RADIO LEVEL NETWORK ANALYSIS FOR VEHICLE COMMUNICATIONS

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The article is the result of a research which has proposed to analyse the best option of on-board communications systems improvement, considering the GSM / GSM-R and TETRA platforms already implemented and adopted in all EU countries. Particularly, the goal is to identify improvement solutions for extending the capacity of existing communication channels by adopting improved modulation models and error reducing solutions.

Keywords: GSM, TETRA, radio, propagation, modulation, QPSK, DQPSK, emission, transmission, error, model, correction

1. Introduction

The continuously increase of the car traffic but also the real-time data exchange needs between vehicles and vehicles-to-infrastructure imply significant improvements to radio infrastructure, but also increase the terminal performances, especially for vehicle to vehicle transmissions.

On the other hand, considering the standard limitations of the emission power, in order to ensure the physical channel relocation in small range area, there is a necessity to consider improved propagation models and continuous emission parameters settings according to receiver feedback.

The author's research starts from existing technologies which are large scale implemented and concentrates on defining a new transmission model, fully compatible with existing infrastructure and also capable to increase significantly the channel capacity.

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2. Motivation

One of the biggest problems of all radio networks is the continuous traffic increase and the physically limitations of the available channels. All systems and technologies capable to increase the data flow using existing channels and also limiting the transmission power to reasonable values – the limited power ensure a reliable usage of the channel, but, on the other hand, reduce the signal to noise ratio and obviously the quality of the received signal.

The traditional trunking radio suffers of the risk of network congestion, considering the physical channel load (L) is:

$$B_1[\%] = \frac{\sum_i \tau_{ci}}{T_d} \cdot 100 = L \quad (1)$$

Where: - *$L=B_1[\%]$ represents one channel load,*

- *i represents the number of users*
- *τ_{ci} - average allocated time for each end-user transmission*
- *T_d – total allocated time for one message transmission*

In case of one physical channel, the statistic availability of the channel / network is:

$$F_1 = \frac{T_d - B_1}{T_d} = \frac{T_d^2 - \sum_i \tau_{ci}}{T_d^2} \quad (2)$$

where *F_1 represents the statistic availability of the physical channel*

Considering a real network with a number of "k" physical channels, the network load is:

$$B_k = \frac{B_{canal}}{k}$$ *- total load of a real network with "k" physical channels* (3)

Thus, the network availability increases proportionally with the number of channels, but it can decrease significant in case of terminal agglomeration. The risk of network congestion can be defined as:

$$B_{logical\ ch}[\%] = m \prod_{i=1}^{m} B_i\,\% = m \prod_{i=1}^{m} \frac{\sum_{im} \tau_{ci(m)}}{T_d} \cdot 100 = L(m)_{logical\ channel}\,[\%] \quad (4)$$

Where: m – total number of physical channels which generate the logical channel;

B_i – load of each physical channel (statistic);

T_i – time of end-user transmission;

T_d – total channel allocation for one message;

B[%]=L(m) – total load of the logical channel (statistic).

Considering a network consists by "m" physical channels, the network availability becomes:

$$F_m = m \prod_{i=1}^{m} \frac{T_d^2 - \sum_i \tau_{ci}}{T_d^2} \cdot 100 \quad (5)$$

Considering the parameter "*N*" as the total number of available channel, the parameters results as follow:

$$\mathrm{L} = \frac{1}{N}\sum_{1}^{N} L^{(K)} \quad (6)$$

– average network load

$$\mathrm{B_N}[\%] = \prod_{1}^{N} \frac{\sum_i \tau_{Ci}}{T_d} \cdot 100 \quad (7)$$

– network congestion probability

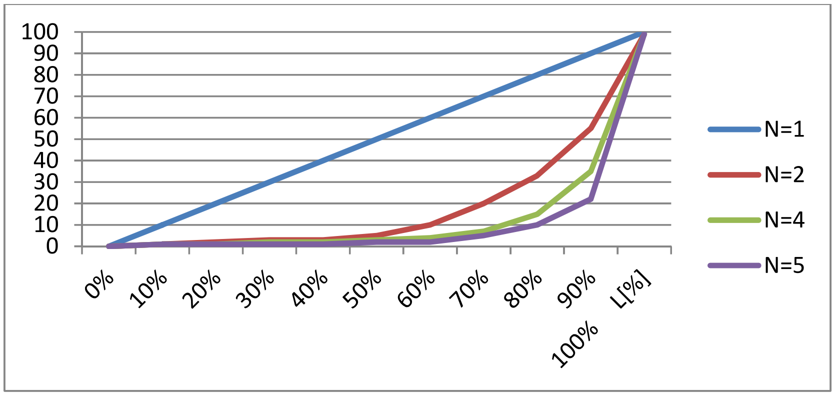

Fig.1. Network congestion probability depending of load and number of channels

By realizing the congestion condition:

$$\left[\prod_{k=1}^{N} L^{(k)}\right]^{\frac{1}{N}} \leq \sum_{k=1}^{N} \frac{L^k}{N} \quad (8)$$

The result is the network congestion probability factor, as:

$$B_N = L^N \quad (9)$$

The analysis demonstrates that for a professional network usage it is realistic to use a physical network with 5 to 20 allocated channels, but increasing over this number it's unreliable, considering the cost-benefit analysis.

