CONTENT

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COMPLEX HYBRID SYMBOLIC ANALYSIS OF NONLINEAR ANALOG CIRCUITS DRIVEN BY MULTI-TONE SIGNALS

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ABSTRACT

The paper presents a general symbolic method for generating the complex hybrid matrix necessary for computing the periodic or nonperiodic steady-state response of a nonlinear analog circuit driven by multitone signals. This method is remarkable by its great efficiency and generality, and it is very useful in frequency-domain approach based on harmonic balance and least square approximation. For the general case of the nonperiodic steadystate response there are three basic methods: frequency-domain approach based on Voltera series; time-domain approach and a frequency-domain approach based on harmonic balance and least square approximation. The last one is significantly more efficient when the total number of nonlinear resistors, inductors and capacitors is significantly less than the total number of linear inductors and capacitors in the circuit, as is often the case in practice.

KEYWORDS: *Symbolic analysis, hybrid analysis, nonlinear analog circuits, multi-tone signals.*

The article is reworked from unpublished 2nd IEEE International Conference on Circuits and Systems for Communications (ICCSC) materials.

I. Introduction

For the general case of the nonperiodic steady-state response there are three basic methods: (1) frequency-domain approach based on Voltera series [1,10-12]; (2) time-domain approach [2,11-12], and (3) a frequency-domain approach based on harmonic balance and least square approximation [3]. The last one is significantly more efficient when the total number of nonlinear resistors, inductors, and capacitors is significantly less than the total number of linear inductors and capacitors in the circuit, as is often the case in practice.

This method requires the following steps: first – all nonlinear circuit elements and independent sources will be "extracted" from the circuit to the terminals, so that the resulting linear *n*-port *N* will contain only time-invariant circuit elements (resistors, inductors, capacitors, linear-controlled sources etc.); next – we must develop a frequency-domain analysis (ac analysis) of the substituted linear and time-invariant subcircuit (obtained by corresponding substitution of the nonlinear circuit elements with voltage or current sources) and an analysis based on harmonic method coupled with the least square approximation of the nonlinear subcircuit.

The frequency-domain (ac analysis) of the linear substituted *n*-port *N* can be efficiently implemented by computing the symbolic hybrid matrix corresponding to this subcircuit for each frequency $\hat{\omega}_k$. The method presented in this paper to generate the complex hybrid matrix for each frequency, necessary for calculating the periodic or not periodic steady-state response of a nonlinear circuit of great complexity, driven by multi-tone signals, is a very useful tool.

II. Frequency–domain analysis of nonlinear analog circuits driven by multi-tone signals

Let us consider the general case when the circuit contains nonlinear elements – resistors, inductors, capacitors, independent voltage and current sources having a dc component and *m* multi-tone frequencies $\omega_1, \omega_2, ..., \omega_m$, and linear circuit elements.

Let us extract all nonlinear elements and all independent sources to the ports. The nonlinear elements on the left ports are described as follows: voltage-controlled resistors: $\boldsymbol{i}_G = \hat{\boldsymbol{i}}_G(\boldsymbol{u}_G)$, voltage-controlled capacitors: $\boldsymbol{q}_C = \hat{\boldsymbol{q}}_C(\boldsymbol{u}_C)$, flux-controlled inductors: $\boldsymbol{i}_\Gamma = \hat{\boldsymbol{i}}_\Gamma(\boldsymbol{\varphi}_\Gamma)$, while the nonlinear elements on the right ports are described by the equations: current-controlled resistors: $\boldsymbol{u}_R = \hat{\boldsymbol{u}}_R(\boldsymbol{i}_R)$, charge-controlled capacitors: $\boldsymbol{u}_S = \hat{\boldsymbol{u}}_S(\boldsymbol{q}_S)$, current-controlled inductors: $\boldsymbol{\varphi}_L = \hat{\boldsymbol{\varphi}}_L(\boldsymbol{i}_L)$.

The linear *n*-port *N* may contain any time-invariant circuit element as: resistors, inductors, capacitors, linear-controlled sources etc. Substituting all the nonlinear elements from the left side by ideal voltage sources and all the nonlinear elements from the right side by ideal current sources, we obtain a linear and time-invariant circuit.

The vector of the unknowns has the following form:

$$\boldsymbol{x}(t) = \left[\boldsymbol{u}_G^{\mathrm{t}}(t), \boldsymbol{u}_C^{\mathrm{t}}(t), \boldsymbol{\varphi}_\Gamma^{\mathrm{t}}(t), \boldsymbol{i}_R^{\mathrm{t}}(t), \boldsymbol{q}_S^{\mathrm{t}}(t), \boldsymbol{i}_L^{\mathrm{t}}(t)\right]. \qquad (1)$$

It may be expressed as:

$$\begin{aligned} \boldsymbol{x}(t) &= \boldsymbol{x}_0 + \sum_{k=1}^{M}\left(\boldsymbol{x}_{2k-1}\cos\hat{\omega}_k t + \boldsymbol{x}_{2k}\sin\hat{\omega}_k t\right) = \\ &= \boldsymbol{x}_0 + \mathrm{Re}\left\{\sum_{k=1}^{M}\left(\boldsymbol{x}_{2k-1} - j\boldsymbol{x}_{2k}\right)e^{j\hat{\omega}_k t}\right\}. \end{aligned} \qquad (2)$$

Expression (2) can be interpreted as a generalized finite Fourier series, where the frequency components include not only harmonics, but also intermodulation frequencies

$$\hat{\omega}_k \overset{\mathrm{d}}{=} m_{1k}\omega_1 + m_{2k}\omega_2 + ... + m_{pk}\omega_p\,, \qquad (3)$$

whith m_{ik}, $i = 1,2,\ldots,m$, satisfying the constraint

$$|m_{1k}| + |m_{2k}| + .. + |m_{mk}| \le p\,,$$

where *p* is the highest order of the frequency components considered (the components beyond this order are negligible).

For a given p, M represents the set of all frequency components satisfying the inequality constraint (4).

The steady-state response of the linear and time-invariant subcircuit, computed by frequency-domain techniques (ac analysis) with respect to the unknown Fourier coefficients $\boldsymbol{x}_0, \boldsymbol{x}_{2k-1}, \boldsymbol{x}_{2k};\ k = 1,2,...,M$, is:

$$\begin{aligned} \boldsymbol{y}(t) &= \boldsymbol{y}_0 + \sum_{k=1}^{M} \left(\boldsymbol{y}_{2k-1}\cos\hat{\omega}_k t + \boldsymbol{y}_{2k}\sin\hat{\omega}_k t\right) = \\ &= \boldsymbol{y}_0 + \mathrm{Re}\left\{\sum_{k=1}^{M} \left(\boldsymbol{y}_{2k-1} - j\boldsymbol{y}_{2k}\right) e^{j\hat{\omega}_k t}\right\}. \end{aligned} \tag{5}$$

The steady-state response of the nonlinear subcircuit in terms of the same unknown, can be expressed as:

$$\boldsymbol{y}'(t) = \boldsymbol{b}_0(\boldsymbol{x}) + \sum_{k=1}^{\hat{M}} \left(\boldsymbol{b}_{2k-1}(\boldsymbol{x}) \cdot \cos\hat{\omega}_k t + \boldsymbol{b}_{2k}(\boldsymbol{x}) \cdot \sin\hat{\omega}_k t\right) \tag{6}$$

In Eq. (6) $\boldsymbol{b}_0(\boldsymbol{x}), \boldsymbol{b}_{2k-1}(\boldsymbol{x}), \boldsymbol{b}_{2k}(\boldsymbol{x}),\quad k = 1,2,...,\hat{M}$ are generalized Fourier coefficients of ***y'***(*t*), which depend on the $\boldsymbol{x}_0, \boldsymbol{x}_{2k-1}, \boldsymbol{x}_{2k},\ k = 1,2,...,M$, and $\hat{M} \geq M$ includes in steady-state response of nonlinear subcircuit all new frequency components generated by the nonlinearities.

In order to compute the coefficient vector $\boldsymbol{b}(\boldsymbol{x})$ we may apply the Discrete Fourier Transformation (DFT), if ***y'***(*t*) is a periodic response or the least square method if it is not periodic [3].

Having the two responses $\boldsymbol{y}(t)$ and ***y'***(*t*) expressed in terms of the unknowns $\boldsymbol{x}(t)$ we do the last step of the algorithm. From the substitution theorem and the method of harmonic balance it results that the coefficient $\boldsymbol{c}_k$ of each frequency component $\hat{\omega}_k$ of $\boldsymbol{y}(t) - \boldsymbol{y}'(t)$ is equal to zero. Because each coefficient $\boldsymbol{c}_k$ is a function of the $2M+1$ unknown Fourier coefficients $\boldsymbol{x}_0, \boldsymbol{x}_{2k-1}, \boldsymbol{x}_{2k},\ k = 1,2,...,M$, for each nonlinear element we will obtain $2M+1$ independent nonlinear algebraic equations:

$$c_0(\boldsymbol{x}) = 0,\ c_1(\boldsymbol{x}) = 0,\ ....,\ c_{2M}(\boldsymbol{x}) = 0. \tag{7}$$

That means a total number of $n(2M+1)$ equations, where n is the total number of nonlinear elements, that can be expressed into a compact form by a nonlinear algebraic equation:

$$\boldsymbol{Fx} + \boldsymbol{S} - \boldsymbol{b}(\boldsymbol{x}) = \boldsymbol{0}\ . \tag{8}$$

This equation can be solved using the Newton-Raphson algorithm obtaining the independent variables $\boldsymbol{x}_0, \boldsymbol{x}_1, ..., \boldsymbol{x}_{2M}$ from equation (2). The first two terms of the equation (8) are obtained by ac analysis of the linear substituted subcircuit. Our main contribution in this paper is to develop an efficient method to compute these terms; in other words to compute the hybrid matrix of the substituted linear *n*-port *N*.

III. Generation of the hybrid matrix of the linear subcircuit at frequency $\hat{\omega}_k$

For a given nonlinear circuit a special tree -called the *normal tree* (*NT*)- is chosen [4,7,9]. The normal tree elements are selected in this strict order: all ideal independent or/and controlled voltage sources; all nonlinear elements extracted on the left side – called nonlinear elements of type one (the associated variables will have the subscript 1); linear capacitors, resistors, and inductors. The corresponding cotree will contain: all ideal independent or/and controlled current sources; all nonlinear elements extracted on the right side – called nonlinear elements of type two (the associated variables will have the subscript 2); linear capacitors, resistors, and inductors. The *NT* will not contain independent or controlled current sources. Let T be a normal tree and L its corresponding cotree.

Remark 1. When the controlling variables of the controlled sources are associated to the linear resistors, capacitors, inductors or they are voltages of the nonlinear elements of type one respectively currents of the nonlinear elements of type two, these variables can be simple expressed at each frequency $\hat{\omega}_k$, starting from their constitutive equations, in respect of the independent variables $\left(\underline{\boldsymbol{U}}_{1\_k}, \underline{\boldsymbol{I}}_{2\_k}\right)$ and of the input quantities $\left(\underline{\boldsymbol{E}}_k, \underline{\boldsymbol{J}}_k\right)$.

Applying the superposition theorem in complex it results at each frequency $\hat{\omega}_k$:

$$\begin{aligned} \begin{bmatrix} \underline{\boldsymbol{I}}_{1\_k} \\ \underline{\boldsymbol{U}}_{2\_k} \end{bmatrix} &= \begin{bmatrix} \underline{\boldsymbol{Y}}_{1\_k,1\_k} & \underline{\boldsymbol{B}}_{1\_k,2\_k} \\ \underline{\boldsymbol{A}}_{2\_k,1\_k} & \underline{\boldsymbol{Z}}_{2\_k,2\_k} \end{bmatrix} \begin{bmatrix} \underline{\boldsymbol{U}}_{1\_k} \\ \underline{\boldsymbol{I}}_{2\_k} \end{bmatrix} + \\ &+ \begin{bmatrix} \underline{\boldsymbol{Y}}_{1\_k,e} & \underline{\boldsymbol{B}}_{1\_k,j} \\ \underline{\boldsymbol{A}}_{2\_k,e} & \underline{\boldsymbol{Z}}_{2\_k,j} \end{bmatrix} \begin{bmatrix} \underline{\boldsymbol{E}}_k \\ \underline{\boldsymbol{J}}_k \end{bmatrix}, \end{aligned} \tag{9}$$

where, for example, $\underline{\boldsymbol{B}}_{1\_k,2\_k}\left(\underline{\boldsymbol{A}}_{2\_k,1\_k}\right)$ represents the matrix of the complex current (voltage) gains of the nonlinear elements of type one (two) in respect of the nonlinear elements of type two (one), and $\underline{\boldsymbol{U}}_{1\_k}\left(\underline{\boldsymbol{I}}_{2\_k}\right)$ is the complex voltage (current) vector of the nonlinear elements of type one (two). The meaning of the other variables results from their subscripts.

In equation (9) the state variables $\left(\underline{\boldsymbol{U}}_{1\_k},\underline{\boldsymbol{I}}_{2\_k}\right)$ and the complementary state variables $\left(\underline{\boldsymbol{I}}_{1\_k},\underline{\boldsymbol{U}}_{2\_k}\right)$ can be expressed as:

$$\underline{\boldsymbol{U}}_{1\_k}=\begin{bmatrix}\underline{\boldsymbol{U}}_{G\_k}\\ \underline{\boldsymbol{U}}_{C\_k}\\ j\hat{\omega}_k\underline{\boldsymbol{\Phi}}_{\Gamma\_k}\end{bmatrix}=\begin{bmatrix}\boldsymbol{u}_{G,2k-1}-j\boldsymbol{u}_{G,2k}\\ \boldsymbol{u}_{C,2k-1}-j\boldsymbol{u}_{C,2k}\\ j\hat{\omega}_k\left(\boldsymbol{\varphi}_{\Gamma,2k-1}-j\boldsymbol{\varphi}_{\Gamma,2k}\right)\end{bmatrix},(10)$$

$$\underline{\boldsymbol{I}}_{2\_k}=\begin{bmatrix}\underline{\boldsymbol{I}}_{R\_k}\\ j\hat{\omega}_k\underline{\boldsymbol{Q}}_{S\_k}\\ \underline{\boldsymbol{I}}_{L\_k}\end{bmatrix}=\begin{bmatrix}\boldsymbol{i}_{R,2k-1}-j\boldsymbol{i}_{R,2k}\\ j\hat{\omega}_k\ \boldsymbol{q}_{S,2k-1}-j\boldsymbol{q}_{S,2k}\\ \boldsymbol{i}_{L,2k-1}-j\boldsymbol{i}_{L,2k}\end{bmatrix},\ (11)$$

$$\underline{\boldsymbol{I}}_{1\_k}=\begin{bmatrix}\underline{\boldsymbol{I}}_{G\_k}\\ j\hat{\omega}_k\underline{\boldsymbol{Q}}_{C\_k}\\ \underline{\boldsymbol{I}}_{\Gamma\_k}\end{bmatrix}=\begin{bmatrix}\boldsymbol{i}_{G,2k-1}-j\boldsymbol{i}_{G,2k}\\ j\hat{\omega}_k\left(\boldsymbol{q}_{C,2k-1}-j\boldsymbol{q}_{C,2k}\right)\\ \boldsymbol{i}_{\Gamma,2k-1}-j\boldsymbol{i}_{\Gamma,2k}\end{bmatrix},\ (12)$$

$$\underline{\boldsymbol{U}}_{2\_k}=\begin{bmatrix}\underline{\boldsymbol{U}}_{R\_k}\\ \underline{\boldsymbol{U}}_{S\_k}\\ j\hat{\omega}_k\underline{\boldsymbol{\Phi}}_{L\_k}\end{bmatrix}=\begin{bmatrix}\boldsymbol{u}_{R,2k-1}-j\boldsymbol{u}_{R,2k}\\ \boldsymbol{u}_{S,2k-1}-j\boldsymbol{u}_{S,2k}\\ j\hat{\omega}_k\ \boldsymbol{\varphi}_{L,2k-1}-j\boldsymbol{\varphi}_{L,2k}\end{bmatrix}.(13)$$

The characteristic equations of the linear circuit elements included both in tree and in cotree, for each frequency $\hat{\omega}_k$, are:

$\underline{\boldsymbol{U}}_{Z_t\_k}=\underline{\boldsymbol{Z}}_{t\_k}\underline{\boldsymbol{I}}_{Z_t\_k}$, respectively $\underline{\boldsymbol{I}}_{Z_t\_k}=\underline{\boldsymbol{Y}}_{t\_k}\underline{\boldsymbol{U}}_{Z_t\_k}$,

$\underline{\boldsymbol{U}}_{Z_c\_k}=\underline{\boldsymbol{Z}}_{c\_k}\underline{\boldsymbol{I}}_{Z_c\_k}$, respectively $\underline{\boldsymbol{I}}_{Z_c\_k}=\underline{\boldsymbol{Y}}_{c\_k}\underline{\boldsymbol{U}}_{Z_c\_k}$,

where

$$\underline{Z}_{t(c)\_k}=R+j\left(\hat{\omega}_kL-\frac{1}{\hat{\omega}_kC}\right),$$

$$\text{and } \underline{Y}_{t(c)\_k}=G+j\left(-\frac{1}{\hat{\omega}_kL}+\hat{\omega}_kC\right). \qquad (14)$$

Denoting:

$$\underline{\boldsymbol{H}}_{11\_k}=\underline{\boldsymbol{Y}}_{1\_k,1\_k},\ \underline{\boldsymbol{H}}_{12\_k}=\underline{\boldsymbol{B}}_{1\_k,2\_k},\ \underline{\boldsymbol{H}}_{21\_k}=\underline{\boldsymbol{A}}_{2\_k,1\_k},\ \underline{\boldsymbol{H}}_{22\_k}=\underline{\boldsymbol{Z}}_{2\_k,2\_k},$$

$$\underline{\boldsymbol{J}}_{s\_k}=\underline{\boldsymbol{Y}}_{1\_k,e}\underline{\boldsymbol{E}}_k+\underline{\boldsymbol{B}}_{1\_k,j}\underline{\boldsymbol{J}}_k,\ \underline{\boldsymbol{E}}_{s\_k}==\underline{\boldsymbol{A}}_{2\_k,e}\underline{\boldsymbol{E}}_k+\underline{\boldsymbol{Z}}_{2\_k,j}\underline{\boldsymbol{J}}_k, \qquad (15)$$

the equation (9) becomes:

$$\begin{bmatrix}\underline{\boldsymbol{I}}_{1\_k}\\ \underline{\boldsymbol{U}}_{2\_k}\end{bmatrix}=\begin{bmatrix}\underline{\boldsymbol{H}}_{11\_k} & \underline{\boldsymbol{H}}_{12\_k}\\ \underline{\boldsymbol{H}}_{21\_k} & \underline{\boldsymbol{H}}_{22\_k}\end{bmatrix}\begin{bmatrix}\underline{\boldsymbol{U}}_{1\_k}\\ \underline{\boldsymbol{I}}_{2\_k}\end{bmatrix}+\begin{bmatrix}\underline{\boldsymbol{J}}_{s\_k}\\ \underline{\boldsymbol{E}}_{s\_k}\end{bmatrix}.(16)$$

