UMTS-based Data Link and Data Network for Telemetry and Time Space Position Information (TSPI) Applications[1][*]

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ABSTRACT

We present an integrated telemetry data link and network architecture system solution, developed by Mayflower for the Air Force, AFFTC, Edwards AFB, CA, based on third generation UMTS cellular standards. The data link, called COTS Affordable Data Link System (CADLS), accommodates high mobility user applications typical of tactical fighter aircraft. The data network, called Telemetry/TSPI Data Network (TDN), uses enhancements such as a multi-tiered network protocol structure to provide flexible IP-based transport, work with multiple air interface protocols, accommodate test platform mobility, and integrate seamlessly with unified infrastructure such as Test and Training Enabling Architecture (TENA). The end-to-end CADLS/TDN datalink network system, described in this paper, is a 2-way, asymmetric IP-based wireless network system, and as such it is a potential candidate technology to support the DoD CETIP integrated Network Enhanced Telemetry (iNET) project. The integrated CADLS/TDN system is at an advanced stage of prototype development. We present the integrated CADLS/TDN system architecture, its features and capabilities, and the laboratory prototype developed under the Air Force program.

Keywords: UMTS, CADLS, TDN, Telemetry, TSPI, TENA, iNET.

1. INTRODUCTION

High dynamics platforms such as Unmanned Aerial Vehicles (UAVs), ballistic missiles, and tactical fighter aircraft have various sensors on them to measure their operation and one or more GPS receivers to track their time-annotated position information. Continuous stream of data from these sensors and the GPS receivers need to be sent to a collection point outside the platforms, so that they may be used to track the operation and trajectory of these platforms. The Quality of Service (QoS) requirements, i.e., the Bit Error Rate (BER) and latency, for this continuous stream of data are stringent on both the wireless data link and the data network. In addition, the wireless data link from the platform to the ground should accommodate multiple simultaneous platforms, each of which may travel at high speeds over a vast range; the data network from the ground to the point of storage or access should accommodate multiple radio access protocols at one end, and secure, intuitive storage and user access at the other.

Current telemetry/TSPI systems for high dynamic platforms ([1] and the references therein) are, typically, single user, point design systems that do not scale easily in users and in range. They, moreover, rely on proprietary communication technology, which results in a higher lifetime cost of maintenance and upkeep, and greater risk of technology obsolescence. The telemetry/TSPI data, once on the ground, need to be delivered swiftly and reliably to their appropriate destinations, by means of a complementary data network system. Current data networking solutions are a patchwork of proprietary protocols that are difficult to upkeep and upgrade.

We present a UMTS commercial standards (see [2]) based data link and network system, which provide an end-to-end telemetry/TSPI solution for high dynamic platforms. The data link is inherently multi-user, so it can scale naturally to accommodate hundreds of simultaneous users such as UAVs, ballistic missiles, and tactical fighter aircraft. Through

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cellular partitioning of coverage and seamless handoff, the range can also be scaled beyond the capability of incumbent systems. Since the said solution is based on commercial standards and, therefore, developed mostly using Commercial Off-the-Shelf (COTS) components, it delivers a significantly lower cost over its lifetime, and it has a lower risk of technology obsolescence. Our data networking solution is IP-based, and it has a flexible radio-side architecture that can accommodate multiple radio access protocols, including incumbent systems such as the Advanced Range Telemetry (ARTM) system presented in [1].

We present the architectural design of our end-to-end telemetry/TSPI system, and the results of the theoretical and simulation analysis of its performance. We have implemented the software of all the network components and the baseband portion of the radio on COTS platforms, most of them embedded, which we discuss in this paper. Ongoing development includes the Radio Frequency (RF) front-end as well as multi-antenna and range extension enhancements to increase data rates and range.

The end-to-end datalink network system, described in this paper, is a 2-way, asymmetric IP-based wireless network system, and as such it is a potential candidate technology to support the DoD CETIP integrated Network Enhanced Telemetry (iNET) project [4]. The iNET project aspires to develop a Telemetry Network System (TmNS) with technology to meet emerging needs within Major Range and Test Facility Base (MRTFB). Current communication links based on IRIG 106 standard are one-way, dedicated links. The iNET project envisions 2-way communication links that can provide flexible operation and improved spectrum efficiency, combined with IP-based networking technology and COTS-based development to meet the needs of the Research, Development, Test & Evaluation (RDT&E) community in a cost effective manner. The end-to-end datalink network system described in this paper consists of 2-way communication links, IP-based wireless networking, and is being developed using COTS standards and technologies; therefore, the system presented herein is a potential candidate technology to support the iNET project.

