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Research Article

Overcoming Numerical Gaps by Using Free Space Optical Communications Technologies: Challenges and Technical Performances Analyses with Focus in a Sahelian Area

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Abstract: In that study we present and analyse statistical data of some Least Developed Countries (LCDs) telecommunications and ICTs sectors in terms of universal access, use and advances, technological challenges and accessibility. We also focused on the opportunity, importance and roles of the Free Space Optical communications (FSO) for developing and expanding rapidly the infrastructure of telecommunications in LDCs and present a case study, in Dakar, an area, in Sahel. Sahel region, like many least developed countries, is characterized mostly by long last mile up to 2 km and an evolution of the network architectures and capabilities covering network core with 2, 5 to 10 Gb/s, metro core covering 2, 5 to 5 Gb/s, metro Edge with rate around 155 Mb/s to 622 and a low and poor access network dominated by wired copper. In our study, we confirm that a minimum range of 2 km is possible at any time for the FSO we used for the simulation with availability up to 99.999%. We also underlined the advantages of FSO, in terms of cost, ease deployment compared to fixed optical fiber and its concurrence in reducing the price of the basics telecommunication services.

Keywords: Fixed telephone, FSO system, ICT cost, internet, mobile telephone, universal access, optical link

INTRODUCTION

Almost one fourth of the world's countries are Least Developed Countries (LDCs). In 2010, the 855 million people living in the 49 LDCs represent 12.3% of the world. The 25% of the countries from the entire world are considered as Least Developed countries (United Nations, 2011).

Historically, in LDCs, the legislative and regulatory frameworks of telecommunication were monopolized by governments. In the recent years, many countries have adopted legal and regulatory reforms aimed to increase the efficiency of their telecommunications and ICTs infrastructures and services (ITU, 2010). Like in middle and high-income countries, the main reform approaches were to increase private sector participation, market liberalization and regulatory provisions to ensure transparency for the competitions within all stakeholders, public and private operators; reforms goals are also undertaken in regard to increase access, availability and efficiency of ICTs services, like, internet, telephone, data and voice, including fixed and mobile phone services (Cambini and Jiang, 2009; Edwards and Waverman, 2006).

LITERATURE REVIEW

Challenges and advances in universal access and use in some LDCS: In most LDCs, regulation activities are independent and separated from operating and development activities. Liberalization was more successful in mobile and Internet services where economies of scale and scope are less significant than in fixed Telephone lines networks (Dath *et al*., 2015a).

An increasing number of LDCs has established regulatory policies to support market openness and clear criteria for competition; at the same time, LDCs face also multiple challenges. Small population numbers and low purchasing power often show difficulties to rely on competition, in particular if a country is seen as politically instable. Figure 1 shows the coverage rate of universal access around some LDCs (Wellenius and Neto, 2010; ITU, 2015). The universal service coverage is weak; all the 49 LDCs countries around the world don't have a complete coverage for universal services access.

In terms of availability and use of information and communication technologies, ITU estimated that LDCs were expected to account 4.7% of the world's mobile cellular subscriptions and 0.8% of all fixed telephone lines., 1.2% of the world's total internet users and

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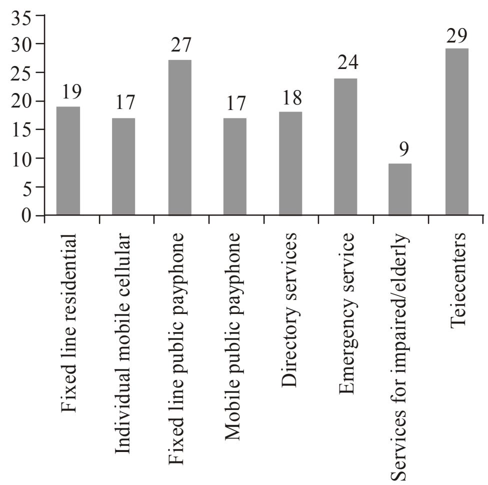