In order to extract the frequency $\hat{\omega}_k$ from the unknown vector, we have to do the following notations:

$$\underline{\boldsymbol{X}}_{1\_k}=\begin{bmatrix}\boldsymbol{u}_{G,2k-1}-j\boldsymbol{u}_{G,2k}\\ \boldsymbol{u}_{C,2k-1}-j\boldsymbol{u}_{C,2k}\\ \boldsymbol{\varphi}_{\Gamma,2k-1}-j\boldsymbol{\varphi}_{\Gamma,2k}\end{bmatrix}=\boldsymbol{X}_{1\_k}^R+j\boldsymbol{X}_{1\_k}^I,$$

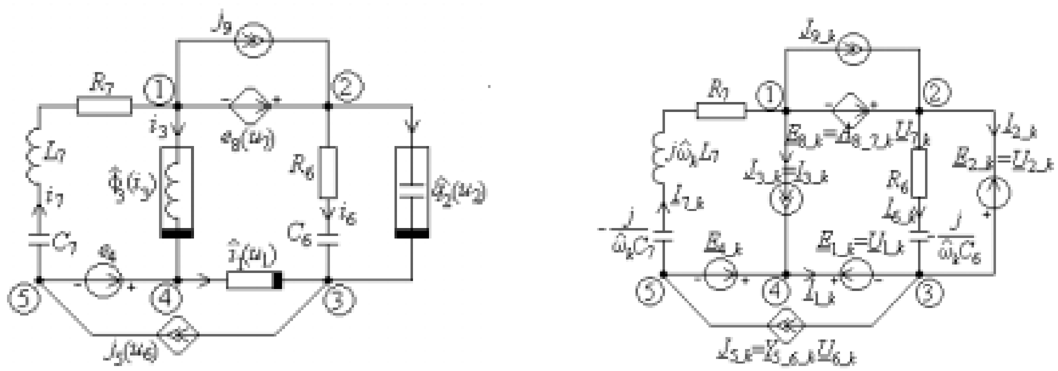
$$\underline{\boldsymbol{X}}_{2\_k}=\begin{bmatrix}\boldsymbol{i}_{R,2k-1}-j\boldsymbol{i}_{R,2k}\\ \boldsymbol{q}_{S,2k-1}-j\boldsymbol{q}_{S,2k}\\ \boldsymbol{i}_{L,2k-1}-j\boldsymbol{i}_{L,2k}\end{bmatrix}=\boldsymbol{X}_{2\_k}^R+j\boldsymbol{X}_{2\_k}^I. \qquad (17)$$

Now the linear and time-invariant response of n-port N can be expressed by the explicit equation:

$$\begin{bmatrix}\boldsymbol{i}_1(t)\\ \boldsymbol{u}_2(t)\end{bmatrix}=\begin{bmatrix}\boldsymbol{i}_{1\_0}\\ \boldsymbol{u}_{2\_0}\end{bmatrix}+Re\left(\sum_{k=1}^{M}\begin{bmatrix}\underline{\boldsymbol{I}}_{1\_k}\\ \underline{\boldsymbol{U}}_{2\_k}\end{bmatrix}e^{j\hat{\omega}_kt}\right)=$$

$$=Re\left\{\begin{bmatrix}\boldsymbol{i}_{10}\\ \boldsymbol{u}_{20}\end{bmatrix}+\sum_{k=1}^{M}\left(\begin{bmatrix}\underline{\boldsymbol{F}}_{11k} & \underline{\boldsymbol{F}}_{12k}\\ \underline{\boldsymbol{F}}_{21k} & \underline{\boldsymbol{F}}_{22k}\end{bmatrix}\begin{bmatrix}\boldsymbol{X}_{1\_k}^R+j\boldsymbol{X}_{1\_k}^I\\ \boldsymbol{X}_{2\_k}^R+j\boldsymbol{X}_{2\_k}^I\end{bmatrix}\right)e^{j\hat{\omega}_kt}\right\}+$$

$$+Re\left(\sum_{k=1}\begin{bmatrix}\underline{\boldsymbol{J}}_{s\_k}\\ \underline{\boldsymbol{E}}_{s\_k}\end{bmatrix}e^{j\hat{\omega}_kt}\right), \qquad (18)$$



(a) (b)

Fig. 2. a) Initial circuit diagram; и) The substituted circuit diagram.

where: $\boldsymbol{i}_{1\_0}, \boldsymbol{u}_{2\_0}$ represent the dc unknowns which will be calculated from the dc analysis; $\boldsymbol{X}^R_{1\_k}, \boldsymbol{X}^I_{1\_k}, \boldsymbol{X}^R_{2\_k}$, and $\boldsymbol{X}^I_{2\_k}$ are the unknowns of the ac analysis corresponding to the frequency $\hat{\omega}_k$ and they are defined by (17); the submatrices $\underline{\boldsymbol{F}}_{ij\_k}$ are obtained from the submatrices $\underline{\boldsymbol{H}}_{ij\_k}$ multiplying by $j\hat{\omega}_k$ the components corresponding to the third row of $\underline{\boldsymbol{X}}_{1\_k}$ or the second row of $\underline{\boldsymbol{X}}_{2\_k}$. Equation (18) contains the first two terms of the equation (8).

We have implemented the above algorithm in a very efficient and flexible computing program that automatically generates the normal tree, the hybrid matrix and the source vector. Then it performs the frequency-domain analysis of the linear substituted *n*-port *N* for each frequency $\hat{\omega}_k$.

IV. Example

Let us consider the nonlinear circuit represented in Fig.1,a where: $i_1 = \hat{i}_1(u_1), q_2 = \hat{q}_2(u_2)$ and $\varphi_3 = \hat{\varphi}_3(i_3)$. Substituting the nonlinear circuit elements by ideal independent sources, according to the procedure described in Section II, we obtain the linear circuit in Fig. 1, b. The normal tree is made up of the branches: $\{\underline{E}_{4\_k}, \underline{E}_{8\_k}, \underline{E}_{1\_k}, \underline{E}_{2\_k}\}$, and the corresponding cotree contains the branches: $\{\underline{J}_{3\_k}, \underline{J}_{5\_k}, \underline{J}_{9\_k}, \underline{Z}_{6\_k}, \underline{Z}_{7\_k}\}$.

Applying the computing program, we obtain the complex hybrid matrix in the following form:

$$\underline{\boldsymbol{H}}_{11k} = \begin{bmatrix} \dfrac{1}{\underline{Z}_{7k}(\underline{A}_{87k}-1)} & \underline{Y}_{56k} - \dfrac{1}{\underline{Z}_{7k}(\underline{A}_{87k}-1)} \\ -\dfrac{1}{\underline{Z}_{7k}(\underline{A}_{87k}-1)} & -\dfrac{1}{\underline{Z}_{6k}} + \dfrac{1}{\underline{Z}_{7k}(\underline{A}_{87k}-1)} \end{bmatrix},$$

$$\underline{\boldsymbol{H}}_{12k} = \begin{bmatrix} 1 \\ -1 \end{bmatrix}, \quad \underline{\boldsymbol{H}}_{21k} = \begin{bmatrix} \dfrac{1}{\underline{A}_{87k}-1} & -\dfrac{1}{\underline{A}_{87k}-1} \end{bmatrix}, \quad .$$

$$\underline{\boldsymbol{H}}_{22k} = [0]$$

The source vectors have the following expressions:

$$\underline{\boldsymbol{J}}_{sk} = \begin{bmatrix} -\dfrac{\underline{E}_{4k}}{\underline{Z}_{7k}(\underline{A}_{87k}-1)} \\ \dfrac{\underline{E}_{4\_k}}{\underline{Z}_{7k}(\underline{A}_{87k}-1)} \end{bmatrix}, \quad \underline{\boldsymbol{E}}_{sk} = \begin{bmatrix} -\dfrac{\underline{A}_{87k}\underline{E}_{4k}}{\underline{A}_{87k}-1} \end{bmatrix}.$$

V. Conclusion

The paper presents a simple method to generate the complex hybrid matrix and the complex source vectors, in symbolic form, for the nonlinear circuit driven by multi-tone signal analysis. This is very useful for steady-state response computation and it may be successfully integrated in the frequency-domain approach based on harmonic balance and least square method. The method is remarkable by its great efficiency and generality.

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TOPICS IN COMMUNICATIONS WITH CHAOTIC SYSTEMS

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ABSTRACT

The use of chaotic systems in communications approaches the threshold for industrial applicability. We shall give here an overview over a few techniques we think are promising. However, this overview does not pretend to be complete and it contains personal views on the subject. Also, the use of chaotic system for information encryption is not discussed at all. Only a choice of methods for coding and modulation for the transmission of digital information will be presented. An overview of a number of techniques to transmit information using chaotic systems is given. The difficulties in obtaining a good performance of such systems with respect to channel noise leads to fundamental question, to which we give a possible answer. In particular it has been confirmed both in theory and by a constructive approach leading to a controlled variant of CSK, that indeed the information generated by free running chaotic systems (as captured by the Kolmogorov-Sinai entropy) is the problem, and the solution is a suitable control that makes this information part of the payload.

KEYWORDS: *Chaos, Communications, Noise performance, information theory, modulation, coding.*

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INTRODUCTION

The main features of chaotic systems that can be advantageously exploited for digital communications are

- Chaotic systems are simple to implement, at least at low frequencies [1]. Analog or mixed signal circuits can be used.
- Chaotic signals, i.e. signals produced by chaotic systems can be designed to have a smooth spectrum. The shape of the spectrum can be engineered [2, 3].

DIRECT CHAOTIC COMMUNICATIONS

In direct chaotic communications [4], the chaotic signal that carries the information is directly sent over the communication channel. Since chaotic signals have a relatively wide spectrum, this method can only be applied in Ultra-Wideband communications. The basic block diagram of such a communication system is very simple (Fig. 1).

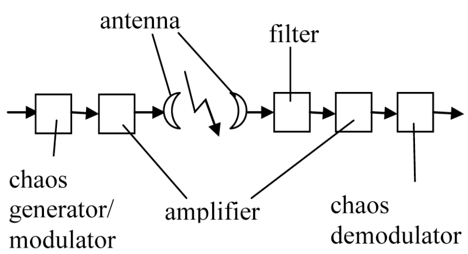

Figure 1. Block diagram for direct chaotic communications

The advantage of this scheme is its simplicity and its low power consumption, by avoiding up- and down-modulation to base- or intermediate frequency bands. The difficulty lies in the realization of a chaos generator of sufficient quality. Related to this is the limitation to relatively simple modulation schemes, such as on-off keying. With respect to more conventional Ultra-Wideband communication schemes, its advantage lies in a smooth power spectrum of the emitted signal and thus lower peaks of its power spectrum for given total power.

SPREADING CODES USING CHAOTIC SYSTEMS

In direct-sequence spread spectrum communications, for each bit that is to be transmitted, a rather long binary codeword is sent. For a whole message, the same codeword is used, multiplied either by 1 or by -1, depending on the value of the bit. This procedure increases the bandwidth of the transmitted signal. For this reason, the term spread spectrum is used and the codeword is called spreading sequence. The exaggerated use of frequency spectrum by a single user is compensated by letting several users with close to orthogonal spreading codes share the same frequency band.

Usually, special pseudorandom sequences, the Gold or M-codes, are used as spreading sequences.

By using discrete-time chaotic systems whose output signal is 1-bit quantized, a large number of other pseudorandom codes can be generated. Usually, iterations of 1-dimensional maps are used to generate the spreading sequences. Careful optimization of the 1-dimensional maps allow to improve performance with respect to interference with other users of the same frequency band [5] (who use different spreading sequences), as well as multi-path interference performance [6].

In this application, no chaotic signal is sent over the communication channel, chaotic systems are only used to produce finite-length binary signals that have properties suitable for serving as spreading sequences in DS-CDMA systems. The merits and drawbacks of DS-CDMA systems are not any different than when conventional spreading sequences are used, except that more efficient spreading sequences can be produced. In addition, the number of good spreading sequences at the disposal of the system designer is increased considerably by using chaotic systems.

CHAOS SHIFT KEYING (CSK) AND DIFFERENTIAL CHAOS SHIFT KEYING (DCSK)

This techniques have been proposed already a decade ago [7, 8, 9, 10] and since then their performance with respect to additive white Gaussian noise in the channel (AWGN-channel) has been studied in depth [11, 12, 13].

This class of techniques mixes the information with a chaotic signal in the base-band or in an intermediate band, and then up-modulates them with a sinusoidal carrier signal. On the receiver side, the signal is first down-modulated before the information is extracted from the chaotic signal (Fig. 2).

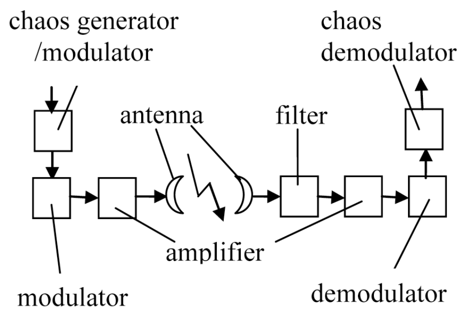

Figure 2. Block diagram for CSK and DCSK

In principle, CSK and DCSK could also be applied for direct communications and therefore avoiding the implementation of power-consuming additional modulators and demodulators, but given the high frequencies involved, this is out of the reach of current technology. A prototype system on the basis of frequency modulated DCSK (FM-DCSK) has been built and successfully tested [14].

The advantages of using chaos for this class of methods are:

- Relatively simple implementation and thus potentially also a lower power consumption.
- Good robustness properties with respect to interferences

It must be admitted, though, that the second point has in general (beyond additive white gaussian channel noise) not been seriously addressed in the research literature, except for DCSK in [15]. The reason is that the performance for AWG noisy channels is not sufficiently good to motivate communication systems engineers to cross the threshold and invest in understanding techniques based on chaos. In fact, so far, to get close to the performance levels of the basic phase shift keying (PSK) or quadrature amplitude modulation (QAM) already is considered an achievement in the chaos communications community.

HELP FROM INFORMATION THEORY

We have wondered whether a better understanding of the situation could be provided by information theory. We were asking whether

- The mediocre performance of CSK, and to a minor extent also DCSK, could be understood by information theoretic arguments
- Whether chaotic signals by their very nature are a bad choice for good performance in communicating over AWGN channels.

Today, we believe that the answer to the first question is “yes” and to the second question “no”. This shall be explained in some more detail.

The principle of CSK is schematically represented in Figure 3.

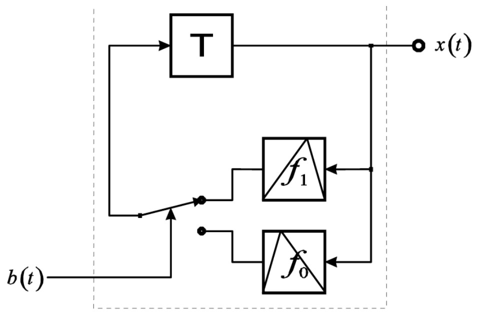

Figure 3. Block diagram of a chaos shift keying (CSK) transmitter

Depending on the transmitted bit at time t (0 or 1), the transmitter sends a certain number of iterations of the function f_0 or f_1 over the noisy channel. This signal, corresponding to a single bit, is the time-discrete but value-continuous spreading sequence. Note that, unlike conventional DS-CDMA, not only the spreading sequence is not quantized, but it also never repeats. This can be considered an advantage, because the power spectrum of the sent signal has no peak at the frequency at which the bit is transmitted. However, it makes the decoding much more difficult.

At the receiver, it has to be decided, whether the noise-corrupted spreading sequence has been produced by f0 or f1. In the early days of CSK, this was done by chaos synchronization [7, 8, 9].

Unfortunately, straight-forward synchronization was too sensitive to noise perturbation in the channel, and more sophisticated demodulation/decoding methods had to be used [11]. Indeed, this improved the noise-efficiency of the method greatly, but not enough to motivate “communication engineers not already committed” to chaos-communications.

Paper [16] gives the answer. It reminds the readers the well known fact that the chaotic signal, due to its expansive nature that amplifies differences in initial conditions, intrinsically produces at each iteration information about the initial condition of the spreading sequence. In CSK, this unused information has to share the channel capacity with the information that interests us, the use of the functions f0 or f1 for each iteration. Therefore, in this context only two approaches can, in principle, get a noise efficiency close to Shannon’s limit, namely to code information on the initial conditions, or to prevent the information about the initial condition to transit on the channel. The second approach will be discussed in the next section.

In paper [11] a clear hint to the fact that chaotic signals can be used for channel coding is given and that nothing of fundamental nature prevents them from achieving Shannon’s limit for AWGN channels. In order to prove this conclusively, one would have to give an explicit block channel coding method, which in the limit of infinite codeword length reaches the performance of Shannon’s capacity, as is been done in the classical proof [17] using stochastic signals. Of course, such a channel coding method would be too complex to be used for any practical purpose, but it definitely would answer the second question posed above. In paper [11], actually decoding is done using only a simple threshold decision. It would be practical, but it does not achieve Shannon’s capacity. Nevertheless it is orders of magnitudes wrong which makes us believe that the answer to question 2 should be “no”.

CODED MODULATION USING CHAOTIC SYSTEMS

We now return to the idea to code information onto the initial condition of the spreading code, or, more generally, on the initial conditions of the chaotic signal sent over the channel, not specifying at this point the method the modulation method.

There is a powerful mathematical theory for chaotic systems, or at least for a substantial subset of them: Symbolic analysis [18]. It associates with a chaotic trajectory, usually but not necessarily in discrete time, a binary signal. This correspondence is usually straight forward, just divide the state space into a two regions, label them with 0 and 1, and associate at each time with the state of the system the label of the region. This immediately gives a method to code binary information onto a chaotic trajectory.

Just send the chaotic signal over the channel whose symbolic signal is the information to be transmitted. The problem with this procedure is that one would have to set the initial conditions of the trajectory with unrealistic precision. The way to avoid this is to control the trajectory with small control inputs. This method of communications using chaos has already been proposed a decade ago [19, 20]. Also, such small perturbation control has been found to be feasible for several "more physical" chaotic oscillators such as the Lorenz system [24].

As a result, we can code the payload information directly onto the symbolic sequence generated by the chaotic system (which is equivalent to assigning different initial conditions to different codewords). While in [11] we have demonstrated the feasibility of such an approach in principle, a constructive solution to the problem requires a careful choice of both the chaotic system (in particular the associated nonlinearity) as well as the set of initial conditions representing the codewords.