Particularly, the GSM / UMTS[1] and TETRA[2] network register a high density of terminals, considering the fact that each vehicle can register onboard an average of 3 or even 4 terminals (eCall terminal, GPS / navigation / vehicle terminal, driver and passenger's terminals), so it is expected that network improvements are necessary. The standards imply TDMA technology with a space of 25kHz (for TETRA[4]) and 200kHz (GSM). As a facility, Tetra standard allows users to operate both under network coverage but also independently, from one terminal to another (DMO - Direct Mode Operation) – for this, Tetra terminals are equipped with supplementary duplex filters and some models can ensure repeating facility (by data buffering).

The particularity of these standards which tried to solve the data flow capacity of the physical channel is the specific modulation, which increases significant the real capacity and also keeps the error level quite low, in order to ensure a good enough quality message out of receiver. The radio interface uses π/4 DQPSK[7] (differential quadrature phase-shift keying) modulation with fixed transmission rate and 2 phase shift. The adopted model in GSM[1] and TETRA[2] use two carriers and quadrature key modulation, with a shift phase of 45° (*π/4 rad*). Currently, the symbols are placed in constellation, in order to ensure statistic error correction – this has also a typical disadvantage, because supplementary errors appears due to wave reflection, fading and Doppler effect shifting at vehicle high speed. A specific propriety of this model is that the successive shift never cross the origin (*π rad*), which ensures that the signal is always in a demodulate phase. Well-known as quadric-phase demodulation, QPSK can be implemented similarly as BPSK (binary phase shift key), but it uses an 8 binary points constellation (4 information and 4 for correction). The symbol representation is as follows:

(10)

– symbol representation

where: n = 1,2,3,4 and generates possible phases as:

f_c- carrier frequency.Thus, the results ensure two representing solutions:

(11)

– 1st phase for symbol

(12)

– 2nd phase for symbol

And the two possible values for each phase are:

) (13)

The ½ factor indicates the fact that the emission power is similar and equal in all transmissions mode.

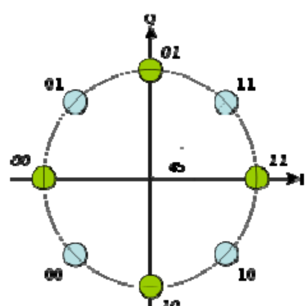

Fig.2. Binary DQPSK [7] modulation polar constellation representation

The error correction for π/4-DQPSK[7] can be made starting from the supposition that the transmission is made in dual mode, using two similar symmetrical components, with π/4 phases shift one to another. Thus, the odd bits are used for main carrier modulation and the even bits are used for the secondary carrier modulation. The error probability for each bit is:

$$P_b = \left(\sqrt{\frac{2E_b}{N}}\right) \quad (14)$$

Where: P_b is the total error probability for a transmission sequence
E_b – Total number of symbols over the message
N – Number of symbols

The differential modulation (DPSK) and quadrature (DQPSK) are two particular forms which change the carrier phase on fixed predefined positions. According to previews analysis, those models can induce a less-precision demodulation, generated by the "constellation rotation phenomenon", which appears especially because of fading, multiple reflections and high speed of the receiver device (antenna) and the result can be up to channel de-synchronization. Generally, statistic correction is possible, but the best results are registered using template data sequences, which ensure recalibration of the receiver.

In order to reduce the error probability (ideally similar with minimal binary phase - BPSK), each symbol is represented by 2 bits and QPSK uses double transmission in each pair (2 bits are transmitted simultaneous). Thus, the error rate for each bit becomes:

$$P_{binar} = 1 - (1 - P_b)^2 = 2Q\left(\sqrt{\frac{E_s}{N_0}}\right) - Q^2\left(\sqrt{\frac{E_s}{N_0}}\right) \quad (15)$$

P_{binar} – total error probability for a transmission sequence using BPSK
Q – statistic channel (logic) quality
N_0 – number of symbols per character

If the noise level is too high or the signal to noise ratio is too low, the error probability can be approximate for each symbol as:

$$P_s \approx 2Q\left(\sqrt{\frac{E_s}{N_0}}\right) \quad (16)$$

- error probability for a transmission, ideal channel

As result, considering real difficult conditions, the error probability for "N" symbols message (plus 2 special signs for signalization) can be approximated as:

$$P_{err_{msg}} = (N+2)\left[1 - (1 - P_b)^2 = 2Q\left(\sqrt{\frac{E_s}{N_0}}\right) - Q^2\left(\sqrt{\frac{E_s}{N_0}}\right)\right]$$

$$\approx 2Q(N+2)\left(\sqrt{\frac{E_s}{N_0}}\right) \quad (17)$$

– total error probability for a transmission for the whole message

The result means that the error probability is apparently directly proportional with the number of signs – this means that for a longer message the risk of errors increase significant and the correction code need to be applied. On the other hand, by using calibration signs, the errors reduce significantly. For highly reliable networks (such as TETRA) the best solution is the adopted TEA[4] and of XTEA[4], [5] cryptanalytic correction algorithm.

