Smart Indoor Optical Wireless - A Review

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Optical Wireless is also called :
- **Free-space Optical (FSO) Communications (FSOC)**
- **Li-Fi**

Presentation Dated Sept. 01, 2016.

1879: Earliest Optical Wireless

"The Photophone"

Alexander Graham Bell Invention Over
Over 130 Years Ago

Figure 1: Schematic of the Bell Photophone, 1879.

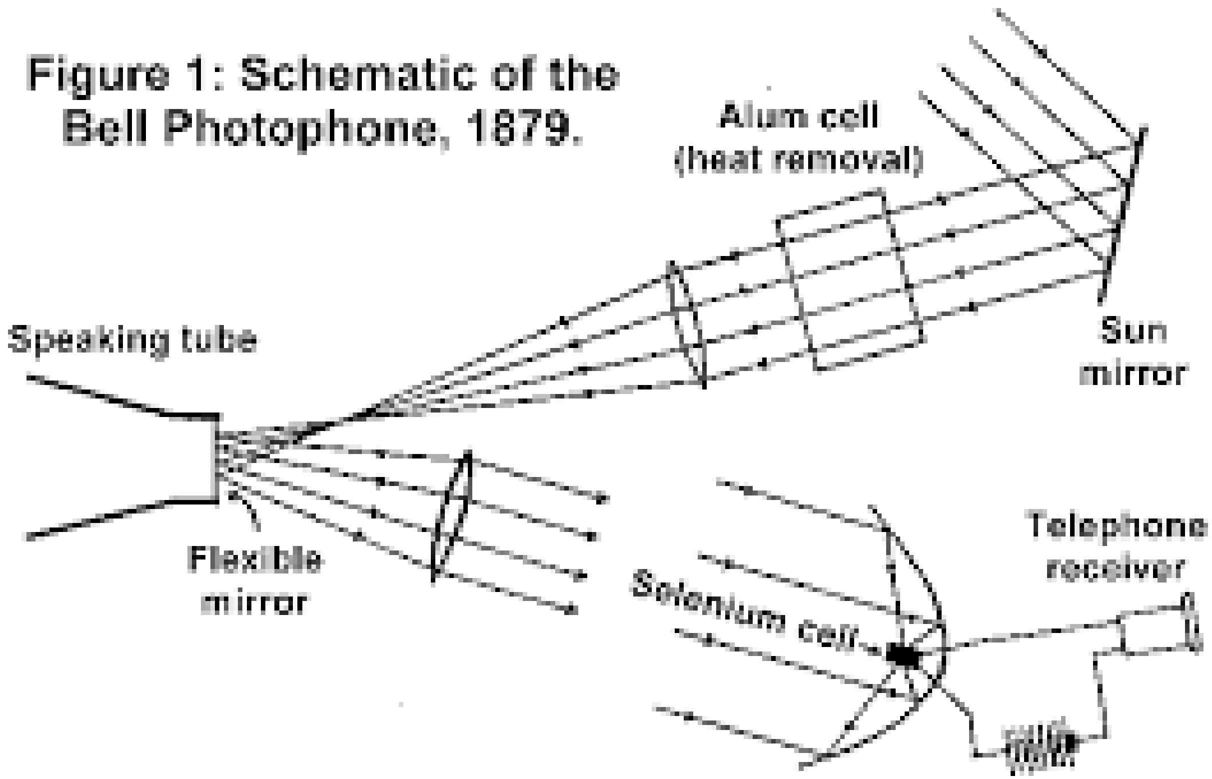


Image from www.bluehaze.com.au

Indoor Wireless: Optical versus RF

The Good News

Optical Wireless	RF Wireless
• Large Bandwidth (Very High Carrier Frequency)	• Large Coverage Area
• Secure (Highly Directional)	• Robust to Blocking
• EMI Resistant	
• Spectrum is License Free	

Decision of Preferred Wireless Technology is Application Dependent.