2. CADLS/TDN HIGH DYNAMICS DATA LINK AND NETWORK

Figure 1 is the conceptual architecture of a UMTS-based end-to-end telemetry/TSPI data link and network solution. The data link portion, which consists of the direct link between the Mobile Stations (MS) and the Base Stations (BS), is under the purview of the Mayflower COTS Affordable Data Link Solution (CADLS). The range of the data link may be extended by the use of airborne relay points, such as the High Altitude Balloon shown in Figure 1, but we defer discussion of range extension to a later paper. We will restrict the discussion in this paper to the direct link between the MS and the BS, as far as data link goes. The MS, as shown in Figure 1, are on high dynamic platforms such as UAVs, ballistic missiles, and tactical fighter aircrafts, and the BS are fixed on the ground, for instance at an air base. Section 2.1 is a detailed discussion of the CADLS data link technology.

The data network, namely TDN, consists of the Radio Access Domain, which encompasses the networking aspect of the data link; the Network Domain, which encompasses the transport of the collected data over a terrestrial network; and the Application Domain, which encompasses the mechanisms of storage and access of the collected data. Section 2.2 is a detailed discussion of the TDN data network technology.

The path from the MS through BS and Radio Access Domain, through the Network Domain, terminating at the Application Host, which may be a storage device, or a terminal from which to access data, and the reverse of this path (i.e., from the Application Host to the MS), are what we call the end-to-end CADLS/TDN system. It should be evident from even cursory inspection of the conceptual architecture in Figure 1, and countenance of the multiple radio access protocols on the data link side, that a variety of disparate components must work in concert in the CADLS/TDN system to achieve the telemetry/TSPI application requirements. In Figure 1, legacy telemetry data links are also shown as a part of the Radio Access Domain, depicting the multi-radio capability of the TDN ground network, which we will elaborate on later; it suffices to say at the moment that this versatility on the radio access side owes to a server/gateway design of the TDN. A similar server/gateway design on the TDN network domain is expected to obviate the integration of the CADLS/TDN telemetry/TSPI system with such comprehensive interoperability and reuse architectures as Test and Training Enabling Architecture (TENA, see [3]).

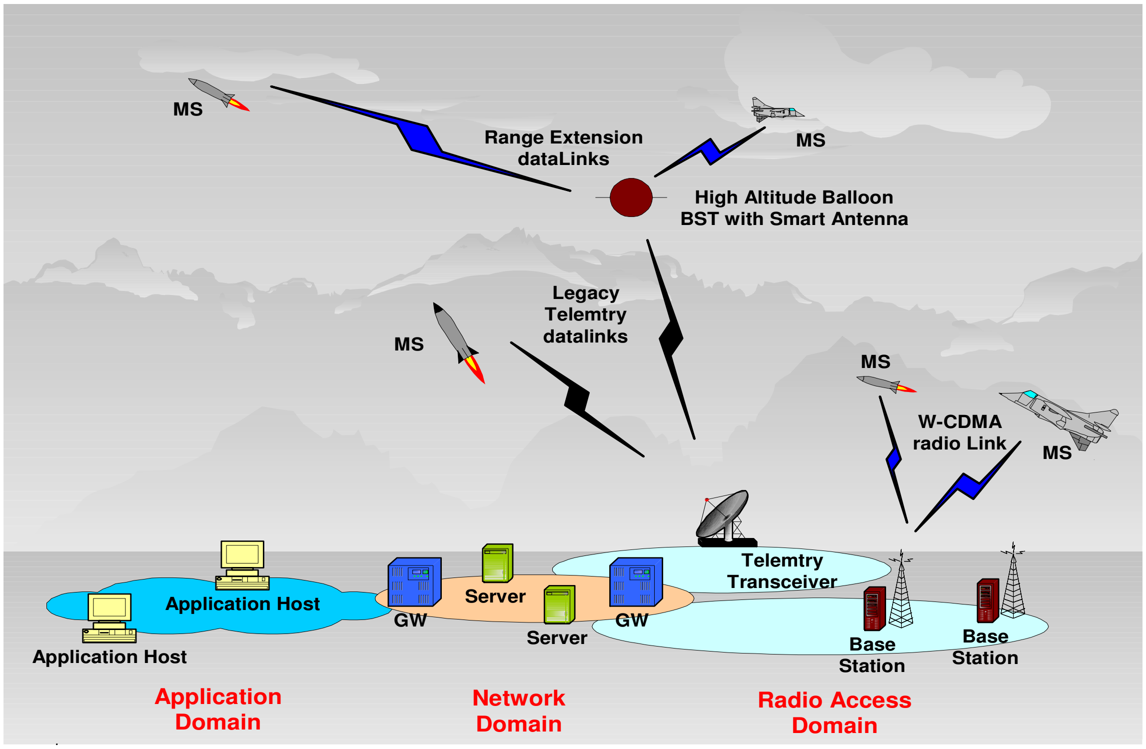

Figure 1—Conceptual architecture of a UMTS-based data link and data network solution for telemetry and TSPI.

