ESA Satellite Wideband CDMA Radio Transmission Technology for the IMT-2000/UMTS Satellite Component: Features & Performance

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Abstract

The recent European Telecommunications Standards Institute (ETSI) decision to endorse for the Universal Telecommunication Radio Access ??? (UTRA) techniques based upon wideband-CDMA approaches for terrestrial UMTS (T-UMTS) paired frequency duplexing band will certainly constitute an important driver to orientate the corresponding choice for the satellite UMTS (S-UMTS) component. In this paper it is shown how a similarity in the S-UMTS access solution not only contributes to making dual-mode user-terminals more cost-effective but also represents a good technical choice. This is despite the fact that the satellite UMTS component faces a number of unique challenging requirements, such as very scarce RF power resources compared to T-UMTS, significant propagation delay, high frequency variations due to Doppler shift (especially for the Low-altitude Earth Orbit (LEO) case), larger cell size. This paper describes the main ETSI UTRA modifications required to obtain an efficient S-UMTS air interface capable of suiting the above listed constraints, while keeping maximum commonality with the T-UMTS. The proposed W-CDMA air interface implements satellite path diversity in both forward and reverse link, burst forward link pilot, blind MMSE forward link interference mitigation, pilot-aided coherent uplink demodulation. The main W-CDMA performance simulation results both at physical and system level are shortly reviewed.

1. INTRODUCTION

The rapidly growing wireless communication market is already introducing data services on top of voice to answer the request for Internet access capability from hand-held or palm-top terminals. Unfortunately, the data rates supported by second-generation digital cellular networks (e.g. GSM, IS-95) are rather limited and not matched to Internet browsing, electronic document transfer and multimedia services such as video-conference.

In the general IMT-2000 standardisation frame pursued by the International Telecommunication Union (ITU), the ETSI-sponsored Universal Mobile Telecommunication System (UMTS) is aiming at the definition of a unified third-generation global wireless system operating in the 2 GHz band. The UMTS is expected to support a wide range of connection-oriented and connectionless services with data rates up to 384 kbit/s in outdoor environments and up to 2 Mbit/s in indoor environments. The service bit rate can be negotiated at call setup or even on a frame by frame basis in a very flexible way. By service and terminal classes definition, the standardisation effort has identified the core network functionalities that are air-interface independent. While the non radio-dependent core network will most likely encompass heterogeneous network technologies, radio technologies are being standardised in order to maximise the global system nature. A large effort is presently devoted to the selection of one or a few air-interface proposals capable to efficiently support the UMTS/IMT-2000 requirements. The global UMTS/IMT-2000 target calls for the service provision in a host of environments ranging from indoor pico-cells to satellite mega-cells.

The unique satellite role to fill-up macro-cells over scarcely populated regions has been widely recognised in UMTS/IMT-2000. For the first time the satellite is seen as an integral part of a cellular global communication network. It is also recognised that, due to technological constraints the satellite services can only represent a sub-set of the Terrestrial-UMTS (T-UMTS). Nonetheless, successful satellite integration in the more general UMTS framework calls for the definition of an efficient, yet flexible, air-interface well matched to the satellite mobile environment.

In this framework, ESA has undertaken a study on the S-UMTS air interface heading to a test-bed demonstration activity the main results of which are summarised in the following. The S-UMTS air interface definition has been performed with a close look to the ongoing ETSI T-UMTS standardisation activities in order to maximise commonality. Exploitation of a common T-UMTS technology will in fact contribute to largely reducing the dual-mode user terminal cost and size[1] thus boosting S-UMTS commercial opportunities.

2. SW-CDMA FOUNDATIONS & RATIONALE

For a W-CDMA option main technical issues are related to the need to offer a very large system capacity and to allow flexible provision of a large set of multimedia services. In particular, optimisation of system capacity may lead to the selection of slightly different approaches. Initial in-depth capacity and quality of service assessment [3], [14] indicated that CDMA/FDMA has the highest potential for a global satellite system. The main CDMA choice drivers are: higher capacity then TDMA, full frequency reuse easing resource allocation, satellite softer hand-off, satellite path diversity exploitation for improved quality of service, fading effects mitigation, MES EIRP reduction, applicability of interference mitigation techniques (MUD), flexible support of a wide range of services, provision of accurate user positioning, graceful degradation under loaded condition, simplified satellite antenna design[2], compatible with adaptive antennas, widely adopted by terrestrial RTTs. For single satellite in view regional systems based on GEO or HEO orbits the adoption of hybrid Code/Time Division Multiple Access (C/TDMA) [1], [2], [3] may also represent an interesting option. However, in the following only the global coverage system exploiting SW-CDMA scheme is considered.