Indoor Wireless: Optical versus RF

The Bad News

Optical Wireless	RF Wireless
• Prone to Physical Blocking	•EMI Sensitive
• Poor Use of Limited Optical Energy	Spectrum Licensing is Country Regulated
•Limited Link Range	•Directionally Insecure Communication (so Easy to Eavesdrop)
• Requires Optically Clear Aperture for Light-to-Electrical Photo-Detection	

1978: Early Indoor Optical Wireless History

1978 (IR LED –Diffused Light)

Diffused Infrared (DFIR) Optical Wireless

- F. R. Gfeller, H. R. Mϋller, and P. Vettiger, IEEE COMPCON 1978.
- F. Gfeller & U. Bapst, Proc. IEEE, 1979.

Robust to Blocking BUT Highly Energy Inefficient

1985 (IR Laser – LOS Light)

Line-of-Sight (LOS) infrared called

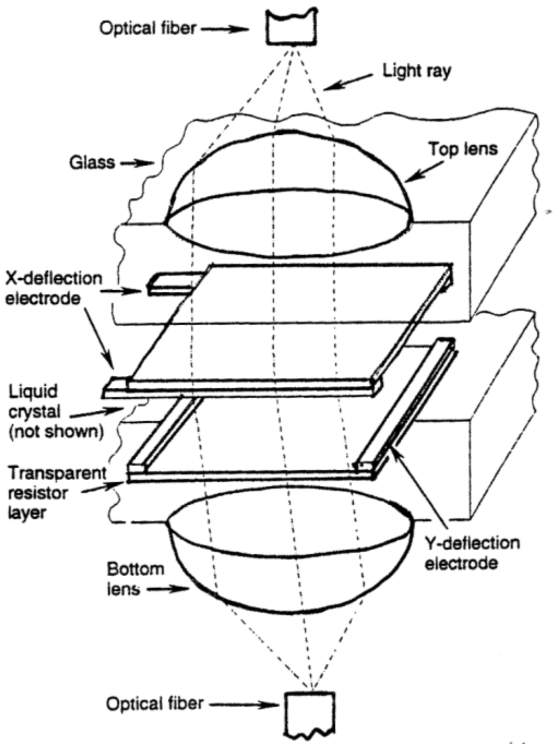
Directed Beam IR (DBIR) Optical Wireless

- C.S.Yen and R.D. Crawford, Proceeding of Globecom 1985.
- Y. Nakata, J. Kashio, T. Kojima, and T. Noguchi, Proc. of the Seventh International Conference on Computer Communications, 1985.

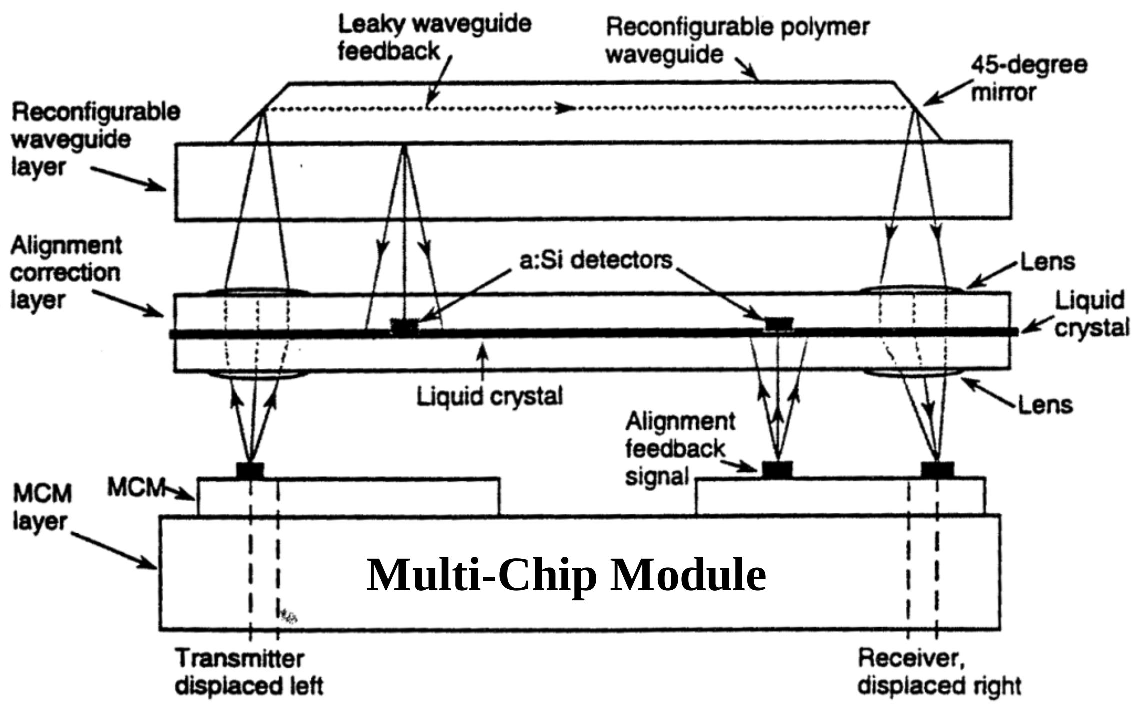
Much Better Energy Efficiency BUT Highly Prone to Blocking & Alignment Issues