2.1. CADLS Data Link

Our investigation of the suitability of UMTS for telemetry/TSPI data link consists of answering three concerns: (1) Is the coverage adequate and scalable? (2) Is the capacity adequate and scalable? (3) Is the performance acceptable under high dynamic conditions?

In order to answer the first question, namely, "Is the capacity adequate and scalable?" we use an RF planning software. We use two base stations with sectorized antennas with three 120^o sectors. The deployment locations of these base stations were picked at random. A more rigorous study would involve placing the base stations at a given predetermined location, designated in a latitude/longitude co-ordinate system or as a GPS location. The Base Station (BS) and Mobile Station (MS) parameters, such as peak transmitted power and receiver sensitivity, were industry-standard numbers.

The four figures, Figure 2, Figure 3, Figure 4, and Figure 5, show the coverage of the data link, both from the MS to BS and from the BS to MS, at MS heights of 2m, 100m, 1000m, and 10000m, respectively, above ground. The shown terrain dimension is approximately 60km x 50km. We see that the coverage area as well as the highest achievable data rates (in case of MS to BS link) improves with increasing mobile altitudes. The coverage exhibited in the figures seems adequate for a flight test range, and the coverage can be scaled by adding more base stations.

The reason for the lower coverage area for the link from the MS to BS, compared to the link from the BS to MS, is because we have assumed the mobile station's maximum transmit power to be limited to -9 dBW, in keeping with the industry standard for a cellular mobile device with strict power constraints owing to the size of the device. In a government spectrum, however, this power constraint can be relaxed and the MS equipped with antennas and power amplifiers that are capable of putting out as much power as the BS, i.e., of the order of 10 dBW or greater. With the higher transmit power constraint, the coverage of the link from the MS to BS can be increased to be similar to the link from the BS to MS.

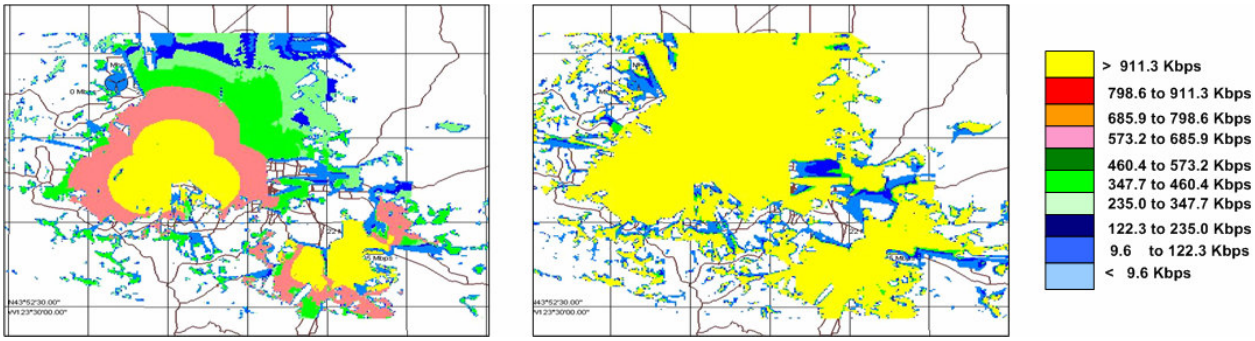

Figure 2—Data link coverage from MS to BS (left), and from BS to MS (right), with the MS at 2m above ground level.

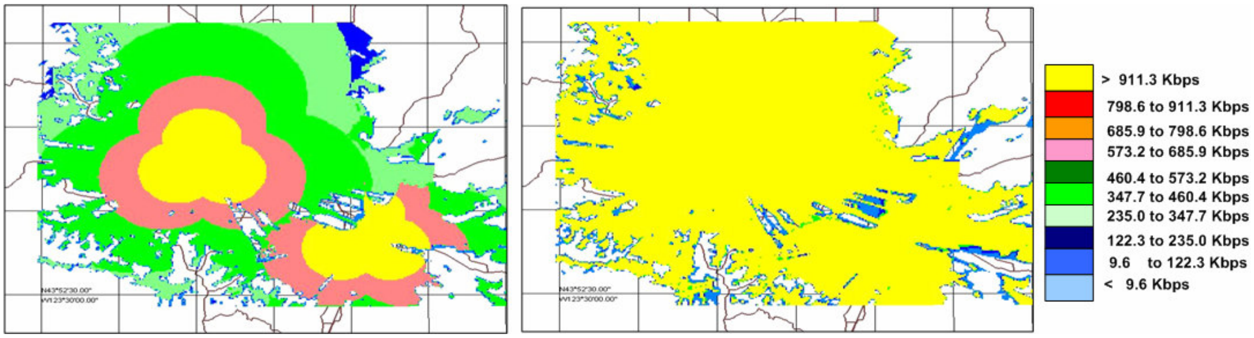

Figure 3—Data link coverage from MS to BS (left), and from BS to MS (right), with the MS at 100m above ground level.