Channel behaviour is different for T-UMTS and (LEO/MEO-based) S-UMTS. The T-UMTS channel is typically affected by Rayleigh fast fading and lognormal short-term power fluctuation. A line-of-sight (LOS) component, which reverts the fast fading to be Rice distributed, can only be expected in specific pico-cellular environments, while in the majority of situations the LOS component is absent. Under this assumption, the presence of a Rake receiver is advisable, as proposed by terrestrial W-CDMA schemes [1], so that the strongest multipath rays may be collected and coherently combined. Rake diversity, provides increased quality of service mitigating fading/shadowing effects and allowing for softer hand-off. Due to the larger LEO satellite free space loss and on-board RF power scarcity, mobile satellite systems are forced to operate under line-of-sight propagation conditions[3]. This typically results in a milder Ricean (or at most Rice-lognormal) channel. The satellite channel scattered multipath power with differential delays exceeding 200 ns most often results to be of insufficient level to be usefully combined by the rake receiver

To fully exploit the advantages of a Rake receiver in a satellite environment, the diversity condition may be artificially realised through usage of more than one satellite (satellite path diversity). In this way the W-CDMA T-UMTS rake advantages can also be exploited also in the satellite framework. Satellite path diversity aims at providing increased efficiency and quality of service, with a proper system and constellation design. As mentioned above, this gives the advantage of allowing the use of Rake receivers, and also allows implementing soft-handover algorithms. In a CDMA system the advantage in terms of increased power level comes for free in the return link, due to the MES antenna omni-directional characteristic. On the contrary, in the forward link to achieve satellite diversity the gateway must purposely deliver the same signal towards two (or three) satellites, and this must be done judiciously not to waste system capacity. It was found that satellite path diversity is indeed essential to provide high quality of service with minimum RF power requirements from both the satellite and the user terminal. While this conclusion is quite intuitive for the reverse link for users equipped with omni-directional antennas, the same can not be easily argued for the forward link whereby path diversity requires resources assignment to the different satellites [COR]. In the forward link satellite diversity is implemented also to assist handover. For the SW-CDMA several approaches in soft-handover implementation have been identified [9].

Differently from terrestrial systems experiencing huge (up to 80 dB) signal dynamic due to path loss and fading/shadowing effects, satellite systems are characterised by a smaller useful signal dynamic. This is due to the different system geometry (reduced path loss variation within each satellite beam), milder fading channel conditions and limited satellite RF power to counteract blocked conditions. Power level fluctuations due to the user location within the satellite beam typically lies in the 5 dB range. Rice fading factors are typically between 7 to 15 dB. A major power level variation effect is due to the local environment in which the MES is located. In fact, the signal level may be severely shadowed by hills, trees, and buildings; the car's body, and the head of the user can also have a non-negligible impact. Shadowing can lead to 10-20 dB of excess attenuation and can cause link outage.

Although the so called near-far effect in S-UMTS is not as bad as for T-UMTS, power control must be implemented not to waste precious power and system capacity. Slow (trackable) required link power level variations are due to different causes such as satellites motion[4] (path loss changes), satellite and user antenna gain variations, specular reflections

[1] This cost/size reduction will be eased by the fact that T-UMTS and S-UMTS are assigned to adjacent frequency bands.

[2] It has been shown that the average I/C and not the worst-case I/C is the key antenna figure on top of gain.

[3] At least for medium-to-high data rates

[4] This effect tends to be compensated by the so-called iso-flux antenna design that attempts to equalize the geometry dependent path loss with antenna gain shaping.

and shadowing (environmental effect), user speed changes, time varying co-channel interference. As in T-UMTS, a combination of open-loop for random access channels and closed-loop power control for connection-oriented links[5] is required. However, due to the longer satellite propagation delay a power control correction per frame (and not per time slot) is typically sufficient in S-UMTS.

The (fast) moving satellite characteristic in LEO/MEO/HEO constellations generates a remarkable Doppler effect that shall be accounted for in the system design. The main Doppler impact is the need of special measures for initial signal acquisition and carrier tracking. Most of the Doppler can however be pre-compensated for[6] thus reducing the frequency uncertainty.

