A. Kerekes, A. Zold
Effect of passive solar gain on the heating energy consumption and peak load of the system 2

E. M. Lobov, N. A. Kandaurov, E. O. Lobova, V. I. Lipatkin
Investigation of the influence of dispersion distortions of wideband signals on the quality of their delay and frequency shift estimation 11

V. M. Joao dos Santos
The current state and trends of the development of digital tele-radio broadcasting systems in the world 17

N. Zhumadil, S. Narbayeva, T. Bakibayev, K. Abeshev, K. Shubenkova
Blockchain for vehicles based on exonum platform 24

N. H. Hoang, T. V. Nghia, L. V. Ky
Implementation of FPGA-based DVB-T2 transmitter for a second generation digital terrestrial television broadcasting system 30

A. Vyukusenge
Dispersion compensation using electronic methods 33

Telecoms Outlook 2021
Corporates, Scope Ratings GmbH 39
EFFECT OF PASSIVE SOLAR GAIN ON THE HEATING ENERGY CONSUMPTION AND PEAK LOAD OF THE SYSTEM

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ABSTRACT

Total heating energy need in its entirety equals to the heat loss. It is covered by utilised passive solar gain, internal gains and the heating system. The last can be decreased offsetting by passive solar gain. At peace with higher peak load considerable energy saving is possible — low built-in capacity does not guarantee low heating energy consumption. The effects of orientation, glazed ratio and heat storage have been analyzed, applying strict elementary requirements of current national regulations. Simulations prove that concepts of classic passive solar architecture are efficient in the case of superinsulated new buildings as well. Interpretation of "renewable share", passive solar gain and heating energy is discussed in the light of European directives.

KEYWORDS: passive solar gain, glazed ratio, renewable share, regulation.

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Introduction

The Energy Performance of Building Directive [EPBD 2010] as well as the national regulations implemented according to its concept aims at low non-renewable energy consumption including that of the heating. Besides this final requirement most of the national regulations has further ones, related to the elements of the building and about half of them (according to the state on June 2019) prescribe an obligatory „renewable share”.

The elementary requirements are formulated typically as the thresholds of $U$ values, sometimes they are accompanied by a threshold of overall heat loss coefficient or the transmission heat loss of a notional or reference building.

Aiming at low heating energy consumption and low built in capacity the elementary requirements are very strict. The strict elementary requirements result in a low heating peak load and suggest on one hand, that the low peak load is their reason, on the other hand create the impression that the low peak load leads to low heating energy consumption. This expectation however seems to be in contradiction with the experiences of classic passive solar architecture. It should be notified that the buildings of classic passive solar architecture exhibit quite good energy performance as far as the heating energy consumption is concerned although they were not well insulated, moreover some of their characteristic constructions (mass wall, Trombe wall) simply excluded the thermal insulation.

Pondering the above facts it seems to be interesting to analyse the interrelation of heating peak load vs. heating energy consumption. In other terms (anticipating our assumption): is it worth to accept higher peak load if it leads to lower energy consumption?

Our analysis focuses on the followings:
- how the lessons of classic solar architecture be applied in super insulated nearly zero energy buildings (in the followings nZEB);
- what is the interrelation of heating energy consumption and peak load;
- how to interpret and account the renewable energy share and the passive solar gain.

Literature review

This literature review is unconventional and brief. Certainly there are several publications on the heating energy consumption of buildings as well as on the utilisation of passive solar gain. Separately these topics are well known and there is no sense to refer the sources since the methods used in the followings do not differ from the long standing ones.

The question of built in capacity for heating is less popular – conventional calculation methods seem to be accepted and free of problem. This general attitude is justified: heat generators’ (boilers, heat pumps) power scale is not continuous, the difference between the capacity of two subsequent products is quite big: certainly the only possibility is to select the capacity which exceeds the calculated peak load. Oversizing of heat generator is not favourable (although improves the designers’ sense of security), but condensing boiler relieve this problem.

Our analysis focuses on the interrelation of the energy consumption and built in capacity. This question itself is worth of interest however provokes an other one: how to take the solar gains into account in the national regulations and energy certificates?

The actuality of the last question is underlined by the recent directives of the EU. The preambulum of the [EPBD 2010] mentions a crookedly worded “definition” of the nZEB suggesting that significant amount of renewable energy should be used. Some studies of institutes which can be considered as “background” ones of the EU published detailed analysis proving that the “renewable share” should be 50-90% in case of residential and office buildings in many Member States [BPIE 2011a, BPIE 2011b, Ecofys 2012, Boermans T. et al].

We consider their statements as subservience to the expectations of policy makers – effectively realistic only if exclusively biomass is incinerated wherever heat is needed, keeping its primary energy conversion factor at an unrealistic low level.

As a consequence some national regulations interpreted this suggestion as an obligatory requirement and prescribed unrealistic „renewable share”. According to [Hermelink A, et al. 2013] Member States distinguish renewable sources for heat production: solar, geothermal, biomass, heat pump. Although this classification is not considered consistent, these forecasts are available (Figure 1.).

The predominance of biomass is at least solicitous. Whilst solar energy is inexhaustible on human scale time horizon the reproduction of biomass needs human activity and the available growing area is limited (and is to be shared for fuel and food production). Transport and storage of solid fuel may be a problem in urban area unless district heating is spoken of.

![The planned share of different renewable energy sources in some Member States](image)

Figure 1. The planned share of different renewable energy sources in some Member States

The predominance of biomass is at least solicitous. Whilst solar energy is inexhaustible on human scale time horizon the reproduction of biomass needs human activity and the available growing area is limited (and is to be shared for fuel and food production). Transport and storage of solid fuel may be a problem in urban area unless district heating is spoken of.
There are several factors which limit the use of solar energy whether it is about heat or electricity generation. These active solar systems need energy collecting elements: even if solar access is not obstructed the roof area comparing with the floor area of a multistory building limit the allocation of enough energy collecting element (collector or PV arrays), sometimes this area is further decreased with elevator engine rooms, fans, cooling towers, boilers, installed on the roof. Other climatic and related energy aspects must not be forgotten, too: experts of urban heat island support the idea of “cool roof” however a roof covered with collectors or PV arrays is anything but not cool since the essence of energy collecting elements is the maximum possible absorbance.

Regarding the soil as the source of heat pumps limited area of building sites in densely built urban environment allows only the application of quite costly bore holes.

We do not state that the above listed facts would normally prevent the use of the renewable energy systems however the expectable occurrences of the above listed or other barriers mean that compulsory application of any renewable share cannot be recommendable unless we are ready to accept many derogation requests.

Practically each building makes use of solar energy for heating with no technical system or other specific element. Passive solar gain is inevitable, its conscious utilisation is the most natural and simplest option. Nevertheless the role of passive solar gain in the renewable share seems to be disputable due to the inaccurate use of concepts and formal statement of the RES directive [RES 2009]. It declares that “Passive energy systems use building design to harness energy. This is considered to be saved energy.”

This statement is misleading: energy for heating as such is not saved! “Only” the energy output of technical heating system can be decreased.

The heat loss of a building in a heating season is

\[ Q = \sum AU + 0.33nV DH_{\text{climatic}} \]

where
- \( A \) – the area of the elements of thermal envelope, \( m^2 \);
- \( U \) – heat loss coefficient, \( W/m^2K \);
- \( n \) – air change rate, \( 1/h \);
- \( V \) – heated volume of the building, \( m^3 \);
- \( DH_{\text{climatic}} \) is the “climatic” degree hours, for each hour when \( t_e < t_1 \).

The precondition of the balance is that the same heat should be delivered into the building. It is the sum of different components:
- utilised fraction of direct passive solar gain;
- utilised fraction of indirect passive solar gain (mass wall, Trombe wall, air collector, double skin façade, sunspace, …);
- ventilation through buried pipe;
- heat recovery from exhaust air (heat exchanger or heat pump).

These components of the energy balance do not decrease the heat losses of the building but cover fractions of heat losses and are to be taken into account as heating with renewable energy. The rest of the heat loss is covered by internal gains from non-renewable sources and by the output of the heating system (Fig. 2.).

The intention of [RES 2009] is acceptable: double counting of utilised passive solar gain must be avoided. It should be considered only once, however correctly, as heating – thus as a component of the renewable share.

Regarding the unexplainable view of [RES 2009] irritating contradictions arise: heat gain from a double skin façade or from an air collector is considered as utilisation of renewable energy if air flow is run by a fan (which requires some electric energy) - why should be excluded the same if the air flow is due to the buoyancy effect?

**Methodology**

Certainly the problem of peak load versus energy consumption strongly depends on the thermal characteristics of the building elements. Interesting results could be obtained with those of the classic solar architecture and other buildings however currently the strict elementary requirements are to be applied to see how this relationship develops in the case of new buildings.

Attempting to illustrate the problem case studies have been carried out. A simple model has been analysed using Energy Plus v.8.4.0 software for simulation. Regarding the climatic conditions Debrecen (second largest city in Hungary \{N 47° 28’\} \{E 21° 37’\} ) have been considered with the data from ASHRAE HUN Debrecen. 128820_IWEC files. To check whether the tendencies are very specific or exhibit typical features some simulations have been repeated for Bergen (Norway, \{N 60° 17’\} \{E 5° 13’\} with the data from ASHRAE NOR_Bergen. 013110_IWEC files.

The yearly heating energy need (to be covered by the heating system) has been calculated. The peak load has been selected from the hourly data.

The model is shown in Fig. 3.
The starting version represented a massive construction, with brick partition walls, 20 cm reinforced floor slab. The layers of the external wall are masonry blocks, thermal insulation and plaster on both surfaces. The minimum glazed ratio is 4.5%. In this version the total heat capacity of the boundary constructions is 23.872 MJ/K.

The glazed ratio has been varied up to 71.7% step by step according to the Table 1. Certainly increasing the window area the total heat capacity slightly decreases. In order to see the effect of the heat capacity it has been systematically decreased halving by each step the original or the previous one (Table 2.). Certainly not all versions correspond to a real construction however this approach facilitates to reveal the effect of heat storage in a wide range.

<table>
<thead>
<tr>
<th>Glazed ratio of the façade %</th>
<th>4.5</th>
<th>16.3</th>
<th>23.7</th>
<th>34.9</th>
<th>71.7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Identification on the diagrams</td>
<td>a</td>
<td>b</td>
<td>c</td>
<td>d</td>
<td>e</td>
</tr>
</tbody>
</table>

| Total heat capacity of the boundary construction with 4.5% glazed ratio MJ/K | 23.872 | 11.936 | 5.968 | 2.984 | 1.492 | 0.746 | 0.373 |
| Identification on the diagrams | 1    | 2     | 4     | 5     | 6     | 7     |

Heat capacity itself was one of the parameters. It is to be mentioned in advance that the last cannot be specified with the sum of the mass of the first 10 cm of the boundary constructions if a longer weather history of 8-12 days is spoken of – during these days the “deeper layers” of the boundary construction become “active” in storing and releasing heat.

The $U$ values are the followings: external wall: 0.24 W/m²K, window glazing: 1.062 W/m²K (Argon gas-filled, three layer 3-13-3-13-3, with Low-e coating, frame: wooden conductance: 0.13W/mK, frame thickness: 61 mm). The $g$ value of the glazing 0.579.

Continuous air change of 0.5/h and a user profile for residential building are taken into account and perfect automatic control of the heating is supposed.

Different orientations have been taken into account. The problem of summer overheating has been ignored considering that movable shading devices facilitate to radically decrease the cooling load.

Certainly the results gained for isolated cells illustrate well the effect of orientation however real buildings have more exposed facades. There is heat flow between two rooms or zones facing e.g. towards North and South. These heat flows are generated by the difference of passive solar gains and depends on the heat transmittance of internal partition between the zones. These heat flows partially offset the difference of passive solar gains. To demonstrate this phenomenon two cells are joined along their backwall. The heat capacity of this, now internal partition wall are changed step by step according to the change of the heat capacity of the rooms. Changing the glazed ratio the ratio of the strength of thermal connection between the rooms and environment to that between the rooms will change, too. Anticipating our assumption that glazed area may exhibit some kind of optimum which depends on orientation different combination of glazed ratio are investigated: first optimum glazed ratio for both orientations, then a set of equal glazed ratio on both facades.

**Discussion**

**Design peak load**

The traditional method of calculation of heating design peak load is based on simple steady state equations. The design external temperature is prescribed either as a conventional value based on experience or derived from statistical analysis at a given risk level. Even a simple steady state equation might include additive components for a conservative value of the daily average passive solar gain (say the diffuse radiation only) and the internal gain. (The last may seem to be risky, however if the building is occupied there is some internal gain, if there is no internal gain, the building is empty thus nobody takes care if the indoor temperature is a little bit below the set point.)

Neglecting the usual method of design peak load calculation the peak load of the heating system has been taken from the hourly results of simulations. It occurs in a given hour of the continuous process of the heating regime and depends on the “weather history” of the days before. Taking into account their thermal performance new buildings have a “long lasting memory”, thus the history of eight–ten days is to be considered.

It is a well-known experience that the coldest day of the winter usually occurs in clear windless days when the long wave radiation towards the sky is intensive. (The effect of the wind is low if the building is well insulated and airtight.) It can easily be imagined that if such days are preceded by overcasted days the building will lose its stored heat even if the external temperature is mild. This expectation proved to be correct: regarding the Hungarian test reference year the peak load occurred in the process...
of such a “weather history” (Fig. 4.). Obviously the date of the occurrence of the peak load depends on the building (orientation, glazed ratio, thermal mass) however the tendencies are similar.