One possible class of chaotic systems for which the problem of both system design and codeword assignment can be solved in a relatively systematic way is the class of iterated piecewise linear Markov maps. Here, the notion of symbolic dynamics is particularly intuitive, as the symbols can be assigned directly to the intervals of the map and it can be shown that such assignment is "sufficient" in the sense that it covers the entire information production of the chaotic system in the sense of a Shannon and Kolmogorov-Sinai entropy.

With a control action given by $x(t+1)=f(x(t)) + b(t)\cdot q/2$ (for suitable maps $f(.)$ such as the Bernoulli shift map or the tent map, and for suitable coupling coefficients q=2-Q), there is in fact a discrete set of 2Q invariant points under this iteration, which allows to control the symbolic sequence [18] with a delay of Q iterations. It has been shown [21] that such a structure can be equivalently represented by a shift register structure with a mapping function generating the output $x(t)$ as a function of its state $b(t)\ldots b(t-Q)$. Such structure is known as a trellis coded modulation in communication theory [22], and the study of the performance of such systems is linked to the study of the embedded convolutional code.

In order to identify chaotic maps which optimize the performance of such schemes, the analysis of the system performance in terms of Minimum distance error events [22] can be carried out [21], illustrating close-to-BPSK performance for the Bernoulli shift map, while for the tent map, the performance is bad.

It turns out that performance can be improved beyond BPSK by combining the classical CSK approach shown in Figure 3 with the small perturbation control such that both inputs (the control sequence and the sequence switching the maps) is driven by the same (payload) data [21] and an appropriate choice of the maps f_0 and f_1. This principle is illustrated in Figure 4 below.

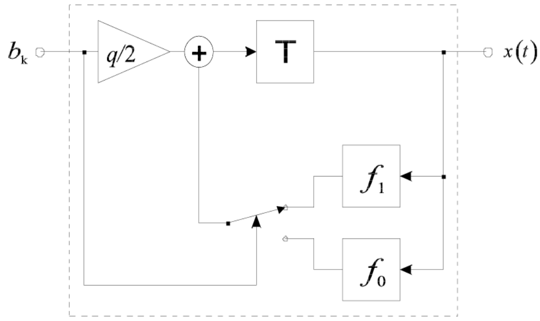

Figure 4. Block diagram of a CSK transmitter with small perturbation controlled symbolic dynamics

This underlines again our answers to the questions 1 and 2 as given above, as for the given example they have both been addressed in a constructive way.

Conclusion

We have given a survey of approaches to communications with chaotic systems developed in the last 10 years. Given the generally mediocre performance of such approaches, we have identified two fundamental questions which should help us pinpoint the main problems with the existing approaches with the help of information theory and communication theory.

In particular it has been confirmed both in theory and by a constructive approach leading to a controlled variant of CSK, that indeed the information generated by free running chaotic systems (as captured by the Kolmogorov-Sinai entropy) is the problem, and the solution is a suitable control that makes this information part of the payload.

We believe that the approach demonstrated for the simple small perturbation controlled CSK transmitter is much more general and will find its application to "more physical" chaotic systems in the near future, leveraging the advantages of chaotic systems as given in the introduction.

ACKNOWLEDGMENTS

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THE ORGANIZING OF A WIRELESS REMOTE LIGHT CONTROL SYSTEM USING BLUETOOTH

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ABSTRACT

With the introduction of the Internet of Things, the research and implementation of home automation are getting more popular. Much of the research attention has been given in academia which made use of different wireless technologies such as Wi-Fi, Bluetooth, ZigBee... etc. to support remote transfer of data. In this paper we design a prototype of a home automation lighting system that can be remotely switched on/off by an android application via Bluetooth. Affordability of smart phones had made majority of people to be attached to their phones. A mobile phone has become an inseparable part of human life which is an opportunity for us to take this advantage to manage power usage at home and provide convenience to users by integrating it in smart home. A lot of countries are suffering from huge power shortages which resulted in serious inconvenience to the socio-economic growth. Consumers had opted for other alternative such as the use of solar energy, generators, biogas and firewood of which some of these means destroy the ecosystem and emit poisonous gases into the atmosphere. As nations, there is need to look for ways that manage and control available power together with load shading.

KEYWORDS: *Internet of things, Bluetooth Low Energy, Home Automation System, Android, Lightning System, Arduino.*

INTRODUCTION

Affordability of smart phones had made majority of people to be attached to their phones. A mobile phone has become an inseparable part of human life which is an opportunity for us to take this advantage to manage power usage at home and provide convenience to users by integrating it in smart home. A lot of countries are suffering from huge power shortages which resulted in serious inconvenience to the socio-economic growth. Consumers had opted for other alternative such as the use of solar energy, generators, biogas and firewood of which some of these means destroy the ecosystem and emit poisonous gases into the atmosphere. As nations, there is need to look for ways that manage and control available power together with load shading.

People tend to forget to switch off their electrical gadgets while leaving their homes and there is need to empower people on the importance of managing available power hence the need for ways to control appliances from afar. With just a click on your phone you can save energy. With this type of systems in place, and embracing affordable smart phones users can save their time and have a greater experience of enjoying the benefits of internet of things**.**

This paper is organized as follows: the II gives an overview of Home Automation System (HAS). The next part III is about Bluetooth Classic and Bluetooth Low Energy (BLE). The IV is more about organize a lightning system using Bluetooth (its requirements, architecture and diagrams) and the last one V gives the conclusion.

INTERNET OF THINGS

Internet of Things (IoT) was first used in 1999 by Kevin Ashton to describe a system in which objects in the physical world could be connected to the Internet by sensors. IoT also can describe as intelligently connected devices and systems which be made up of smart machines, environments, objects and infrastructures and Radio Frequency Identification (RFID) and sensor network technologies [1].

HOME AUTOMATION OVERVIEW

Home automation principle is one of amazing concepts which was embraced some decades ago although there are no specific dates of invention and was even seen in science fiction movies of 1920s. Home automation technology was not a one day experiment. It gradually came into existence with only insignificant improvement having the previous step almost the same as the next step. It takes time for consumers to accept automation technologies as they were no standardized solution to carry out every job that they could think of. Most of the negative issues associated with on-off remote control devices can be eliminated and with full automation there is an increased level of control to nearly all the appliances in the home.

This technology of automation has found its use in security systems, environment, Medical field, Home Automation etc. The table 1 below shows comparison of different wireless home automation technologies [2].

Table 1

Wireless automation technologies

Protocol	Bluetooth	Wi-Fi	ZigBee
Frequency	2.4GHz	2.4GHz, 5GHz	868MHz, 915MHz, 2.4GHz
Modulation	FHSS	QPSK, COFDM, QAM	BPSK, Q-QPSK
Error control	CRC (16-bit)	CRC (32-bit)	CRC (16-bit)
Range	10m	100m	10m-100m
Network size	8	2007	64000
Power consumption	Medium	High	Very Low

A lot of research work on home automation has been done across the globe using different platforms mentioned above. The most important aspect in automation is to minimize human intervention by connecting devices and sensors

BLUETOOTH CLASSIC VS. BLUETOOTH LOW ENERGY (BLE)

The Bluetooth Classic radio, also referred to as Bluetooth Basic Rate/Enhanced Data Rate (BR/EDR), is a low power radio that streams data over 79 channels in the 2.4GHz unlicensed industrial, scientific, and medical (ISM) frequency band. Supporting point-to-point device communication, Bluetooth Classic is mainly used to enable wireless audio streaming and has become the standard radio protocol behind wireless speakers, headphones, and in-car entertainment systems. The Bluetooth Classic radio also enables data transfer applications, including mobile printing [3].

The Bluetooth Low Energy (BLE) radio is designed for very low power operation. Transmitting data over 40 channels in the 2.4GHz unlicensed ISM frequency band, the Bluetooth LE radio provides developers a tremendous amount of flexibility to build products that meet the unique connectivity requirements of their market. Bluetooth LE supports multiple communication topologies, expanding from point-to-point to broadcast and, most recently, mesh, enabling Bluetooth technology to support the creation of reliable, large-scale device networks. While initially known for its device communications capabilities, Bluetooth LE is now also widely used as a device positioning technology to address the increasing demand for high accuracy indoor location services. Initially supporting simple presence and proximity capabilities, Bluetooth LE now supports Bluetooth® Direction Finding and soon, high-accuracy distance measurement [3].

Table 2 below shows a comparison between Bluetooth classic and Bluetooth Low Energy [3].

Table 2

Comparison between Bluetooth classic and BLE

	BLE	Bluetooth Classic
Frequency Band	2.4GHz ISM Band (2.402 – 2.480 GHz Utilized)	2.4GHz ISM Band (2.402 – 2.480 GHz Utilized)
Channels	40 channels with 2 MHz spacing	79 channels with 1 MHz spacing
Channel Usage	Frequency-Hopping Spread Spectrum (FHSS)	Frequency-Hopping Spread Spectrum (FHSS)
Modulation	GFSK	GFSK, π/4 DQPSK, 8DPSK
Data Rate	[2 Mb/s - 125 Kb/s]	[3-1] Mb/s
Communication Topologies	Point-to-Point (including piconet) Broadcast Mesh	Point-to-Point (including piconet)
Positioning Features	Presence (Advertising) Proximity (RSSI) Direction (AoA/AoD) Distance (Coming)	None

When a link is established between two Bluetooth devices a secure connection is made. To secure the link level, four entities are used; the Bluetooth devices address which is unique for each Bluetooth device, private authentication and encryption keys, both which are 8 to 128 bits in length, and finally a random number which changes frequently. These entities are used to generate a key or Personal Identification Number (PIN) which is then used between the devices to connect or transfer data. The link protection was meant for protection against eavesdropping [4].

AN OVERVIEW OF ANDROID TECHNOLOGY

Android, by Google Inc. provides an opensource platform for the development of android mobile based applications. The Android framework is distributed under the Apache Software License (ASL/Apache2), which allows for the distribution of both open and closed source derivations of the source code. Android application developers can distribute their applications under whatever licensing scheme they prefer. Developers can write opensource freeware or traditional licensed applications for profit and everything in between. Android applications are written in the Java programming language. Android SDK tools are found on the Android website on free charge of after agreeing to SDK License terms. Tools for code creation and data packaging are offered on Android SDK and are then stored with 'apk' file extension. Android devices use the 'apk' file to install the application [5].

The incorporation of android with Bluetooth APIs allows wireless connection to any nearby Bluetooth devices. As a result, it is possible to establish connections with other Bluetooth devices, enquire information about any paired Bluetooth devices, easy data transfer to and from other devices and to manage multiple connections.

CHALLENGES OF BLUETOOTH BASED HAS

Bluetooth technologies have their own flaws which limit its functionalities as shown below.

– Limited transmission range: Bluetooth operates in a range of 10-100m hence there is need to merge it with internet technologies so to increase the range of connectivity.

– High interference rate: Bluetooth operates in the free band which is prone to interference with other systems which operate in that same range for example microwave oven, cellular phones, Wi-Fi and ZigBee.

– Wireless technologies are prone to security threats hence there is need to look for ways to mitigate these problems.

– Resource constraints: higher power processing sensor are preferred unlike the other sensors which suffer from limited battery, low memory and limited processing power. Merging both Wi-Fi and Bluetooth technology consume more power as a result a constant power supply unit should be used.

– People may fail to embrace the system due to its initial cost and fear to have everything done automatically.

– Power constraints issues are resolved through embracing the new version of Bluetooth Low Energy (BLE) technology. BLE is used in very low power network and Internet of Things (IoT) solutions aimed for low-cost battery-operated devices that can quickly connect and form simple wireless links. Target applications include HID, remote controls, sports and fitness monitors, portable medical devices and smart phone accessories, among many others that are being added to a long list of BLE supporting solutions.

BENEFITS OF THE PROPOSED SYSTEMS

The adoption of an automated system come along with several advantages to the users as mentioned below

• Able bodied people cannot fully appreciate the need of automation unlike the disabled who understand the difficult of turning ON/OFF a simple light switch.

• Energy cost can be minimized by controlling and monitoring power usage through automatic turning ON/OFF electrical appliance in question.

• Deployment of wireless technology is much easier and cheaper as some nodes may be placed everywhere where cabling is impossible.

• Incorporation of Bluetooth technology is an advantage since almost every smart phone has a Bluetooth application in it. Mobile devices can be easily integrated as they can allow easy accessibility so long the device is in network vicinity.

• here is improved personal safety

• Tim and a lot of effort is saved

• There is increased independence and greater control of the environment.

SCOPE OF THE WORK

The project will mainly work on the lighting system and allow remote control of lights via Bluetooth. This will cover a radius of 10m in which the Bluetooth strength will be felt. The system will not control multiple appliance.

There are some assumptions of the research are:

• Greater part of the population is in possession of an android smart phone.

• Every smart phone has a Bluetooth facility.

• Proper hardware components are available for the implementation of the system

The Limitation of our system is that the system will only control lighting system.

Research Questions are:

1. Does the system provide remote control to lights?

2. How secure are the systems to be developed from tempering by unauthorized users?

THE PROPOSED SYSTEM

We will present a system interconnected with Arduino Uno board (microcontroller), electrical devices and an android based mobile application (Fig. 1-3). The mobile application provides a communication mechanism between the microcontroller and the user over Bluetooth link. The system control and connection utilities is offered on user interface of android mobile cellular phone. The system will be quite different as it will also make use of security mechanism to guard against malicious user. An authentication mechanism using biometric (finger print) will be used. We will make use of relay drivers, microcontrollers, Bluetooth module and LEDs for hardware development.

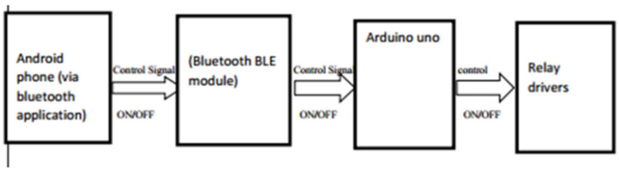

Figure 1. Block diagram of HAS system

The home automation system via Bluetooth is implemented using:

I. Arduino microcontroller.

II. Bluetooth enabled Android smart phone.

III. Hc-06 Bluetooth module.

IV. Rel and LEDs.

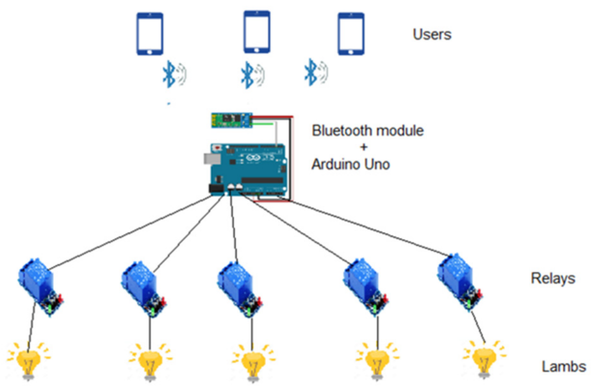

Figure 2. System topology

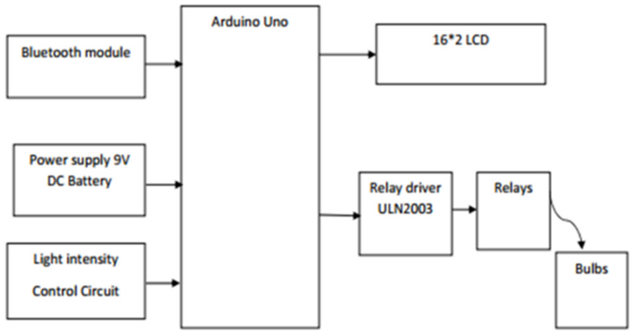

Figure 3. System architecture

This project is aiming at designing a Bluetooth based home automation using Arduino Uno. The third-part user will be able to use his or her android phone to control all the lights in the house. The Arduino board is the brain of the project. A mobile application has the capability to control the lighting system. The android phone sends commands to the microcontroller via Bluetooth module. The microcontroller responds to send commands by comparing it to the predefined ones. When the signal is identified, the microcontroller will activate a corresponding relay attached to it by sending a 5V through. To switch off appliance, the microcontroller will send a 0V signal to the respective relay.

SYSTEM REQUIREMENTS

Functional requirements

These are statements of services the system should provide, how the system reacted to particular inputs and how the system should behave in particular situation. Functional requirements reveals the expected behavior of the intended system which may be expressed as task, functions and services. The statements below shows the expected results of our system.

• The system should provide users with a facility to scan and store their fingerprints to be used in the authentication process.

• System should allow authorized users to control the appliances.

• The system should allow new users to pair their mobile devices with the hardware for easy Bluetooth connectivity.

• System should ge erate energy consumption report.

Non-functional requirements

They do not reflect specific behavior of system but rather reveals system operation. They are the constraints of the application. Below are the non-functional requirements of the application:

Confidentiality – Data in transit should be kept secure as it is prone to interception. The system must provide necessary security to its users and data must be free from errors.

Reliability – The system must be able to provide specified service to authorized users

Availability – The system must provide service whenever a valid user needs it.

Portability – the system application should be easily transferred to different android mobile device without problem.

Usability – the application interface must be user friendly such that a naïve user must feel free to operate it.

PROJECT DIAGRAMS

1) Use case diagrams are there to model the functional requirements of the system. It reveals a relationship between actors and use cases. The diagram below shows the use case diagram of HAS system (Fig. 4-6).

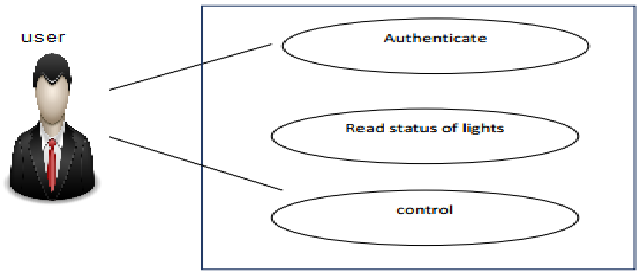

Figure 4. Use case diagram

User acts as a main actor who can read the status of appliances in ON/OFF state through the LCD and mobile application. A service of authentication is offered to users to identify authorized users. In addition, users control home appliances by sending request to microcontrollers which then responds to specific needs.

2) Sequence diagram:

A remote control system is used to operate each HAS. The operation of the remote-control is explained by the sequence diagram. A mobile device facilitates communication between the user and microcontrollers.

Authentication: Flow of events:

1. When a user connects to the remote system, user should use valid fingerprint to log in. After consecutive 5 failed login attempts, system will lock for security reasons.
2. When a user is done, user shall log out to terminate the session.