1994: First Use of Electronic Lens in Short Range Optical Wireless

Uses Electronic Lens for SMF-Freespace-SMF & TX-Freespace-RX Interconnects To Enable Robust Alignments for Low Loss Links



SMF-Freespace-SMF

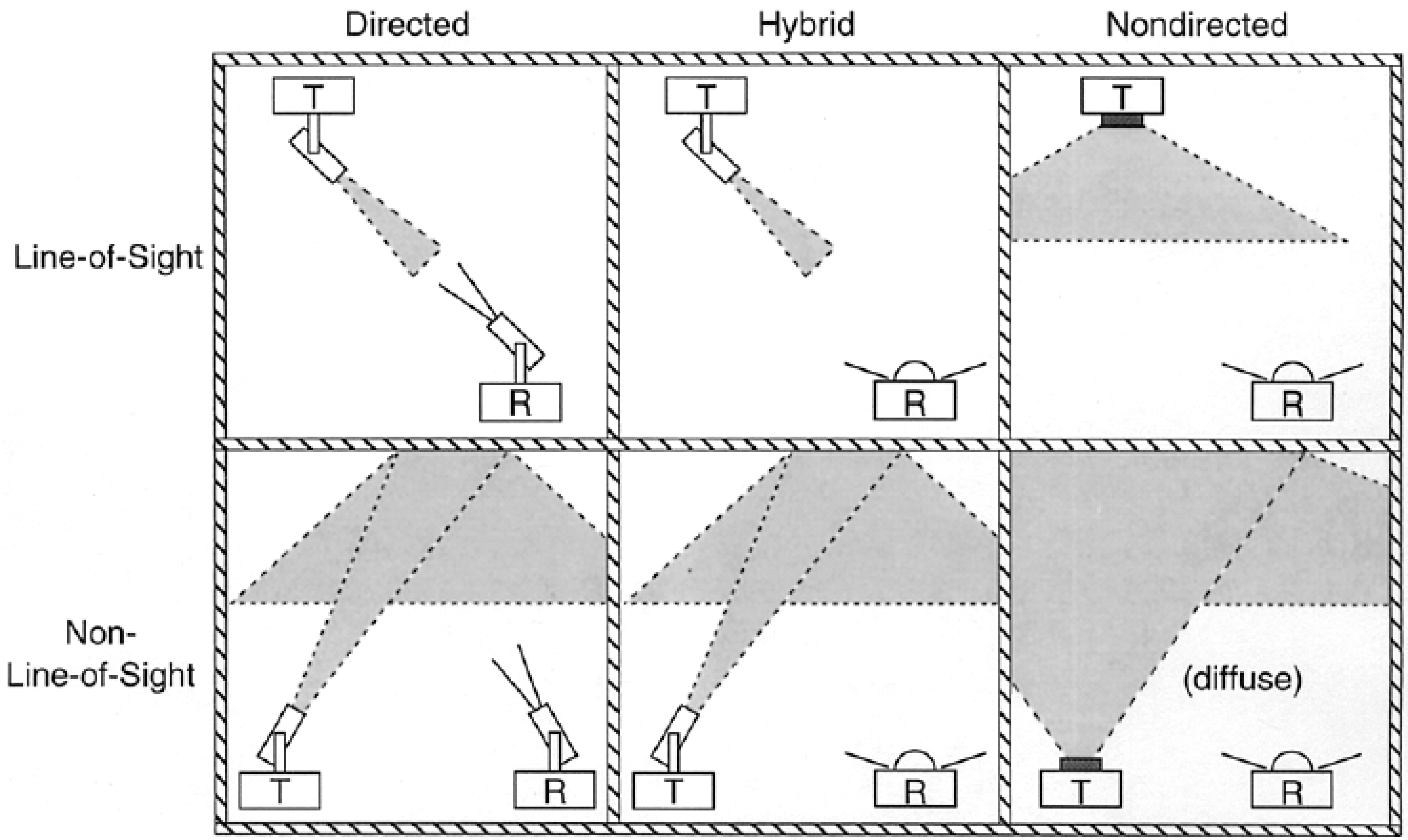


TX-Freespace-RX

N. A. Riza and M. C. DeJule, "A novel programmable liquid crystal lens device for adaptive optical interconnect and beamforming applications," Proceedings International Conference on Optical Computing, Edinburgh, Scotland, 22–25 August 1994.
N. A. Riza and S. Yuan, "Demonstration of a liquid-crystal adaptive alignment tweeker for high-speed infrared band fiber-fed free-space systems," SPIE Optical Engineering Journal , vol. 37, no. 6, pp. 1876-1880, 1998.