Fig. 1: Universal service coverage in 2009, by number of LDCs

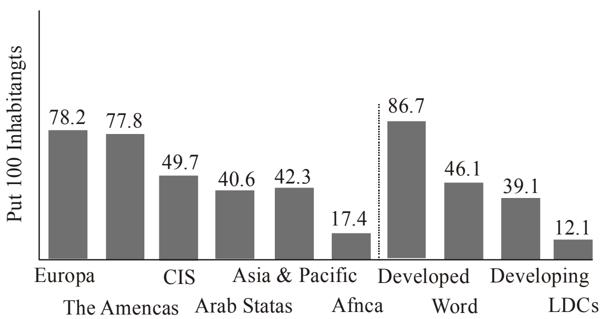

Fig. 2: Mobile broadband cellular penetration in 2010

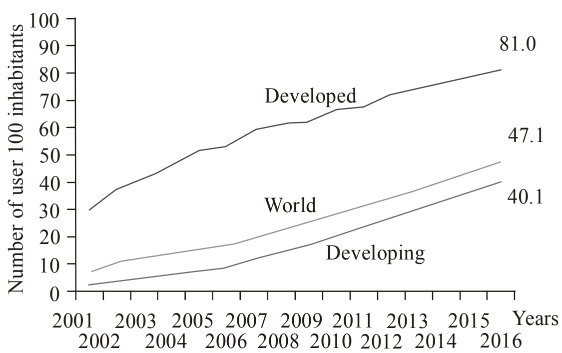

Fig. 3: Internet users per 100 inhabitants, from 2001-2016

globally, 0.2% and 0.5% of all fixed and mobile broadband subscriptions (ITU, 2010; Guillaumont, 2010).

Access and use of Mobile telephony has been, without doubt, the 21st century's ICT success story. The number of mobile cellular subscriptions worldwide has increased from about 740,000, to over 5 billions, by the end of 2010, when mobile cellular penetration reached over 75%.

Figure 2 shows the mobile cellular phone penetration in LDCs during 2015.

Mobile-broadband penetration levels are highest in Europe and the Americas, at around 78 active subscriptions per 100 inhabitants. Africa is the only region where mobile broadband penetration remains below 20% and below 13% for the all LDCs despite of significant growth noted from 2000 to 2015.

It's also very important to know that in many Least developed countries mobile networks are the main communication networks and by the way, acting as services provider from fixed and mobile telecommunications infrastructures, particularly in rural and isolated areas as in Sahel region. In the same approach, the use of internet in LDCs is increasing but remains low in term of availability and access compared to developed countries. Figure 3 shows the use of internet in the world; it shows users per 100 inhabitants from 2000-2015.

Figure 3 shows also a comparative study of internet use between developing and developed countries in 2015. In this study it is shown in average, that in developed countries, online connected people were at least 2 times more important than people online connected in LDCs and developing countries,. Additionally, considering information on internet distribution in the Africa and some LDCS,.

We can say that in the vast majority of LDCs, specially in those located in Africa, the bandwidth per user is less than 100 bit/s; this is also true in the west African Sahelian states like Senegal, Mali, Mauritania, Benin, Togo (Bauer, 2010).

Technological challenges and opportunities of FSO technologies: We remind that, most LDCs are facing economic vulnerabilities and poverty trap issues including low income, high variability in population density and very low skilled human resources. So challenges are to bring affordable technologies with respect to a good ratio of quality-prices (Lai and Chen, 2015; Guillaumont, 2010).

LDCs also tend to suffer from weak government and regulatory capacity. We show in the Table 1, the evolution of people covered by cellular networks and by percentage of coverage by broadband access.

Mobile cellular signal coverage in LDCs vary from 50% in 2005 to approximately 61% in 2010; during the same period, the rest of the world coverage vary from 68% to more that 90% (Bauer, 2010; ITU, 2010).

This means that big effort need to be made for universal services access, when knowing that mobile cellular networks is essentially the infrastructure of telecommunication in LDCs, like in Sahelian areas, characterized by rural and isolation aspects

Analyzing the internet gap in terms of bandwidth, we can refer to the gfigure called Table 2; showing bandwidth distribution and evolution around the world and some LDCs countries and developed countries.