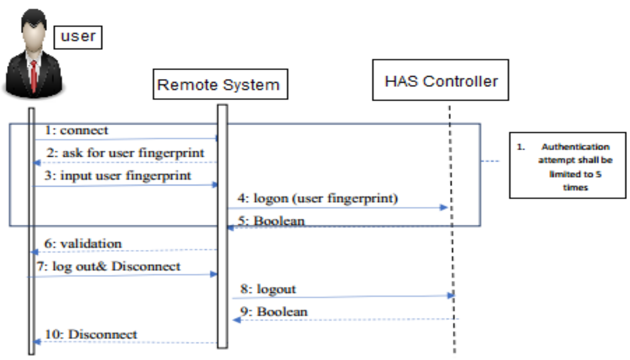

Figure 5. Sequence diagram for authentication

Operate lights: Flow of events:

1. When a user log in, the remote device shows a list of rooms with lights.
2. The user chooses the room and send commands to the controller to turn ON/OFF lights.
3. The lights will respond to the command and status of results is shown.

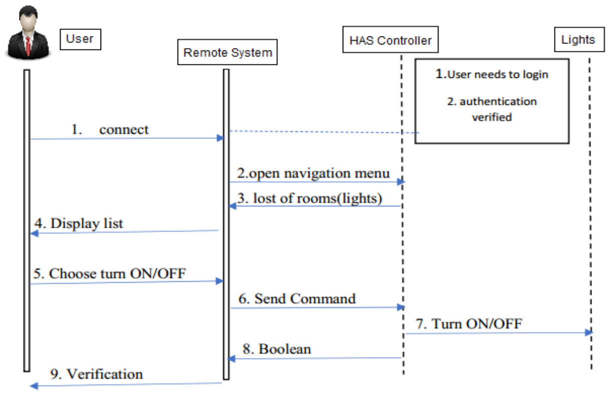

Figure 6. Sequence diagram for lights operation

3) The flow chart clarifies the logic of the code and how we implemented a real time control algorithm (Fig. 7).

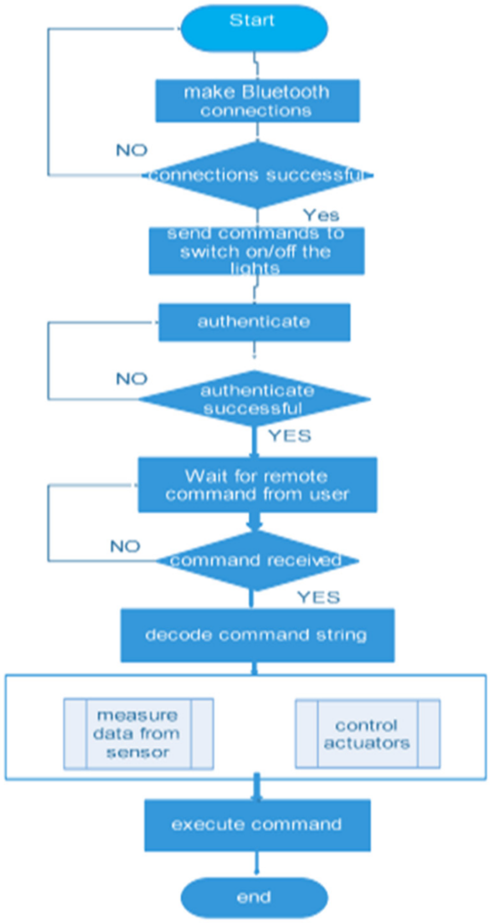

Figure 7. Flow chart

CONCLUSION

Considering that a large part of the population owns an Android smartphone and every smartphone has a Bluetooth facility, the proposed system for smart home lighting using Bluetooth technology is the most effective because it is easy-to-use, stable, low cost, and has good expansibility.

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MEDICAL IMAGE ENHANCEMENT BASED AI TECHNIQUES: A REVIEW

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ABSTRACT

Image enhancement is a type of image processing that improves the image's suitability for specific uses. Image enhancement's primary goal is to improve an image's visual look, or to provide a "higher transform features of an image". The goal of the paper is to analyze and formulate several image enhancing strategies that can be used in a variety of medical applications. A survey of various picture enhancement techniques is presented in this work. More specifically, the suggested research would focus on improving medical photos captured in low-light conditions, foggy environments, and speckle noise, among other things. Developing algorithms to aid clinicians in diagnosing the disease at its earliest stages.

KEYWORDS: *ANN, FuzzayLogic, Image enhancement, Image noising.*

I. INTRODUCTION

An image is a set of signals with a two-dimensional function written by f(x,y), where x and y are spatial coordinates and the intensity or gray level of each point is supplied by the amplitude of f at any pair of coordinates (x,y).The image is called as digital image when the amplitude values of f, x and y are all finite discrete quantities. A digital image is composed of a finite number of elements which is referred as a pixel and it has a particular location and value. The elements of a digital image is usually denoted by the pixel. Image enhancement consists of techniques that seek to improve the visual appearance of an image or it makes an image better suited for analysis by a human or a machine. The Image enhancement techniques can be categories into three groups. Spatial domain methods: It directly operate on pixels. Frequency domain methods: It operate on the Fourier transform of an image. Fuzzy domain: When it comes to human perception, it is difficult to determine what good image enhancement is. If it looks good, quantitative measures are used to determine which techniques is most appropriate, when image enhancement techniques are used as pre-processing tools for other image processing techniques. This paper is organized as follows. In section II we introduce related work. In section III, we presented ANN. In section IV fuzzy logic. section V, Image processing.

II. RELATED WORK

This section summarizes a review of literature of several image enhancing approaches carried out by different researchers. It's been proven that the corona virus exists. In pathological diagnostics, a real-time PCR (polymerase chain reaction) is a commonly used diagnostic tool. Chest x-rays are a better option than PCR for COVID-19 screening. In this scenario, however, precision of results is crucial. This research proposes a diagnosis recommender system for reviewing lung pictures that might assist physicians while also reducing their effort. To achieve the highest degree of precision, CNN is used [1]. A fusion of convolutional neural network (CNN), support vector machine (SVM), and Sobel filter is given to detect COVID-19 using Xray images. A new X-ray picture collection was obtained and handled with a high pass filter utilizing a Sobel filter to get the edges of the images.

The pictures are then fed into a CNN deep learning model, which is subsequently followed by a ten-fold cross validation SVM classifier. According to our findings, the proposed CNN-SVM with Sobel filtering (CNN-SVM+Sobel) has a maximum classification accuracy of 99.02 percent in successfully detecting COVID-19 [2].

The Contrast Limited Adaptive Histogram Equalization (CLAHE) and Convolutional Neural Networks (CNN) approaches are utilized to assess the dataset with two scenarios in order to obtain detection results. The results of this study reveal that when applying CNN and CLAHE, the accuracy of Covid-19 detection is likely to suffer. Furthermore, the CNN basic model outperforms the VGG16 transfer learning method [3]. A tooth caries diagnosis system based on a back propagation (BP) neural network is developed for analyzing dental X-ray images. The neural network used the inter-pixel autocorrelation as an input feature. The classification accuracy is satisfactory when compared to the diagnosing technique performed by a rule-based computer assisted software and a group of doctors, and tooth caries detection is clearly improved [4].

The author de-noises, enhances, segments, and detects edges in the X-ray image to extract the nodule's area, perimeter, and shape. These retrieved features are sent into a neural network, which is trained and utilized to determine if a nodule is cancerous or not. This research focuses on recognizing nodules that develop in the lungs of cancer patients at an early stage. The bulk of the nodules are visible after a careful selection of parameters. The training dataset of X-ray images is processed in three steps to increase the quality and accuracy of the result [5].

The method used in this research is an image processing technique that employs various filters to reduce noise and segment the lung in order to detect anomalous sections in the X-ray image, as well as extracted regions that depict the area, perimeter, and shape characteristics of lung nodules. These form traits are utilized to train a neural network that determines if a site is a malignant nodule or not. This research focuses on recognizing nodules that develop in cancer patients' lungs during the early stages of the disease. The bulk of the nodules are visible after a careful selection of parameters. The training dataset of lung cancer X-ray images is processed three times in order to increase the quality and accuracy of the observational results [6].

Comprises five image processing steps: noise reduction with a high boost filter, enhancement with adaptive histogram equalization, statistical feature extraction, and classification. To categorize the given input X-ray photographs into the categories head, neck, skull, foot, palm, and spine, probabilistic neural networks, back propagation neural networks, and support vector machine classifiers are employed. The results reveal that the proposed technique may be used to classify X-ray images with a 92.3 percent overall accuracy [7].

A hybrid technique that combines a Bayesian classification framework and a Hopfield Neural Network has been proposed for neonatal skull segmentation (HNN). Because of the non-homogeneity of skull intensities in MR images, local statistical parameters are used for adaptive training of Hopfield neural networks based on Bayesian classifier error. The experimental results, which were obtained using high-resolution T1-weighted MR images of nine neonates with gestational ages ranging from 39 to 42 weeks, show that our approach [8]. The CHEFNN (competitive Hopfield edge-finding neural network) is a two-layer Hopfield neural network that locates the edges of CT and MRI images.

The CHEFNN extends a one-layer 2-D Hopfield network at the initial picture plane to a two-layer 3-D Hopfield network with edge detection that can be implemented in the third dimension, unlike typical 2-D Hopfield neural networks. The improved 3-D architecture of the network allows it to incorporate contextual information about a pixel into the pixel-labeling procedure [9].

III. ARTIFICIAL NEURAL NETWORKS

It is usually called as "Neural Network" (NN), are computing systems made up of interconnected nodes that function similarly to neurons in the brain and a computational system that tries to simulate the structure and functional aspects of neural networks [12]. They can discover hidden patterns and correlations in raw data using algorithms, cluster and categorize it, and learn and improve it over time. The basic processing element of neural network are called neurons. Artificial neural networks (ANN) come in a variety of shapes and sizes. These networks are known as formal operations and a set of parameters that must be met in attempt to decide the result.

They processes information using connectionist approach to computation. NN are nonlinear statistical data modeling tools. They can be used to find patterns in data & also to model complex relationships between inputs and outputs. It is one of the simplest mathematical model which is defined as a function $f: X \rightarrow Y$. NN is very popular because of its learning capability. Learning can be supervised, unsupervised and recurrent. An important concept in learning is a C cost function which is a measure of how far away are from an optimal solution to the problem that are solving. In order to find a function that has the smallest possible cost, learning algorithm search through the solution space [4] in general the main content of neural network input layer, hidden layer and output layer as shown in Figure 1.

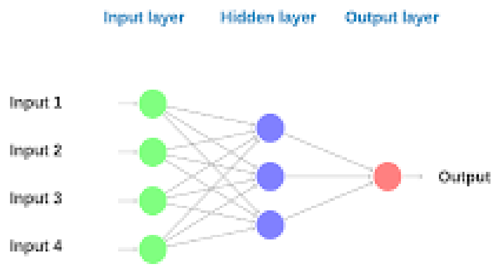

Figure 1. Simple structure of ANN [14]

A. Feed forward Neural Network – Artificial Neuron

One of the most basic types of ANN is one in which the data or input only moves in one direction. The information is sent through the input nodes and out the output nodes. The hidden layers may or may not be present in this neural network. In simple terms, it uses a classifying activation function to produce a front propagated wave with no back propagation. Feed forward neural networks are used in computer vision and speech recognition to identify target classes that are difficult to classify.

B. Radial basis function Neural Network

Consider the distance between a point and the center. RBF functions contain two layers: the inner layer combines the features with the Radial Basis Function, and the outer layer considers the output of these features while calculating that very same output in the following time-step, which is essentially a memory. This neural network has been applied in Power Restoration Systems.

C. Kohonen Self Organizing Neural Network

Map is a discrete map made up of neurons that accepts input vectors of any dimension. The map must be trained in order for it to organize the training data on its own. There are either one or two dimensions to it. The position of the neuron remains fixed when training the map, but the weights vary depending on the value. To recognize patterns in data, the Kohonen Neural Network is employed. Its use in medical analysis to group data into distinct groups is a good example.

D. Recurrent Neural Network (RNN) – Long Short Term Memory

Works on the premise of preserving a layer's output and sending it back into the input to aid in forecasting the layer's outcome. The first layer is built in the same way as a feed forward neural network, with the sum of the weights and features as the product. Once this is computed, the recurrent neural network process begins, which means that each neuron will remember some information from the previous time step from one time step to the next. Recurrent Neural Networks (RNNs) are used in text to speech (TTS) conversion algorithms.

E. Convolutional Neural Network

Resemble feed forward neural networks in that the neurons' weights and biases can be learned. It has been used in signal and image processing, and it has replaced OpenCV in the field of computer vision. Because of their accuracy in picture classification, convolutional neural networks dominate computer vision approaches.

F. Modular Neural Network

Having a variety of diverse networks all working together and contributing to the final product In comparison to other networks creating and performing sub-tasks, each neural network has a set of inputs that are unique. In order to complete the tasks, these networks do not communicate or signal one another. Several distinct neural networks are trained for a specific sub-task at the same time, and their outputs are then integrated to accomplish a single task.

IV. FUZZY LOGIC

In image processing applications, fuzzy logic is used. Because it provides an intuitive tool for inference from faulty data, fuzzy image processing is an attempt to convert this skill of human reasoning into computer vision problems.

In comparison to other computer vision approaches, fuzzy image processing is unique. It does not describe a specific solution for a specific problem, but rather a new class of image processing approaches. It introduces a new methodology to complement classical logic, which is an essential component of any computer vision program [10].

It is necessary to establish a new sort of visual comprehension and treatment. Fuzzy image processing can be a stand-alone image processing technique or an add-on to a larger image processing chain. Fuzzy logic has become increasingly important in control theory and computer vision during the last few decades. Simultaneously, it has been relentlessly criticized for two key reasons: It was once thought to be devoid of a solid mathematical foundation and to be nothing more than a cunning cloak for probability theory. It. Fuzzy systems are made up of two main components: fuzzy sets and fuzzy set operations. These operations define fuzzy logic rules, which are based on combinations of fuzzy sets. Every image appears or does not appear at all.

In addition, noise may cause the edge to be distorted. A noisy edge can be recognized using probabilistic methods that compute the likelihood of the noisy measurement belonging to the edge class. Classify an image with a gray-value slope by defining the edge. Even if all noise is eliminated, a noisy slope remains a slope. If the slope extends throughout the entire image, it is not commonly referred to be an edge. However, if the slope is "steep" enough and only stretches over a "limited" area, it is more likely to be referred to as an edge. The question immediately arises: how big is "high" and what does "narrow" mean?

To quantify the shape of an edge, you'll need to have a model. The probabilistic technique then allows us to extract model parameters that represent edges in different shapes. But how can we deal with this issue if we don't have a model to work with? Many real-world applications are too complex to model all of the aspects required to quantitatively characterize them.

Models are not required for fuzzy logic. It can deal with ambiguous data and incomplete knowledge, and integrate it using heuristic principles within a well-defined mathematical framework. The most compelling argument to study the possibilities of fuzzy approaches for image processing is that fuzzy logic offers a robust mathematical foundation for representing and interpreting expert knowledge. The concept of linguistic variables, as well as the fuzzy if-then rules, are important here. Fuzzy inference engines can be constructed employing expert knowledge to enable human-like processing.

Define abbreviations and acronyms the first time they are used in the text, even after they have been defined in the abstract. Abbreviations such as IEEE, SI, MKS, CGS, sc, dc, and rms do not have to be defined. Do not use abbreviations in the title or heads unless they are unavoidable.

V. IMAGE PROCESSING

G. Method in Image Enhacement

There are certain methods for Image Enhancement some of them are listed below [11-12]:

- Histogram matching: Histogram matching is the process of altering an image so that its histogram aligns with a specified histogram. The well-known equalization approach for histograms is an uncommon example in which the specified histogram is continuously applied.
- Contrast-limited adaptive histogram equalization (CLAHE): By altering the grayscale image assumed as I, it is used to improve the contrast. Instead of working on the entire image, CLAHE focuses on tiles, which are small portions of the image. Because the contrast of each tile is increased, the output region's histogram closely resembles the histogram defined by the "Distribution" option.
- Wiener filter: is a filter that uses linear time-invariant (LTI) filtering of an observed noisy process, accepting known stationary signal and noise spectra, as well as additional substance noise, to generate a gauge of a desired or target arbitrary process. Between the evaluated random process and the desired method, the Wiener filter restricts the mean square error.
- Median filter: The median filter is a nonlinear computational filter that is commonly used to remove noise from images. Noise reduction is a common pre-processing procedure used to improve the outcomes of subsequent processing, such as image edge identification. Because it keeps edges while reducing noise under certain conditions, median filtering is widely used as part of digital image processing.
- Linear contrast adjustment: In this the contrast adjustment block changes the contrast of an image by linearly scaling the pixel values amongst lower and upper limits. Pixel values that are below or above this range are saturated to the lower or upper limit value, individually.
- Unsharp mask filtering: Unsharp masking (USM) is an image sharpening method, frequently accessible in digital image processing software. The "unsharp" of the name gets from the way that the procedure utilizes an obscured, or "unsharp", negative image to make a mask of the original image. The unsharped mask is then joined with the positive (original) image, constructing an image that is less blurred than the original. The subsequent image, in spite of the fact that clearer, might be a less precise portrayal of the image's subject.
- Deep neural network: Execute image processing undertakings, for example, removing noise from images and constructing high-resolution images from low-

resolutions images, utilizing convolutional neural networks. Deep learning utilizes neural networks to learn valuable portrayals of highlights straightforwardly from information. For instance, you can utilize a pertained neural network to recognize the images and remove various type of noise from images.

H. Image Noise

Image noise is a sort of electronic noise that causes erratic changes in image brightness or color information. It can be done with the image sensor and electronics of a scanner or digital camera. Image noise can also be caused by film grain and the unavoidable shot noise of an ideal photon detector.

There are many type of Gaussian noise: It's statistical noise with the same probability density function (PDF) as the normal distribution, generally known as the Gaussian distribution [13]. Salt and pepper noise is a type of noise that appears on photographs from time to time. It's sometimes referred to as impulse noise [13]. Sharp and rapid disturbances in the visual signal might create this noise. It appears as white and black pixels that are poorly distributed.

The statistical nature of electromagnetic waves like x-rays, visible lights, and gamma rays causes this noise to appear. The number of photons emitted per unit time by the x-ray and gamma-ray sources [13]. Brownian Noise or Fractal Noise Brownian noise, pink noise, flicker noise, and 1/f noise are all examples of colored noise. The power spectral density of Brownian noise is proportional to the square of frequency over an octave. i.e., its power falls on ¼ th part (6 dB per octave). Brownian motion produces Brownian noise. Brownian motion is observed in fluids due to the random movement of suspended particles [13].

I. Challenge in Image Enhancment.

The need to use technology to continually improve the quality of care, the need to cope with ever-growing image utilization needs, and the problems associated with a fragmented IT infrastructure are all imaging concerns for enterprises that come with new technologies. Adaptable image analysis methods enable for more efficient development. The goal is to create tools and methodologies for creating ground truth data quickly and efficiently. Another challenge is developing medical image processing techniques for a wide range of image data.

