the communication data link in order to evaluate its suitability with the considered protective and monitoring functions set.

To address this problem an experimental test bed, based on an IED equipped with a bi-directional LEO satellites communication unit, has been employed, in order to evaluate the main figures of merit characterizing the satellite data link performance.

4. Performance analysis of LEOs based data services for power system communication

4.1. The experimental test bed

The proposed IED architecture is based on a ZWORLD-BL2100 unit, an advanced single-board computer that incorporates the Rabbit 2000™ microprocessor (operating at 22.1 MHz), 128KB static RAM and 256KB flash memory, 40 digital I/O channels, 11 12-bit A/D converter inputs, four 12-bit D/A converter outputs, RS-232/RS-485 serial ports.

This IED, shown in Fig. 1, has been equipped with a satellite based telecommunication system in order to assure the external connectivity required to support the remote management functionalities.

![Fig. 1. The experimental test bed: (a) the microcontroller based unit and (b) the satellite based communication unit.](image)

In this regard the Qualcomm™ GSP-1620 modem has been employed. This telecommunication unit, utilizes the satellite services proposed by the consortium Globalstar®, that employ a constellation of 48 LEO satellites picks up signals from over 90% of the Earth’s surface. It can handle both packet and asynchronous data connections.

For packet data, it offers full duplex transmission and receives at a data port rate of 9600 bps using the Point-to-Point Protocol (PPP) as the transport mechanism for data packets. Standard networking software establishes, manages, and tears down the PPP session.

For asynchronous data, it offers full duplex transmission and receives at a data port rate of somewhat less than packet data’s 9600 bps, due to additional overhead for asynchronous data.

The software interface between the satellite based communication unit and the microcontroller have been programmed using an integrated development environment (Dynamic C™ premier) that includes an editor, a C compiler, and a debugger.

Table 4

<table>
<thead>
<tr>
<th>Activity</th>
<th>Estimated time (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>System access</td>
<td>289</td>
</tr>
<tr>
<td>Call set-up</td>
<td></td>
</tr>
<tr>
<td>Setup traffic resources</td>
<td>287</td>
</tr>
<tr>
<td>Physical layer and RLP set-up</td>
<td>1226</td>
</tr>
<tr>
<td>Encryption</td>
<td>342</td>
</tr>
<tr>
<td>Service option negotiation</td>
<td>315</td>
</tr>
<tr>
<td>Data connection set-up</td>
<td></td>
</tr>
<tr>
<td>RLP negotiation</td>
<td>380</td>
</tr>
<tr>
<td>PPP negotiation</td>
<td>1366</td>
</tr>
</tbody>
</table>
As far as the protective and monitoring functionalities implemented are concerned, they are based on advanced modeling techniques of power component thermal dynamics [11]. They allow, in particular, the accomplishment of the following main tasks:

- Adaptive thermal overload protection: the adopted protective methodology working on the load current the actual component thermal state and taking into account other measured meteorological parameters, permits to recognise the hot spot temperature pattern [12] without requiring complex and invasive measurements.

Fig. 2. Experimental test beds considered in assessing the data latency. Server web connection realized by: (a) an Enterprise Local Area Network (case 1), (b) a Public Switched Telephone Network (PTSN) (case 2), (c) a satellite modem (case 3) and (d) a GPRS modem (case 4).
• Dynamic load capability assessment: it is carried out, once the real component thermal state and the forecasted environmental conditions are given, by solving iteratively the predictive models for a set of overloads comprised between 1 and 2 pu. The corresponding hot spot and ageing profiles allow us to identify the maximum allowable duration for each hypothetical load level [13].

• Short term load forecasting: a local database is employed in order to evaluate the load current evolution on short term horizons by a dedicated assessment procedure.

• Alarms management: when the hot spot temperature is expected to reach a maximum allowable value an alarm is generated in order to activate dedicated procedures for alleviating the component overload.

All these functionalities can be remotely managed by dedicated TCP/IP-based data exchange function that assures the external connectivity to a central server.

As far as the communication functionalities both packet and asynchronous data connection can be adopted by selecting a status flag in the unit setting window. Moreover, as far as the packet data connection, both fixed and dynamic IP addressing can be programmed.

With a fixed IP address, the central server uses a given specific IP address that is permanently assigned to the IED. With dynamic IP addressing, the gateway assigns a dynamic IP address to the IED that remains constant until the PPP session is terminated. In the first case the central server can manage the IED functionalities by accessing directly its web page at a fixed address. In the second case the IED should communicate its dynamical IP address once a new PPP connection to the gateway is established.

As far as the asynchronous data connection between the central server and the remote IED, it can be established by a dedicated point-to-point (PPP) link over the full-duplex satellite communication channel. In this case, once an incoming call is detected, the remote IED activates a PPP connection by using the following functional steps:

- Authentication phase using the Password Authentication Protocol (PAP);
- PPP negotiation;
- TCP/IP initialization.

Once the PPP connection is established, the central server can access directly the IED web page.

4.2. Experimental results

This section will report the experimental results obtained applying the proposed LEOs based IED to the protection of a real power component.