Here, we show that broadband subscription from 2009-2016 for LDCs is 0.2% meaning 2 per 1000 users; that value is extremely low compared to developing

Table 1: fixed broadband subscriptions from 2009-2016

Year	Developed	Developing	World
2009	112.1	58.2	68.0
2010	113.3	68.5	76.6
2011	113.5	77.4	83.8
2012	116.0	82.1	88.1
2013	118.4	87.8	93.1
2014	122.7	91.4	96.8
2015	125.7	93.0	98.6
2016	126.7	94.1	99.7

Table 2: Percentage of population covered by a mobile cellular network signal

Year	Developed	Developing	World
2009	45.5	12.4	18.4
2010	44.6	11.9	17.8
2011	43.4	11.5	17.2
2012	42.2	11.2	16.7
2013	40.8	10.6	15.9
2014	39.7	9.9	15.1
2015	38.5	9.3	14.3
2016	37.3	8.8	13.7

countries reaching an average value of 4.4 users per 100, or 44 users per 1000. In the same time, developed countries reached an average maximum of 24.6 per 100 or 246 per 1000.

Despite of all, progresses registered on reducing numerical gaps and disparities in LDCs in terms of coverage, we consider in another approach that access for end users, is very low. This access and availability (bit rate) is globally very weak and their related costs are very high, in the countries with low incomes (ICT Facts and Figures, 2010).

ANALYSES AND RESULTS

The FSO capacity and core networks evolution in Sahel: The FSO systems have similar capability to fiber optic in term of speed and bandwidth. The advantages of FSO systems over fiber are cost and time of deployment (Kruse *et al*., 1962). In that context, Free Space Optics (FSO) systems can play a key role in terms of backhauling and back-up links for the telecommunication infrastructure of operators and for the governmental intranets, in regard to ensure access and services availability (Dath *et al*., 2015b).

In Sahel, telecommunications systems are emerging with deployment of core and metro core access in optical fiber as well as Digital Subscriber Lines (DSL) in regard to provide high data rate transfer to users for voice and data services, in dense regions and even in rural areas (Dath *et al*., 2015a). By the way, data are available in the core network, in the metro core and even in the metro core access, but bringing high data rate to end users, like home and enterprise still being a problem because the Metro Core Access (MCA) and the DSL still being far to the so called last mile, in most cases (Weichel, 1990).

This architecture above (Fig. 4) represents the most frequent architecture of fiber networks in Sahel with capability attaining STM-16 to STM-64. The access infrastructure was used to be a coaxial cable or Microwave systems attaining rarely a STM-1 and shared with many users (Kruse *et al*., 1962).

Fiber used in that kind of network is essentially the G652 standards of the ITU, with different performances specifications in the two optical windows of operations: the 1300 nm and 1550 nm.

From the Fig. 5, we can see that the network is dispatched in four parties: Core network, metro core, metro edge and metro access. The G652 fiber used in the former Core network is displaced in the metro edge and metro core. The actual core is built by new types of fiber, like G655 or G657; these new fibers are also used in the metro access and the access. Sometimes the G653 and G654 are used but not frequently because these two types of fiber are not very reliable. Rapidly, they have been replaced by the new standards especially the G655 and G657. They are most useful in the third optical window which is the windows for new telecommunications services and corresponding to the