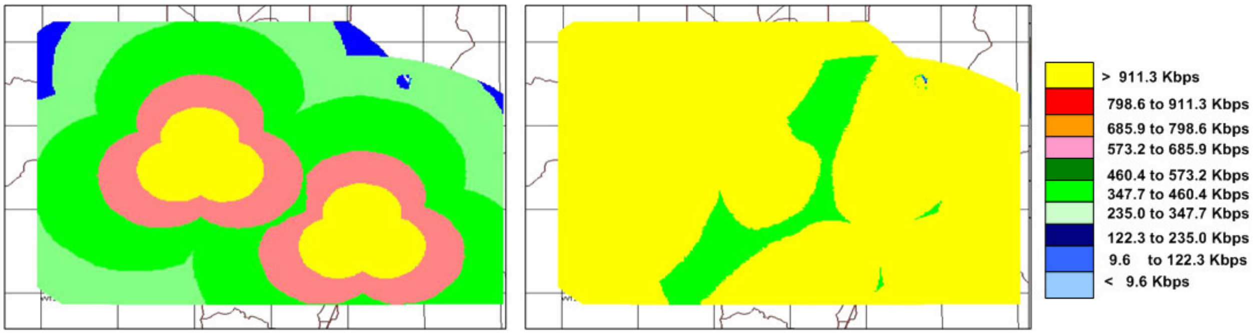

Figure 4—Data link coverage from MS to BS (left), and from BS to MS (right), with the MS at 1000m above ground level.

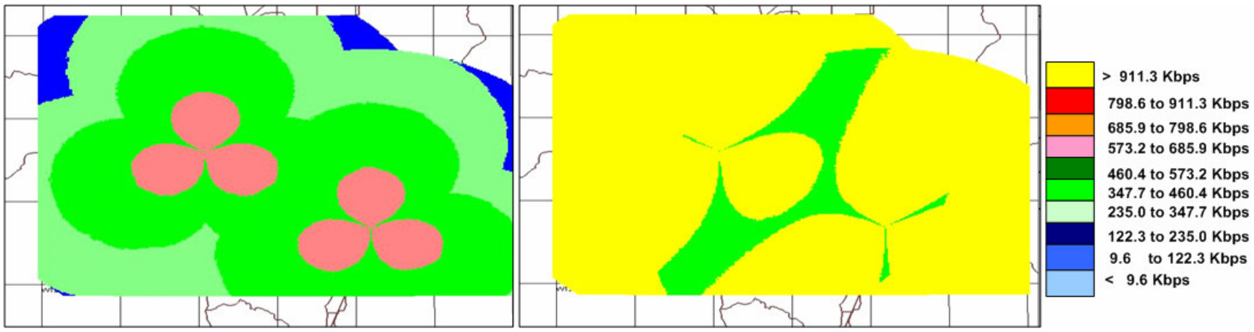

Figure 5—Data link coverage from MS to BS (left), and from BS to MS (right), with the MS at 10000m above ground level.

Now we will attempt to answer the second question, namely, "Is the capacity adequate and scalable?" Table 1 captures the performance of the link from the BS to MS; since the largest achievable data rate with the UMTS standards used for the physical layer of the CADLS is 1.024 Mbps, this essentially is the capacity of the link from BS to MS. The UMTS standards on which CADLS system is based mandates channel coding in the form of a rate R = 1/3 turbo or convolutional coding, and this overhead is taken into account in the capacity numbers. Without channel coding, we can increase the capacity of the BS to MS link to greater than 3 Mbps.

Table 1—Capacity and coverage of the link from BS to MS, for a data link system with two BS.

BS to MS	**MS elevation (above ground level)**			
	2.0 m	**100 m**	**1000 m**	**10000 m**
Capacity	**1.024 Mbps**	**1.024 Mbps**	**1.024 Mbps**	**1.024 Mbps**
Coverage Area	**60 %**	**80 %**	**> 98 %**	**> 98 %**

The analysis of the link from MS to BS is much more complicated. The received SNR of each user is affected by the presence of other users in the system, and this multi-user nature of the system must be taken into account. We use static Monte Carlo analysis in order to determine the capacity of the link from MS to BS. The objective of our Monte Carlo simulation was to determine the largest number of mobiles (statistically located anywhere in the service region) that can be serviced by the base stations deployed in the region. As the number of mobiles increases, the cumulative interference on each of the mobiles in the service region increases proportionately thereby reducing the received SNR at the base station receiver. The limiting number of mobiles would be the largest number of mobiles that the system can service, beyond which any further increase in the number of mobiles would degrade the SNR at the receiver for all the mobiles that reliable reception becomes impossible. The purpose of determining the largest number of serviceable mobiles in the region is to determine the simultaneous number of users that can effectively share the bandwidth (and hence the data rates).