The error probability for DQPSK is quite difficult to be evaluated in every different real condition, considering the continuous environmental and radio condition changes generated by the mobility of the terminal. On the other part, it can be approximated with the two-sign (binary) transmission:

$$P_{DQPSK} = \frac{1}{2} e^{-\frac{E_b}{N_D}} \quad (18)$$

– real condition error probability approximation

The research proposed is to extend the transmission constellation, inserting in the actual model a new set of pre-defined shifts and completion of the corresponding table, such as:

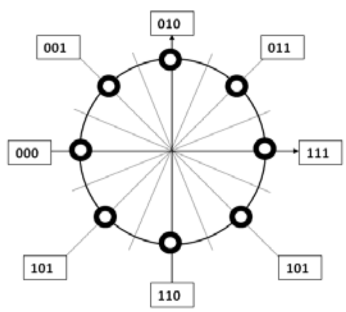

Fig. 3. Proposed 3 bit - DQPSK modulation polar constellation representation

The proposed method splits the free intervals in 2 equal sectors, the separation line being considered as the border between two separated consecutive symbols. Ideally, the transmission is set on fixed shift angles, but because of propagation phenomenon there will be considered an acceptable interval for approximate of correction, if necessary.

Considering the proposed constellation, the main difference between the first method and the proposed one is that the safety gap is reduced to just *π / 8 rad* (practically half of the initial model), but it is able to transmit 8 different signs instead of just 4, like in the previous version – thus, the total transmission capacity becomes quite double, without any intervention over the transmission infrastructure.

The symbol representation becomes as follows:

$$S_i^3(t) = \sqrt{\frac{4E_s}{T}} \cos\ (2\pi f_c\, t + (2n - 1)\frac{\pi}{8} \quad (19)$$

– symbol representation considering the proposed model, for a sequence with n combinations in constellation

where: n = 1,2,3,4,5,6,7,8 and generate possible phases as:

$$\frac{\pi}{8}, \frac{\pi}{4}, \frac{3\pi}{8}, \frac{\pi}{2}, \frac{5\pi}{8}, \frac{3\pi}{4}, \frac{7\pi}{8}, \frac{\pi}{1}, \frac{9\pi}{8}, \frac{5\pi}{4}, \frac{11\pi}{8}, \frac{3\pi}{2}, \frac{13\pi}{8}, \frac{7\pi}{4}, \frac{15\pi}{8}, \frac{2\pi}{1}$$

Considering real propagation conditions, the error probability for an “N” symbols message (plus 4 special signs for signalization) can be approximated as:

$$P_{err\,msg}^{\;3} = (N + 4)\left[1 - (1 - P_b)^3 = 2Q\left(\sqrt{\frac{E_s}{N_0}}\right) - Q^3\left(\sqrt{\frac{E_s}{N_0}}\right)\right]$$

$$\approx 2Q(N + 4)\left(\sqrt{\frac{E_s}{N_0}}\right) \quad (20)$$

– total error probability approximation for the proposed model

The result is that the error probability appears to be directly proportional with the number of signs, similar to the classic version.

3. Results and Conclusions

The differential quadrature modulations (DQPSK) ensure an error probability quite similar to other modulation systems (for example the binary one) and the loss data level is acceptable low. On the other hand, the DQPSK ensures at least the following two significant advantages:

- The real channel capacity increases significant, compared to all other modulation systems;
- The complexity of the receivers is significantly reduced; on-chip low power receivers become available, which ensure the accessibility of this technology in mobile and portable terminals industry.

The physical implementation (using discrete parts as demonstrator or on-chip embedded) can be easy made, using programmable fixed phase modulator chips and eventually low cost microcontrollers (for message decoding at receiver level).

For the next level developments, the DQPSK model can be improved at signalization level, using a three-state representation (total representation of 8 signs per constellation), which is expected to increase the channel capacity with at least 85%, keeping the error level at approximately the same levels, but also ensuring improved channel immunity against local existing transmissions. Combining this performance with the simple embedded one-chip implementation, the large scale implementation can be made with very low costs, using also existing chips (by simply reprogramming) and keeping radio interfaces as they are. Practically, the model improves the general performance of data radio systems (increasing capacity to double but also improving the reliability), keeping the implementation costs as minimum possible.

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