V. CONCLUSION

We thoroughly examined the numerous image enhancement research approaches employed by various researchers. The merits and negatives of the reviewed work are described in a comparative study. However, it has been shown that a superior technique, based on a hybrid approach of ANN and fuzzy logic, is required to successfully and efficiently enhance the image.

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EARTH OBSERVATION AND GLOBAL NAVIGATION SATELLITE SYSTEMS

ANALITICAL REPORT PART II (TIMING & SYNCHRONISATION OF TELECOMMUNICATION NETWORKS, MARITIME AND INLAND WATERWAYS, RAIL AND AUTOMOTIVE TRANSPORT)

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ABSTRACT

The EU Space Programme is a business growth enabler that stimulates the econo my and pushes the bar of innovation. The EUSPA EO & GNSS Market Report is the ultimate guide to anyone who seeks to make the EU Satellite Navigation and Earth Observation technologies part of their business plan and develop new space downstream applications. More than ever society relies on innovative solutions to deal with the big data paradigm. Earth Observation (EO) and Global Navigation Satellite System (GNSS) data is becoming increasingly important to these innova tive solutions through dozens of applications that are emerging or already in use by citizens, businesses, governments, industry, international organisations, NGOs and researchers around the world. The study provides analytical information on the dynamic GNSS and EO markets, along with indepth analyses of the latest global trends and developments through illustrated examples and use cases. Using advanced econometric models, it also offers market evolution forecasts of GNSS shipments or EO revenues spanning to 2031. This article represent the brief overview essential role of space data across market segments including, timing & synchronisation of telecommunication networks, maritime and inland waterways, rail and automotive transport.

KEYWORDS: EUSPA*, GNSS, rail and automotive transport, synchronisation, telecommunication networks.*

Brief description based on the Copernicus Programme report, which is coordinated and managed by the European Commission and is the European Union's Earth Observation and Monitoring Programme (www.euspa.europa.eu).

I. INTRODUCTION

Coordinated and managed by the European Commission, Copernicus is the European Union's Earth Observation (EO) and Monitoring programme. Most data generated by Copernicus are made available to anyone globally based on a Full, Free and Open (FFO) data policy. They are accessible through various services, including a set of cloud-based platforms called Data and Information Access Services (DIAS).

European Union Agency for the Space Programme (EUSPA) with the support of VVA, Egis, Evenflow, FDC, Université Gustave Eiffel and LE Europe, to introduce the first published EUSPA Earth Observation (EO) and Global Navigation Satellite System (GNSS) Market Report [5].

The European Association of Remote Sensing Companies (EARSC) is a not-for-profit organisation which coordinates and promotes the activities of European companies engaged in delivering Earth Observation-derived geo-information services. Acting as a bridge between industry, decision makers and users and covering the full EO value chain, the organisation's members span across 25 countries and include over 130 companies (including SMEs and start-ups) [1].

The objective of the EU GOVernmental SATellite COMmunication (GOVSATCOM) initiative is to ensure the availability of reliable, secure and cost-effective satellite communication services for EU and national public authorities managing emergency and security-critical missions, operations and infrastructures.

II.TIMING & SYNCHRONISATION OF TELECOMMUNICATION NETWORKS

In July 2020, the International Telecommunication Union (ITU) released a technical report on the use of GNSS as the main time reference in telecommunications. The report contains information related to optimal GNSS reception in telecom applications where highly accurate time recovery is critical. In particular, it provides guidelines for the design and operation of GNSS-based telecommunications clocks for applications with accurate time recovery. In addition, the report mentions several relevant GNSS vulnerability reports prepared by the Telecommunications Industry Solutions Alliance. (ATIS) [2].

5G networks will enable new applications across a wealth of sectors. The expected high data rates, low latency and massive type communications on the same mobile infrastructure leads to stringent time and phase accuracy requirements, but also tight security and robustness requirements. The need for synchronisation in the radio access network has grown as new radio technologies and network architectures emerge to boost efficiency and support demanding 5G use cases [8-13]. GNSS is instrumental in the global distribution of a UTC-traceable reference. A GNSS-based solution installed directly at base station sites can provide cost-efficient, accurate and predictable time synchronisation of the radio network without any support from the transport network. 5G efficiency relies, among other things, on signal strength and coverage to reach remote areas and enable the high-speed transmission of large amounts of data. On the EO side, Sentinel-2-derived land cover maps are being used for 5G infrastructure planning. Other means of EO such as Radio Frequency (RF) sensing can be applied to map wireless spectrum and available infrastructure to optimise wireless networks at planning stage or in monitoring (e.g. to detect and localise interference) [14, 15].

5G may be a crucial enabler in the uptake of EO usage. In smart farming for instance, it would enable (two-way) transmission of EO data and integrate it into agricultural applications in real-time [23-28]. At the same time, concerns around interference created by 5G networks impacting satellite-based weather forecasts need to be addressed by regulators and standardization [55-56].

The GNSS Infrastructure Timing and Synchronisation market witnessed solid growth over the last decade favoured by the deployment of modern communication infrastructure such as 4G, small cells and, more recently, data centres. In particular, DCN operators, which benefited from the 4G base stations rollout, have driven the growth of the GNSS T&S market with more than 40% of the TSCI revenues in 2020 (and 28% of shipments). More recently, shipment growth was observed during the pandemic as the demand for high data transfer rate, high reliability and low latency connectivity positively affected the market.

This trend is expected to sustain market growth in the future. This is also the case of the newly analyzed GNSS T&S data centre market that has gained importance thanks to an increased level of required timing accuracy and the need to comply with regulation. Consolidation is increasingly taking place in the data centre market towards hyperscale data centres; this growth should remain robust after 2020.

Online video gaming has steadily progressed over the last decade in terms of audience and volume of data broadcast. According to Mordor Intelligence, the global gaming market was valued at €135 billion in 2020 and is expected to reach a value of €245 billion by 2026, registering a CAGR of 10.5% over that period. In particular, the emergence of cloud gaming is driving the market with a strong recent boost of video game live streaming that has gained further traction during the COVID-19 pandemic.

To ensure an engaging user and spectator experience, voice and video must be precisely synchronised in streaming applications and online gaming. Maintaining precise time synchronisation across the network is paramount to support seamless operations of digital infrastructure used in online gaming, such as ensuring the chronological order of play in multiplayer games. GNSS is expected to be among the most relevant solutions to ensure this T&S function, and is therefore expected to benefit from this market development.

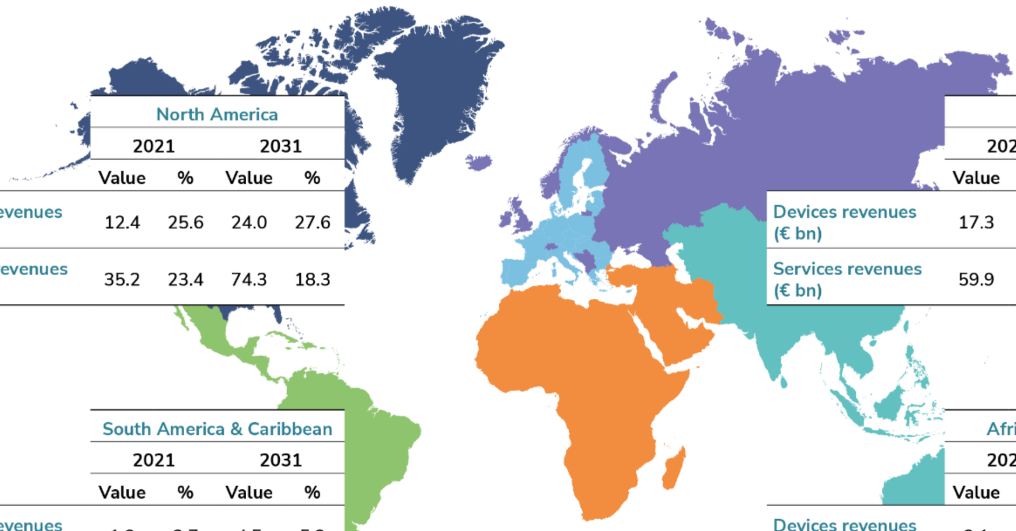
GNSS is used in several forms of transport infrastructure (e.g. Airport, Railway and Maritime), in particular for Timing and Synchronisation, which are both critical components for this infrastructure to operate [16-18].

However, the GNSS interference threat is rising, as pinpointed by US Coast Guards or by several pilots in NASA's Aviation Safety Reporting System. Several technology providers have therefore developed solutions to increase situational awareness at the level of local infrastructure (e.g. ports, airports, etc.) to ensure that the 'Timing' service is provided safely.

This technology consists of monitoring GNSS observables and comparing the expected GNSS signal characteristics with observed characteristics in order to detect anomalies. Some systems can identify the type of interference as well as pinpointing the location of the devices causing the interference, allowing authorities to take immediate remedial action. These time monitoring systems can be combined with atomic clocks and trusted time distribution to secure the communications network. Although they are not quantified in this report, new business opportunities and services are appearing that ensure protection and greater resilience of the transport infrastructure that relies on GNSS.

Wide-scale 5G deployment is still at its early stage in several regions, with EU27, Asia Pacific and North America leading the telecommunication infrastructure modernisation (with over 60% of global shipments combined). The peak of GNSS T&S sales is expected around 2024, coinciding with the most intense period of 5G rollout. Regarding the newly analyzed GNSS T&S data centre market, Asia Pacific (22% of shipments in 2021 and 29% in 2031) is expected to close in on North America (39% of shipment in both 2021 and 2031) within the next decade, at the expense of EU27 (22% of shipments in 2021 and 17% in 2031). Overall, the demand for more sophisticated devices should only impact the Telecom market marginally. Price stability or limited growth is expected in the coming years with new functionalities appearing (e.g. anti jamming, anti spoofing, integrity, multi bands and multi constellations).

At the same time, construction activities are expected to show significant growth again (after a drop in 2020 due to COVID-19), with this effect spilling over to a steady growth of related GNSS shipments. This covers handheld devices and those used in heavy machinery, both powering geomatics applications where the use of GNSS has undoubted value (Fig. 1).



European Union (EU27)	2021 Value	2021 %	2031 Value	2031 %
Devices revenues (€ bn)	12.1	25.0	21.6	24.8
Services revenues (€ bn)	27.4	18.2	53.7	13.3

Global	2021 Value	2031 Value
Devices revenues (€ bn)	48.4	87.0
Services revenues (€ bn)	150.5	405.2

Russia & Non-EU27 Europe (Non-EU27 Europe)	2021 Value	2021 %	2031 Value	2031 %
Devices revenues (€ bn)	2.7	5.6	7.6	8.7
Services revenues (€ bn)	7.4	4.9	20.7	5.1

North America	2021 Value	2021 %	2031 Value	2031 %
Devices revenues (€ bn)	12.4	25.6	24.0	27.6
Services revenues (€ bn)	35.2	23.4	74.3	18.3

Asia-Pacific	2021 Value	2021 %	2031 Value	2031 %
Devices revenues (€ bn)	17.3	35.7	24.0	27.6
Services revenues (€ bn)	59.9	39.8	185.3	45.7

South America & Caribbean	2021 Value	2021 %	2031 Value	2031 %
Devices revenues (€ bn)	1.8	3.7	4.5	5.2
Services revenues (€ bn)	7.9	5.2	22.1	5.5

Africa & Middle East	2021 Value	2021 %	2031 Value	2031 %
Devices revenues (€ bn)	2.1	4.3	5.3	6.1
Services revenues (€ bn)	12.7	8.4	49.1	12.1

Figure 1. GNSS demand world map

III. MARITIME AND INLAND WATERWAYS

GNSS and EO contribute substantially to the maritime and inland waterways sector, assisting a diverse pool of stakeholders ranging from vessel operators and recreational boaters to port authorities in their day-to-day operations and activities.

In addition to safe and efficient navigation, GNSS devices provide a multitude of applications for inland waterways and port operations, while High Accuracy Services enable automation. Combined with EO, navigation efficiency can be optimised, and further explored in areas previously considered too dangerous or inaccessible such as new maritime routes or shallow inland waters.

Besides supporting different synergetic applications with GNSS, EO data itself provides precious insights for ocean services such as ocean monitoring, forecasting and ocean climate records, generating many coastal and marine environment applications.

Maritime sector is sailing towards a more green, autonomous and digital future. Maritime has been profoundly impacted by COVID-19, with global changes to trade and a highlighting of the fundamental importance of uninterrupted supply chains. Maritime tracking insights obtainemeasuringd via GNSS data from Automatic Identification System (AIS) are a great method for the impact of the the pandemic on trade. GNSS has allowed various bodies to track global changes to shipping patterns and frequency and provide important information. Data from Marine Traffic and other providers has offered an overview of the decline in port calls in 2020 relative to the same period in 2019, while companies such as the Maritime intelligence specialist VesselsValue are using AIS data to map cruise ship activity throughout the pandemic [33-34].

In addition, the COVID-19 pandemic has shown that digitalisation has become more important than ever, as has reducing staff onboard while ensuring safety, thus paving the way for automated solutions.

5G is accelerating the path towards automation, enabling vessels, port vehicles and port equipment such as gantries to operate more autonomously (due to its high bandwidth and low latency capabilities), and in larger quantities (given its ability to support a massive amount of connected devices) [51-54]. 5G trials are ongoing at ports around the world, including Hamburg, Rotterdam, Singapore, Shanghai and Antwerp.

The port of Antwerp, in particular, created a 5G-connected tugboat to relay images and radar data of the port's conditions in real-time, with a view to employ autonomous ships and trucks in the near future. The trend towards 5G in ports in turn is increasing the adoption of GNSS-based navigation tools, as equipment that was previously manually operated becomes auto-mated.

In addition to automation, 5G has the potential to impact a wide range applications within ship-to- ship, ship-to-shore, and onboard communication. As part of the H2H Project, SINTEF has looked into the potential applications of 5G communication within the context of maritime operations in various waters.

The IMO has issued Resolution MSC.428(98) for maritime cyber-risk management, effective from January 2021. The resolution focuses on cyber threats against the integrity and availability of technology systems.

An increase in shipping cyberattacks has been seen during the COVID-19 pandemic, as hackers attempt to exploit the vulnerabilities of maritime systems during a period of reduced staffing. The long-term focus for maritime users will be on ensuring continuity of service and protection against cyber-threats.

With low-cost spoofing devices being easily available and such cyber attacks becoming a recurring issue, a key role for authenticated GNSS is envisioned as a response to the growing threat of spoofing at sea or at ports. EU projects such as Prepare Ships and Bluebox Porbeagle are addressing this issue by creating secure devices equipped with authentication services [4].

Increasing cybersecurity risks, ship traffi and volume, in combination with the advanced automated function of vessels and future autonomous capabilities, together make the integrity concept for maritime positioning of utmost importance. Maritime positioning requirements for integrity services are assessed by organisations such as the Resilient Navigation and Timing Foundation (RNTF) and the Royal Institute of Navigation (RIN), stressing the needs of users.

To tackle this challenge, the R-MODE BALTIC project is developing and demonstrating a new maritime backup system for position, navigation and time purposes. It provides a safe ship navigation solution when

the established GNSS fail due to interference or jamming. In fact, the project promotes the fi st worldwide operational test area for a new maritime system for PNT as a backup for GNSS in the Baltic Sea.

Another project (MarRINav) has explored the vulnerabilities of the GNSS PNT solutions to complement current GNSS performance by adding layers of integrity and resilience

Once only available to military and professional users, Augmented Reality as a navigational aid is now becoming a reality for any ship-owner. Systems such as Raymarine's ClearCruise AR integrated with its Axiom chart plotters use real-time video to overlay a view of the horizon with AR markers, which highlight ships or buoys and display information such as their distance, identity and heading. AR eases the navigation by helping understand complex navigational situations and increase safety, especially in difficult meteorological conditions.

On top of this, AR provides real situational awareness, thus improving decision making via maintenance assistance for machinery and remote assistance from land offices. AR can also be used for training with real-world videos, when advanced technology equipment are introduced to the crew.

In future, AR technology could be improved with AI-based object recognition features to tag ships which do not have AIS identification. By combining natural and digital experience, AR technology can revolutionise many maritime operational tasks.

GNSS authentication, both at data level and at range level, is important for the overall trustworthiness of the service. OSNMA, as an integral part of Galileo OS, will be a data authentication function available worldwide for free, which will protect from service disruption (jamming and spoofing) and incidents.

Galileo High Accuracy Service (HAS) will be gradually rolled out for the benefit of the Maritime sector. This will be useful specifically for Merchant Navigation and Pilotage operations in Ports, Inland Waterways, Offshore supply vessels with dynamic positioning, Autonomous Surface Vessels and others (Fig. 2).

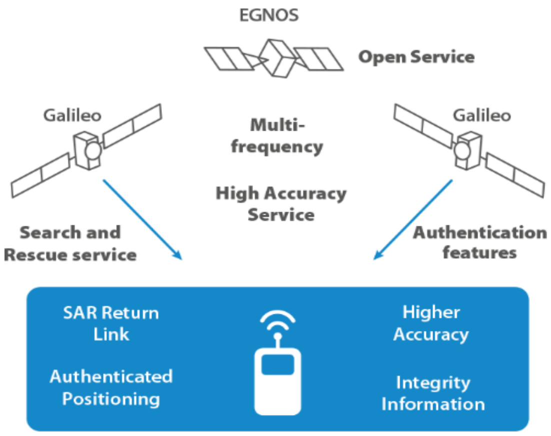


Figure 2. Enhanced devices and advanced data for better performance in maritime activities

The ASGARD project was launched under the Fundamental Elements R&D funding mechanism supporting the development of EGNSS-enabled chipsets, receivers and antennas. It is a research project targeting de-development of shipborne double-frequency receivers [3]. ASGARD focused on developing a multi-constellation and double frequency (E1/E5) maritime receiver that uses Galileo and that complies with European and International specifications. This receiver must implement the required algorithms to process OSNMA encrypted GNSS signals.

ASGARD shipborne receiver will take benefit of all Galileo OS features (improved performance and robustness thanks to dual-frequency and OSNMA capabilities), which in turn will ease the use of the Resilient PNT concept in maritime navigation [3].

The ‘PREPare SHIPS’ project develops a collaborative resilience navigation solution. It aims to develop and enhance existing software solutions by exploiting the distinguished features of the Galileo signals as well as combining it with other nautical information and sensor technologies [38-44]. The accurate position of the solution is based on EGNSS, data and machine learning. The project is also using the Copernicus Marine Service Analysis and Forecast model products for wind, current and waves. The project is using eight EO products (one example being analysis-forecast outputs).