Figure 4. Example of the „weather history” before the occurrence of the peak heating load (marked) in Debrecen

Similar phenomenon can be observed in Bergen (Fig. 5.)

Figure 5. Example of the „weather history” before the occurrence of the peak heating load (marked) in Bergen

Certainly different “weather histories” of the whole heating season determine the heating energy consumption.

Energy consumption – orientation and thermal mass

To prevent any misinterpretation it is to be emphasized that the total heating energy need in its entirety equals to heat losses - in the following context the “heating energy need” relates to the energy, required from the heating system. Increasing the glazed ratio of the façade results in higher transmission heat loss and higher solar gain. With given $U$ and $g$ values, it depends on the orientation whether the augmentation of loss or gain is more intensive. If the augmentation of gain prevails, increasing the glazed ratio from a very low starting value at the beginning the energy need decreases since the excess solar gains will exceed the excess heat loss whilst the gain/load ratio remain modest and most of the gain will be utilised. Further increasing the glazed ratio the solar gain will continuously exceed the heat loss however due to the higher gain/loss ratio less and less fragment of the gain will be utilised. At a given glazed ratio the heating energy need exhibits minimum. In the North-East sector this is at 15-25% glazed ratio however the energy saving is quite modest. For Northern orientation the minimum might occur at an unrealistic low glazed ratio. Nevertheless moving towards East and South the increasing glazed ratio is accompanied by considerable energy saving parallel with increasing peak load (Fig. 6).

Figs. 7.-9. exhibit the interrelation of peak load and consumption for Hungarian reference year, for South, East and North orientation. The parameter of the curves is the thermal mass, the crossing trajectories belong to a given glazed ratio.

It can be observed that due to the orientation the augmentation of solar gain is stronger than that of the heat loss for South and – in a less extent – for East orientation. It cannot be applied for North orientation, when the augmentation of the loss is stronger than that of the solar gain.

Analysing the results for South and East orientation it can be seen that a local extreme value occurs which shows a kind of optimum glazed ratio, resulting in a minimum of heating energy consumption at the cost of higher peak load. For massive constructions the glazed...
ratio can be increased up to the technical limits: the consumption decreases continuously whilst the augmentation of the peak load is relatively slow.

For North facing facades however the smallest glazed ratio – not surprisingly – results in the lowest energy consumption and peak load.

It is obvious that the thermal mass has decisive role in this process. Figurs. 7, 8 and 9 shows the results for Debrecen for different orientations. The parameter of the curves is the heat capacity, that of the trajectories is the glazed ratio. In case of South facing façade there are either optimum glazed ratios or the heating energy need can be decreased up to or beyond 70% glazed ratio. Not surprisingly the less is the heat capacity of the boundary construction the lower is the glazed ratio where the heating energy need is the lowest. The dashed parts of the curves show the parameter combinations which are not rational.

Figure 7. Heating energy need vs. heating peak load, South orientation, Debrecen. Parameters: 1...7 heat capacity (decreasing), a...e: glazed ratio (increasing), indentifications are given in Tables 1. and 2.

In the case of East orientation similar phenomena can be observed. Evidently the minimum energy need belongs to smaller glazed ratio comparing to the Southern orientation.

No doubt, the “price” of the lower heating energy consumption is the higher peak load. Therefore if the slope of the curves is near to vertical this price is to be pondered since the change of the heating energy need becomes modest.

Figure 8. Heating energy need vs. heating peak load, East orientation, Debrecen. Parameters: 1...7 heat capacity (decreasing), a...e: glazed ratio (increasing), indentifications are given in Tables 1. and 2.

As far as North orientation is concerned increasing glazed ratio leads to higher heating energy need as well as to higher heating peak load. The same applies for any orientation if the solar access is obstructed.

Figure 9. Heating energy need vs. heating peak load, North orientation, Debrecen. Parameters: 1...7 heat capacity (decreasing), a...e: glazed ratio (increasing), indentifications are given in Tables 1. and 2.
Repeating the simulation for Bergen the results are similar as it is illustrated in Fig. 10. for South orientation.

![Figure 10](image)

**Figure 10.** Heating energy need vs. heating peak load, South orientation, Bergen. Parameters: 1…7 heat capacity (decreasing), a…e: glazed ratio (increasing), identifications are given in Tables 1. and 2

**Utilised passive solar gain**

It is obvious that in the case of our model the only reason of the differences in energy consumption is the different amount of utilised passive solar gains. The possible saving of energy consumption depends on the orientation, glazed ratio and heat capacity of the boundary construction. Figure 11 shows the saving of heating energy need in % in the function of glazed ratio: continuous lines are for South facing façade, dashed lines belong to East orientation.

![Figure 11](image)

**Figure 11.** Saving of heating energy need. Parameters: 1…7 heat capacity (decreasing), identifications are given in Table 2

The parameter is the heat capacity of the boundary construction – its effect is decisive. Nevertheless even if a light weight construction is considered, the glazed ratio can be as high as 40% resulting in about 20% saving of heating energy need in case of South facing façade. For heavier constructions the optimum cannot be seen, only the increase of energy saving slows up.

For East orientation (dashed lines) the available energy saving does not exceed 10% and for medium weight buildings the optimum glazed ratio is around 30%. The available energy saving in light weight buildings is modest and the glazed ratio should not exceed 20%.

It should be noted that the base of the % calculation is the minimum glazed ratio (4.5 %), not the windowless wall.

Heating energy need is to be covered by the heating system. The results show that utilised passive solar gain can cover a considerable part of heating energy need.

![Figure 12](image)

**Figure 12.** Increase of heating peak load. Continuous lines: South, dashed lines East orientation. Parameters: 1…7 heat capacity (decreasing), identifications are given in Table 2

The price of the lower heating energy consumption is the higher peak load (Fig. 12.), consequently the higher built-in capacity. Although the data may seem to be shocking some facts should not be forgotten:

- the built-in capacity is typically oversized, partly due to the discrete selection of boilers, heat pumps, partly because designers intend to be on the “safe side”;
- many times heat for space heating and domestic hot water is generated in the same system. The last is a given value, thus the change of the total built-in capacity is relative smaller.

**Balancing effect of thermal zones**

Real buildings have more facades. The passive solar gains for different orientations lead to significantly different thermal balance in differently oriented rooms – particularly if North-South pairing is spoken of. Nevertheless there is thermal connection, thus heat flow between these North and South facing rooms.
Its balancing effect depends on the ratio of the strength of thermal connection between the room and the environment to that between the differently orientated rooms.

As far as glazed ratios are concerned two approaches can lead to interesting results. The first is to have optimum glazed ratio for both orientations. Such a solution can be applied in residential buildings if the building is not very deep. In this case living rooms and similar ones where the insolation and daylight is of importance can be oriented toward South whilst the others (bath, kitchen, wardrobe, staircase...) towards North. Not surprisingly the lowest energy need occurs when on both sides the optimum glazed ratio is applied. Increasing the glazed ratio towards North both the energy need and peak load increase. Having lower glazed ratio on the Southern façade the same tendency can be seen: the energy need is higher, the peak load is lower. The results are influenced by the heat capacity, see Figure 12 for massive, Figure 13. for light weight buildings. Certainly in the last case both the energy need and peak load are higher.

The different uses of premises justify the significant differences in the glazed ratio together with the different appearance of the facades. This is the well proven design strategy of buffer zone concept in the classic solar architecture.

In case of deep residential buildings (where complete flats have windows only on one facade or if the use of rooms is identical on both sides (e.g. office building) it is an understandable expectation that due to the identical use the facades should be identical or at least of similar appearance. Therefore sets of identical glazed ratios on both sides have been analysed. Here at the first sight it may be surprisingly that the higher glazed ratios results to the lower heating energy need, no doubt at the cost of high peak loads (Figs. 12 and 13), thus the effect of balancing heat flow is very strong. This is the consequence of the fact that the thermal connection between the rooms is multiple times higher than that between the rooms and the environment in superinsulated buildings.

**Conclusion and Policy Implications**

Interpreting correctly the energy performance of building the aim is to decrease the non renewable primary energy need for heating. It should not be confused with low built-in capacity which does not guarantee low heating energy consumption: on the contrary at peace with higher peak load considerable energy saving is possible.

The essence of this phenomenon is that passive solar gains cover a part of the heat losses, thus decreases the necessary heat output of the technical heating system. This experience is long ago well known and has been exploited in classic solar architecture. Nevertheless in the era of superinsulated buildings this experience seemed to be forgotten. Even with the high quality contemporary windows the transmission heat loss of building increases with the glazing ratio and this seemed to contradict the nZEB concept.

Our analysis illustrate that the passive solar gain coundervails or exceeds the increase of transmission losses and in case of Equator facing orientation significantly decreases the energy consumption of technical heating system. More modest but not negligible saving can be achieved in case of less favourable orientations. Certainly the utilisation of passive solar gain depends on the heat capacity of the building, too. For several input combinations optimum glazed ratio can be defined.

Not surprisingly favourable results have been obtained by pairing rooms of opposite orientations. Providing the depth, the layout and the use of premises facilitate the application of buffer zone concept and the radically different glazed ratio of different facades are acceptable the lowest energy need can be achieved if the glazed ratio on both sides is optimum. Providing the use of rooms is similar on both sides and therefore identical glazed ratios are applied the higher ones are better in case of North-South pairing.

Man-made formal rules make confusing the consideration of passive solar gain as heating with renewable energy.

![Figure 13. Sum of heating energy need vs. heating peak load of a pair of North and South facing room, high heat capacity](image)

![Figure 14. Sum of heating energy need vs. heating peak load of a pair of North and South facing room, low heat capacity](image)
The question of interpretation would not have any importance if some of the national regulations would not require (sometimes unrealistic) “renewable share” of which utilised passive solar gain, however, is excluded.

Those national regulations of Member States which are ready (concept accepted or already implemented) exhibit wide variations regarding renewable energy. Some of them do not use “renewable share” as compulsory indicator. Others “softly” encourage the use of renewable energy but rank the building as nZEB even if (pro forma) no renewable energy is applied, providing the specific non renewable primary energy consumption does not exceed the threshold. (“Pro forma” since all buildings exposed to the Sun use renewable energy disregarding the formal man made rules.) Interesting example is the Estonian regulation which does not define the minimum of renewable share rather B energy class has to be achieved without renewable energy.

Other national regulations cannot break away from the hasty wording of the EPBD.

Bulgaria and Ireland prescribe renewable share, 15 and 20% respectively with no further specifications. In Southern Member States (IT, ES, PT) compulsory renewable share (30-70%) for domestic hot water supply is typical. Considering the climate it is understandable and seems to be justified – the questions are the unobstructed solar access and the ratio of available roof area to the total floor area.

In Austria different options are possible:
- by solar thermal energy net final energy yields at least 10% (up to 20%) of the final energy demand for domestic hot water or
- through heat recovery least 10% (up to 20%) net final energy yields for heating or;
- by photovoltaic the net final energy yields at least 10% (up to 20%) of the final energy demand for household electricity or operating current.

The last option needs clarification since “household electricity” is not taken into account in the EPBD labelling systems. Nevertheless the extension of “renewables” with heat recovery is a salutary and justifiable concept.

As a frightening example the Slovak regulation is to be mentioned which prescribe 50% renewable share (parallel with the maximum pay back time of 15 years!).

It can be seen that the implementation of new national regulations is in the process of long lasting parturition. Likely the unclear regulation is one of the reasons which make harder the agreement of policy makers and professionals. Clear interpretation of heat losses and heating energy will create a clear situation. Even if a Member State insist on renewable ratio as compulsory or informative indicator consideration of utilised passive solar gain as part of the renewable share may make easier the fulfillment of this (otherwise disputable) requirement. Agreeing with the statement of [RES 2009] that passive solar gains must be accounted only once it is evident that heating with solar energy is to be included in the renewable share.

Regulation should be clear, realistic and convincing, free of contradictions and ambiguous guidance. The Commission and the Parliament are more often than not blamed with exaggerated bureaucracy and over-regulation. The current situation in the analyzed subject area raises the suspicion of lack of cooperation between decision-making bodies themselves as well as between policy makers and the professional society.

References

INVESTIGATION OF THE INFLUENCE OF DISPERSION DISTORTIONS OF WIDEBAND SIGNALS ON THE QUALITY OF THEIR DELAY AND FREQUENCY SHIFT ESTIMATION

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ABSTRACT

The article investigates the quality of algorithms for estimate the main parameters of wideband signals in the problem of over-the-horizon radar under conditions of dispersion distortions in the Earth's ionosphere. The boundary values of the variances of the estimates of propagation delay, frequency shift and phase, wideband phase-shift keyed signals are investigated. It is shown that dispersion distortions of the radar signal lead to a correlation between the estimates of the delay and frequency shift. The curves of the dependence of the frequency-time ratio depending on the length of the used pseudo-random sequence and the degree of dispersion distortions are obtained. Analytical curves of the Cramer-Rao lower bounds are constructed for the variances of estimates and the values of the correlation coefficients of the estimated parameters in the presence of dispersion distortions, which are confirmed by the results of simulation.

The reported study was funded by RFBR, project number 19-29-06055.

KEYWORDS: broadband signal, ionosphere channel, frequency dispersion, joint estimation, frequency-time ratio, quality of the estimation.
Introduction

Over-the-horizon radar systems operate in the shortwave range and are designed to detect targets at distances of the order of several thousand kilometers. The quantitative indicators of the quality of the radar system can be improved through the use of wideband signals. However, wideband signals are sensitive to the frequency dispersion of the ionospheric channel, which is the reason for a significant decrease in the quality of their detection [1-13]. In this paper, we study the influence of the frequency dispersion of the ionospheric channel on the quality of the joint estimate of the Doppler frequency shift, delay, and initial phase.