Within the ESA project [2] an existing software simulation tool (SATLIN) [7] was improved to evaluate LEO system performance in the presence of all main kind of impairments and countermeasures which can be present in the S-UMTS scenario. For both forward and return links, system impairments taken into account are power fluctuations due to both the geographical effect over spherical earth, and the environmental effects due to shadowing under varying elevation angles, and time-variant interference produced by other users. For different multiple access schemes, including CDMA, several countermeasures have been considered, taking into account realistic power control strategies for both links, satellite diversity, and interference reduction techniques [7].

In the satellite forward link (gateway station-to-mobile terminal), where all signals per spot can be easily synchronised, a single common pilot can be inserted to achieve coherent detection at the MES and to initially adjust power level in return direction (open-loop power control). Also time domain multiplexing of pilot symbols (TDMP) in the useful data stream in pre-assigned time slots is possible to support adaptive satellite antennas. In the return link a pilot can be paired to each information signal. The reduction in power level (around 10-20% power on pilot is typical) is balanced by the benefit of coherent detection at the gateway [8]. Code division multiplexing of an auxiliary channel carrying pilot symbols and signalling information (rate information, power control bits..) (CDMP) was found preferable from the system perspective.

3. SW-CDMA VS UTRA

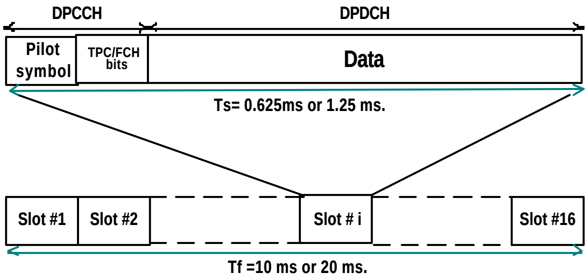
As stated before, ESA SW-CDMA proposal[7] was derived from the ETSI UTRA proposal, incorporating the minimal changes needed to suit the specific satellite environment constraints. The main driving factors, in addition to the harmonisation with the terrestrial T-UMTS proposals, were the introduction of new advanced features aiming at improving the power and spectrum efficiency and the flexibility of the satellite system[8]. In particular, the following features are supported:

- a wide range of bearer services (from 2.4 Kb/s up to 144 kbit/s),
- power and spectral efficiency through: path diversity exploitation, coherent demodulation on the return link, multi-user detection scheme on both the forward link and return link, overhead reduction due to the use of a common pilot/beam approach, compatibility with adaptive antenna systems),
- MES localisation capabilities.

Two chip rate options are supported: a 4.096 Mchip/s option (the same as the basic chip rate in UTRA proposal) and a half-rate option (2.048 Mchip/s) which may be more suitable in a multi-operator environment where bandwidth limitation may arise.

The same types of physical channels as in the UTRA proposal are defined. Hence, for each dedicated data channel (DPDCH) a dedicated control channel exists (DPCCH) which has the same purpose as in the T-UMTS system, i.e. to support coherent demodulation (TDMP pilot insertion scheme), power control functionsand data rate agility.

Fig. 1 shows the frame structure of the DPDCH and DPCCH. The frame length can be either 10 ms (as in UTRA) or 20 ms when the half chip rate option is adopted. The forward link modulation and spreading strategies are similar to those of the UTRA proposal. However, BPSK modulation instead of QPSK modulation is proposed for the lowest data rate services (2.4 kbit/s) to reduce the sensitivity to phase and frequency jitter. Also, Transmit Power Control (TPC) bits are coded together with (Frame Control header (FCH) bits using a bi-orthogonal code spanning the whole frame. Hence, the up/down power control commands rate is reduced compared to UTRA to a single command/frame, this being fully adequate taking into account the large satellite propagation delay.



[5] For both forward and reverse link.

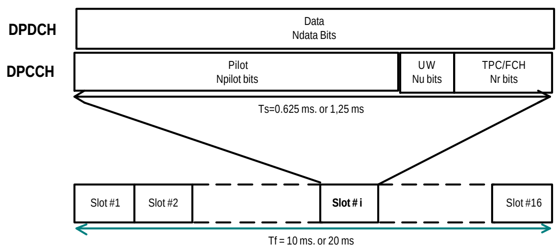
[6] At least for feeder link part (satellite-to-gateway) and for the downlink center-of-beam.