Table 2 captures the system performance of the link from MS to BS. Since this link is a multi-user link, we perform static Monte Carlo analysis to determine the number of users that the system can handle. Each of these mobile users is assumed to be a low data rate (voice) user with a data rate of < 10 Kbps. The Monte Carlo analysis places mobile stations randomly in the terrain and for each mobile computes the received SNR at the base station. If this SNR (in the presence of interfering users in the system) is larger than the minimum required SNR to maintain the link, then the mobile is flagged as being serviced. On the other hand, if the received SNR for a particular mobile falls below the threshold SNR then the mobile is flagged as soft-blocked. The percentage of mobiles that remain in soft-block determines the number of mobiles that cannot be serviced. The average single user data rate in the table is determined by performing a weighted average of the maximum achievable data rates. As expected, the average single user data rate increases with increasing altitudes of the mobile station up to a point beyond which the received signal strength begins to diminish because of increased distances between the mobile and base stations. The coverage is determined by the Monte Carlo analysis as well, by using the uplink soft-block probability as a measure. The coverage numbers are the probability that a mobile user at any random location within the field of deployment will be able to establish a link with the base station.

Table 2—Capacity, coverage, and average single user data rate for the link from MS to BS, for a data link system with two BS.

MS to BS	**MS elevation (above ground level)**			
	2.0 m	**100 m**	**1000 m**	**10000 m**
Capacity (Number of MS)	**236.64**	**253.34**	**261.5**	**245**
Capacity	**2272 Kbps**	**2432 Kbps**	**2510 Kbps**	**2352 Kbps**
Coverage	**91 %**	**> 98 %**	**> 98 %**	**> 98 %**
Average Single User Data Rate	**160.8 Kbps**	**245.0 Kbps**	**269.4 Kbps**	**132.7 Kbps**

From Table 2, it is apparent that over 200 mobiles can be accommodated with just two base stations, with greater than 98% coverage above the altitudes of 100m, and at a total data rate capacity of over 2 Mbps (the combined data rate supported by the two base stations. These are respectable numbers for a typical flight test range. The data rates can be boosted to over 10 Mbps using multi-antenna enhancements and more complex constellations. The coverage and the number of supported mobiles, as well as the cumulative data rate capacity, can be increased by adding more base stations.

The third question we attempt to answer is, “Is the performance acceptable under high dynamic conditions?” High speed mobility/high dynamics stresses the portions of the system that are affected by coherence time and Doppler. Channel estimation and equalization, for instance, bear the brunt of the high dynamics. To illustrate, Figure 6 shows the channel fluctuations for two different relative velocities. The blue curve shows the fluctuations in the channel attenuation (envelope) for a relative velocity of 1 Mach, while the red curve shows the channel gain for a relative velocity of 10 Mach. *It is clear that the faster the platforms move, the faster the channel fluctuates (“fast fading”), in the order of microseconds, resulting in the loss of reliable wireless communication.*

We have developed an adaptive channel estimation and tracking technique to counter fast fading. The technique uses a decision directed algorithm to keep up with the fluctuations in the channel. The next plots, Figure 7, illustrates how the incorporation of the decision directed channel tracking algorithm increases the reliability of communication at supersonic speeds. The error rate curves are generated for a CADLS receiver with diversity algorithm employing three receiver antennas. The bottom curve (blue diamond) shows the performance of an ideal RAKE based maximum ratio combining (MRC) receiver when *the mobiles are stationary*: this is the best possible performance of the communication system. The top curve (red star), on the other hand, is the performance of the receiver when the transmitter and the receiver are moving at a relative velocity of 2 Mach, and no channel tracking is employed. *We see that the error rate in this case is 50%, and hence communication is not possible*. The middle curve (black circle) shows the performance of the receiver that incorporates decision directed channel tracking. It is seen that the performance of the Mayflower decision directed tracking-based receiver *at 2 Mach mobility* is close to the performance of the ideal receiver *without mobility*: the performance gap is of the order of 1 dB at error rates $\leq 10^{-5}$! From Figure 7 it is apparent that reliable telemetry performance is indeed achievable under high dynamic conditions.