The signal and the channel model

The complex signal at the output of the quadrature demodulator is presented as a mixture of the information signal, distorted by the frequency dispersion of the ionospheric channel, and white Gaussian noise

\[ \hat{x}(t, \varphi, \tau, f_d, s) = e^{-j\varphi}e^{j2\pi(f_d-\tau)} \hat{x}(t-\tau, s) + \hat{n}(t), \]

\[ t = -T_s/2 + T_s/2 \]

where \( \hat{x}(t, s) = \hat{x}(t) * \hat{h}(t, s) \) – complex envelope of the useful signal distorted by the ionospheric channel, \( \hat{h}(t, s) \) – complex envelope of the impulse response (IR) of the ionospheric channel, \( \hat{x}(t) \) – complex envelope of the useful signal undistorted, \( f_d \) – the Doppler frequency shift, \( \tau \) – delay, \( s \) – the slope of the dispersion characteristic which characterize the effect of frequency dispersion on the signal, \( \varphi \) – an unknown phase shift, \( \hat{n}(t) \) – complex envelope of white Gaussian noise with zero mean and variance \( \sigma_n^2 \), \( T_s \) – signal duration.

As a model of a channel with frequency dispersion, a channel model with a linear dependence of the signal group delay on the central frequency (linear dispersion characteristic with slope \( s \)) [1] is adopted. The transfer function of the ionospheric channel in the absence of multipath signal propagation can be written in the form

\[ H(j2\pi f) = e^{-jSf_s^2}, f \in [-\Delta f/2; \Delta f/2] \]

where \( \Delta f \) – width of the transfer function of the ionospheric channel, \( S \) – the slope of the dispersion characteristic. The phase-frequency response of the channel is described by a quadratic dependence on frequency, and the group propagation delay is described by a linear one with a slope \( S \) μs/MHz. We will assume that the slope of the dispersion characteristic \( S \) μs/MHz is known at the receiving side, while the delay \( \tau \), the Doppler frequency shift \( f_d \) and signal phase \( \varphi \) – unknown non-energy parameters that need to be estimated.

To estimate the parameters under study, it is proposed to apply the method of the maximum likelihood (ML). When using the ML method, the decision about the proximity of one or another estimate value to the true value of the parameter being determined is made according to the following rule (in the case of coherent receiving) [14]:

\[ \lambda = \max \left\{ \Re \left[ \int_{-T_s/2}^{T_s/2} y(t)u^*(t, s, \hat{f}_d, \hat{\varphi}, \hat{\tau}, \hat{\phi}) dt \right] \right\}, \]

where \( y(t) \) – additive mixture of useful signal quadratures and white Gaussian noise in continuous time, determined by (1), \( u(t, s, \hat{f}_d, \hat{\varphi}) \) – reference signal generated on the basis of a priori information about the useful signal, \( \hat{f}_d \) – the Doppler shift estimate, \( \hat{\varphi} \) – delay estimate, \( \hat{\phi} \) – estimate an initial phase, * – complex conjugate symbol.

To analyze the effect of dispersion distortions on the quality of the estimate, we define the variance and cross-correlation \( \hat{\tau}, \hat{f}_d \) and \( \hat{\varphi} \).

The estimation variance lower bound

The correlation of the estimate of unknown parameters in the first approximation [14]

\[ K_{ab}(1_a, 1) = \frac{A_{ab}}{\rho_{ab}^2 \Omega}, \]

where \( \Omega \) – determinant of a matrix \( W \), consisting of a set of partial derivatives \( \frac{\partial^2 S}{\partial \varphi \partial \tilde{\varphi}} \), \( S \) – real part of the signal component of the correlation integral (3), \( A_{ab} \) – algebraic complements of a matrix \( W \), \( 1_a \) – vector of parameter estimates, \( 1 \) – vector of estimated parameters, \( i = 1 + K \), \( k = 1 + K \), \( K \) – the number of estimated parameters (in the case considered in the article \( K = 3 \)), \( \rho_{SNR}^2 = 2E_s / N_0 \) – signal-to-noise ratio (SNR), \( N_0 \) – power spectral density (PSD) of white Gaussian noise. For coinciding indices \( i \) and \( k \) (4) corresponds to the variances of estimates of the parameters under study.

Having carried out all the necessary mathematical transformations and calculations over expression (4), we obtain formulas that allow us to calculate the variances and cross-correlations of the estimates of the studied parameters in the first approximation:

\[ D(\hat{f}_d) = \frac{1}{4\pi^2 \rho_{SNR}^2 T_{eff}^2 (1 - \rho_{f_d}^2)}, \]

\[ D(\hat{\varphi}) = \frac{1}{4\pi^2 \rho_{SNR}^2 T_{eff}^2 (1 - \rho_{\varphi}^2)}, \]

\[ D(\hat{\tau}) = \frac{1}{4\pi^2 \rho_{SNR}^2 T_{eff}^2 (1 - \rho_{\tau}^2)}, \]

\[ D(\hat{\phi}) = \frac{1}{4\pi^2 \rho_{SNR}^2 T_{eff}^2 (1 - \rho_{\phi}^2)}. \]
\[ K\left(\hat{f}_d, t\right) = \frac{1}{4\pi^2\rho^2_{\text{SNR}} T_{\text{eff}} F_{\text{eff}} \left(1 - \rho^2_{t\hat{f}_d}\right)}, \]  
\[ K\left(\hat{f}_d, \phi\right) = \frac{-f_0 \rho_{t\hat{f}_d}}{2\pi\rho^2_{\text{SNR}} F_{\text{eff}} \left(1 - \rho^2_{t\hat{f}_d}\right)}, \]  
\[ K\left(\hat{\tau}, \phi\right) = \frac{-f_0}{2\pi\rho^2_{\text{SNR}} F_{\text{eff}} \left(1 - \rho^2_{t\hat{f}_d}\right)}, \]  
\[ \text{where} \quad T_{\text{eff}} = \int_{-\infty}^{\infty} \left|\mathbf{x}(t)\right| dt \quad \text{active signal duration}, \]  
\[ F_{\text{eff}} = \int_{-\infty}^{\infty} \left|\hat{X}(j2\pi f)\right|^2 df \quad \text{effective signal width}, \]  
\[ \rho_{t\hat{f}_d} = \frac{\int f_{\text{eff}}(t)\left|\mathbf{x}(t)\right| dt}{F_{\text{eff}} T_{\text{eff}} \int \left|\mathbf{x}(t)\right|^2 dt} \quad \text{frequency ratio}, \]  
\[ f_{\text{eff}}(t) = \frac{d\gamma(t)}{2\pi dt} \quad \text{frequency modulation law signal}, \]  
\[ \gamma(t) = \arg \hat{\mathbf{x}}(t), \mathbf{x}(t) = |\mathbf{x}(t)| e^{i\gamma}. \]

### Simulation results

To confirm the theoretical results, simulation modeling was carried out for a single rectangular pulse and a sequence of rectangular pulses with a spectral width \(\Delta F = 400 \text{ kHz}\). Doppler frequency shift has been set \(f_d = 0 \text{ kHz}\), delay \(\tau = 0.1 \mu\text{s}\), phase shift \(\phi = 90\) degrees. As a result of the simulation, graphs of the dependences of the frequency-time ratio \(\rho_{t\hat{f}_d}\) on \(\rho = \frac{\Delta F}{N_{\text{coh}}}, N_{\text{coh}} = \sqrt{\frac{4}{\pi s}}\) – channel coherence bandwidth for different types of signals.

1. Shows this dependence for a single rectangular pulse and short sequences of rectangular pulses based on the Barker code of different lengths [15].

2. Shows the dependence of \(\rho_{t\hat{f}_d}\) on \(\rho\) was obtained for a sequence of rectangular pulses based on Gold sequences of different lengths which obviously has small values of \(\rho_{t\hat{f}_d}\).

From the dependences shown in the figures, it can be concluded that the effect of frequency dispersion increases the value of \(\rho_{t\hat{f}_d}\), thereby making the correlation ellipse ever narrower, which negatively affects the quality of the joint measurement of the delay and of the Doppler shift.

### Figure 1. Time-frequency ratio versus \(\rho\)

### Figure 2. Time-frequency ratio versus \(\rho\) for long sequences

Also, during the simulation, the values of the parameters \(\hat{f}_d, \hat{\tau}\) and \(\hat{\phi}\) were obtained, the standard deviation and cross-correlation of estimates for different SNR values were calculated. The simulation was performed under \(s = 70 \mu\text{s/MHz}\) for a sequence of rectangular pulses of length \(N = 7\).

Figure 3 – 11 show the dependences of theoretical and sample standard deviation of the \(\hat{f}_d, \hat{\tau}\) and \(\hat{\phi}\) estimates, and their cross-correlation functions and coefficient of cross-correlation versus SNR.
Figure 3. Standard deviation of the $\tau$ estimate versus SNR

Figure 4. Standard deviation of the $f_d$ estimate versus SNR

Figure 5. Standard deviation of the $\phi$ estimate versus SNR

Figure 6. Cross-correlation between $f_d$ and $\tau$ versus SNR

Figure 7. Coefficient of cross-correlation between $f_d$ and $\tau$ versus SNR

Figure 8. Cross-correlation between $f_d$ and $\phi$ versus SNR
The above analysis of dependencies can draw the following conclusions:

1. The figures show that the standard deviation of the estimates of all the parameters studied in the article during their joint estimation is greater than if all parameters were estimated separately from each other. This is due to the appearance of cross-correlations between estimates.

2. The results of theoretical studies and simulation modeling showed the presence of a cross-correlation between the investigated estimates: 
\[ K(\hat{f}_d, \hat{\tau}) \neq 0, \]
\[ K(\hat{f}_d, \hat{\phi}) \neq 0, \]
\[ K(\hat{\tau}, \hat{\phi}) \neq 0. \] Cross-correlation coefficients in the figures 7, 9, 11 shows that the cross-correlation between the estimates \( \hat{f}_d \) and \( \hat{\tau} \), \( \hat{f}_d \) and \( \hat{\phi} \), \( \hat{\tau} \) and \( \hat{\phi} \) is significant, therefore, between the estimates of these parameters there is an obvious correlation, which affects the quality of their joint estimate.

Conclusion

The article investigated the effect of frequency dispersion on the quality of the joint estimates of Doppler frequency shift, delay and initial phase. In the present work, theoretical expressions are obtained for the variances and cross-correlations of estimates of the indicated unknown parameters for a signal with an arbitrary spectrum. It is shown that the effect of frequency dispersion increases the value of the time-frequency coupling coefficient, thereby making the correlation dependences between the investigated estimates stronger, which negatively affects the quality of the joint measurement of the delay and the Doppler frequency shift.

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References


THE CURRENT STATE AND TRENDS OF THE DEVELOPMENT OF DIGITAL TELE-RADIO BROADCASTING SYSTEMS IN THE WORLD

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ABSTRACT

The object of the research is to make an analysis of the current state of the digital tele-broadcasting systems in the world and the transition trends from analogue to digital systems recommended by the International Telecommunication Union (ITU-R) for use in this area are considered. Therefore, the current trend of global transition to digital tele-broadcasting is due not only to the lack of a frequency resource, but also to society's growing demands for up-to-date information, the need to introduce common global standards and systems for broadcasting systems. Expansion of digital tele-broadcasting in the context of globalization, as well as the presence of this transmission technology. In this work, he is dedicated to considering the sustainable development trends of digital satellite broadcasting in the world in the phase of migration from analog to digital technologies in this area. In the final part, the results obtained based on the research and analysis made in recommendations and in the ITU-R database are presented.

KEYWORDS: tele-radio, terrestrial, broadcasting, digital, systems, frequencies, transmitters, transition, satellite, broadcasting, International Telecommunication Union

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The Radiodifusion and digital television use the internet and 4G technology through cable, satellite, and mobile communications systems to keep the population informed. Despite the rapid development of 5G technology, there is a transition to active digital broadcasting systems and recommended by the International Telecommunication Union ITU-R for application in this area. This is mainly due to the additional benefits offered by digital television technologies and their expansion in the world. These benefits include [1, 13]:

- the ability to create single frequency networks, which significantly saves the radio frequency resource, and increases the efficiency of the use of the radio spectrum;
- improve image and sound quality, the ability to switch to surround, stereo and multichannel broadcasting;
- guarantee the protection of broadcast programs and other information against unauthorized access, which makes it possible to create paid broadcast programs;
- creation of interactive systems of tele-broadcasting, using which, the viewer and/or listener has the opportunity to work on the broadcast program, to request programs of interest to him at a time convenient for him;
- improve the quality and number of programs broadcast in the long wave (LF), medium (MF) short (HF) bands, with significant energy savings by radio devices and transmitters;
- the possibility of receiving high-quality mobile digital radio broadcasting programs, both in megacities and in places with compact populations, and in remote and inaccessible territories with low population density;
- the possibility of transmitting alerts to the population, governmental organizations, special services, state-owned companies, and in emergency situations.

Therefore, the current trend of global transition to digital tele-broadcasting is due not only to the lack of a frequency resource, but also to society's growing demands for up to date information, the need to introduce common global standards and systems for broadcast systems. Expansion of digital tele-broadcasting in the context of globalization, as well as the presence of this transmission technology. This work is dedicated to considering the sustainable development trends of digital satellite broadcasting in the world in the phase of migration from analog to digital technologies in this area.

The development of an analog television program eventually led to the spread of three main standards in the world for color television: NTSC, SECAM, PAL [1]. Television in these formats is still watched in many countries, almost half a century after its creation.