The benefits generated by this smart positioning solution are: reduction of the environmental impact (in line with IMO targets); prediction behaviour of vessels; decreased risk for collisions; and more energy-effective manoeuvring. Those potential benefits are of critical importance, taking into consideration the current challenges the industry is facing, including vulnerability of safety critical applications, increased automation and increased traffic.

To address these challenges, ‘PREPare SHIPS’ is focusing on a support system covering EGNSS resilience positioning, Real time dynamic predictor, Ship-to-ship/ship-to-shore interaction and geo-fencing [4].

IV. RAIL TRANSPORT

GNSS and EO serve the rail sector in many ways. First, GNSS plays a role in rail digitalization; from asset management to infrastructure monitoring and enhanced passenger information, GNSS is already largely deployed in non-safety critical applications [45-50]. Moreover, a large number of initiatives are preparing for the introduction of GNSS in High- and Low-Density Command & Control Systems, paving the way for new train operations.

Furthermore, satellite-based imagery offers solutions around track deformation monitoring, vegetation encroachment detection and natural hazard risk assessments, leading to reduced needs for on-site inspections.

GNSS and EO therefore both increase safety and reduce the cost of infrastructure management and operations compared to legacy solutions. The number of global initiatives demonstrates the consideration given to GNSS and EO-based developments in Rail.

In order to increase rail efficiency and attractiveness, railway stakeholders are taking advantage of new digital and computer- based technologies to become increasingly user-centred and to improve passenger and freight management services.

GNSS is part of the digitalisation that is reflected in the development of new applications, allowing passengers to get real-time journey information and to reserve and to purchase tickets. These also aim to drive shipping back towards rail freight by proposing means to facilitate freight tracking.

Railway operators and infrastructure managers benefit from digitalisation because it improves asset management and maintenance, thereby reducing the operational costs. A growing number of operators are deploying real-time remote diagnostics monitoring systems (e.g. SNCF Logistics with Traxens, DB Cargo, etc.). They collect various pieces of data such as the loading of wagons, within-wagon temperature and humidity, and the position and condition of cargo and rolling stock (which can subsequently be remotely controlled). Such data and its analysis will increase rail freight efficiency, allowing the planning of preventive maintenance actions with greater efficiency.

Digital transformation is also driven by the development of digital twins, particularly for the predictive maintenance of railway infrastructure and rolling stock and for predicting future incidents. These models are based on the collection of real data, some of which is provided by GNSS and EO services [19-22].

Whereas classical infrastructure monitoring procedures rely on the use of measurement vehicles with dedicated runs, new methods based on EO data provided by satellites or drones are being introduced. The use of these technologies meets railway exploitation challenges and allows a global high-frequency monitoring capacity at lower costs [29-32].

Among the potential railway applications of EO, vegetation supervision is currently the most industrialised. For the last two years, some railway operators, such as SNCF or Deutsche Bahn, have been using very high-resolution optical Earth-imaging satellites to get large amounts of information on vegetation development along tracks. This data is used to assist vegetation management teams to operate more efficiently.

Moreover, industrial R&D projects are carried out to study the potential wide operational deployment of satellite-based synthetic aperture radar interferometry (InSAR) or LiDAR acquisition by drones.

Train location is a key element in enhancing railway capacity and fostering new concepts within the sector. Use of GNSS to compute train location may improve position accuracy and integrity at the same time as decreasing operational costs by reducing the need for trackside equipment. However, in a railway environment with tranches, vegetation and urban buildings, GNSS may suffer from performance degradation regarding accuracy or availability. In order to improve train positioning performances, multi-sensor architectures and data fusion algorithms are essential, and have been investigated in several R&D projects (see projects in section on European GNSS).

In June 2020, Alstom was certified to implement its data fusion algorithms using both GNSS and inertial movement in a new odometry system to accurately and safely measure the location and speed of trains. It is one of the first safety-related GNSS applications within railway signalling.

The development of fail-safe location systems must be accompanied by the development of validation tools. Due to safety needs and the complexity of the railway environment, stakeholders require highly controllable laboratory tools. Some developments are supported by the Shift2Rail programme (Gate4rail project) and ESA (Sim4Rail project). The testbeds developed intend to simulate the behaviour of these future solutions under both nominal and extreme conditions [5].

With the development of drones, new railway applications can be envisioned. First of all, projects such as RADIUS (EUSPA) or In2Smart (Shift2Rail) study the potential of drones being used to inspect railway catenary lines and other vital aspects of railway infrastructure, such as the alignment of tracks and switching points. These activities are currently performed by humans and are highly demanding in terms of personnel labour costs and operational constraints. The use of drones will allow these inspections to be performed more regularly with improved safety, reliability and punctuality of the service, all while reducing operational costs.

Galileo-enabled receivers already serve millions of passengers using SNCF high-speed trains (TGV) with the provision of enhanced services (e.g. real-time, precise train location information in stations). Furthermore, GNSS receivers are currently used to track rolling stock (more than 50,000 freight wagons of multiple EU railway undertakings are already equipped with GNSS-based telematic solutions).

The on-going development of fail-safe applications involves the investigation of the multi-frequency potential of EGNSS for more availability, accuracy and integrity.

Although the refinement of the railway users' specific needs and requirements is progressing, there is some concern on how an EGNSS-based safety service must be tailored to answer these requirements.

The High Accuracy Service (HAS) and authentication features could support an attractive and robust localization solution for the future digital rail agenda (Fig. 3).

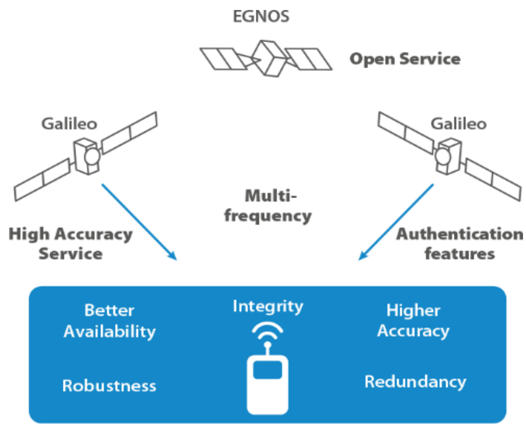


Figure 3. Integration all kinds of train location-based applications

To use EGNSS for rail safety applications such as signalling, sensor data fusion will be necessary to mitigate the known impact of local effects on GNSS performances. Two studies under H2020 have been launched to investigate this topic.

The CLUG project has developed a proof-of-concept of an on-board continuous and safe localisation unit providing information on the train's position, velocity and acceleration. This localisation unit may be useful in replacing or enhancing the existing on-board equipment, such as odometry and balise readers. The cost of trackside equipment should therefore decrease whilst new railway concepts are fostered, such as the moving block for ERTMS.

The HELMET project has developed an augmentation and integrity monitoring platform for rail and road, given that railways and highways are often close to each other and share the same electromagnetic environment and similar requirements. A multimodal architecture has been designed, using Satellite-Based Augmentation Systems (SBAS) and Galileo services, to support a high integrity and high accuracy positioning service [6].

V. ROAD AND AUTOMOTIVE

Mobility is an important part of everyone's daily lives. The Road and Automotive market segment encompasses services and products offered to and consumed by the automotive industry. This includes road transport operators, road infrastructure operators and OEMs (Original Equipment Manufacturers, i.e. passenger and commercial vehicle makers and suppliers).

GNSS is used in safety-related applications in scenarios of potential harm to humans or damage to a system/environment (e.g. connected and autonomous cars, emergency assistance), liability applications (e.g. road user charging, smart tachographs) and fleet management systems including tracking of dangerous goods. Satellite navigation systems therefore significantly contribute to reducing congestion and associated emissions, improving the safety and efficiency of road transportation.

When it comes to smart mobility applications (e.g. distribution of traffic and real- time information to users and infrastructure managers), the contribution of GNSS is strengthened by fusion with satellite imagery.

EGNSS impact will be especially strengthened by important future developments including automated mobility and smart traffic management systems, smart applications and 'Mobility as a Service' where Galileo is expected to deliver new accuracy and reliability for location-dependant services to enhance urban mobility.

Robustness and availability are key GNSS requirements for forward-looking vehicle-to-everything (V2X) communication and automated driving technology. Continuous lane-accurate positioning is seen as an important milestone in the expansion of autonomous capability and situational awareness. The most important value added is safety achieved through redundancy (where GNSS-based lane determination acts as an independent source to supervise the vision-based systems) and alleviating tasks from the perception system (which can focus on changing surroundings). In such a way incorporating precision GNSS into LiDAR-based systems can unlock robustness and additional fallbacks for safety and utility, while high-integrity GNSS lane determination integrated into vision-based architectures can unlock lane-level manoeuvres and provide oversight to guarantee safety.

V2X is a communications technology for smart infrastructure, the exchange of information between vehicles helps avoid accidents, and information exchanges to road infrastructure in order to improve traffic efficiency. As autonomous vehicles will target operating beyond specific routes and cities, GNSS can emerge as a global standard to ensure interoperability across autonomous systems and act as a common reference for precise position and time information.

Autonomous driving is among the most demanding road applications as its high accuracy requirement must be coupled to a high level of integrity. Reaching accuracies and integrity performance metrics simultaneously is enabled by GNSS receivers that can utilise data received from a sufficient number of satellites and correction services. Various industry players are developing Autonomous Driving Systems (ADS), relying on a range of sensors including GNSS for absolute localisation, HD maps, LiDAR, radar and Internal Measurement Units (IMUs). With ongoing trials, the emerging approach is that GNSS is a key component of the sensor fusion system contributing to the safety of autonomous systems. This is the case for Navya, who reached a new milestone with its level 4 fully autonomous shuttle (tested without an operator on board) and VW who plan to roll out a first fleet of self-driving test cars in Hefei (China). Similarly, this combination of sensors in Sensible 4's autonomous driving software allows operation in various weather conditions and environments. Its performance will be tested in the north of Europe, together with Ruter and Holo, on Toyota vehicles to explore the integration of AVs into public transport service and new mobility services. In such a way GNSS continues to play a key role in the development of ADS with robustness (integrity) and availability as key requirements.

With 80% of the world's road network not paved, road networks tend to be particularly vulnerable to environmental, weather and vehicle-related damage with direct impact on its users.

The start-up Bareways combines different data sources (e.g. ground sensors, Sentinel data, historical data) in a mobility platform to give users a unified view of specific road conditions (thus helping avoid risks, delays and fatal incidents).

Current road condition information will be made available to the vehicle navigation system, together with other criteria for route planning and optimisation such as vehicle type, load fragility and driver safety needs. The platform is expected to boost e-mobility applications by suggesting routes depending on battery charge status and possibilities for regenerative braking.

The development of telematics services contributes to the persistent growth in the automotive sector as insurance telematics reached almost 18 million units in 2020, witnessing the highest historical CAGR of 35%, compared with other applications.

Another application substantiating market growth is emergency assistance, which is linked in the European market to the growing number of cars equipped with the mandatory eCall system since 2018.

Finally, during the pandemic, micro-mobility has once again emerged as a sustainable alternative to personal car usage. In particular urban bike sharing (along with e-scooter sharing) schemes account for about 7% of GNSS shipments in 2020 (Fig. 4).

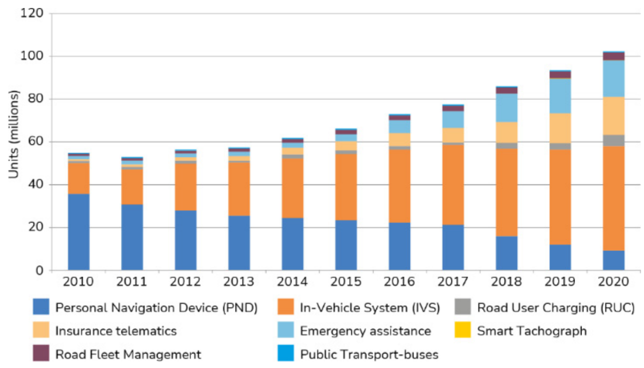


Figure 4. Shipments of GNSS devices by application

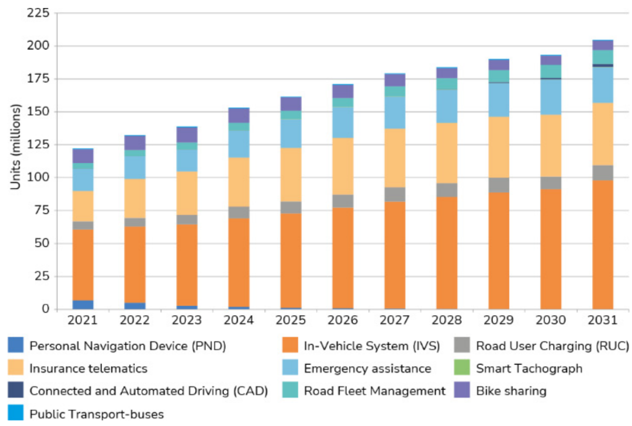


Figure 5. Reinforced trend of IVS becoming the primary PNT source

Geolocation technologies open up new opportunities to improve public mobility through various initiatives, such as demand-responsive transit services (on-demand buses) explored in the H2020 Galileo 4 Mobility project. The pilot was organised by Pildo Labs in collaboration with the Metropolitan Area of Barcelona (AMB), and aimed to tackle the low usage of bus services in the area. Taking advantage of the willingness of the local authorities to permanently implement an on-demand bus service for small villages in the area, Pildo launched a spin-off to commercialise developments performed within the project in the form of NEMI, a tool enabling flexible bus routes and making mobility in low-density areas feasible. A similar platform powered by satellite navigation, Shotl, supports the transition of companies with on-site employee movement to sustainable mobility.

After a significant slowdown of smart tachograph adoption in Europe with a 50% drop in annual shipments registered in 2020, the market is expected to pick up in the coming years due to regulatory developments. An extension of the tachograph's scope to light commercial vehicles, retrofitting provisions for vehicles with analogue and digital tachographs (expected by winter 2024), as well as introducing the first version of the smart tachograph by autumn 2025, will drive annual shipments up to 167,000 units by 2025.

Although globally new vehicle sales are unlikely to return to pre-pandemic levels until 2023, the penetration of GNSS-enabled applications is expected to grow substantially over the next decade (Fig. 5).

Comprehensive evaluation of performance and safety considerations is critical to successful deployment of autonomous systems. International organisations contributing to proving safety for autonomous vehicles include ISO (standards related to safety of execution, performance and intended functionality, as well as requirements for Electrical/Electronic/Programmable Electronic systems), Radio Technical Commission for Maritime Services (RTCM), standards related to Integrity for High Accuracy GNSS-based Applications, Third Generation Partnership Project (3GPP) standards linked to mobile GNSS assistance data and the emerging European standard EN16803.

Focusing on this latest development by CEN-CENELEC, EN16803 explores the use of GNSS positioning in the automotive framework and in particular the assessment of the basic performance of GNSS positioning terminals. In the ongoing phase, the main effort is concentrated on security performance including definition and validation of future testing scenarios.

Ongoing standardisation activities continue to unlock the benefits of autonomous features in cars and pave the way towards a driverless future, which is in turn associated with increased road safety.

Road safety is one of the major elements of the European Union's transport policy; eCall continues to contribute to the reduction of road fatalities and alleviating the severity of road injuries. One of the ongoing initiatives that is looking to expanding eCall reach to L3 vehicle categories (2-wheeled powered vehicles or motorcycles) is H-Gear.

This project aims to develop a system composed of a device integrated into the motorcycle (provided by Honda), a software suite for the monitoring and control of the eCall and Anti-Theft services and a user mobile application for the interaction with the driver.

The H-Gear system will leverage on EGNSS features such as spoofing incident from the Galileo navigation message detection and mitigation using OSNMA, as well as the use of GNSS raw measurements (jointly with accelerometer data) during the alert/theft or accident mode, in order to verify the motorcycle's movement and position [7].

Present in all European new vehicle types equipped with eCall, Galileo is already contributing to improved safety and transport efficiency on European roads.

EGNOS improves GPS accuracy and provides information on the reliability of the positioning information. Together with Galileo and shortrange communications technologies implemented in smart tachographs, EGNOS contributes to enforce EU legislation (social regulation) on professional drivers' driving and resting times (Fig. 6).

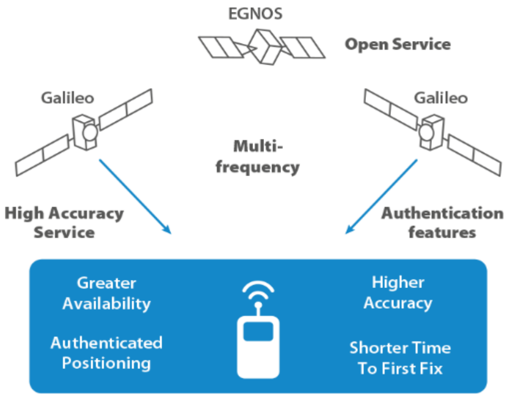


Figure 6. Smarter and more sustainable mobility

Galileo will provide significant added value to the connected and automated vehicles of the future, thanks to its dual-frequency, high accuracy and unique authentication feature.

Galileo's Open Navigation Message Authentication (OSNMA) feature will contribute to addressing the security challenge faced by many applications as potential targets of spoofing attacks, including smart tachographs used in trucks, taxis and ride-sharing vehicles, and tracking devices used in commercial cargo.

The introduction of automated vehicles in cities represents a unique opportunity for a fundamental change in urban mobility. An effort lead by UITP, together with over 50 partners covering the whole urban mobility sector, aims to place public transport at the centre of automated vehicles revolution. SPACE will bring a high-level reference architecture to ensure a seamless integration of driverless vehicles with other IT systems in the mobility ecosystem. This will in turn help operators and cities make the right technical decisions when integrating AVs into the public transport network, speeding up the deployment of driverless mobility services.

An effective integration of AVs as shared vehicles in the public transport network (e.g. shuttle buses, car or ride-sharing schemes) is expected to drastically reduce car ownership, regain essential urban space, and result in better mobility for all.

MOLIERE is a joint initiative led by Factual to coordinate a consortium formed, among others, by SEAT. The study's main goal is to unlock much more precise, accurate and highly available location data enabled by Galileo through an open Mobility Data Marketplace underpinned by blockchain [35-37].

VI. CONCLUSION

Earth Observation (EO) refers to remote sensing and in-situ technologies used to capture the planet's physical, chemical, and biological systems and to monitor land, water (i.e. seas, rivers, lakes) and the atmosphere. Satellite-based EO by definition relies on the use of satellite-mounted payloads to gather data about Earth's characteristics. As a result, satellite-based platforms are suitable for monitoring and identifying changes and patterns for a range of physical, economic, and environmental applications globally. Once processed, EO data can be assimilated into complex models to produce information and intelligence (e.g. forecasts, behavioural analysis, climate projections, etc.), and complemented by in-situ measurements.

The Report applies utilises advanced forecasting techniques applied to a wide range of input data, assumptions, and scenarios to forecast the size of the GNSS and EO markets. The GNSS market is quantified according to shipments, revenues and installed base of GNSS devices.