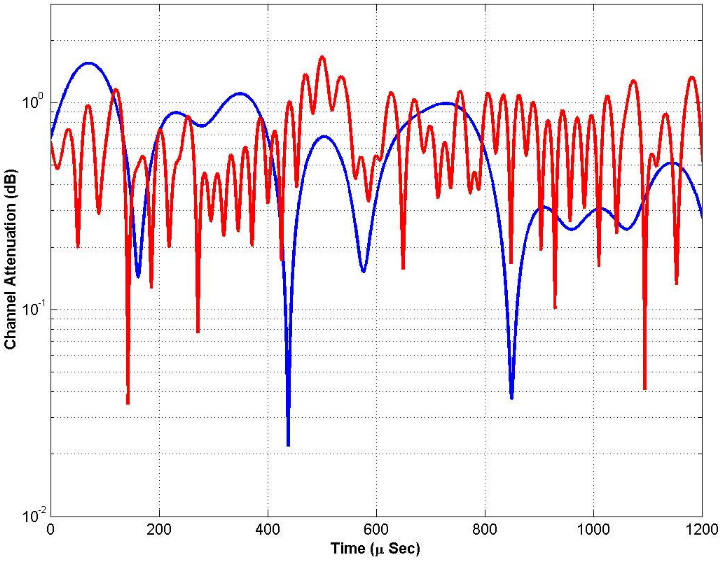

Figure 6—Fast fading effects due to high speed mobility in the instantaneous channel envelope power.

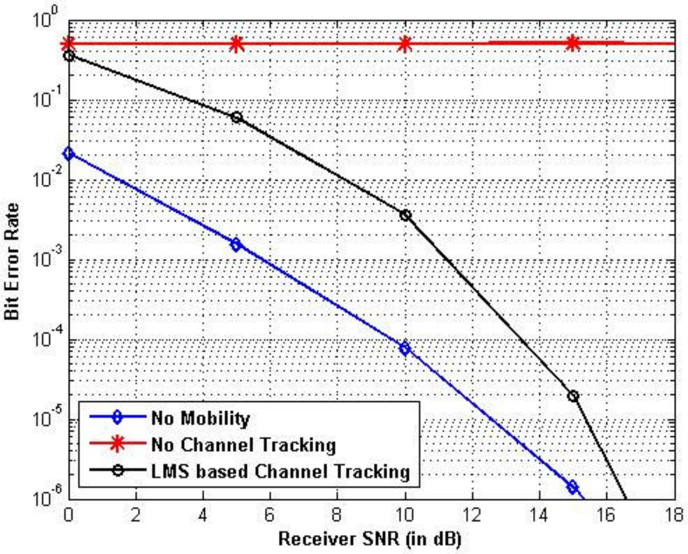

Figure 7—Error rate performance of the Mayflower decision directed channel tracking receiver at high speed mobility of 2 Mach.

2.2. TDN Data Network

TDN is an Internet Protocol (IP)-based networking system that links the ground-based application entities and the peer application entities in the MS. Figure 8 depicts the overall architecture of the TDN, which shows the two subnetworks within a TDN deployment: the IP Radio Access Network (IP RAN) and the IP Core Network (IP CN). The IP RAN consists of radio base stations and an IP Radio Network Controller (IP RNC). The signaling and data paths of RNC are implemented separately in server/gateway architecture, with the signaling handled by a Radio Resource Server (RRS) and the data processing by a Wireless Access Gateway (WAG). This design choice elucidates the integration of multiple radio access technologies within the same RAN. The TDN deployment in Figure 8, for instance, shows a satellite radio link, a terrestrial radio link (CADLS), and an "other," perhaps a legacy radio link. The CADLS data link has an effective range of, say, a hundred kilometer. When the mobile travels outside the range of the CADLS link, it may switch to a satellite radio link and thus be still able to connect to the ground network.

The IP CN is responsible for IP network connectivity, with service establishment and data routing falling into its purview. The CN mirrors the RNC with a server/gateway implementation of its own: the Media Signaling Server (MSS) implements the signaling path and the Media Gateway (MGW) implements the data path. This is an eminently more flexible and scalable solution. Protocol agnostic service provision is handled by the servers and the stock data processing is handled by generic data processing equipment, the gateways. Changes and upgrades to the server and the gateway functionalities can be made independent of each other. An important consideration for this design is the use of COTS hardware for the development of TDN equipment while retaining UMTS standards compliant protocols and interfaces.