The NTSC system (National Television System Committee) is used in North and Central America, in several countries in the eastern part of South America, as well as in Japan, South Korea and in several countries in the Southeast Asian [1]. The SECAM system (Séquentiel Couleur á Mémore – Sequential Color With Memory) is used in Russia, the countries of Eastern Europe and the Commonwealth of Independent States (CIS), France, most countries in North Africa and Southeast Asia [1, 2].

The PAL (Phase Alternate Line) system is used in most western and northern European countries, India, China, Australia, Brazil, Argentina, Angola, and other countries [1].

Among the digital terrestrial television transmission systems recommended by ITU-R for application in this area, two from the DVB (Digital Video Transmission) family are particularly noteworthy: DVB-T, DVB-T2 (where T is Terrestrial), and for the satellite system two are also worth noting: DVB-S (Digital Video Transmission via Satellite), DVB-S2. The DVB-T2 system (figure 1) is perhaps one of the most common Digital TV systems recommended by ITU-R for use in the VHF (Very high frequencies, 30 ... 300 MHz) and UHF (Ultra-High Frequency) bands 300 ... 3000 MHz). The European Telecommunications Standards Institute DVB-T standard emerged in 1996 [1, 3, 4]. Figure 1. We show the number of countries and their respective digital broadcasting systems.

![Figure 1. Number of countries and respective digital broadcasting systems](image)

In February 2006 (within the scope of the DVB consortium), the creation of a study committee for this mission was established. This committee had to assess the potential of various digital television technologies and start to develop an improved standard, called DVB-T2, which also implements several business requirements:

- the ability to receive programs on existing simple home antennas;
- the transition to a new standard should not require a change in the transmission network infrastructure;
- an increase of at least 30 to 50% in productivity compared to the DVB-T system under identical transmission conditions;
- increase the flexibility of using the radio band’s frequency band, and the possibility of diversification;
- the presence of a mechanism to reduce the peak power of the transmitted signal to the average value and several other less important requirements.
The above recommendations were implemented in the development of the DVB-T2 standard in 2010. The decision to implement the DVB-T2 standard was taken by the administrations of Austria, Great Britain, Germany, Denmark, India, Spain, Italy, Kazakhstan, Slovakia, Ukraine, Finland, Czech Republic, Sweden, South Africa, Russia, and many other countries in transition. In addition, in several countries in the world, the transition to digital TV has already been completed [1, 25]. In some countries, it did not even begin as (Bangladesh, Belize, Central African Republic, Eritrea, Jamaica) as shown in Figure 2.

![Figure 2. Number of countries and their status for transition from the Digital TV system](image)

We emphasize once again (figures 1 and 2) that the DVB-T2 system, which currently has the best characteristics, is the most used among the countries that have already opted for the digital television system (figure 1). The transition from analogue to digital television systems, established by the ITU-R Regional Radiocommunication Conference in Geneva in 2006 (RRC-06), was due to be completed in June 2015 [4]. However, due to several reasons (organizational, economic, and technical), this period was later postponed to 2020 [4].

The observed decrease in the cost of equipment for digital television networks of the DVB-T2 standard will allow that by the year 2030, highly efficient systems will be created for the delivery of digital content to users. At the same time, the limited volume spectrum is released due to the migration from analog to digital television for other types of use, mainly for mobile communication systems. We can say that in the world there is a process of transition to digital TV, which has not yet been fully concluded.

As for digital broadcasting systems, the situation is much more complicated: in many countries there is a clear delay in terms of switching to the “digit” in the very high frequency range (VHF 30...300 MHz), intended (according to with the ITU-R recommendations) mainly for the use of high quality stereo broadcasting systems. Recommendations ITU-R.BS.1114-6 [22] and ITU-R.BS1660-6 (08/2012) [23] ITU-R present the construction resources, technical characteristics, and network planning of the following terrestrial digital broadcasting systems:

- **T-DAB** (Digital Audio Broadcasting), digital radio system in a 174...240 MHz frequency band, VHF III [10];
- **ISDB-T** (Integrated Services Digital Broadcasting Terrestrial), is a system recommended for television channels with a width of 6, 7 or 8 MHz for the transmission of sound programs, a segment is allocated as a fourteenth of the frequency range of the television channel, the frequency range of that segment is 429 kHz (6/14), 500 kHz (7/14), 571 kHz (8/14) [29];
- **DRM +** (Digital Radio Mondiale), recommended by ITU-R for use in the LF (30...300 kHz), MF (300...3000 kHz), HF (3...30MHz) and VHF (30...300 MHz) bands where bands of specific frequencies are allocated for other transmission purposes [8];
- **IBOC HD Radio FM** (In Band On Channel), recommended by the ITU-R for use in the VHF band [9];
- **RAVIS** [1, 24], is a Russian audiovisual information system in real time, recommended by the ITU-R for use in the VHF band. Note that the IBOC HD Radio FM and IBOC HD Radio AM technologies are combined under one standard. The same observation applies to DRM and DRM + systems. Of the above-mentioned systems, Digital broadcasting, only two are the most universal, recommended by ITU-R for use in all frequency bands allocated for transmission (LF, MF, HF, VHF bands). These are the DRM and IBOC HD radio systems.

From the data in table 2, it follows that the DAB system is currently the most widely used [6].

Initially, the Digital Audio Broadcasting (DAB) system was positioned by the developers only as a digital broadcasting system, designed to transmit quality sound programs, different information related only to digital data.

The **DAB** (Digital Sound Broadcasting) system is a system for use in megacities, as well as in areas with high population density, where the construction of a single frequency network is beneficial. However, this does not exclude its use either at the regional level, or simply at radio stations operating separately, which is also provided by the standard. Later, more efficient digital audio data compression algorithms were developed and standardized [5,16,17,18,19]. They were added to the new second version of the standard, called DAB +, which appeared in 2006 [5]. In particular, compression algorithms were added in the HE-AAC v.2 (High Efficiency- Advanced Audio Coding) encoder of the MPEG-4 standard (Moving Picture Experts Group). Moving Images) ISO/IEC 14496-3 [18] (International Organization for Standardization-International Organization for Standardization and International Electrotechnical Commission-International Electrotechnical Commission) and MPEG D (Group of Experts in Moving Images) Surround [19]. The ability to use the MPEG-1 ISO/IEC 11172-3 Layer II compression algorithm remained in this version of the standard for the DAB + system.

The **DAB +** (Digital Sound Radio) system is a much more flexible technology when used in small towns, it is possible to receive mobile data in a simple whip antenna.
from a wide variety of multimedia information, including mobile television. Note that the subsequent processing of the digital data of the subchannels in the DAB + system has not changed compared to the DAB system. In 2009, there was an addition to the DAB + system, dedicated to the transmission of video information (video services), which transforms it into a complete multimedia system focused on mobile reception and television transmission [6,14,20].

According to the ITU-R recommendations, regular transmission of DAB / DMB family systems is carried out in 41 countries, and experimental transmission in 18 other countries. Since 2005, the T-DMB system started broadcasting in Seoul (South Korea). At the beginning of 2006, there were already 18 projects in the world to introduce DMB technology based on the terrestrial transmission infrastructure of the existing T-DAB system. In Europe, the main projects were launched in Germany, France, Norway, the Netherlands, Finland, England and Italy [14, 15]. The leader in this process is Germany, where in June 2006 there were already 39 T-DMB transmitters operating in 12 cities based on the use of transport mechanisms in the DAB + system.

In 2016, the most recent version of the standard for the DAB system appeared [10]. The specification [19] transforms the DAB / DAB + system in terms of its characteristics into multimedia A systems (also known as T-DMB), [20,12,21]. On a 1.54 MHz radio channel using transport mechanisms, DAB systems can be transmitted simultaneously:

- several sound programs with different levels of quality;
- several television programs with monophonic or stereo accompaniment;
- various data, relevant information for entrepreneurs, fixed and mobile images, text and graphic information, etc.

<table>
<thead>
<tr>
<th>Technical characteristics</th>
<th>DVB-S2 System</th>
<th>DVB-S System</th>
</tr>
</thead>
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<tr>
<td>1. Data input</td>
<td>Multiple transport flow and generic encapsulation (GSE)</td>
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<td>2. Mod</td>
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<td>Constant and modulated coding</td>
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<td>3. Error correction (FEC)</td>
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<td>Reed – Solomon (RS) ½, 2/3, ¾, 5/6, 7/8</td>
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<td>4. Modulation</td>
<td>QPSK, 8PSK, 16APSK, 32APSK</td>
<td>Single carrier QPSK</td>
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<td>5. Satellite E1 (dBW)</td>
<td>53.7</td>
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<td>6. Modulation and coding</td>
<td>QPSK 7/8</td>
<td>QPSK 2/3</td>
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<td>7. C (27.5 MHz)</td>
<td>7.8</td>
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<td>8. Transfer fee per (Mbit/s)</td>
<td>58.8 (+32%)</td>
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<td>10. Number of channels HDTV</td>
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No. 1. 2021 SYNCHROINFO JOURNAL 21
The DRM (Radio Digital Mondiale) system is a multifunctional digital transmission system, which was first standardized by the European Telecommunications Standards Institute (ESTI) in 2001 [8]. Originally, he intended to operate in the long wave (LF), medium (MF) and short (HF) transmission bands, that is, in the frequency sections of up to 30 MHz allocated by the ITU-R for audio transmission.

In 2009, a new version of this standard was published, in which the operating frequency range was expanded to a frequency of 240 MHz [14].

In this version of the standard, operation mode E, version of the system itself, is added, when operating in this mode, in a series of publications that received the name of DRM +. The latest version of this standard was published in January 2014 [1,14, 27, 28, 29].

Unfortunately, although there is no mass production of receivers of this format, the distribution of this system in the world is much slower, but still the number of countries focusing on its use is quite large (Table 3). For this reason, this system is recommended for countries with large territory and low population density.

Table 3. Distribution of digital transmission systems via satellite recommended by the ITU for application in this area [30,31].

As for the countries of North and South America, the American IBOC HD Radio system is spreading in some countries (Table 2).

Conclusion

1. In almost all documents and recommendations of the International Telecommunications Union for application in television and satellite broadcasting, digital systems have some transversal characteristics common in the processing and transmission of digital image and sound data, among which must be attributed: the compression of digital data, the permissible noise, the encoding of the audio and video-frame level, randomness of the digital data, which is necessary for a more balanced distribution of the signal energy in a frequency range of the radio channel, channels coding with different levels of protection of individual parts of digital streams, temporarily alternating digital data, alternating a cell modulation frequency during OFDM-character formation; multiple frequencies with OFDM or COFDM modulation, but with different configurations. It is the difference of these small details that ultimately determine their efficiency, quality, and the choice of countries for application in their respective territories.

2. Different publications by individual authors have been analyzed, reports and ITU-R recommendations show that the world is currently in constant transition from digital tele-broadcasting systems under the responsibility of two digital technology platforms for these systems, with emphasis on Europe (the DVB-T, DVB-T2, DVB-S, DVB-S2 system). Currently 102 countries in the world have adopted the European DVB-T2 standard.

3. The promotion of DRM and ISDB-T systems, despite their high efficiency, quality is slow enough, which apparently is the lack of mass production, the high cost of receivers of a given format. With the pandemic moment we are experiencing, the technological industries stop producing equipment on a large scale, so the process has become slower.

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ABSTRACT

We propose a new vehicle monitoring system based on Exonum blockchain platform. This system may help autonomous vehicles to make decisions. This system can also help in investigating crimes and traffic offense. The article describes the main trends in the field of intellectualization of transport systems and mobility. The blockchain technology and its capabilities in enhancing cybersecurity are described through the creation of a safe and reliable system for sending the parameters of the current state of each vehicle through its neighbours. The proposed system will serve as an important step towards the development of a motion control system for connected and autonomous vehicles.

KEYWORDS: road safety, traffic accident, methods, blockchain, Exonum.
Introduction

The article is devoted to the current security problem, which excludes the intervention of the human factor in forging and altering data. Despite the fact that the blockchain distributed database is one of the most secure in the world, this article additionally considers a number of cases related to data changes to ensure the security of the system. New blockchain-enabled platforms will make it easy to coordinate documents in a shared, distributed ledger, making physical documents unnecessary. Based on the analysis, the proposed system will serve as an important step towards the development of a traffic control system for connected and autonomous vehicles, as well as attracting companies to use Blockchain based on the Exonum platform. This direction further optimizes processes that make it easy to coordinate documents in a shared distributed ledger, which makes physical documents unnecessary.

Intelligent vehicle technology is evolving very quickly, and recent advances suggest that autonomous vehicle navigation will be possible in the near future. At intersections, traffic lights and a stop-light enable drivers to safely navigate the intersections in their vehicle. However, will it make sense in the future for cars with on-board computers "behind the wheel", controls that have been designed with today's human drivers in mind? These advantages, which are being used for intelligent robotic drivers - more precise control, better sensors and less time - we believe that car travel in the future can be safer and easier, but also much more efficient.

In this regard, we believe that absolutely all vehicles will have a full-fledged on-board computer, using secure applications with access to navigation and other sensors in read mode. Therefore, the implementation of blockchain solutions will be quite affordable without additional hardware modifications [1].

Blockchain and transport

Continuing efforts to resolve the situation indicate that the logistics situation remains problematic. Whether it's blockchain, smart contracts, or escort fees, the industry needs a solution. Without it, shippers and carriers continue to lose money, or at least miss out on opportunities to be more efficient.