Key input assumptions are collected from market reports and studies to help inform the penetration of GNSS, the average lifetime of a devices, device prices, EO data and services sales, and more. Input assumptions and outputs are subject to internal and external validation with consortium and industry experts to ensure emerging trends are captured as soon as they are identified.

Where possible historical values are anchored to actual data in order to ensure a high level of accuracy. Application-level model results are cross-checked against the most recent market research reports from independent sources before being validated through an iterative consultation process with European and international sector experts and stakeholders.

The model makes use of publicly available information and additional data and reports purchased from private publishers..

This Market Report considers the EO market to be defined as: activities where satellite EO-based data and value-added services enable a variety of applications across multiple segments.

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GLOBAL CONNECTIVTY REPORT 2022

CHAPTER 1. UNIVERSAL AND MEANINGFUL CONNECTIVITY: THE NEW IMPERATIVE

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ABSTRACT

In the 30 years since the creation of the ITU Telecommunication Development Sector in 1992, the number of Internet users surged from a few million to almost five billion. This trend has enabled a digital transformation that has been, and is, transforming our societies and our economies. Yet the potential of the Internet for social and economic good remains largely untapped: one-third of humanity (2.9 billion people) remains offline and many users only enjoy basic connectivity. Universal and meaningful connectivity – defined as the possibility of a safe, satisfying, enriching, productive, and affordable online experience for everyone – has become the new imperative for the 2020-2030 Decade of Action to deliver on the Sustainable Development Goals (SDGs). The Global Connectivity Report 2022 takes stock of the progress in digital connectivity over the past three decades. It provides a detailed assessment of the current state of connectivity and how close the world is to achieving universal and meaningful connectivity, using a unique analytical framework. It goes on to showcase solutions and good practices to accelerate progress. This article presents a short version of the report (Part I)

KEYWORDS: *ITU, Digital onnectivity, Internet of Things (IoT).*

CHAPTER 1. UNIVERSAL AND MEANINGFUL CONNECTIVITY: THE NEW IMPERATIVE

In 1984, the Independent Commission for World-Wide Telecommunications Development convened by ITU published *The Missing Link* – a seminal report that for the first time identified the social and economic benefits of telecommunications and promoted connectivity as a right and a priority for all countries. The report noted that it was "not right" that only a minority of the world benefits from "remarkable new technologies".

Since the publication of that report, there has been tremendous progress in connecting the world. The Internet – a remarkable technology that did not exist in 1984 – is now woven into the entire fabric of our daily lives. And the minority has become the majority: two-thirds of humanity use the Internet. Yet despite this progress, "the link is still missing": one-third of the world's population remains offline and many among the online population are not meaningfully connected. The "missing link" has morphed into multiple digital divides, across and within countries, between men and women, between youth and older persons, between cities and rural areas, between those who enjoy a fibre connection and those who struggle on a spotty 3G connection.

Linking everyone is no longer enough. Universal and meaningful connectivity, the possibility for everyone to enjoy a safe, satisfying, enriching, productive, and affordable online experience, has become the new imperative for the 2020-2030 decade.

Depriving vast swaths of humanity from the possibilities offered by the Internet is unacceptable and costly, as it stunts economic development and deepens inequalities. The COVID-19 pandemic has led to a sharp uptake in usage of the Internet. For those privileged enough to be connected, the Internet allowed a measure of continuity. However, for others, the pandemic exacerbated the cost of digital exclusion.

Connectivity has a profound and far-ranging impact. The catalytic and enabling role of connectivity for sustainable development is recognized in the Sustainable Development Goals. The Internet offers significant economic benefits and the potential to enhance welfare for individuals throughout their lives. It enables new forms of communication, entertainment, expression, and collaboration. It enables access to services where traditional services are lacking, access to an enormous amount of knowledge, learning resources, and job opportunities. The benefits of connectivity are considerable for everyone, including marginalized and vulnerable groups, who are often the least connected.

In this Decade of Action, three challenges have emerged:

• Closing the coverage gap: Even though 95% of the world population is now within range of a mobile broadband network, at least 390 million people have no possibility to connect to the Internet.

• Closing the usage gap: One in three individuals who could go online choose not to, mainly due to prohibitive costs, xlack of access to a device, and/or lack of awareness, skills, or purpose.

• Achieving universal and meaningful connectivity: This means upgrading connectivity from basic to meaningful for all.

As the use of the Internet increases, so too does the exposure to the downsides of connectivity such as privacy infringements, cybercrime, harmful content, and the outsized power of large companies. Addressing these issues is part of the journey to universal and meaningful connectivity. Finally, digital connectivity alone cannot solve any of the global challenges the world is facing. It is only one of many enablers of sustainable development. "Analogue complements", including governance, security, health, education, transport infrastructure, and entrepreneurship are needed.

In 1983, ITU established the Independent Commission for World-Wide Telecommunications Development and tasked it with identifying ways of stimulating the expansion of telecommunications across the world. Chaired by Sir Donald Maitland, the Commission published its recommendations in December 1984 in the seminal report *The Missing Link* (ITU 1984). The Commission recognized several disparities in the worldwide distribution of telecommunications. Notably, it estimated that three-quarters of the 600 million telephones in the world were concentrated in just nine industrialized countries.

The report underlined that it "cannot be right that in the latter part of the twentieth century a minority of the human race should enjoy the benefits of the new technology while a majority lives in comparative isolation". How has this situation changed and what has been the response to the recommendations of the Commission?

Since the publication of that report, there has been tremendous progress in connecting the world (for an overview at the end of the chapter). The Internet a technology that did not exist in 1984, is now woven into the entire fabric of our daily lives. The minority has become the majority: two-thirds of humanity use the Internet. Yet to a large extent "the link is still missing". A third of the world's population remains offline and many among the online population are not meaningfully connected. Their connection may be too slow, unreliable, or costly. Lack of skills may compromise their ability to get the most out of devices and services. This limited connectivity is simply not sufficient to change the basic blueprint of their lives.

The "missing link" has morphed into multiple gaps and divides across and within countries, between men and women, between youth and older persons, between cities and rural areas, between those who enjoy a fibre connection and those who struggle on a spotty 3G connection, between the technology savvy and those who fall victims of the Internet's dark side.

The Internet offers formidable possibilities. Depriving vast swaths of humanity from such possibilities is becoming less acceptable and more costly, as it is deepening social and economic inequalities. And the COVID-19 pandemic has magnified the costs of digital exclusion.

Connecting everyone is no longer enough. The possibility of making meaningful use of the Internet, leveraging it to its full extent depends on a myriad of factors. The connectivity challenge has become even more arduous. Championed by ITU, the United Nations specialized agency for ICTs *universal and meaningful connectivity* is the possibility for everyone to enjoy a safe, satisfying, enriching, productive, and affordable online experience. Only by achieving universal and meaningful connectivity will the world fully realize the promise connectivity holds for digital transformation and for socio-economic development [27-34].

The COVID-19 pandemic has led to a sharp uptake in usage and reliance on the Internet for many individuals, businesses, schools, and governments. The Internet has enabled continuity during periods of lockdown, quarantine, and social distancing. Those who had fast, reliable, and affordable connectivity also had access to education, health care, shopping, social life, and entertainment. For others, the pandemic increased the cost of digital exclusion. School closures affected millions of students, and an estimated two-thirds of all school children were deprived of essential education services because they had no fixed broadband access at home (UNICEF and ITU 2020). In addition, jobs in sectors not conducive to telework tend to be at the bottom of the pay scale and are held disproportionately by lower-skilled, younger, and less educated workers. The pandemic profoundly disrupted those sectors with a high proportion of such jobs in tourism, logistics, and services, thus contributing to a deepening of social inequalities [35-43].

THE PROMISES OF CONNECTIVITY

The impact of connectivity is profound and far-ranging, extending to individuals, businesses and governments. The Internet has significant economic benefits and the potential to enhance welfare for individuals throughout their lives. The Internet enables access to online services where traditional services are lacking and to new forms of entertainment, expression, collaboration, and communication. It enables access to knowledge, learning resources, job opportunities, and drastically reduces search costs.

The Internet enables businesses to expand their customer base and to integrate global value chains. It improves efficiency and reduces transaction costs (World Bank 2016). It provides access to online resources for upskilling and reskilling, enables remote working and gives access to a larger pool of talent. The Internet enables innovation, leading to new business models. By generating productivity gains and innovation, the Internet contributes to job creation and economic development.

Governments use the Internet to deliver essential public services such as education and health care – and not just during the pandemic – and some services are available at reduced cost and with greater reach. The Internet can also be used for other government services such as business registration and tax collection, and to deliver benefits, especially useful in areas of a country where there are few traditional government offices.

An ITU study shows that a 1% increase in fixed broadband penetration increases gross domestic product (GDP) in a country by 0.08 per cent, while a 1% increase in mobile broadband penetration increases GDP by 0.15% (ITU 20181). While the economic impact of fixed broadband is greater in more developed countries, mobile broadband benefits are maximized in developing countries, where mobile tends to be the way most people access the Internet. In Africa, a 1% increase in mobile penetration is estimated to increase GDP by 0.25% (ITU 2019). Mobile broadband penetration in Africa increased from just under 30%in 2018 to just over 40% in 2021 (ITU 2021), and this 10 percentage-point increase corresponds to an increase of 2.5 percentage points in GDP [1].

The Internet: a lifeline for the marginalized and the vulnerable

In addition to economic advantages, the benefits of connectivity are considerable for society. There exists a very close relationship between connectivity and human development (Fig. 1), although the relationship works both ways, connectivity drives development and more development leads to more connectivity.

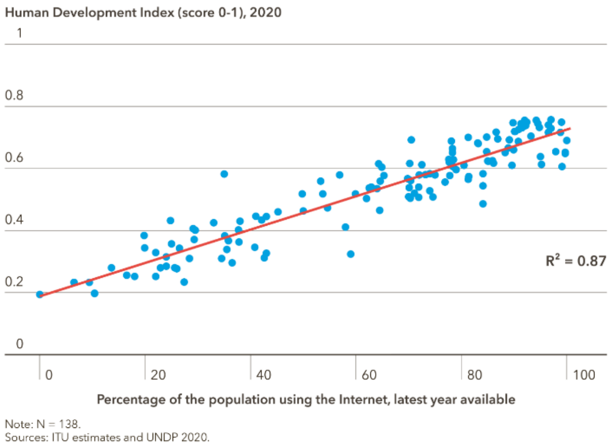

Figure 1. Connectivity and human development

The benefits of connectivity are considerable for the marginalized and vulnerable. Such groups are typically the least connected populations. For refugees for example, connectivity will keep them in touch with their communities, and will provide them with online services including education, employment, and financial support.

Connectivity for refugees

"Connectivity is not a luxury for refugees. It is a lifeline." *Filippo Grandi, United Nations High Commissioner for Refugees* [2].

There are 84 million forcibly displaced people worldwide, of which 48 million are internally displaced and more than 26 million are refugees [3].

This number will rise in the mid- to long-term, as climate change impacts agriculture and sea levels, and as other disruptive events force people to migrate. This will add to the number of displaced people fleeing civil war, sectarian violence, and poverty. For these people, connectivity is an absolute lifeline, and the challenges to its delivery are considerable.

Once displaced, people need connectivity to communicate with family and friends, to let them know they are safe. As they move, they need to remain connected. They need information about their situation and options, and some of them will be able to continue with their livelihoods online. Connectivity is core to delivering a humanitarian response, such as cash transfers via mobile phone, education, and other essential digital services. People sacrificing food for connectivity and buying connectivity by the minute with precious cash to send messages (UNHCR 2016) are striking examples of how important connectivity is to them in their hour of need.

Connectivity challenges in hosting countries

It is a challenge to stay online for displaced people. According to the United Nations High Commissioner for Refugees (UNHCR), 85% of refugees are hosted in developing countries. More than a quarter (27%) are hosted in least developed countries [4], often in rural areas where connectivity is typically below the average for the country. In addition, displaced people may not only lack the necessary papers to obtain a mobile phone, but their difficult financial circumstances means that help will be needed if affordable and accessible coverage is to be provided.

Focus on tackling connectivity challenges

Key organizations are addressing the connectivity challenge of displaced people. For example, UNHCR has a *Connectivity for Refugees* initiative to bring refugees online with available, affordable, and usable connectivity [5]. The Broadband Commission for Sustainable Development (2019) reported on broadband connectivity for refugees in 2019, and experts developed a Global Broadband Plan for Refugees in 2016 [6].

The GSM Association (GSMA) Mobile for Humanitarian Innovation project develops research, creates partnerships for new services, advocates for enabling policy environments, and evaluates performance [7]. The GSMA published a Humanitarian Connectivity Charter in March 2015 that was signed by 159 mobile operators in 111 countries, and endorsed by members of the international humanitarian community, including UNHCR [8]. GSMA forecasts that it is on track to reach 7 million people with access to mobile services by early 2022.

The Sustainable Development Goals and the Decade of Action

The United Nations 2030 Agenda for Sustainable Development sets 17 Sustainable Development Goals (SDGs) for humanity. They address deep-seated challenges, such as ending poverty and hunger, protecting the planet, and fostering peaceful, just, and inclusive societies. Progress towards achieving many of the SDGs has been slow, and in 2019, the UN Secretary-General declared 2020-2030 the Decade of Action [9]. While the COVID-19 pandemic has made progress all the more critical, it has also made it harder to gain ground in achieving the SDGs, and progress continues to stall [10].

The role of connectivity in sustained, sustainable, and inclusive development and growth is recognized in the SDGs (Table 1). Target 9.c focuses specifically on connectivity to "*Significantly increase access to information and communications technology and strive to provide universal and affordable access to the Internet in least developed countries by 2020*".

Table 1 highlights additional indicators related to connectivity under Goals 4, 5, and 17. The benefits of connectivity and its applications extend to the achievement of virtually every SDG. This table also shows ITU initiatives contributing to the SDGs and lists relevant ITU initiatives that contribute to specific goals [11].

Impact of mobile money: achieving the SDGs

Mobile financial services [21] are important in developing countries, where the level of fixed connectivity is low, and the number of unbanked individuals is high. At the end of 2019, there were 2.3 billion users of mobile financial services, including more than 1 billion registered mobile money accounts. The most famous of these services is M-PESA in Kenya, offered by Safaricom, which now generates 11 billion transactions a year, and has clearly helped address pandemic restrictions [22].

Greater financial inclusion lowers the cost of transactions, eliminates risk from handling cash, allows full and fair wage and social payments, and facilitates savings and loans. One study showed that women particularly benefited in developing countries, moving out of agriculture and into business, with increased financial resilience and savings. This same study (Suri and Jack 2016) showed that 194 000 households were lifted out of poverty as a result, some 2% of all households in Kenya.

Table 1

The contribution of connectivity and the SDGs

SDG	Description	Role of connectivity Related connectivity indicator (if relevant) Selected relevant ITU initiatives
1 NO POVERTY	*End poverty in all its forms everywhere*	Digital financial inclusion helps to lift individuals out of poverty by reducing transaction costs, providing access to loans, and reducing theft (see below). ITU has worked to accelerate digital financial inclusion in developing countries.
2 ZERO HUNGER	*End hunger, achieve food security and improved nutrition and promote sustainable agriculture*	Connectivity can help to make agriculture more data-driven to increase crop yields. It can also enable farmers to check the prices of their crops to increase their income. ITU and the Food and Agriculture Organization of the UN have a partnership to help promote ICT innovation in agriculture [12]
3 GOOD HEALTH AND WELL-BEING	*Ensure healthy lives and promote well-being for all at all ages*	Health services can be delivered over the Internet, to enable interactions with patients among other benefits. For instance, reminders can be sent to patients to take their medication, and data can be gathered from individuals about their symptoms and from entire populations to track diseases. ITU has several partnerships with the World Health Organization to help deliver health services, including Be He@lthy Be Mobile [13]
4 QUALITY EDUCATION	*Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all*	Connectivity can provide access to online education in general, as well as helping to develop the digital skills needed to work online and find jobs. Indicator 4.a.1: Proportion of schools offering basic services, by type of service, includes 'Internet' and 'computers' among the services Indicator 4.4.1: Proportion of youth and adults with ICT skills, by type of skills ITU is partnering with the International Labour Organization (ILO) to develop digital skills for youth to promote employment [14]. See also the Giga initiative under SDG 16.
5 GENDER EQUALITY	*Achieve gender equality and empower all women and girls*	The benefits of connectivity should be available to all equally, but currently there is a digital gender gap. Indicator 5.b.1: Proportion of individuals who own a mobile telephone, by sex ITU is involved in a number of gender equality initiatives, including EQUALS, a global network to improve women's access to technology, and that promotes female leadership in the tech sector [15]
6 CLEAN WATER AND SANITATION	*Ensure availability and sustainable management of water and sanitation for all*	Internet of Things (IoT) devices can facilitate smart water and sanitation management, for instance to measure consumption and for quality monitoring. The ITU Focus Group on Smart Sustainable Cities examines key trends in urban smart water management [16]
7 AFFORDABLE AND CLEAN ENERGY	*Ensure access to affordable, reliable, sustainable and modern energy for all*	Smart power grids can build more efficient energy systems with fewer emissions, for instance by enabling consumers to monitor and moderate their usage. ITU has addressed smart power grids, along with helping develop greener ICT equipment.
8 DECENT WORK AND ECONOMIC GROWTH	*Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all*	Internet connectivity can offer opportunities for innovation and entrepreneurship to create jobs and companies, and digital transformation can generate economic growth. ITU has a Digital Innovation Framework to help accelerate these impacts, and established I-CoDI, the International Centre of Digital Innovation, to work with partners to develop strategies to accelerate digital transformation [17]
9 INDUSTRY, INNOVATION AND INFRASTRUCTURE	*Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation*	The Internet is a key enabler of digital infrastructure, the digital economy and innovation. Target 9.c addresses connectivity specifically. Indicator 9.c.1: Proportion of population covered by a mobile network, by technology ITU works to close the digital divide, including as part of the Broadband Commission for Sustainable Development in partnership with UNESCO.