An IP backbone network, shown in Figure 8 as a Packet Data Network (PDN), connects the IP CNs of several TDN deployments into a seamless TDN system that allows the MS to roam between TDN deployments. The TDN roaming capability is implemented using Mobile IP (MIP). With MIP, the roaming MS provides an assigned "care of" IP address provided by the "visited" range to its "home" range. With this arrangement, the home range forwards all IP packets received for this MS to the visited range to be relayed to the MS. MIP is available in IPv4 as an extension and is a native protocol in IPv6. QoS provisioning in TDN is through the TDN Bearer Service between the MS and the MGW. The TDN Bearer Service description, which consists of a set of attributes, includes all the aspects required to provide a set of QoS already negotiated between the MS and the TDN infrastructure. The TDN Bearer Service consists of two parts, the Radio Access Bearer Service on the IP RAN side and the Core Network Bearer Service on the IP CN side. The Radio Access Bearer Service provides signaling and data transport between MS and WAG, at a default QoS for signaling, and at the negotiated QoS for data. Core Network Bearer Service connects the WAG with the MGW, and the MGW to the external PDN. The role of this service is to efficiently control and utilize the backbone network in order to provide the negotiated TDN bearer service.

The TDN supports four QoS classes for its network services:

a) Conversational Class,

b) Streaming Class,

c) Interactive Class, and

d) Background Class.

The main distinguishing factor between these classes is the support of delay-sensitive traffic. Conversational class is used for traffic which is very delay sensitive while Background Class is used for the most delay insensitive traffic. Conversational Class and Streaming Class are designed to carry real time traffic, such as streaming video application. The Interactive Class and Background Class are used for file transfer applications. Table 3 lists the main characteristics of the four supported QoS classes.

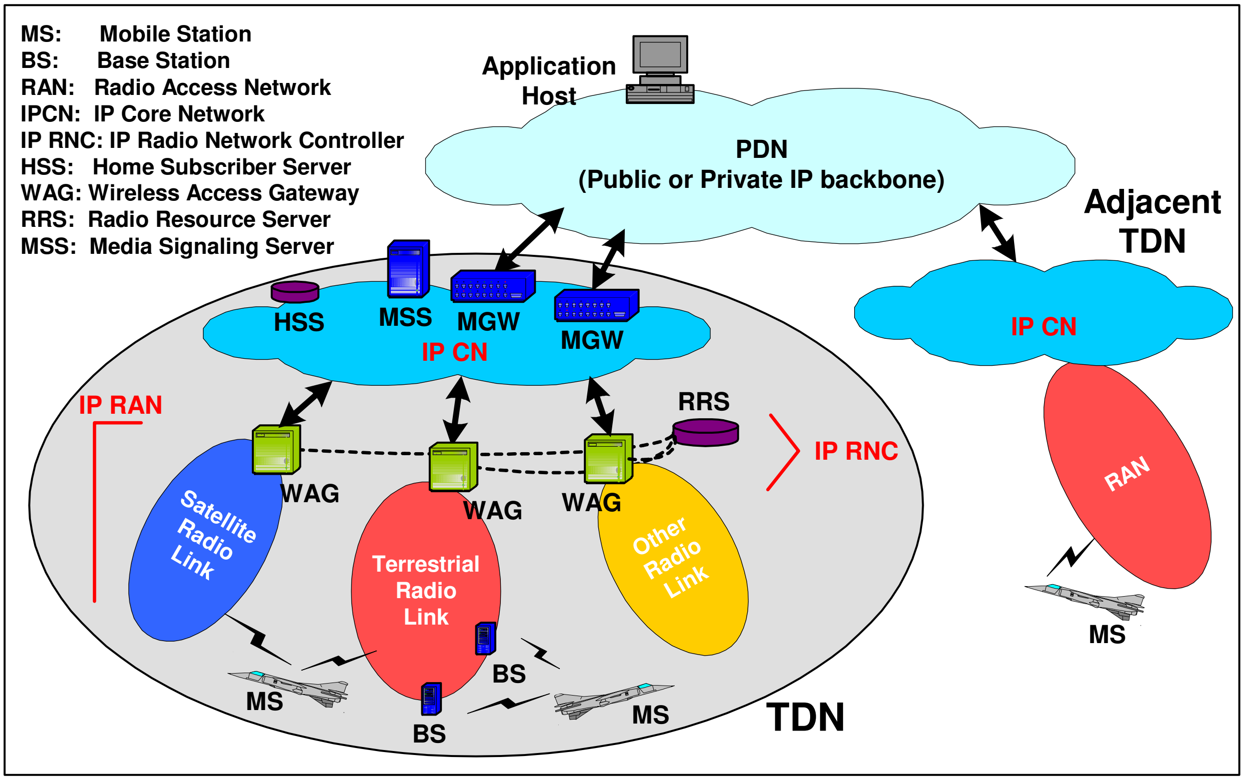

Figure 8—Conceptual architecture of the Telemetry/TSPI Datalink Network (TDN).