Logistics is clearly seen as one of the priority blockchain applications. And here we are talking not only about projects. The giants of the logistics industry are using blockchain to increase their competitiveness. Maersk [4], in collaboration with IBM, launched the TradeLens ecosystem in 2018 for tracking vehicles, containers and cargo, as well as supply chain management. The platform collects and integrates cargo traffic data from industry partners into a single secure blockchain network and provides secure access to information for all stakeholders.

The system allows you to automate almost all document flow and digital business processes associated with transportation logistics, including such operations as obtaining a bill of lading, financial transactions, customs duties and transfer of ownership/ responsibility. To do this, TradeLens uses smart contracts and IoT technologies.

At the time of launch, the platform accounted for about 15% of the market, now it is 35%. Among TradeLens partners (users) you can find 15 of the largest shipping carriers, including Seaboard Marine, KMTC, ZIM, Safmarine, Boluda, Sealand, Namsung and APL.

In collaboration with MIT, Toyota [5] began recruiting a number of partners who specialize in various aspects of Blockchain technology so that they can explore how this technology could be applied to the automotive industry.

Toyota has already unveiled a number of projects that it hopes will help allay human concerns about handing over control to an autonomous vehicle, or "third space," as they now call it, for example Yui, its artificial intelligence (AI) satellite. It is now clear that they want to go further, which means developing a platform that can track and disseminate information about the safety of individual vehicles, how their owners use them, and reduce fraud.

“Building safe and reliable autonomous vehicles may require hundreds of billions of miles of human driving data,” says Chris Ballinger, director of mobility services and chief financial officer at Toyota Research Institute, and manufacturers are shortening the time to reach this goal, thereby increasing the safety, efficiency and usability of autonomous driving technology.

The purpose of this work is to implement tracking of car actions using a modified blockchain platform, namely, a safe and reliable system for sending the parameters of the current state of each car through the neighboring ones. In our system, vehicles confirm messages from neighboring vehicles within a radius of 100 - 150 meters. Messages are signed by the senders and every neighboring vehicle equipped with such a system.

Intelligent Transport Systems Trends

Below are examples of intelligent systems embedded in modern vehicles.

Xiu-feng Chen [13], when analyzing improved transport in China, argues that vehicles equipped with ITS technology are able to predict well any hazardous situations on the vehicle in advance, and therefore reduce reaction times, which leads to improved road safety and leads to a decrease in the number of accidents in transport.

In Italy, Benza [13] et al. Argue that in these areas of freight management, ITS improves the management of freight vehicles and vehicle parking, and provides information on weather and other critical traffic situations.

Making the most of ITS implementation methods is showing increased potential in the following areas: raising driver awareness of the current road situation, road safety and precautions, which will simultaneously have an impact on good transport management.
ITS solutions and applications are wide and varied. One of the most common vehicle ITS is the airbag, which accumulates information just before a collision.

One aspect is related to the introduction and adaptation of advanced technologies within the vehicle boundaries to communicate with other moving vehicles, as well as with the vehicle environment, which will help the driver to better and more accurately assess his driving situation.

McDonald [13] argues that this advanced driver assistance system was initiated to create improved technology integration using sensor and communication expertise so that the vehicle driver can maneuver more appropriately to avoid collisions, complex road network negotiations, and it is safer to follow other vehicles.

Collision Notification and Collision Avoidance is an application of intelligent vehicle technology that is designed and engineered to detect and communicate the magnitude as well as the exact location of incidents to agencies and services responsible for coordinating appropriate emergency response actions in the shortest possible time.

The following collision rates are used:
- 10 Hz for vehicle emergency warning, intersection collision warning and collision risk warning.
- 2 Hz for slow vehicle indication, motorcycle approach indication and optimal traffic light speed.
- 1 Hz to 10 Hz for speed limit notification.

Collision Warning and Collision Avoidance: It uses an intelligent technology system to warn the vehicle driver of an unfavorable approach to a nearby vehicle through the use of sensor radars, audio alerts and video on the screen.

Logi and Ritchie [14] described a real-time knowledge-based system (KBS) to support decision-making in the selection of integrated traffic management plans after non-recurring congestion. In this study, two algorithms were developed - an algorithm for combining data for congestion analysis and an algorithm for selecting control plans. The test results showed that the use of Traffic Congestion Management (TCM) reduced travel times from 1.9% to 29.0%, and the average stopping speed decreased from 14.8% to 55.9%.

Fagri and Hamad [14] studied the use of GPS in traffic management. In their study, GPS applications were involved in collecting traffic data such as travel time, speed and delay on 64 major roads in Delaware. When comparing the mean and variance of the results obtained by both methods, no significant differences were observed. GPS data was found to be 50% more efficient in terms of labor force.

Hernandez et al. [14] incorporated the use of artificial intelligence techniques in traffic management and presented a multi-agent architecture for intelligent traffic management systems. To support real-time traffic management decisions, two knowledge-based multi-agent systems, InTRYS and TRYSA2, have been developed. The performance of both systems was evaluated and the general applicability of multi-agent architectures for intelligent traffic management was given.

Zhenlin et al. [14] studied the effectiveness of the Beijing Intelligent Traffic Management System (ITMS). In this study, urban transport systems, socio-economic system and energy environment system were adopted as the input system, and the efficiency of traffic management and urban transport as the output system. Field data for Beijing from 2000 to 2010 are used for empirical analysis. The results of the study showed that ITS improved the overall efficiency of Beijing transportation.

Blockchain technology in terms of applicability in transport systems

The provenance, immutability, transparency and security of data are becoming integral parts of the Blockchain and all industries are trying to investigate this. One such industry where blockchain can prove useful is the transportation industry.
When we talk about the transportation industry, you should know that it is an integral part of the supply chain. In fact, transport is the foundation for all industries. Thus, it becomes imperative that companies have a seamless supply chain. Hence, it is essential that the transport industry runs smoothly.

Before understanding how Blockchain can revolutionize the transport industry, it is important to understand the challenges this sector is facing. From dispute resolution to administrative efficiency and order tracking, Blockchain has a solution to the problems that have plagued the transportation industry for decades. Let's take a look at some of these issues.

1. **Tracking**

One of the main challenges facing the transport industry is payment and dispute resolution. Did you know that about $140 billion is tied to transportation dispute settlement payments every day? It is time consuming and in many cases the transport industry depends on a third party, but with Blockchain there is no need for a third party. With an efficient Blockchain tracking system, we can easily track vehicles and know their status.

2. **Transportation of temperature controlled products**

The problem arises with temperature controlled goods, with approximately 8.5% of sensitive pharmaceutical shipments reportedly experiencing temperature swings. This adversely affects the shipment of such products as they exceed their specified temperature specifications. This results in loss of travel costs. Let's see how Blockchain can solve this problem.

Using Blockchain to authenticate data, IBM is partnering with other global companies to launch a platform that can guarantee the required efficiency, authenticity and transparency in the supply chain. When we talk about temperature controlled products, transportation depends on on-time delivery, and this is increasing with Blockchain.

3. **Smart contracts**

This is another area where we can find blockchain applications in the transportation industry. Having a smart contract ensures how and when the product is delivered, the smart contract is executed, and payment begins. Smart contracts are one of the best Blockchain technology applications. It is a preprogrammed contract that defines the terms and conditions. These conditions are predefined, after these conditions are met, payment is made.

4. **Tracking loading and unloading**

This is another area of application for blockchain. Similar to record tracking, Blockchain can be helpful in validating a driver record. This becomes beneficial when the freight broker is trying to achieve the load capacity at a specific location. If the broker identifies a new carrier, he can use the Blockchain ledger to verify the carrier and assign the load. With Blockchain technology, we can have a decentralized system in which all media records across the entire industry can be stored.

5. **It makes the loading on board more reliable**

One of the common problems faced by the transport industry is the cargo platform. In a traditional system, it is possible that the data can be changed and therefore create the wrong load. With Blockchain, shippers can easily submit time stamped shipments that are verified by the Blockchain network. These data are unchanged.

6. **IoT for communication with the car**

Many companies are implementing V2V or vehicle-to-vehicle communication. This system allows various cargo vehicles to communicate, thus providing fuel savings. This data, when stored in the Blockchain, can help transport companies optimize their operations.

Exonum is a platform that allows you to create decentralized, secure and reliable applications on the blockchain. The platform is designed for companies, organizations and even governments. Using the Exonum solution, these organizations can create their own private network that meets the needs of a particular company and provides unprecedented security by integrating the project with the blockchain.

Exonum is the fastest private blockchain that can process up to 9000 transactions per second. Programs for the Exonum blockchain platform are written in Rust, which Bitfury experts call the safest programming language, guaranteeing no memory management problems. A Rust program compiles directly to machine code, so it runs faster than virtual bytecode.

At the moment, the Exonum platform is used for pilot projects in the state registries of three countries: Georgia, Ukraine, Russia.

This largely applies to the management of large systems, to which the transport belongs. Failure to follow simple rules and recommendations can lead to serious consequences, including causing a traffic collapse.

**Basic system architecture**

Figure 3 shows the basic diagram of the proposed vehicle tracking system using blockchain technology.

![Figure 3. System architecture](image-url)
1. The main vehicle determines its position using any global positioning system, draws up a message containing the following information:
   - his identification number
   - its geographic coordinates
   - exact current time and date
   - message signature (the signature key is issued by the registering authority).

2. The main vehicle sends this data through a short distance transceiver module similar to the NRF24L01. It should send wireless signals at a distance of up to 150 meters so that only those vehicles that are nearby (nearby vehicles) are involved in the communication process [2,3].

3. Each adjacent vehicle receives a signal and composes a new message that includes the following information:
   - his identification number
   - its geographic coordinates
   - full unmodified copy of the original message

   Please note that it is not necessary to include the current date and time on adjacent vehicles. They are automatically recorded by the back-end system (blockchain). Although it is important that the main vehicle turns it on, this is important for safety reasons.

   We assume that the terminals use the following equipment:
   1. Some simple PC boards like Arduino or Rasberry Pi.
   2. 3G / 4G mobile internet module that supports sending messages to a SIM card with a request to sign it.
   3. A transceiver like NRF24L01 must operate with the same protocol and cover at least a 150 meter radius area.
   4. Any global positioning system that provides accurate geographic coordinates.

   **System security**

   Although we use the Blockchain system (Exonum) to ensure that no one can add any information backdated, and no one can edit any information that is already stored, there are several other security issues that we need to take care of [4].

   **Case 1.** The nearest car is trying to spoof the received message.

   He may try to change the vehicle ID, position or time. In this case, the signature of the main vehicle will not match. An attempt to forge a signature takes too long, the system checks if the difference between the time in the message and the current system time does not exceed 1 minute. At the same time, 1 minute is a fairly large interval that will allow you to have some inaccurate timing systems.

   A nearby vehicle may keep the sequence of messages in some position and try to fake the same position later. This would not be possible since the date and time stamp in the messages is also signed by the main vehicle. This is why it is important to include it in the message of the main vehicle, rather than include it in the messages of neighboring vehicles.

   **Case 2.** The main vehicle is trying to spoof its ID, time, or location.

   The problem of time has already been considered in the previous case. Faking an id is not easy, as you need to have a vehicle signature and it is securely stored inside the SIM card.

   So, we need to consider the problem of spoofing its location. If the main vehicle sends a different location, neighboring vehicles shouldn't worry about it, they still send the message further into the blockchain [5-7]. But nearby vehicles are also sending their own locations, so the system can detect that the distance between the two vehicles is too great (more than 1 km) and flag it as a potential scam. 1 km should be enough for a SIM card to sign a message.

   **Case 3.** Both the main vehicle and nearby vehicles try to fake the location of the main vehicle.

   Consider a case where several vehicles are hacked and they are trying to fake the location of one of them (the main vehicle). This scenario is possible and the system can save all the data exactly as it was sent.

   Having a full track with the date and time stamp of the main vehicle, it is easy to check other vehicles that have declared their position at the same time and in the same position up to 150 meters. It would also be suspicious that all messages from the main vehicle are corroborated by the same nearby vehicles [8].

   Unfortunately, if there were no other vehicles in the path of the vehicle, it is very difficult to verify with a 100% certainty whether the case has been tampered with. Although, verification of this case is still possible: since all data is sent via the mobile Internet. Thus, having the IP addresses of nearby vehicles, it is possible to query the communication provider which stations were used by this client.

   **Conclusion**

   This work will serve as an important step towards the development of traffic control systems for connected and autonomous vehicles, contributing to the solution of the problem of cybersecurity, as well as in the investigation of various types of crimes.

   In this paper, the cases of the presence of some fixed terminals were considered, which do not necessarily use a real global positioning system and mobile Internet connection, but are installed by the system supplier to act as nearby vehicles along some roads in the city or on highways at some intervals [4- five]. These clients can help control vehicles with 100% reliability. Even a single message signed by the terminal would have been enough to assert that the car was passing by.

   The paper considers a system that is safe and allows you to register the movement of a large number of vehicles. Given your location data at any given time, it is relatively easy to calculate the average speed as well as the speed at a given time. If the car is used for some
criminal purpose, this system will help us calculate it. Of course, in the event of a violation of the law, attackers can disable the internal warning system, then a car with the system turned off is already an object of special attention and will be suspicious for entire system. Also, in order to prove that the vehicle did not take part in any offense, it is enough to check the system logs, this will be reliable proof of innocence.