[7] Which has also been translated into a formal ESA IMT-2000 RTT submission to the ITU [10].

[8] As independent as possible from the specific global constellation characteristic.

[9] Due to the large satellite propagation time, up/down power control commands rate is reduced compared to UTRA to a single command/frame.

a) forward link



b) return link

Figure 1: *Frame Structure of the Forward and Return Link Dedicated Physical Channels (DDPCH/DCPCH).*

Another difference with respect to the UTRA proposal is the use of a short randomisation (scrambling) code[10] (an extended Gold codes of length 256 chips) since benefit may arise from the use of adaptive linear interference mitigation techniques even on the forward link [11], [12]. Differently from the terrestrial case, in fact, the forward link in a satellite environment is likely to represent the actual bottleneck as far as capacity is concerned. On-board power is a scarce resource and its use has to be optimised. In this respect, mitigation of interference on the forward link may thus lead to a reduction of the required satellite power and/or capacity and quality of service increase. A practical yet efficient MUD technique applicable to the SW-CDMA is the so-called Complex Blind-Adaptive Interference mitigating Detector (EC-BAID). The EC-BAID is essentially an adaptive (constrained) FIR filter, described in Ref. [12], [13], whose coefficients are updated according to a modified minimum mean square error (MMSE) rule. This scheme has been recently extended to cope with practical LEO/MEO satellite working conditions.

Common Control Physical Channels (CCPCH) will be available on the forward link. In particular a Primary CCPCH will carry the Broadcast Control CHannel (BCCH) as well as reference symbols to support initial acquisition, coherent demodulation and time ambiguity range extension as necessary for supporting satellite diversity operation on the forward link. The primary CCPCH has a fixed transmission rate (16 kbit/s in the full chip rate option and 8 kbit/s in the half chip rate option. To support time ambiguity range extension for satellite diversity operation, a Unique Word (UW) is modulated on some of the reference symbols carried by the DPCCH. A similar approach as in UTRA is proposed for the Random Access CHannel (RACH)[11]. A CDMP pilot insertion scheme has been selected for the reverse link.

Initial forward link acquisition is performed by means of ad-hoc unmodulated referece symbols inserted in the primary CCPCH. One of this special purpose reference symbols is inserted at the beginning of each time slot. Hence, even in case the long randomization (scrambling) code option is selected, always the same 256 chips are used by such reference symbols. These periodically inserted reference symbols act as a common bursty[13] pilot as far as initial acquisition is concerned.

Being the 256 chips long pilot channelization code also known (typically the all zero sequence code[14]), a mobile terminal at the switch on must only search for the randomisation code of the common pilot. If neither mobile location information nor satellite positioning information is available, the mobile terminal has to search for all possible randomisation codes. Randomisation code allocation can be done according to several strategies also depending on the constellation and payload (transparent or regenerative) types as well as the degree of synchronisation accuracy of the Land Earth Stations (LES). For regenerative payloads (or transparent payloads with synchronised LES), each satellite will typically use a single randomisation code. Different cyclic shift of the same randomisation code will be assigned to adjacent beams of the same satellite. Frames on adjacent beams are offset by a small integer number of symbols plus few chips representing the cyclic shift of the code. To reduce the number of codes to search, especially in case the satellite constellation is composed by a large number of spacecraft, scrambling code reuse between different satellites may be planned in order that satellites having the same coverage area never reuse the same code. Clearly, knowing the mobile position and satellite ephemerides could accelerate the search process. For transparent satellites, with non-synchronised LES, a different scrambling code can be assigned to each couple LES-satellite with an increase of the total number of codes to be searched. Code reuse can still be planned, however, to limit the number of codes to be searched during cold start-up. For a given code to be searched, if a satellite using that code is actually in visibility, more correlation peaks, in a single code period, will be usually detected, each corresponding to the different phases of the same scrambling code used in adjacent beams. The highest peak will be chosen.

[10] An optional slot length (2560 chips) longer randomisation code is proposed for SW-CDMA in case non forward link mitigation techniques are adopted.

[11] Analysis showed that a longer preamble sequence is however needed for the satellite application (48 symbols against 16 in UTRA).

[12] Detailed analysis showed the bursty pilot advantage for initial signal acquisition compared to conventional continuous pilot IS-95-like (assuming equal average energy per chip). The bursty pilot has approach is common to the UTRA proposal.