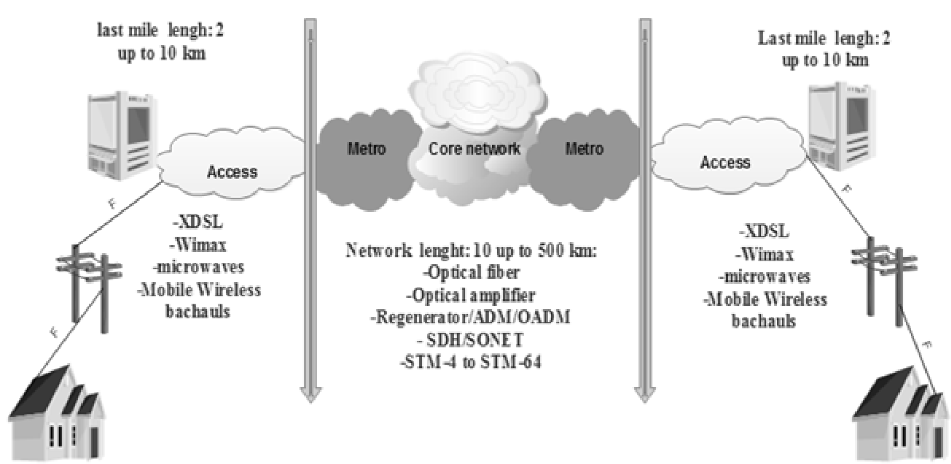

Fig. 4: First backbones networks architecture of SDH and allied optical fiber technologies in Sahel

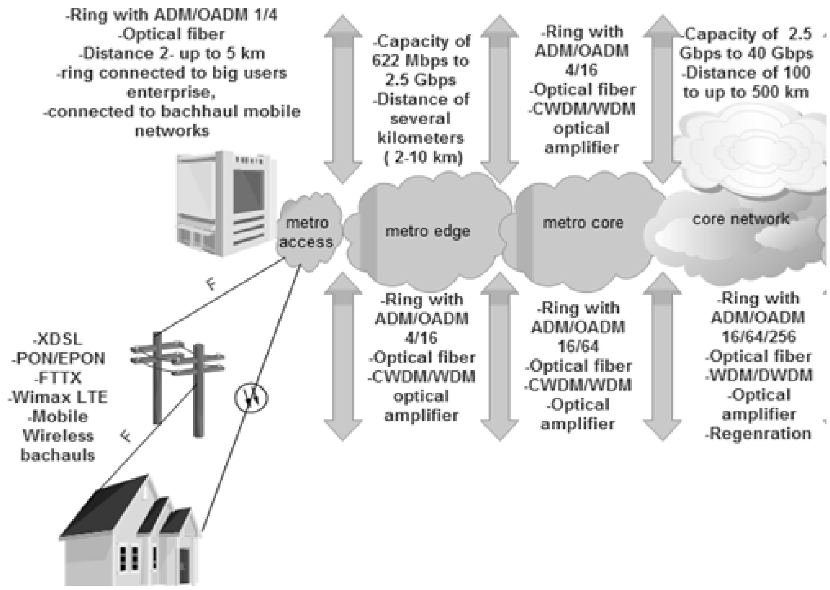

Fig. 5: Most existing architecture of telecom network with SDH/WDM and allied technologies

Table 3: FSO signal attenuation in different visibilities conditions

Air condition	Precipitation		Visibility (km)	dB loss per (km)	dB loss per (km)
				785	1550
Dense fog			0.050	315.0	272
Thick fog			0.200	75.3	60
Moderate fog			0.500	28.9	21
Light fog			0.770	18.3	
			1	13.8	9
Thin fog	Heavy rain	25 mm per hour	1.9	6.9	4
			2	6.6	
Haze	Medium rain	12.5 mm per hour	2.8	4.6	
			4	3.1	2
Light haze	Light rain	2.5 mm per hour	5.9	2.0	
			10	1.1	0.4
Clear	Drizzle	0.25 mm per hour	18.1	0.6	
			20	0.54	0.2
Very clear			23	0.47	
			50	0.19	

spectral zone of operation of the new optical amplifier, called Erbium Doped Fiber Amplifier (EDFA), allowing by the way, optical fibers to reach longer haul and big transport capacity and capability, for SDH and even for multichannel transport systems, like WDM of combination SDH/WDM.

Weather dependency and reliability of FSO links availability in Sahel: The FSO systems reliability is depending of the atmospheric composition and weather condition (Lee *et al*., 2011; Willebrand and Ghuman, 2002). The resulting effects of weather and atmospheric elements are absorption, diffusion of the signal which interact with the particles like aerosol, molecules. Table 3 shows the attenuation of an optical signal for the windows of 755 and 1550 nm (Willebrand and Ghuman, 2002; Refai *et al*., 2003). This table include a large range of meteorological conditions, including those concerning Sahelian zones. The Sahelian area we studied, which is Dakar and rounding area, was characterized by a visibility vary from 5 to 9 km. Referring to Table 3 we get the status of a typical FSO signal evolution (Refai *et al*., 2003; Al Naboulsi, 2005). Addtionally, we compute and analyses visibility data from 2003 to 2004, for simulating the availability of the FSO systems.