References

IMPLEMENTATION OF FPGA-BASED DVB-T2 TRANSMITTER FOR A SECOND GENERATION DIGITAL TERRESTRIAL TELEVISION BROADCASTING SYSTEM

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ABSTRACT

Nowadays, with strong development of Science and Technology, integrated circuits continue to dominate not only in the field of digital information. Over the last several years, Technological television industry has taken huge strides and powerful transformation to meet with government's policy about digitization of television all over the country in period 2015 - 2020. Stemming from the practical needs of "localization of products" and mastering of technological design of DVB-T2 transmitter (Digital Video Broadcasting - Terrestrial for Second generation), the authors have made an effort to research in algorithm, designed and tested in Field Programmable Gate Array (FPGA) technology. DVB-T2 is mainly aimed to replace the current standard DVB-T. The main motivation of DVB-T2 is to provide broadcasters with more advanced and efficient alternative to DVB-T standards. In DVB-T2 transmitter system, digital audio, video, and other data are compressed into a single signal to be transmitted on a single RF channel, using orthogonal frequency-division multiplexing (OFDM) with concatenated channel coding and interleaving. The higher offered bit rate makes it a suited system for carrying HDTV signals on the terrestrial TV channel. The next generation broadcasting systems should be designed to make full use of spectral resources while providing reliable transmissions in order to enable services like multichannel HDTV (High Definition Television) and innovative data casting services. The efficient usage of the radio spectrum can be achieved by the introduction of Single Frequency Networks (SFN). Digital transmitter DVB-T2 implemented on FPGA using a software Xilinx System Generator for DSP tool and Xilinx ISE Design Suite 14.7. System Generator for DSP is in conjunction on environment MATLAB-Simulink that is capable of simulating the proposed hardware structures that is synthesized and implemented by the programmable elements in Field-programmable Gate Arrays. In this project, adaptative MPEG-TS bitrate converter is designed to allows to increasing or reducing the MPEG TS rate by adding or filtering NULL packets. The entire digital transmitter DVB-T2 is integrated in one chip Xilinx FPGA Kintex-7 XC7K325T-1FFG676. Experimental design on development Kit NetFPGA-1G-CML of Digilent Corporation is performed at design department of technology center of Vietnamese Communications Television Development JSC. Authors are continuing to improve products, put into practical applications to replace the digital terrestrial television broadcasting stations that are being used in Vietnam. The article named "Implementation of FPGA-based DVB-T2 transmitter for a second generation digital terrestrial television broadcasting system" presents the research results, design methods, test results to compare, evaluate the accuracy of algorithm implementation. The results open up new directions for technological television in Vietnam.

KEYWORDS: cardiovascular diseases, random forest, k-nearest

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The article presents the main results obtained in Vietnamese OJSC "Development of communication-television", on the implementation of second-generation terrestrial digital television system transmitter (European standard DVB-T2 on FPGA).

The block diagram is shown in Figure 1.

The input processing module (MBO) is considered in the mode of a single-stream (in mode 'A' [1, 8-10]) physical layer channel (PLP). MBO assembles data from an MPEG-TS transport stream into groups called streaming (Baseband) frames (BB frames) according to modulation and coding parameters. As in the conference report [2], a specific implementation of MBO on FPGA with optimization of resources and processing speed is presented. Parameters for DVB-T2 system can be selected in [3]. In MBO (Figure 2 [1]) two parts are included: mode adaptation (ingress interface, convolutional CRC-8 coding, BB header addition) and stream adaptation (padding insert, BB frame scrambling).

To achieve the desired bit rate from the MPEG generator, the MPEG signal is fed over the coaxial cable to the Bitrate adapter [4].

During the design phase, pseudo-random data generated in the FPGA chip is received to evaluate each block of the system. The generator polynomial and the diagram (Fig. 2) for generating the MPEG data stream is proposed in Fig. 2 [5].

Diagram of DVB-T2 system on FPGA, including control points, is shown in Figure 3 [5].

Post-MBO data stream will be protected by Bose-Chowdhury-Hawkingham Error Correction (BCH) coding and Low Density Parity Check (LDPC) coding. Processing of data streams by MBO module and a combination of BCH and LDPC coding meets the requirements of the DVB-S2 satellite digital television system. With its strong error correction capability, combining BCH and LDPC, the DVB-T2 system achieves high power over DVB-T by 50% in multi-frequency networks. In addition, the constellation rotation in DVB-T2 has the ability to receive a signal with a large coding ratio.

BCH correcting coding ($N_{bch}$, $K_{bch}$) must be applied to every BBFRAME frame to form an error-proof packet. Where, $K_{bch}$ is the length of the BBFRAME of the frame that enters the BCH code, $N_{bch}$ is the length of the data block, including the BBFRAME frame and the BCH data behind it. $K_{ldpc} = N_{bch}$ is the length of the data block that is received in the LDPC code. $N_{ldpc}$ is the length of the data at the output of the LDPC code. Parameters $N_{bch}$, $K_{bch}$ are selected in table 6a/6b [1]. The generator BCH polynomial of the encoder to correct $t$ errors is obtained by multiplying the first $t$ polynomials in table 7a/7b [1].

![Diagram 1](image1)

**Figure 1**

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<td>67%</td>
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<td>60</td>
<td>890</td>
<td>6%</td>
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<tr>
<td>Number of DSP48E1s</td>
<td>72</td>
<td>840</td>
<td>8%</td>
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</tbody>
</table>

Таблица 1
A code with a low density of parity checks is a code used in information transmission, a special case of a block linear code with a parity check. Special feature is low density of check matrix significant elements, due to which the relative simplicity of coding tools implementation is achieved, containing mainly zeros and a relatively small number of ones. Positions of the units are shown in Appendix A and B [1].

After the bit interleaver, the data is modulated. The framing unit implements the mapping of data cells after modulation and rotation of the constellation and signaling into subcarriers. To improve the spectral characteristics of signal, subcarriers are frequency interleaved.

The OFDM shaping module uses a large number of closely spaced orthogonal subcarriers. Each subcarrier is modulated in a conventional modulation scheme at a low symbol rate, maintaining the overall data rate as conventional single carrier modulation schemes in the same bandwidth. In practice, OFDM signals are obtained by using an FFT (Fast Fourier Transform).

As a result of the inverse fast Fourier transform (IFFT) of N carriers, a pulse signal is generated for the value of difference between the maximum peak value and target power value. Therefore, PAPR method is designed to reduce peak-to-average power ratio.

Each block and module is separately implemented on FPGA. The results of processing from control points are compared with reference dataset [6].

DVB-T2 system is implemented on Xilinx Kintex-7 XC7K325T-1FFG676 chip of Digilent NetFPGA-1G-CML Development Kit [7]. The entire system is integrated on a single chip with resources shown in Table 1.

The results are shown in Figures 2-3.

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DISPERSION COMPENSATION USING ELECTRONIC METHODS

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ABSTRACT
System distortions due to chromatic dispersion (CD), polarization mode dispersion (PMD), laser phase noise and fiber nonlinearities have a significant impact on the performance of high-speed fiber optic networks [1]. In connection with the need to improve the quality of information transmission in high-speed fiber-optic communication systems, coherent detection with a digital signal processing unit is of particular interest. The main goal of the DSP block is to reduce the impact of linear and nonlinear effects that degrade the quality of information transfer. In this direction, the use of adaptive filters with adaptation algorithms for filter coefficients plays an important role. The Constant Modulus Algorithm (CMA) and the Least Mean Square (LMS) method used to compensate for dispersion distortions are presented. The load on transport networks based on fiber-optic transmission systems is increasing at an accelerating rate. This paper discusses the possibility and limitations of increasing the throughput of fiber-optic transmission systems by reducing the distance between carriers. A comparison is made between fixed and flexible grids in terms of the spectral bandwidth efficiency. It is concluded that the use of flexible mesh technology is promising when switching to channel speeds above 100 Gbit/s.

KEYWORDS: Equalizers, weights, digital signal processing, digital filtering algorithm, Bandwidth, fixed mesh, flexible mesh, number of channels, spectral efficiency, fiber optic transmission system.
Introduction

Due to the high spectral transmission efficiency and robust resistance to fiber nonlinearities, coherent optical detection using modern modulation formats and digital signal processing (DSP) has become one of the most promising solutions for the next generation of high-speed fiber-optic transmission systems [2]. Since both amplitude and phase information from the received signal can be extracted using a coherent optical receiver, distortions caused by the above influences can be effectively compensated or reduced using powerful DSP algorithms. HD and PMD can be well compensated with digital filters in the time and frequency domains [3].

Digital filters have become the most promising alternative approaches to dispersion compensating fibers. These implementations result in significant reductions in complexity and cost as well as improved fiber nonlinearity immunity for high performance fiber optic transmission systems. Filters used to compensate for dispersion can have both constant parameters and adaptive [1]. In the case of using digital equalizers, implemented on the basis of constant parameters for the implementation of static compensation of intersymbol interference, it is necessary to have a priori knowledge of the signal and interference in the transmission line [5].

However, in switched fiber optic networks, the signal path between two end nodes can change over time according to different network conditions, where the transmission distance and accumulated dispersion in the light path cannot be predicted in advance. Therefore, it is advisable to consider adaptive dispersion compensation in such optical transmission networks.

The main feature of an adaptive system is the presence or absence of an exemplary or reference signal. If it is available, the adaptation process is called supervised learning, and the adaptive filter seeks to make its input signal as close as possible to the exemplary signal. If there is no exemplary signal, then the adaptation is called blind, or unsupervised learning, which is a more complex computational problem.

Electronic dispersion compensation techniques

Digital signal processing using both recovery algorithms and the development of a component base for a digital-to-analog converter makes it possible to eliminate linear optical interference, such as HD, PMD, and phase shift [6]. Adaptive filters play an important role in the implementation of digital compensation.

An adaptive filter (AF) is a system whose parameters are adapted (adjusted) to a signal with a previously undefined statistical model during its processing. Among adaptive filters, linear adaptive feedback filters implemented on the basis of FIR filters are most widely used due to their ease of use.

AF input receives two signals simultaneously:
- input signal $x(k)$ is unknown in advance; desired signal $d(k)$
- signal $d(k)$ is known in advance; $x(k)$ is unknown

The performance of an FIR filter can be expressed as a vector of values known as tap weights. It is these weights that determine the performance of the filter. These values are expressed in vector column form as:

$$W(k) = [w_0(k), w_1(k), ..., w_{N-1}(k)]^T$$

This vector represents the impulse response of the filter of order $N$. The output from the FIR filter is defined [4]:

$$y(k) = X^T(k)W(k) = \sum_{i=0}^{n} w_i(k)x(k-i)$$

where $X(k) = [x(k), x(k-1), ..., x(k-n+1)]^T$ column vector of complex filter input.

In theory, given a sufficient number of taps, an adaptive filter can compensate for any kind of linear distortion by adjusting the coefficients of the FIR filter [1-3].

With adaptive compensation, the weights are updated at each time step with the following ratio:

$$\bar{w}(k+1) = \bar{w}(k) + \mu \varepsilon(k)x(k)$$

where $\varepsilon(k)$ – signal recovery error at the $k$ step, $\mu$ – step size. This is a convergence parameter that is associated with filters to update the weights. Some difficulty arises when analyzing its behavior, because the higher its value, the faster the convergence, but the accuracy becomes low. On the other hand, a low value gives high accuracy, but slows down convergence.

It is necessary to find such filter coefficients $\bar{w}(k)$, which ensure the maximum proximity of the filter output signal to the reference, that is, minimize the error $\varepsilon(k)$ [3].

Various adaptive algorithms are used to control the equalizer coefficients. Constant Modulus Algorithm (CMA: Constant Modulus Algorithm) and Least Mean Square (LMS: Least Mean Square) are some of the most widely used algorithms used to compensate or reduce the effects of variances in the electrical domain. Both methods rely on the implementation of adaptive filters whose coefficients are updated to minimize RMS error due to intersymbol interference and noise.
Least mean square method (LMS)

Purpose of least mean square method is to calculate the difference between reference signal and output of adaptive filter, \( \varepsilon(k) \), which is called an error signal and is fed back to the adaptive filter, and its coefficients are changed algorithmically to minimize a function of this difference, known as a cost function [5].

\[
\varepsilon(k) = d(k) - |y(k)|^2
\]

If the output of adaptive filter is error-free, then the output of filter converges to desired signal. Larger the error at filter output, greater the deviation between filter output signal and desired signal.

Figure 2 shows the result of dispersion compensation using an equalizer based on LMS algorithm. Dispersion distortions were compensated, but this method converges rather slowly and has increased error variance, as shown by convergence plot.

Constant modulus algorithm (CMA)

The use of a constant modulus for calculating the error is based on the fact that the PSK signal without distortion (PSK) has a constant power level. Therefore, the goal is to minimize power level fluctuations by comparison with a constant modulus [5].

\[
\varepsilon(k) = 1 - |y(k)|^2
\]

It follows from Figure 3 that CMA algorithm is also more efficient for large phase noise, since the performance of LMS algorithm will be significantly degraded due to the large phase noise.

Each of these algorithms has its own advantages and disadvantages. Equalizers based on CMA are difficult to apply directly to M-QAM modulation formats, the envelope of which has a multi-level structure [4]. Equalizers based on LMS, in turn, are sensitive to fluctuations in the carrier phase, which will prevent convergence of the filter coefficients. Therefore, the removal of phase and frequency errors before or during LMS adaptation is essential.

To adapt the filter coefficients, a combined scheme of CMA and LMS algorithms can be applied. In this case, a CMA-based equalizer is first applied to achieve preliminary convergence, followed by frequency and phase equalization, and finally a less reliable but more accurate LMS algorithm is applied. After the adaptation stage, the equalizer coefficients are fixed and used to equalize the received signal.