10 REDUCED INEQUALITIES	*Reduce inequality within and among countries*	Access to technologies and the knowledge that can be reached through connectivity can provide jobs and enable remote work to help reduce inequalities. ITU's work to reduce the digital divide can contribute.
11 SUSTAINABLE CITIES AND COMMUNITIES	*Make cities and human settlements inclusive, safe, resilient and sustainable*	Smart technologies can help to make cities more sustainable, helping to manage traffic, trash collection, and air quality. ITU has a partnership with the UN Economic Commission for Europe (UNECE) and UN-Habitat to help with the transition to smart sustainable cities [18]
12 RESPONSIBLE CONSUMPTION AND PRODUCTION	*Ensure sustainable consumption and production patterns*	e-waste from ICTs is significant and increasing. ITU has initiatives to address the challenge of sustainable management of e-waste, including the Global E-waste Monitor, a collaborative effort with other partners to monitor and reduce e-waste [19]
13 CLIMATE ACTION	*Take urgent action to combat climate change and its impacts*	ICT products and services consume energy. ITU has been developing standards on green data centres and power feeding systems to reduce the energy footprint of connectivity. On the other hand, as highlighted during the pandemic, Internet services can reduce the need for commuting to work or traveling for business.
14 LIFE BELOW WATER	*Conserve and sustainably use the oceans, seas and marine resources for sustainable development*	Satellite imagery plays a significant role in monitoring oceans and terrestrial ecosystems. ITU allocates the use of spectrum needed to operate the satellites and coordinates the satellite orbits.
15 LIFE ON LAND	*Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss*	
16 PEACE, JUSTICE AND STRONG INSTITUTIONS	*Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels*	Connectivity can be used to deliver government services to all, particularly underserved citizens, including for schools and hospitals, and it can also be used for general social inclusion and to assess the delivery of services. ITU is working with UNICEF on a programme called Giga to deliver connectivity to schools (as described below).
17 PARTNERSHIPS FOR THE GOALS	*Strengthen the means of implementation and revitalize the global partnership for sustainable development*	Public-private partnerships are key to delivering connectivity to all, particularly in un- or underserved areas. Indicator 17.6.1: Fixed Internet broadband subscriptions per 100 inhabitants, by speed Indicator 17.8.1: Proportion of individuals using the Internet ITU is partnering with the International Labour Organization (ILO) to develop digital skills for youth to promote employment [20]. See also the Giga initiative under SDG 16. ITU works on such partnerships, including the ones in this table, to help achieve the SDGs.

HOW IS MOBILE MONEY HELPING ACROSS THE SDGS?

SDG 1: No Poverty. In Burkina Faso, mobile money users are three times more likely to save for unpredictable events and emergencies, shielding them from economic shocks. In Uganda, a study showed that mobile money helped small businesses to save and make payments, benefiting owners and workers.

SDG 2: Zero Hunger. Mobile money can help farmers increase their productivity by demonstrating creditworthiness to buy equipment and can help to reduce food insecurity by providing financial services used to purchase food.

SDG 3: Good Health and Well-Being. Mobile money allows individuals and households to save for health emergencies, to purchase health insurance, and to pay their bills, enabling increased access to health services.

SDG 4: Quality Education. Mobile money helps households to manage their savings for education and make school payments efficiently, also lowering cost for providers. It can also lower the cost and risks of schools making payments to teachers.

SDG 5: Gender Equality. Mobile money empowers women by giving them control over their money and reducing cash insecurity. In Côte d'Ivoire, men are twice as likely to have a traditional account with a financial institution as women, but there is no such gap with mobile money accounts. Mobile money also helps women to get credit to start businesses.

SDG 6: Clean Water and Sanitation. Pay as you go (PAYG) solutions enable users with mobile money accounts to pay for water, including a loan for their initial water connection, allowing users to pay in small instalments and have access to services.

SDG 7: Affordable and Clean Energy. PAYG solar panels enable the use of mobile money to pay for electricity in small amounts, when it is needed, thereby also purchasing the solar panel over time. As a result, children can study and businesses can operate after dark. Around 4.2 million panels were sold in Africa in 2019, increasing access to a clean source of power.

SDG 8: Decent Work and Economic Growth. In addition to using mobile money for payments, individuals earn income by becoming mobile money agents – there were 7.7 million in 2019. Small businesses use mobile money to efficiently and safely receive payments from their customers and pay their vendors, thereby increasing their revenues.

SDG 10: Reduced Inequalities. Financial remittances are important for migrants and their families, and the cost of sending them is significantly lower using mobile money. The average cost is actually below the 3% target of SDG 10.C. These remittances, in turn, contribute to progress across many of the SDGs with increased income and resources.

SDG 11: Sustainable Cities and Communities. Mobile money enables easy access to public transportation and enables payments for ride-sharing platforms to lower the cost of commuting.

SDG 16: Peace, Justice and Strong Institutions. Mobile money transfers help reduce fraud and theft. For instance, when the Afghan National Police began to be paid with M-PESA instead of cash, salaries increased up to a third for some officers, while payments to ghost workers were stopped.

In order to promote digital payments, ITU works as part of the Financial Inclusion Global Initiative (FIGI) with the World Bank Group and the Committee on Payments and Market Infrastructure of the Bank for International Settlements [23].

Digital financial services offer broad benefits for development, and mobile money is especially powerful given its availability, the convenience it brings, and its usefulness. Mobile money is a platform for a wealth of services that help progress in achieving the SDGs.

The downsides of connectivity

As the range of Internet uses continues to increase, exposure to the downsides of connectivity also increases. Concerns have intensified in recent years as Internet access has proliferated, such as privacy, cybersecurity, harmful content, and the outsize power of large companies.

The data protection balance

Privacy and data protection regulations are important in determining how personal data is used and protected. On the other hand, countries have to enable official access for law enforcement to counter terrorism and to prevent money laundering. This tension generates difficult policy discussions on the use of encryption and access to data stored in other countries.

Online harm: the world is struggling with an array of issues

The focus on protecting individuals – especially children – has intensified in recent years. How can we best ensure adults' and children's safety, while at the same time protecting freedom of expression?

There are challenges even with non-harmful content: many channels exist where only one viewpoint is expressed – an "echo chamber" – where views, sometimes extreme, are reinforced and unchallenged. Excessive amounts of time spent online, particularly for the young in their formative years, can impact adversely on their personal relationships and on the wider community. Events where misinformation and disinformation have been injected into this void are well documented, sometimes with long-term, far-reaching political consequences.

During the pandemic, greater use of sensitive services has added to privacy concerns, while more access from home, with lower cybersecurity, has seen higher levels of attacks. In addition, harmful content has had serious consequences, not least life and death consequences as COVID-19 misinformation and conspiracy theories have flourished.

Online platforms: the role of regulation is still unclear

Recently, the tide has begun to turn against harmful content on online platforms, in part to prevent misinformation about the pandemic. Online platforms such as Twitter provide a medium for direct communications between politicians, officials, voters and other users, generally staying clear of editorial decisions and allowing for endless points of view and broad discussion.

Platforms in many countries are allowed to operate with no editorial responsibility other than an obligation to remove illegal content when notified. Platforms can develop their own policies to guide decisions on how to moderate content.

However, these policies have proven difficult to formulate and enforce due to the subjectivity and sheer quantity of uploaded content.

Some platforms are increasing controls on misinformation

One consequence of a lack of regulation on social platforms has been the rise of populist politicians using these platforms to make direct appeals to voters. Evidence has emerged that organized misinformation and disinformation campaigns have impacted outcomes in the 2016 elections in the United States and United Kingdom. In the light of such evidence, platforms have begun to address such issues by flagging, blocking, and banning some users. For example, a number of platforms now have in place policies that prohibit the posting of conspiracy theories and remove anti-vaccination content.

The impact of digital distrust

Digital distrust was highlighted during the pandemic by the public's response to contact tracing applications. Countries where manual contact tracing was used to isolate those who came into contact with people infected with COVID-19 were soon overwhelmed and attention quickly turned to the use of smartphones in automating contact tracing.

In April 2020, an Oxford study suggested that if 60% of the population used contact tracing apps, the pandemic could end earlier, and that surveys had indicated people would use them.24 Concerns quickly emerged about data privacy however as apps traced individuals' location and proximity to others. And while Google and Apple collaborated in developing an 'Exposure Notification' application that addressed these concerns, take-up remained far below 60 per cent. While studies showed contact tracing apps did indeed prevent infections, their efficacy fell short of expectations.

Connectivity both contributes to, and helps mitigate, emissions

Connectivity and data centres require increasing amounts of power and contribute to the generation of greenhouse gases.

Bitcoin "mining" is estimated to consume enough energy per year to power a country such as Malaysia or Sweden (Carter 2021). More positively though, digital connectivity facilitates working from home and online meetings, thereby reducing the environmental impact of travel, a trend that exploded during the pandemic and is likely to endure (Pearson *et al*. 2021). Moreover, connectivity contributes across a wide range of fronts that help mitigate climate change.

A balanced view: connectivity is not an end in itself

Addressing the downsides of connectivity is a balancing act and will become more so as meaningful connectivity becomes universal. The challenge is to harness the potential of online interaction and open a world of connections, while mitigating the harms, a particularly difficult challenge given the borderless nature of communications and the freedom of online platforms to devise their own content policies.

However, connectivity is a means to an end, not an end in itself. For instance, to achieve SDG 2 (zero hunger), connectivity can help increase agricultural production with an ICT application designed specifically for a particular crop and region. To have full effect however, such an application needs the support of crucial elements such as a skilled farm workforce, transport, and well-functioning markets.

A dual approach is needed to support a balanced development. First, the Internet must be made universally accessible. Second, stronger "analogue complements" are needed to ensure that the Internet provides for economic and social development (World Bank 2016). These analogue complements then ensure that there is a strong policy and regulatory framework, inclusive skills training, and accountable institutions.

3. Charting a path to universal, meaningful connectivity

There are three clear challenges in this Decade of Action:

1. Closing the coverage gap. Ninety-five% of the world population is within range of a mobile broadband network (3G or above). However, lack of infrastructure and services in the poorest areas of the world mean that blind spots remain (Fig. 2).
2. Closing the usage gap. ITU estimates that one in three individuals (33 per cent) who *could* go online today, choose *not* to do so.
3. Achieving universal and meaningful connectivity. Closing the digital divide means much more than getting everybody online. Meaningful connectivity allows for a safe, satisfying, enriching, and productive online experience at an affordable cost. Increasingly, the digital divide is defined as the ability to make meaningful use of connectivity and to enjoy the full benefits of the digital age.

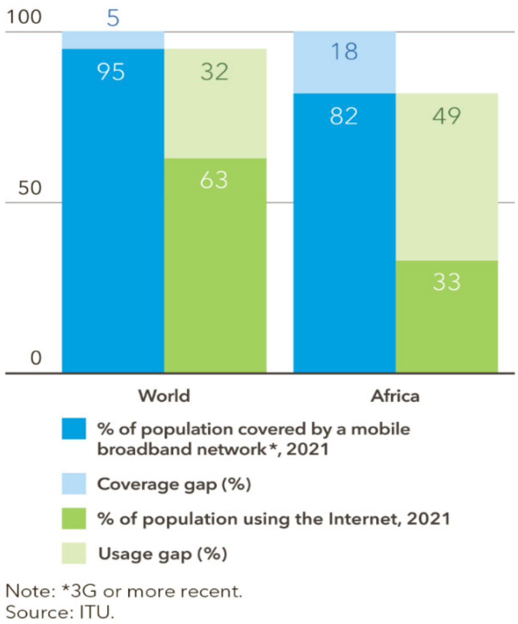

Figure 2. Coverage gap and usage gap

How the usage gap is closed and universal and meaningful connectivity is achieved depends on a number of elements that are covered in the following chapters of this report:

• Infrastructure. Coverage, speed, reliability in infrastructure underwrites the possibility of connecting and the quality of online experience.

• Affordability. More affordable services will enable many people to come online, while those already online will be able to extend their usage.

• Digital skills. Improving digital literacy is essential. Many people do not use the Internet because they do not know what it is or how to use it, while many users fear or are unable to navigate cyberattacks, scams, fake news, or harmful content.

• D vices. Internet-enabled devices need to be affordable, taking into account that device sharing is limiting and that basic devices will make for a less enriching online experience.

• Safety and security. We need to strive for an Internet that is safe and secure, one that will engender trust when people go online.

Addressing any one of these elements is a considerable challenge, and incremental improvements are required for *all* of them. If just one is neglected, meaningful connectivity will not be achieved. Policy-makers and other stakeholders can intervene using a number of tools at their disposal and further chapters in this report showcase examples of successful policies, regulation, and investments across all areas [25].

The pandemic has not only magnified the importance of connectivity but also the heavy cost of its absence. It has also highlighted the need to strive beyond universal connectivity towards meaningful connectivity that enables remote work, education, health care, and entertainment.

To achieve this goal, the work needed to counter the downsides of connectivity should be fully recognized. Meaningful connectivity will help advance the achievement of the SDGs and ensure that the Decade of Action delivers tangible social and economic benefits for all.

A HISTORY OF DIGITAL CONNECTIVITY

Connectivity has gone through three main stages over the past decades. Understanding these stages helps understand how the digital divide has developed and how to address it.

Since the 1990s, the Internet has grown beyond its academic roots in user numbers and in the depth of online use. Access has migrated from dial-up fixed access to broadband, while mobile broadband was introduced with continuous upgrades of generations. Devices moved from static personal computers to smart devices and to the Internet of Things (IoT). And finally, services morphed from text-based serial communications and downloads to real-time multimedia interactions.

The Internet of today is unrecognizable compared to the one that existed when Tim Berners-Lee conceived the World Wide Web in 1989 in Geneva. The commercialization of the web brought the Internet into popular view. The Internet has increased steadily from almost zero users in 1990 to an estimated 4.9 billion users within three decades [26].

Stage 1: 1990s dial-up, fixed broadband, and the emergence of mobile

In the 1990s, connectivity used fixed infrastructure. Fixed telephone networks were fairly universal in developed countries, enabling early analogue dial-up services – slow access speeds and a phone call was needed to go online. The introduction of integrated services digital network (ISDN) provided a digital connection at speeds that could exceed those offered by dial-up connections, but take-up was relatively low.

Towards the end of the decade came the introduction of fixed broadband. Fixed telephone networks were upgraded to offer broadband using digital subscriber line (DSL) technology, while some countries also had widespread cable television networks that were upgraded to offer broadband. Increased fixed-broadband bandwidth enabled new multimedia content and was always-on connectivity and spawned new services. However, many developing countries had limited fixed-telephone networks, with long waiting lists, offering few opportunities for Internet access.

As a result, the connectivity focus in developing countries was necessarily on extending fixed networks, which is costly and slow, and limited the promise of connectivity. At the same time, mobile-cellular networks were emerging, leap-frogging cumbersome fixed networks and offering voice services to users in more and more countries. Mobile Internet services did nothing less than transform the connectivity landscape.

Stage 2: The rise of mobile broadband in the new millennia

In the 2000s, mobile broadband emerged as the primary means for many to go online, beginning with 3G services. Mobile broadband had three advantages. First, the cost of upgrading existing mobile cellular networks to offer broadband was relatively low. Second, the deployment cost of mobile networks was significantly lower than deploying fixed networks and adding mobile Internet to voice revenues made it financially viable. Third, while fixed networks have many attributes of a natural monopoly, mobile services could be offered competitively, as was the case in most countries.

Early uses of mobile Internet were restricted by the device. Either a device captured the signal for use with a personal computer, effectively turning mobile into a fixed service, or it was used with basic devices that enabled e-mail and rudimentary web services. The release of the iPhone in 2007 and the Android phone in 2008 coupled with the launch of third-party apps accelerated adoption and the mobile Internet revolution.

The smartphone transformed use of the Internet. Not only did it give access to existing services where there was no fixed coverage, it also enabled new services based on features such as location-awareness. By the end of the decade, the penetration of mobile Internet had significantly outpaced fixed broadband, particularly in regions where there was little fixed connectivity, notably in Africa. It was clear that the future of connectivity in those regions was to be built on mobile (Fig. 3).

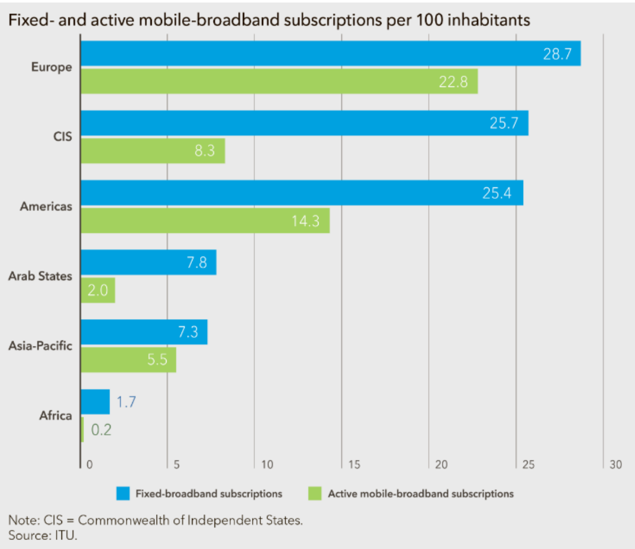

Figure 3. Broadband penetration, 2010

Stage 3: Global dominance of mobile broadband from 2010

From 2010 onwards, mobile broadband spread throughout the world, building on existing cellular networks and then expanding and upgrading to new generations of networks. As a result, the connectivity challenge in developing countries was fully – and positively – turned on its head. In the 1990s, the challenge had been the supply of connectivity. In the following decades, the population coverage of mobile broadband networks quickly overtook demand. And since it was inexpensive to upgrade mobile networks to offer broadband, the supply of mobile broadband was able to come on-stream at high volume. Furthermore, as mobile broadband networks expanded, they did so with 3G technology, offering mobile broadband, and then 4G as it began to be rolled out.

Figure 4 compares the population coverage of mobile broadband with the uptake of mobile broadband services in 2021. Mobile broadband coverage is nearing 100% in many regions of the world, and in many countries within those regions it is at 100 per cent. But there is a big usage lag in certain regions, even allowing for multiple subscriptions, and with adoption lower than availability, particularly in Africa. This reveals a major shift: the connectivity challenge is shifting from the supply-side, where fixed broadband deployment lags, to the demand-side, where mobile broadband nears ubiquity, in most parts of the world.

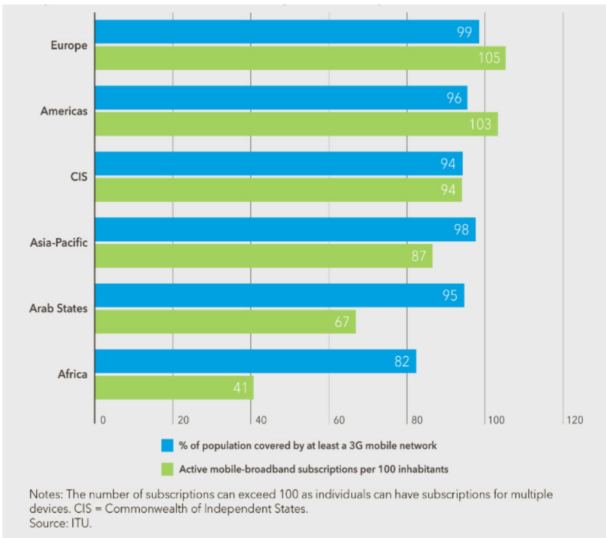

Figure 4. Mobile-broadband coverage and subscriptions, 2021

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