Free Space Optics (FSO) transmission is subject to absorption and scattering of the light due to the Earth's atmosphere. The atmospheric transmittance is obtained using the Beer-Lambert's law (Refai *et al*., 2003; Al Naboulsi, 2005):

$$\tau(L) = \frac{P(L)}{P(0)} exp^{(-\gamma(\lambda)L)} \quad (1)$$

The total extinction coefficient is, on a qualitative basis, limited to the extinction due to aerosol according to the below formula, proposed by Kruse (Al Naboulsi, 2005):

Table 4: Comparison of the cost of operation and maintenance of different support and technologies

Access medium	Speed (Mbps)	Equipment (US Dollars)	Mbps (US dollars)	Monthly cost (US dollar)	Mbps/Mo (US dollar)
Dial-Up	0.056	-	-	20	357
Satellite (DBS)	0.4	-	-	50	125
Cable Modem	1.5	-	-	50	33
DSL (Min)	0.144	-	-	49	340
DSL (Max)	8	-	-	1200	150
T-1	1.54	-	-	300	195
T-3	45	-	-	3000	67
RF (Medium price for 6 vendors)	155	45,000	290	1250	8
FSO (price of SONABEAM for 155 Mbps equipment, operating at a distance of 2 km)	155	20,000	130	555	4

$$\gamma(\lambda) = \beta_a(\lambda) = \frac{3.912}{V}\left(\frac{\lambda_{nm}}{550}\right)^{-q} \quad (2)$$

Coefficient q has been established within many experimental studies and may take the values below, subject to the visibility range and can take the following values according to KRUSE (Refai *et al*., 2003; Al Naboulsi, 2005):

$$q = \begin{cases} 1.6 \; if \; V > 50 \; km \\ 1.3 \; if \; 6km < V < 50 \; km \\ 0.585V^{1/3} \; if \; V < 6 \; km \end{cases} \quad (3)$$

The link margin for a point to point link is given by the following formula (4):

$$M_{liaision} = P_e + |S_r| - Att_{Geo}(dB) - Att_{Atm}(dB) - P_{tot}(dB) \quad (4)$$

$$Att_{Geo} = \frac{S_L}{S_{capture}} = \frac{\frac{\pi}{4}(L\theta)^2}{S_{capture}} \quad (5)$$

where, Pe, Sr, AttGeo AttAtm, Ptot are the emitted power, receiver sensitivity, geometric loss, atmospheric loss and system loss respectively, the free space optic was simulated for an emitting power of 10 mW, in the 1550 nm window. We use this wavelength because this is the almost used windows by the wired optical network, so that an FSO systems working in the same window can extend easily, without changing frequencies (Willebrand and Ghuman, 2001).

Geometric loss related to divergence and distance for the analysis are comprised between -23 and -44 dB, respectively for distance of 3,00 and 2,000 m and receiver sensitivity is around -46 dBm (Lee *et al*., 2011; Willebrand and Ghuman, 2002). In this study, the system loss was assumed to vary around 6dB (10). In this context, the link margin using equation (4), for a 2 km is varying from 0.5 to 6 dB, that mean an availability of the link at 100% (up to 99.999%). The simulation was performed by using visibility data recoded from 2003 to 2013.

DISCUSSION

Communication links employing FSO technology are highly immune to electromagnetic interference and operate at the optical windows of 850 and 1550 nm. These two windows are out of regulation in many countries because national regulatory authorities do not regulate frequency use above 300 GHz (Wang and Kahn, 2002). FSO transmitters and receivers are highly invulnerable to interference from other optical radiations sources (Refai *et al*., 2003; Al Naboulsi, 2005). The installation of a fiber based solution to connect the end-users to the optical network can cost between $100,000 and $200,000 per km in metropolitan areas where as much as 85% of the cost is attributed to trenching and installation costs (Korevaar *et al*., 2003). However, the purchase and installation cost in FSO is estimated from $10,000 USD to $25,000 USD for medium and long-distance (Korevaar *et al*., 2003).