INCREASING THE BANDWIDTH OF FIBER OPTIC TRANSMISSION SYSTEMS BY DECREASING THE DISTANCE BETWEEN THE CARRIER

The current period of development of information and communication technologies (ICT) sector is characterized by widespread introduction of a variety of multimedia services, rapid development of Internet networks, emergence of data processing centers, massive introduction of mobile applications requiring high bandwidth and advanced technologies for high-speed packet transmission. Implementation of these trends necessitates a sharp increase in the throughput of fiber-optic transmission systems (FOTS).
Obviously, under these conditions, of particular interest is a transmission medium that has a high potential throughput and makes it possible to multiply the amount of transmitted information. Thus, fiber-optic cables act as the main transmission medium of the transport network, on the basis of which a layer of transparent optical channels is formed using the technology of spectral multiplexing (DWDM). The data transfer rate achieved by fiber-optic systems over the past 30 years has increased by more than four orders of magnitude [7].

Traffic forecasting in the construction of optical communication networks is a difficult job, which requires the development of methods to increase the bandwidth of FOTS without significant costs for the modernization of expensive line-cable facilities. In this regard, in order to expand the physical network, it is advisable to make more significant efforts to improve the efficiency of fiber-optic information transmission systems. One of the ways to effectively use the capabilities of optical fiber is to increase the number of channels in a frequency band by reducing the distance between channels, the path along which the developers of the G.692 standard have gone [13].

Applying a fixed grid

The number of channels, channel spacing, width of each channel and the channel bandwidth are important parameters in the design and construction of a high-speed communication network.

In traditional DWDM systems, optical spectrum in the C-band, consisting of approximately 4.1 THz, is divided into hard spectrum intervals of 50 GHz as defined in ITU-T Rec. G.694.1. This forms a “grid of wavelengths, where the center frequencies of adjacent channels have fixed spectral intervals of 50 GHz. The frequency grid defined in this recommendation supports a variety of fixed channel spacings from 12.5 GHz to 100 GHz or more (integer multiples of 100 GHz), as well as a flexible grid [8].

When using DWDM technology, one can try to estimate the limiting value of the equivalent FOTS bandwidth, a parameter defined as the product of the transmission rate in the optical channel \( B_{th} \) for the number of channels \( N \).

\[
B_{\text{max}} = B_{th} \times N, 
\]

Using the standardized range (192.10 – 196.10 THz), the total frequency width is 4.1 THz. If the channel spacing is 50 GHz, a maximum of 81 channels can be accommodated. If the channel spacing is reduced to 25 GHz, this range can accommodate 163 channels, and thus double the bandwidth of the FOTS.

While systems with reduced channel spacing will be able to provide significant FOTS bandwidth, this reduction places more stringent demands on the devices used in the system, which reduces the number of potential equipment manufacturers as well as increases costs. From the transmitter's point of view, wavelength stability becomes very important, since even a small drift can cause serious inter-channel interference [9]. With small values of inter-channel gaps, the influence of the effect of four-wave mixing and cross-phase modulation increases, which begins to limit the maximum range of non-regenerative information transmission due to a decrease in the signal-to-noise ratio. A small inter-channel distance can also limit the ability to transmit information at a high channel rate, since there is an overlap of spectra of adjacent channels (Fig. 4).

Interchannel interference together with intersymbol interference presents itself as serious influencing factors that degrade the quality of signal reception. They generate two-dimensional (2D) interference that must be efficiently processed by digital signal processing at the receiver [10].

In the absence of interchannel distortion, intersymbol distortion can be compensated for by an adaptive equalizer and an FEC decoder. Addressing the combined effects of this interference requires some form of joint processing of spectrally overlapping asynchronous WDM channels [10].

![Figure 4. Multiplexing of STM-64 and STM-16 channels at intervals of 100 GHz and 50 GHz](image)

The use of advanced modulation formats and photonic techniques allows signals to be transmitted at a channel rate of 100 Gbit/s in WDM with a fixed grid of 50 GHz. However, for higher traffic rates such as 400 Gbps and 1 Tbps, the required bandwidth using standard modulation formats becomes too wide to fit into a 50 GHz grid. To prevent channel-to-channel crosstalk, one option may be to increase the fixed mesh width from 50 GHz to 100 GHz. The disadvantage of using a wider grid is not only that fewer wavelengths will be transmitted, but also that channels with low speed channels will use a grid up to 100 GHz each, which leads to a decrease in the efficiency of spectrum resource use. Another attempt would be to use higher spectral efficiency (SE) modulation formats such as QPSK and QAM. This option leads to a reduction in the transmission range due to the increased requirements of the optical signal-to-noise ratio (OSNR).

Flexible mesh application

To overcome the aforementioned disadvantages when moving to a transmission rate of more than 100 Gbit/s, Flex Grid technology was proposed, defined in ITU-T Recommendation G.694.1, based on a 12.5 GHz channel spectral separation (Fig. 5). With this technique it becomes possible to flexibly spectral shaping of any channel, including a super channel in a certain frequency range and optical zooming optical network capacity [11].
The possibility of using Flex Grid technology in commercial systems appeared only after the creation and start of mass production of tunable wavelength selective switches (WSS), using LCoS (liquid crystal on silicon) technology [12].

In [11], a theoretical analysis was carried out comparing flexible mesh and standard mesh, taking into account optical channels between 10 Gbps and 400 Gbps. The characteristics of the signals of each grid type (modulation format, spectrum efficiency in bits / symbol and guard band) are given in Table 1 derived from data from several transmission studies.

As you can see from the table, a 10 Gbps channel using the NRZ-OOK modulation format requires a 25 GHz slot (two slots) in a flexible mesh, while 50 GHz is used for a fixed mesh. The rest of the channel types (40, 100 and 400 Gbps) use DP-QPSK as the modulation format, reaching a spectral efficiency of 4 bits / symbol. The bandwidth of the spectrum shown in table 1, takes into account a 7 GHz guard band between optical channels.

The effect of forward error correction is also taken into account by increasing the data rate by 12%. In the case of a fixed mesh, the 400 Gbps link requirements are served by four 100 Gbps links, so 4 carriers are used (total 200 GHz in the case of a 50 GHz grid). The values in the last column indicate that using the DP-QPSK modulation format, the total FOTS bandwidth can theoretically be increased by 33.3% with 100 Gbps links or 60% with 400 Gbps links.

The overall increase in FOTS throughput using Flex Grid technology, coupled with the ability to transfer speeds in excess of 100 Gbps over long distances, are consecutive reasons for the development of flexible grid technology. However, from the perspective of the network operator, it is important to know when this increase in FOTS capacity will represent a viable solution for their networks and how this can be implemented.

Depending on the existing fixed grid infrastructure, some solutions may not be supported due to the required spectrum bandwidth. For example, transmissions above 100 Gbps using the DP-QPSK or OFDM-DP-QPSK modulation formats are not possible within the fixed 50 GHz grid. Although there are modulation formats with higher spectral efficiency, such as DP-16-QAM, which can fit into a fixed 50 GHz grid, such formats cause a drop in the maximum transmission range.

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**Table 1**

<table>
<thead>
<tr>
<th>Transfer rate, [Gbps]</th>
<th>Modulation format</th>
<th>Number of wavelengths</th>
<th>Spectrum [GHz]</th>
<th>Number of slot</th>
<th>Spectrum [GHz]</th>
<th>Capacity gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>NRZ-O</td>
<td>1</td>
<td>5</td>
<td>2</td>
<td>25</td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>SE= 16πt/λ</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>DP-QP</td>
<td>1</td>
<td>5</td>
<td>2</td>
<td>25</td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>SE= 46πt/λ</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>DP-Q</td>
<td>1</td>
<td>5</td>
<td>3</td>
<td>37.5</td>
<td>33.3%</td>
</tr>
<tr>
<td></td>
<td>SE= 46πt/λ</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>400</td>
<td>OFDM-DP-QPSK</td>
<td>4</td>
<td>20</td>
<td>10</td>
<td>125</td>
<td>60%</td>
</tr>
<tr>
<td></td>
<td>SE= 46πt/λ</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>

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**Figure 5.** ITU-T G.694.1 flexible frequency grid based on 12.5 GHz grid
Conclusion

With high-speed FOTS, it is necessary to improve the quality of information transmission. The use of digital signal processing methods with adaptive filtering algorithms allows you to compensate or reduce the influence of linear and non-linear effects of optical fiber. The algorithms CMA and LMS, which allow to align the received signals by adjusting the coefficients of the FIR filter, are considered. CMA is designed to work with modulation formats that have a constant modulus, that is, a constant amplitude, so the adaptation process is not affected by the presence of a frequency and phase shift. The LMS algorithm is sensitive to phase fluctuations, which requires the removal of phase and frequency errors before or during adaptation based on it.

To achieve high results, a combined algorithm scheme can be considered.

As the ICT industry develops, so does the need to increase bandwidth and maintain bandwidth flexibility. Reducing the distance between channels is one of the ways to increase the bandwidth of the FOTS. However, the effect of co-channel interference (the effect of four-wave mixing and cross-phase modulation), leading to a decrease in the signal-to-noise ratio, must be taken into account. Comparison of flexible mesh and fixed networks for different bit rates and modulation formats showed the advantage of flexible mesh in bandwidth efficiency. The use of flexible grid technology (Flex Grid), which allows spectrum management, is the prospect of increasing the efficiency of FOTS operation at channel speeds above 100 Gbit/s.

References

Executive summary

The credit outlook for European telecommunication operators remains stable, with the sector displaying considerable resilience during the first phase of the Covid-19 crisis. The progressive introduction of 5G networks is neutral for credit quality.

Governments postponed several auctions of 5G spectrum in 2020. Operators will likely incur the cost of acquiring spectrum this year but it will remain well within their financing capacity in the absence of new entrants in national markets to bid up auction prices. We see limited opportunities for large mergers and acquisitions while operators will continue to sell infrastructure assets, leaving the sector’s overall credit quality unchanged despite a likely slow, uneven economic recovery.

The main trends we expect for 2021 are:

- Stable revenues and margins despite the economic disruption caused by the pandemic: telecommunications are essential services which make up a modest percentage of household spending.
- Auctions of 5G spectrum should lead to sales at reasonable prices partly through the absence of new entrants in the mature mobile market which would otherwise push up prices. Capex will not increase as 5G is rolled-out as operators are simply replacing previous technologies (2G, 3G) and reducing spending on 4G. Any increase in capex will be rather driven by investment in fibre-to-the-home (FTTH).
- M&A will remain limited. Transnational deals offer few synergies, while national “consolidation” will be rare as targets are scarce, for fixed-line operators, or out of bounds for mobile on competition grounds.

Key trends for 2021

In an industry characterised by its stability, we expect no significant changes in 2021 for European telecom operators compared with last year. The Covid-19 crisis has demonstrated, once again, that the industry is almost immune to economic cycles, as telecom services have become indispensable while representing a small proportion of a typical European household budget — about 2.5% — and thus less exposed to downward pressures on consumer spending.

The roll-out of 5G mobile technology is still making the headlines, as the pace of introduction varies from one country to another: 5G trials, spectrum auctions, network roll-out, service introduction, new handsets, search for a “killer application”... But beyond the hype, the impact on revenues and capex will not be significant. Capital expenditure continues to increase slowly, driven in 2021 by further investment in fibre networks around Europe. M&A will remain limited with few opportunities in such a mature market. European telecom operators will continue to bolster their credit profiles mostly from the full or partial sale of infrastructure assets such as mobile towers and some fibre networks.
Stability proven in the Covid-19 crisis

The telecommunications operators have demonstrated the fundamental stability of their business during the Covid-19 crisis to date. Revenue figures published by several European regulators for the nine months to end-September showed little change from the same period in 2019, particularly in comparison with the scale of the economic shock and recessions across Europe.

In terms of profitability, some operators recorded improved margins in Q3 from the same quarter a year ago despite subdued international tourism in Europe during the summer when the companies typically benefit from an increase in mobile roaming fees. In addition, nearly all operators have maintained their sales and earnings guidance for 2021. The recent trend of stable profit margins remains intact despite the economic impact of the pandemic.

Also noteworthy is the operational resilience of Europe’s industry which experienced no network failures despite the increase in traffic during the lockdowns and the shift toward remote working. Helping operators cope with the rise in usage was that the surge in traffic took place mostly during the day when usage was usually low, pre-pandemic, rather than in the evening, typically the period of peak usage.

Operators are at risk of a more material adverse impact from the pandemic should further economic disruption, as governments reimpose various restrictions to contain Covid-19, trigger more bankruptcies and business closures. Offsetting that risk is growing digitalisation of corporate activity, accelerated by the pandemic and pressure on business to cut costs. We believe that, overall, the impact of a second phase of coronavirus infections would be negligible.

Delay in 5G auctions: delay in outflows for operators

5G ACTION PLAN

5G SPECTRUM

Figure 1. European telecoms revenues for select countries (% change, Q1-Q3 2020 vs 2019)

Figure 2. European telecom operators’ reported EBITDA margin, 2013-2019

The second, indirect, effect of the Covid-19 crisis was the delay in planned 5G auctions in many European countries last year: Poland, Romania, Spain, Sweden and the UK. In France, the auctions were delayed, but finally took place in the second part of the year. In some instances, operators chose to launch 5G in 2020 over spectrum bands already in use (2 GHz spectrum, for instance).

Most of these auctions will now take place in 2021, with the notable exception of Netherlands that only auctioned 700 MHz spectrum in July 2020; the 3.5 GHz spectrum - this band typically is the most costly 5G band due to its width and ability to deliver higher speeds - is due to be auctioned in March 2022.