[13] Detailed analysis showed the bursty pilot advantage for initial signal acquisition compared to conventional continuous pilot IS-95-like (assuming equal average energy per chip). The bursty pilot has approach is common to the UTRA proposal.

[14] The channelization code of the reference symbols is the same as that of the other symbols of the primary CCPCH in case of the long randomization code option. Viceversa, a channelization code different from that of the other symbols in the primary CCPCH has to be used in case of the short randomization code option.

Once a pilot has been acquired, the primary CCPCH can be despread being the primary CCPCH spreading (channelization) code a system constant. The BCCH also contain a list of candidate satellites with the associated scrambling codes in order to accelerate the other satellite acquisition.

4. PERFORMANCE RESULTS

An extensive analysis and simulation work was started with the aim to validate the proposed S-UMTS access. Some of the obtained results are here summarised. Fig. 4 shows the mean time to acquisition of the forward link pilot evaluated as a function of the chip energy to thermal noise density, E_c/N_0. The computation assumes that the user is at the cross-point of three equal loaded beams and that in each beam only 3.3% of the beam power is dedicated to the pilot. The possibility that the frequency is in error of up to 20 KHz was considered.

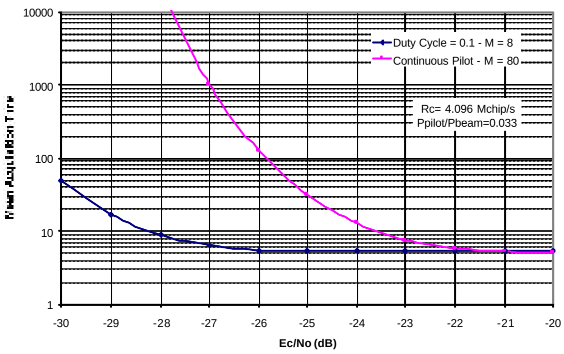


Figure 2: *Forward link mean acquisition time (ms.) versus pilot thermal E_C/N_0 for a continuous and bursty pilot.*

It was found that the UTRA bursty pilot outperforms the continuous pilot (for the same average thermal E_C/N_0) for what concern initial acquisition time and was therefore selected for SW-CDMA. A great effort has been dedicated to the trade-off between BPSK, dual-BPSK and QPSK modulation on the forward link as well as between coherent and non-coherent modulation on the return link. In the absence of non-ideal effects such as carrier phase synchronization errors QPSK with real spreading was found optimal from the MMSE interference-mitigating detector point of view [14]. Fig. 3 shows the forward link performances, also including the effect of frequency/phase/timing jitter (in addition to phase noise) coming from a practical carrier frequency offset estimator. The advantage provided by the Blind MMSE interference mitigating detector [13] is apparent.

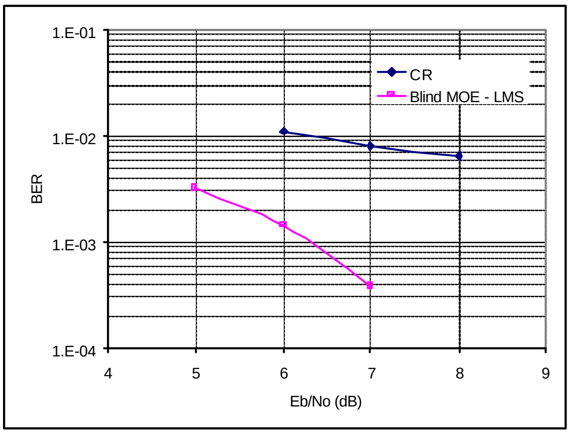


Figure 3: *Forward link performance in presence of slow fading, single and dual diversity. (TO BE UPDATED)*

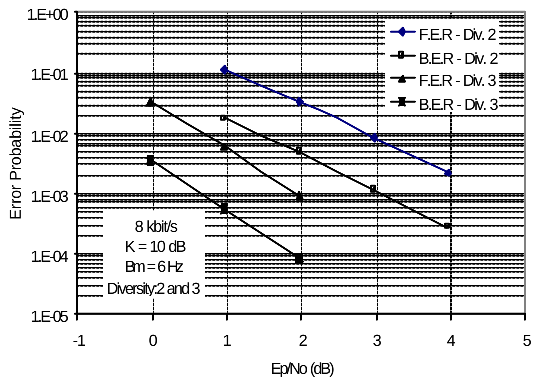


Figure 4: *Reverse link performance in presence of slow fading, single, dual and triple diversity. (TO BEUPDATED)*

In the reverse link, CDMP quasi-coherent uplink was found to provide a gain higher than 1 dB compared to the 64-WH modulation even at very low symbol rates (up to 2.4 kbit/s). Reverse link simulation results of Fig. 4 for the worst-case slow fading conditions shows performances in slow fading. It appears that path diversity advantage is dramatic even when not considering the blockage probability and MES EIRP reduction benefits provided by satellite diversity.