A network of FSO can be built with only 10% of the cost. Of its equivalent network in optical fiber.

This Table 4 shows a cost operation and maintenance for a FSO at 155Mb/s (Mehdi, 2015). The comparison uses information from most popular technologies in Sahel, like DSL, satellite and terrestrial radio frequencies technologies.

Table 4 shows the cost of operation for different types of technologies and supports including bite rate per US dollar. Here we conclude that a bite rate of STM-1(155Mb/s) with FSO is 2.25 times less expensive or 2.25 times more accessible. We also note that, for FSO with high capacity, like STM-4, STM-16, the relation cost/bit rate is very explicit and shows a clear cost reduction.

We can also add an analysis based on distance and haul cost reliability. For a link haul of 210 m to 1 km, the cost of FSO is varying in the scale of 8,000 to 50,000 US dollars and at the same time the cost for a wired optical technology varies from 200,000 to 250,000 for a haul of 210 m, to reach up to 550,000 Us dollar for 700 m of distance. This means that FSO is more accessible for longer distance, like urban connectivity's, up to ten times, as resumed in the Table 5.

For LAN applications and for distance lower than 500 m, the cost of FSO is 2, 5 to 8 times lower that a wired optical fiber, as mentioned in the Table 6.

The growing of new access technologies, PON (Passive Optical Networks) become an attractive solution for the establishment of high speed access

Table 5: Comparison of price for access service by FSO and by optical fiber for urban

Distance (m)	Fiber cost in US dollars	Cost in US dollars with FSO
210	200,000 to 250,000	8,000-50,000
350	300,000-400,000	8,000-50,000
400	300,000-400,000	8,000-50,000
500	350,000-450,000	8,000-50,000
600	400,000-500,000	18,000-50,000
700	450,000-550,000	18,000-50,000

Table 6: Comparison of price for access service by FSO and by optical fiber for campus applications

Distance (m)	Fiber cost in US dollars	Cost in US dollars with FSO
100	75,000-125,000	8,000-50,000
250	75,000-125,000	8,000-50,000
300	75,000-125,000	8,000-50,000
500	150,000-200,000	8,000-50,000

networks and supported by FSO infrastructure (PON/FSO)..

In another approach, mobile data traffic is becoming a significant part of the global IP traffic and is expected to grow 11-fold between 2014 and 2019, which is three times faster than the growth of fixed IP traffic; as mobile traffic grows, the centralized data centers and gateways become a bottleneck. In addition, high availability requirements by end-users put more emphasis on network flexibility in terms of resource utilization and lower latency (Zhang *et al*., 2016).

CONCLUSION

The Sahel region, in light of LDCs world, gained a big improvement due to concurrence of ICTs services, impacting the development in the field of health, education, money transfer services and commerce. The impact of TICs is also verified in the reduction of poverty in general and also in reduction of poverty gap around the population in a same LDCs country, between rural areas and urban zones. The boom of mobile cellular telephony in LDCs has transformed this technology from a communication tool into a platform for service delivery able to transform lives through innovative applications and services (Röpke and Holz, 2016).

A study shows that the reduction in communication costs of mobile telephony is indirectly, improving the agricultural and labor market efficiency and economic benefit in the countries (Naudts *et al*., 2016; Guillaumont, 2010). Mobile communications can create a sustainable infrastructure for the development of other vital services to LDC citizens, such E-commercce, E-banking, E-santé, E-learning, others government services and by the way, reducing problems related to rural and isolated zones, still being so far to the big urban cities.

The free space optical technology which is suitable and reliable up to 2 km in Dakar, a Sahelian coastal zone proves that FSO systems can play a key role for the development of network infrastructure, including mobile network.

The affordability of the access analysis in term of cost is very important when knowing that Sahel is one of the poorest regions in the world. This study and analysis should be extended into others kind of Sahelian areas, as the continental dry and dustiest zones and also the desertic areas, in regards to extend the reliability studies of FSO.

CONFLICT OF INTEREST

We, Authors and co-authors, don't have financial interest that may have influenced the development of the manuscript.

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