Paying for 5G: auction prices expected to remain reasonable

The main 5G-related issue for the sector’s credit outlook will still be the outcome of spectrum auctions in the coming quarters. As we anticipated a year ago, 5G auctions have not led to fierce bidding and exorbitant prices as ini-
entially was the case in Italy in 2018 and in Germany in 2019. We believe the main reason for the elevated auction prices in Italy and Germany was the participation of new bidders — Iliad SA in Italy and 1&1 Telecommunication SE in Germany. In 2020, there were no auctions with a new entrant. In Hungary, smaller operator Digi PLC tried to join the auction, but the regulator rejected its application.

We expect no new entrants in any of Europe’s biggest markets to compete for spectrum this year: the industry is mature with mobile penetration in Europe around 130%. Please see Figure 9 for the results of the latest auctions (including Italy and Germany) and our expectations for the forthcoming ones in the largest countries in Europe representing about 80% of the EU market. The only exception is Portugal, where the regulator opened the door for a new entrant, the Spanish group Grupo MasMovil.

At the time of writing, bids in auctions currently underway remain reasonable.

Mobile capex stable even with 5G

The introduction of 5G services in Europe will lead to no significant increase mobile capex in the coming years. The 5G investment replaces spending on older technologies 2G, 3G and diminishing investment in 4G and involves the re-use a significant part of existing infrastructure including masts and backbone networks and benefits from lower equipment prices as the technology matures.

Most operators have stopped reporting separate spending on mobile and fixed segments, so the best way to illustrate the trend is the reported mobile capex, excluding spectrum, in the French market disclosed by the French regulator (Arcep) over the past 15 years. In this period, mobile capex remained pretty stable, with an average annual level of EUR 2.5bn — with a low of EUR 2bn in 2010 and a peak of EUR 3.3bn in 2006 — even while various technologies (3G, 3G+, 4G, 4G+...) were successively rolled out.

This stability persisted despite the introduction of a new fourth mobile operator (Free Mobile in 2012) and a massive jump in network usage: voice traffic multiplied 2.2 times over the period, SMS traffic multiplied 13 times and data traffic more than 40,000 times. This trend is not unique to France. Similar data are available in other European countries including Finland and Italy.

Revenue impact of 5G likely modest

We expect that 5G will not increase mobile revenues, following the pattern with the introduction of 3G and 4G. The newer technology simply replaces the preceding technology. For instance, it is nowadays almost impossible to buy a 3G mobile phone. We just buy a "mobile phone" equipped with the technology of the day, currently 4G. As 5G spectrum has not been fully allocated in Europe, 5G handsets are still rare and relatively expensive. The 5G network roll-out will take at least five years to offer full coverage so 5G adoption will be slow and progressive. In Finland, the first European country to allocated 5G spectrum (3.6 GHz spectrum allocated in September 2018), the leading operator Elisa only introduced commercial 5G service in July 2019, with coverage of the Finnish population of only 35% as of December 2020. We note also that Elisa first reported the number of 5G subscribers with its Q4 2020 results which, at nearly 200,000, represented 5% of Elisa’s mobile customers in Finland – 18 months after commercial introduction.

Recently, in France, Free Mobile introduced a 5G service as part of its normal plans, without any specific tariff plan, or price premium. It is sold as what we expect 5G will be sold everywhere in future in Europe: simply a “mobile service”. We guess that by this time, European operators will be hyping 6G.

Fixed revenues will continue to decline in Europe, as the sharp drop in fixed telephony (typically – 15% per year) is no longer compensated by the now slow increase in broadband revenues. Total telecoms revenues in Europe will be at the best flat, or more probably, slightly declining. We note that many European telecom operators have stopped giving revenue guidance.

Capex mostly driven by further fibre (FTTH) roll-out

Telecoms spending in France (Figure 4, above) shows very clearly that the key driver for capex is investment in the fixed network. Fixed capex in Europe peaked in the late 70s and early 80s and started to decline fast when the copper-wire networks were fully built. The next 25-30 years were ones with almost no capex in the copper local loop which typically represent about 70% of the cost of fixed networks, except some marginal investment, such as DSL at about EUR 100 per line, which allowed operators to offer early broadband services using the existing copper network.

The move to fibre broadband is driving the increase in telecoms capex in Europe, progressively replacing the old copper network, which is starting to be decommissioned. The relation of fixed capex increases with the fibre investment cycle is well illustrated by the following chart (Figure 6), comparing total fixed capex in France with the number of FTTH (fibre-to-the-home, the most complete, and expensive, fibre network structure) lines installed. We estimate that at the end of 2020, there were around
23.5 million FTTH lines available, of which 10 million were in service, representing about 33% of the total broadband customer base in France.

But the advance of fibre varies significantly among EU countries. Among large European economies, Sweden, Spain, Romania, Norway, and Portugal are the most advanced in terms of fibre roll-out, as shown in the latest set of figures from the OECD.

To move to high-speed broadband, some operators have preferred to roll-out intermediate technologies (VDSL, G-fast, vectoring,...) using existing copper networks on rely on a limited fibre roll-out (fibre-to-the-node or fibre-to-the-curb or FTTC), allowing them to limit capex. The OECD chart above includes only FTTH as fibre. The fibre-lite approach is now under consumer and political pressure in countries where operators pursued it. These companies are now belatedly announcing more FTTH spending, suggesting capex will rise in the years ahead.

Proceeds from tower, fibre-network sales to underpin credit quality

Asset sales remain an important part of reorganisation of the Europe industry, playing a far more important role than largescale M&A. Previously, operators have sold foreign subsidiaries in emerging economies as the local telecoms businesses are starting to mature as Europe began to 15 years ago.

Today, European telecoms operators are focused more on selling infrastructure, including mobile towers where they have created an active market, and parts of their fibre network. The buyers tend to be specialised companies (tower companies) or financial investors such as private equity and investment funds.

Among the most important asset disposals last year was Hong Kong's CK Hutchison Holdings Ltd.'s sale in September of about 25,000 towers in Europe (UK, Italy, Austria, Ireland, Denmark, Sweden) to Spain's Cellnex Telecom SA for almost EUR 10bn. In January 2021, Telefonica subsidiary Telia Telecom - part owned by private-equity firm KKR and others - sold about 37,000 towers in Europe and Latin America for EUR 7.7bn to American Tower Corp. Just two weeks later, Orange finalised the sale of 50% of Orange Concession, the entity that owns the fibre networks for French local government with 4.5m fibre lines, to French financial partners for about EUR 1.5bn. Vodafone has created its own Tower Company, with about 68,000 towers in nine European countries, which is to be listed in Frankfurt this year.

Even so, given the operators' increased investment in fibre, we expect no significant decline in financial leverage for telecom operators in Europe this year.
We expect that European telecoms operators will undertake little largescale M&A this year. Large transnational deals, such as the much-rumoured tie-up between Deutsche Telekom-Orange, offer no synergies: telecom services are local, not exportable, so combining companies offers no extra revenues and few cost savings. National deals are now almost impossible as most cable operators in the EU have already been bought. In the wireless segment, mobile-mobile deals are de facto blocked by the regulatory authorities, notably the European Commission, on competition grounds.

<table>
<thead>
<tr>
<th>Country</th>
<th>Price per MHz per pop (€)</th>
<th>Total</th>
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<tr>
<td>Germany</td>
<td>83.0€/pop</td>
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<tr>
<td>700 MHz (60 MHz) 2015</td>
<td>0.20</td>
<td>1,000</td>
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<tr>
<td>900 MHz (70 MHz) 2015</td>
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<td>1500 MHz (40 MHz) 2015</td>
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<td>2 GHz (2 GHz) 2015</td>
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<tr>
<td>3.6 GHz (300 MHz) 2015</td>
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<td>4,175</td>
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<tr>
<td>Total (June 2019)</td>
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Deutsche Telekom (2,160), Vodafone (1,947)
Telefonica Deutschland (1,472), Vodafone (1,079)

<table>
<thead>
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<th>France</th>
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<td>600 MHz (60 MHz) 2011</td>
<td>0.72</td>
<td>2,640</td>
</tr>
<tr>
<td>2600 MHz (160 MHz) 2011</td>
<td>0.10</td>
<td>936</td>
</tr>
<tr>
<td>700 MHz (60 MHz) 2015</td>
<td>0.70</td>
<td>2,800</td>
</tr>
<tr>
<td>3.6 GHz (310 MHz) 2015</td>
<td>0.13</td>
<td>2,789</td>
</tr>
<tr>
<td>Total (October 2020)</td>
<td></td>
<td>2,789</td>
</tr>
</tbody>
</table>

To be allocated later
26 GHz (1,000 MHz)
Not scheduled yet
Orange (554), Alcatel (729)
Bouygues (802), Iliad (605)

<table>
<thead>
<tr>
<th>United Kingdom</th>
<th>65.7€/pop</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>3.5 GHz (150 MHz) 2018</td>
<td>0.13</td>
<td>1,307</td>
</tr>
<tr>
<td>2.3 GHz (60 MHz) 2018</td>
<td>0.99</td>
<td>231</td>
</tr>
<tr>
<td>Total to be allocated in 2021</td>
<td></td>
<td></td>
</tr>
<tr>
<td>700 MHz (60 MHz)</td>
<td>0.25</td>
<td>1,334</td>
</tr>
<tr>
<td>3.7 GHz (120 MHz)</td>
<td>0.17</td>
<td>1,381</td>
</tr>
<tr>
<td>Total 5G in 2021</td>
<td></td>
<td>2,896</td>
</tr>
</tbody>
</table>

BT, Vodafone, Telefonica, Hutchison

<table>
<thead>
<tr>
<th>Italy</th>
<th>60.4€/pop</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>700 MHz (96 MHz) 2015</td>
<td>0.35</td>
<td>2,040</td>
</tr>
<tr>
<td>3.6 GHz (200 MHz) 2015</td>
<td>0.38</td>
<td>4,350</td>
</tr>
<tr>
<td>26 GHz (1,000 MHz) 2015</td>
<td>0.003</td>
<td>194</td>
</tr>
<tr>
<td>Total (September 2018)</td>
<td></td>
<td>6,954</td>
</tr>
</tbody>
</table>

Telecom Italia (2,400), Vodafone (2,400), Wind-Tre (517), Iliad (1,194)

<table>
<thead>
<tr>
<th>Spain</th>
<th>49.9€/pop</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>3.6 GHz (200 MHz) 2016</td>
<td>0.05</td>
<td>438</td>
</tr>
<tr>
<td>To be allocated in H1 2021</td>
<td></td>
<td></td>
</tr>
<tr>
<td>700 MHz (60 MHz)</td>
<td>0.35</td>
<td>1,388</td>
</tr>
<tr>
<td>Total 5G in 2021</td>
<td></td>
<td>1,388</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Poland</th>
<th>30.0€/pop</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>26 GHz (1,000 MHz)</td>
<td>To take place in 2022</td>
<td></td>
</tr>
<tr>
<td>Telefonica, Vodafone, Orange, MaxMovil</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Romania</th>
<th>10.4€/pop</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>3.6 GHz (255 MHz) 2015</td>
<td>0.022</td>
<td>10</td>
</tr>
<tr>
<td>To be allocated in H1 2021</td>
<td></td>
<td></td>
</tr>
<tr>
<td>700 MHz (75 MHz)</td>
<td>0.08</td>
<td>116</td>
</tr>
<tr>
<td>800 MHz (10 MHz)</td>
<td>0.06</td>
<td>12</td>
</tr>
<tr>
<td>1500 MHz (40 MHz)</td>
<td>0.08</td>
<td>78</td>
</tr>
<tr>
<td>2600 MHz (80 MHz)</td>
<td>0.08</td>
<td>124</td>
</tr>
<tr>
<td>3.6 GHz (60 MHz and later 400 MHz)</td>
<td>0.04</td>
<td>316</td>
</tr>
<tr>
<td>2100 MHz (120 MHz lic. Extension 2021)</td>
<td>0.05</td>
<td>155</td>
</tr>
<tr>
<td>Total 5G in 2021</td>
<td></td>
<td>790</td>
</tr>
</tbody>
</table>

To be allocated later
26 GHz (1,000 MHz)
Not scheduled yet
Orange, Deutsche Telekom, Play, Plus

<table>
<thead>
<tr>
<th>Netherlands</th>
<th>17.3€/pop</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>800 MHz (60 MHz) 2012</td>
<td></td>
<td></td>
</tr>
<tr>
<td>900 MHz (70 MHz) 2012</td>
<td></td>
<td></td>
</tr>
<tr>
<td>All bands average</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1600 MHz (140 MHz) 2012</td>
<td>0.61</td>
<td>3,802</td>
</tr>
<tr>
<td>1900 MHz (15 MHz) 2012</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2100 MHz (75 MHz) 2012</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A total of 360 MHz allocated in 2012</td>
<td></td>
<td></td>
</tr>
<tr>
<td>700 MHz (60 MHz)</td>
<td>0.45</td>
<td>474</td>
</tr>
<tr>
<td>1600 MHz (40 MHz)</td>
<td>0.39</td>
<td>269</td>
</tr>
<tr>
<td>2100 MHz (120 MHz)</td>
<td>0.24</td>
<td>489</td>
</tr>
<tr>
<td>Total (July 2020)</td>
<td></td>
<td>1,332</td>
</tr>
</tbody>
</table>

To be allocated later
3.5 GHz (150 MHz) ? in March 2022 | 0.15 | 389 |

| July 2020 | KPN (416), Deutsche Telekom (277), Vodafone Ziggio (416) |

Figure 9. Detailed 5G spectrum auctions in the eight largest EU countries (EURm)

Limited M&A possibilities

We expect that European telecoms operators will undertake little largescale M&A this year. Large transnational deals, such as the much-rumoured tie-up between Deutsche Telekom-Orange, offer no synergies: telecom services are local, not exportable, so combining companies