Reverse link results with CDMA interference mitigation techniques have been derived by simulation. Both blind-MMSE [13] and Turbo MUD [14] have been considered. The centralized gateway architecture, whereby many traffic channels are simultaneously demodulated, will make possible to implement true MUD schemes. However, Blind-MMSE showed also its potential application for situations whereby the satellite differential chip clock Doppler is bounded to a few chip/s.

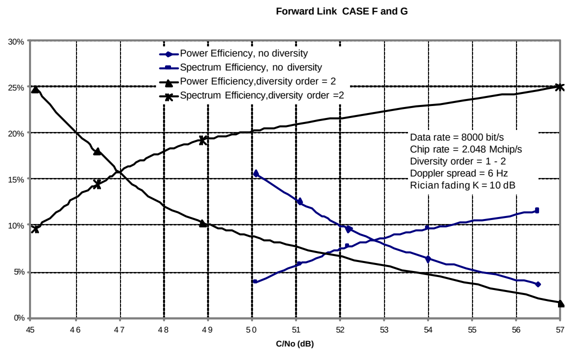


Figure 5: *Forward link power and spectral efficiency for single and dual path diversity.*

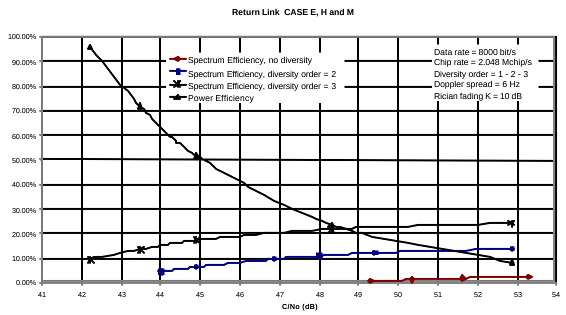


Figure 6: *Reverse link power and spectral efficiency for single and dual path diversity.*

Extensive system link budgets computations both using the SATLIN dynamic system simulation tool and the more conventional link budgets have been performed according to the ITU methodology described in [10]. In all cases no interference mitigating detectors have been included. Fig. 5-6 show that power efficiency decreases when increasing spectrum efficiency; the choice of these parameters, then, should be exploited considering all system constraints and traffic loading. The lower reverse link efficiency is mainly related to the non-orthogonal intra-beam CDMA interference not present in the forward link. For what concerns *slow fading* cases some considerations can be done on the benefits related to diversity adoption. Considering the forward link, the improvement achieved with diversity order 2, in term of spectrum efficiency, is shown in Fig. 5 (referring to data rate = 8 Kbit/s). It can be noticed that same values of power efficiency correspond to higher values of spectrum efficiency; this benefit could also be expressed in term of power efficiency improvement due to diversity for the same spectral efficiency. Link budgets relative to return link clearly show macro-diversity benefits, in terms of terminal EIRP reduction with respect to cases where diversity is not employed. Diversity advantage increases with the actual diversity order. Fig. 5 shows how spectrum efficiency increases with diversity order for a case of slow fading in the reverse link. It should be observed that, contrarily to the forward link, the power efficiency curve of Fig. 5 applies to all diversity orders.

The power control operation is very similar to the terrestrial one discussed in terrestrial RTTs [1]. Some minor adaptation to the satellite longer propagation delay is however required

The proposed closed loop power control is able to counteract a deep fading due to shadowing which may be promptly recovered in a time which is typically less than 1 sec, depending on the satellite orbit height. Simulations showed that the power control loop transient consequent to a sudden received 10 dB signal power drop in a Ricean fading channel can be recovered within less then 0.5 sec. The simulated system had a total loop delay of 120 ms. and a power control step of 0.5 dB. Simulation indicated that a margin of about 1 dB is required to satisfy the target 10^{-2} FER with power control for the slow fading case. This value should be compared with the much larger margin that would otherwise be required in absence of power control. Finally, it shall be underlined that the power control margin is not significantly dependent on the loop delay as shown in Fig. , at least for loop delay in excess of 100 ms. and Doppler spread exceeding a few Hz. *This makes the shown system performance practically constellation height independent under line-of-sight conditions.*