Table 3—Main characteristics of the TDN QoS classes.

Class	Conversational Class	Streaming Class	Interactive Class	Background Class
Fundamental Characteristics	**1. Preserve Time relation between information entities of the stream** **2. Conversational pattern (stringent and low delay)**	**1. Preserve time relation between information entities of the stream**	**1. Request response pattern** **2. Preserve payload content**	**1. Destination is not expecting the data within a certain time.** **2. Preserve payload content**
Example applications	**Two way video**	**Streaming video**	**Data file transfer**	**Background download**

The security aspects of the TDN operation are organized in four major security feature groups. Each of these feature groups can be designed to meet certain threats and accomplish certain security objectives. The security feature groups are as follows:

1. Network access security: the set of security features that provide the users with secure access to the TDN services, and which in particular protect against attacks on the used radio access links;

2. Network domain security: the set of security features that enable nodes in the external packet data network (PDN) to securely exchange signalling data, and protect against attacks on the wireline ground network;
3. User domain security: the set of security features that protects against access to MS by unauthorized users; and,
4. Application domain security: the set of security features that enable applications in the MS and in the external PDN to securely exchange messages.

3. CADLS/TDN DATA LINK AND NETWORK PROTOTYPE

We are currently developing a CADLS/TDN prototype. The TDN network components have been implemented mostly on embedded COTS platforms—in particular, processor cards housed in 6U compact PCI (cPCI) chassis. The CADLS data link baseband has been developed on a DSP/FPGA PCI Mezzanine Card (PMC), housed in cPCI chassis with 3U form factor for the mobile station (MS) and 6U form factor for the base station (BS). The IF and RF components of the data link are currently under development, based on COTS components.

All the components of the prototype under development are COTS. The mobile, for instance, consists of a processor card, a DSP/FPGA card, an IF card, and a RF card, all COTS. The processor card has a Pentium processor and it implements the host program and the MAC layer, and also provides system I/O on the front panel. The DSP/FPGA card, which has four Analog Devices TigerSHARC 201 DSPs and one Xilinx Virtex Pro II FPGA, implements the PHY layer. The MAC layer, additionally, may be moved to the embedded PowerPC processors in the Xilinx FPGA in order to integrate the PHY and the MAC tightly. The IF card has A/D and D/A converters and a Xilinx Virtex Pro II FPGA, and it translates between the baseband signal from the DSP/FPGA card and the 70 MHz first IF frequency; the FPGA on the IF card is used to implement interpolation, decimation, and digital mixing. The RF card, as yet not in the system, converts the 70 MHz IF frequency to a second IF frequency at 374 MHz, and then to RF in the 2.4 GHz ISM band.

The data link portion of the CADLS/TDN system consists of the mobile and the base station, currently connected together using a baseband-to-baseband linkport. Once the IF and RF cards are integrated in the system, this baseband-to-baseband umbilical cord will be replaced by a wireless link. The base station is connected to the Wireless Access Gateway (WAG) of the TDN system. This end-to-end setup may be tested by connecting an application to the mobile at one end and the MGW at the other. We use a Video and Voice over IP (VVoIP) application, using a webcam and a Voice over IP (VoIP) phone for this test. The video data stream requires high throughput and the voice data stream requires low latency; between them, both the throughput and the latency performance of the CALDS/TDN end-to-end system are tested.

Table 4 shows the current performance of the CADLS baseband prototype together with the TDN system. For the video data stream, 15 picture frames per second are transmitted in each direction, each frame with a data size of 2900 Bytes. For the voice data stream, G.711 compliant voice packets, each of 800 Bytes, are used. The total data rate is 444 Kbps in each TDD direction, with 10 msec end-to-end latency for the voice packets. The cumulative end-to-end system data rate currently achieved by the CADLS/TDN baseband prototype in a single UMTS TDD channel is close to 900 Kbps.

Table 4—The CADLS/TDN end-to-end system performance in Video and Voice over IP (VVoIP) tests in the laboratory.

Link Direction	PHY Layer Voice Packet Size (Bytes)	PHY Layer Video Frame Size (Bytes)	Total Data Rate (Kbps)
MS to BS	**800**	**2900**	**444 Kbps**
BS to MS	**800**	**2900**	**444 Kbps**

4. CONCLUSIONS

We presented the system architecture and design details of an UMTS-based data link and data network solution for high dynamic telemetry and TSPI applications. We also presented the results of simulation and analysis that show the performance of the said solution. The end-to-end data link and network solution is currently under development as a COTS-based prototype. In subsequent papers, we will detail the results of the prototype effort. We are also working on extending the data link with multi-antenna MIMO technology for higher data rates and longer range, the results of which will be the topic of future papers.

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