![Fig. 3. Statistical characterization of the data latency evolution for the considered case studies.](image)
In order to evaluate the performance of the communication data link for both the data connection several figures of merit have been considered. They comprise in particular the connection times, the degradation of services, and the data latency.

4.2.1. Connection times evaluation

Regarding the connection times, the Globalstar® communication protocol involves several activities once a module originated packet data call is set up. They comprise in particular the system set-up, the physical layer set-up, the encryption and the service option negotiation. Several field trials have provided the average results reported in Table 4.

4.2.2. Degradation of service

As far as the degradation of the service, the frame error rate (FER), that is a measure of the radio link quality, has been evaluated.

The FER exhibited by the Globalstar® Air Interface (GAI) traffic channel is of the order of 1–3%. Traditional data protocols work poorly on physical layer with such a high data rate. Consequently, data Radio Link Protocol (RLP) is designed as a link layer protocol to compensate for the relatively high FER of GAI traffic channel. It carries packet mode data over GAI traffic channel. Depending on the size of the packets, the RLP may stuff several upper layer packets into one or more RLP frames for transmission over Globalstar® Interface. The RLP automatically uses Negative Acknowledgement (NAK) and a re-transmission method to reduce the Frame Error Rate to typical data network bit error rates of $10^{-6}$ or better.

4.2.3. Data latency

The data latency is the time delay caused by getting a network message from the host server to the remote IED, and getting a response back again. This time delay can be made larger by:

- propagation delay;
- transmission delay;
- router delays;
- packet loss, recovery, and re-transmission.

The data latency of the satellite based data link has been analyzed by connecting the IED to the Internet by the Globalstar® satellite gateway and considering several web based connections for the host server. These comprise, in particular, Internet connections based on both enterprise Local Area Networks (e.g. the Sannio University Campus LAN) and private Internet Service Providers (ISPs). In the latter case both wired (analog modem connected on a Public Switched Telephone Network (PSTN)) and wireless (GPRS and satellite) technologies have been considered for the Server/ISP connection. The overall connection topologies set adopted in the experimental activity is schematically depicted in Fig. 2.

Thanks to the adoption of these facilities the data latency of the satellite data link has been estimated measuring, for a fixed time period, the packet round trip times at the transport level of the ISO/OSI stack. In this connection it is important to underline that this value is expected to be highly random since it is influenced by several drive factors such as communication links congestion, communication protocols, GPRS link quality and so on. To deal with these phenomena a worst case scenario, characterized by higher expected levels of satellite data link congestion (connection time around 12 am), has been considered for the measurements. The statistical characterization of the measured time delays for the considered case studies are reported in Fig. 3 and summarized in Table 5.

Analyzing this data it is worth observing that the wired based connection topologies have exhibited the best performances in terms of both mean delay times (order of 1 s.) and reliability (0% packet loss).

As far as the wireless technologies, the satellite based connection compared to the GPRS has exhibited lower mean delay times but higher levels of lost packets. These performances could be improved connecting the host server to the Internet by the same gateway adopted for the remote IED.

In all the cases herein considered it is evident that the data latencies measured make difficult the employment of the LEOs based data link in high performance-time critical applications.

<table>
<thead>
<tr>
<th>Case</th>
<th>Trials number</th>
<th>Estimated times for a complete packet route</th>
<th>Packet loss (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Minimum (ms)</td>
<td>Maximum (ms)</td>
</tr>
<tr>
<td>1</td>
<td>820</td>
<td>750</td>
<td>2010</td>
</tr>
<tr>
<td>2</td>
<td>820</td>
<td>771</td>
<td>1582</td>
</tr>
<tr>
<td>3</td>
<td>250</td>
<td>1082</td>
<td>2794</td>
</tr>
<tr>
<td>4</td>
<td>250</td>
<td>1347</td>
<td>4042</td>
</tr>
</tbody>
</table>

Table 5: Mean results
5. Conclusion

In this paper, the main performances of low earth orbit satellites based communication services for power system communication have been analyzed. To address this problem, an experimental test bed based on an IED equipped with a bi-directional satellite communication system for remote monitoring and protection of power components has been prototyped.

Thanks to the adoption of this facility, several figures of merit characterizing the main performances of the satellite based TCP/IP services have been analyzed. These experimental activities have been developed connecting the IED to the Internet through the Globalstar® satellite gateway, taking into account several web-based connections for the host server. These comprised, in particular, Internet connections based on both enterprise Local Area Networks and private ISP. In the latter case, both wired and wireless technologies have been considered for the Server/ISP connection.

The results obtained show the application of LEOs based communication technologies allows system operators to overcome some of the intrinsic limitations of the classic geostationary satellite based communications exhibiting a set of intrinsic advantages particularly useful in power system communication as rapid-connect packet data, asynchronous dial-up data availability, reliable network services, reduced overall infrastructure support requirements.

As far as the data latency, the LEOs based communication services have exhibited better performances compared to other satellite based communication technologies, mainly due to the orbital period being much shorter than a day. Anyway, the measured values appear not directly suitable for high performance-time critical applications.

All these factors make the employment of LEOs based communication services very promising in several fields of power system communication as far as automation, remote monitoring and supervision are concerned.

References