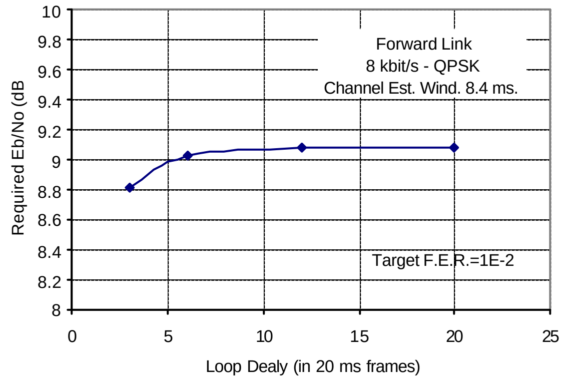


Figure 7*: Required Eb/No for F.E.R.=10^{-2} as a function of the loop delay (power control gain step=0.5 dB) for a slow fading case (Doppler spread= 6 Hz).*

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5. CONCLUSIONS

The ESA SW-CDMA IMT-2000 radio transmission technology represents an efficient *open* S-UMTS air interface proposal for global systems closely derived from the emerging T-UMTS W-CDMA. The proposed approach will soon be thoroughly validated by means of a comprehensive test-bed that will be developed under ESA support as part of the on-going activity.

BIBLIOGRAPHY

[1] http://www.itu.int/imt/ Radio/Proposals.

[2] European Space Agency Contract No. 12497/NL/97/NB, *Robust Modulation and Coding for Personal Communication Systems.*

[3] B. Lyons, B. Mazur, J. Lodge, M. Moher, S. Crozier, L. Erup, "*A High Capacity Third-Generation Mobile Satellite System Design",* European Trans. On Telecommunications, vol. 9, No. 4, July/August 1998.

[4] Square-Peg Communications Inc. "*A Transmission System for Future Satellite Mobile and Personal Communications*", Final Report ESA Contract No. 11515/95/NL/US, May 1997.

[5] E. Biglieri, G. Caire, G. Taricco, *System Capacity*, Technical note ESA contract N. 12497/NL/97/NB.

[6] F. Adachi et al., *Tree Structured Generation of Orthogonal Spreading Codes with Different lengths for the Forward Link of DS-CDMA*, Electronics Letters, Vol. 33, No.1, pp.27-28.

[7] F. Vatalaro, G. E. Corazza, C. Caini, C. Ferrarelli, *Analysis of LEO, MEO, and GEO global mobile satellite systems in the presence of interference and fading*, IEEE J. Sel. Areas in Commun., Vol. 13, N. 2, Feb.1995, pp. 291-300.

[8] G. E. Corazza, R. De Gaudenzi, *Pilot-aided coherent uplink for mobile satellite CDMA networks*, to appear on IEEE Trans. on Comm., 1999.

[9] G. E. Corazza, "*Evaluation for the CDMA Option Definition*", Technical Note to ESA Contract No. 12497/NL/NB/97, Robust Modulation and Coding for Personal Satellite Communication Networks.

[10] http://www.itu.int/imt/ Radio/Evaluation/esa.

[11] P. B. Rapaijic and B. Vucetic, *Adaptive Receiver Structures for Asynchronous CDMA Systems*, IEEE J. Selected Areas in Commun., vol 12, pp. 685-697, May 1994.

[12] M. Honig, U. Madhow and S. Verdu', *Blind Adaptive Multiuser Detection*, IEEE Trans on Inf. Theory, vol 41, pp. 944-960, July 1995.

[13] R. De Gaudenzi, J. Romero-Garcia, F. Giannetti, M. Luise, "*A Frequency Error Resistant Blind Interference Mitigating CDMA Detector",* IEEE 1998 Fifth International Symposium on Spread-Spectrum Techniques and Applications, Sun City, South Africa, September 1998.

[14] P. D. Alexander, A. J. Grant, M. C. Reed, *"Iterative Detection in Code Division Multiple Access with Error Control Coding",* European Trans. on Telecommunications, Vol. 9, No. 5, September/October 1998.