A 1997 Classification Study of Infrared (Laser & LED: 850 -1550 nm)

Optical Wireless Links Classified on Degree of Directionality of Transmitter & Receiver and Whether LOS or Non-LOS Diffused Light Link is used



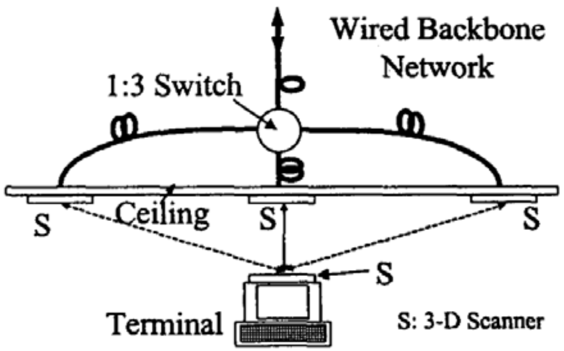
Hybrid Option 1: LOS with Directional Transmitter and Non-Directional Receiver
Hybrid Option 2: Non-LOS with Directional Transmitter and Non-Directional Receiver

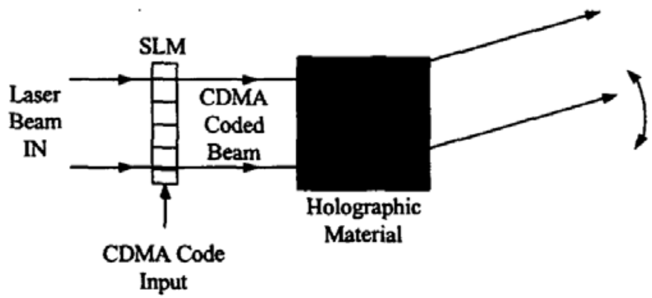
J. Kahn and J. Barry, "Wireless Infrared Communications," Proc. IEEE, vol. 85, pp. 265-298 1997.

1999: A New* Hybrid Indoor Wireless Method

Called Hybrid Diffused-LOS Optical Wireless Method

Uses Spatially Agile LOS Beams via Use of 3-D Optical Scanner In Effect: DFIR+DBIR





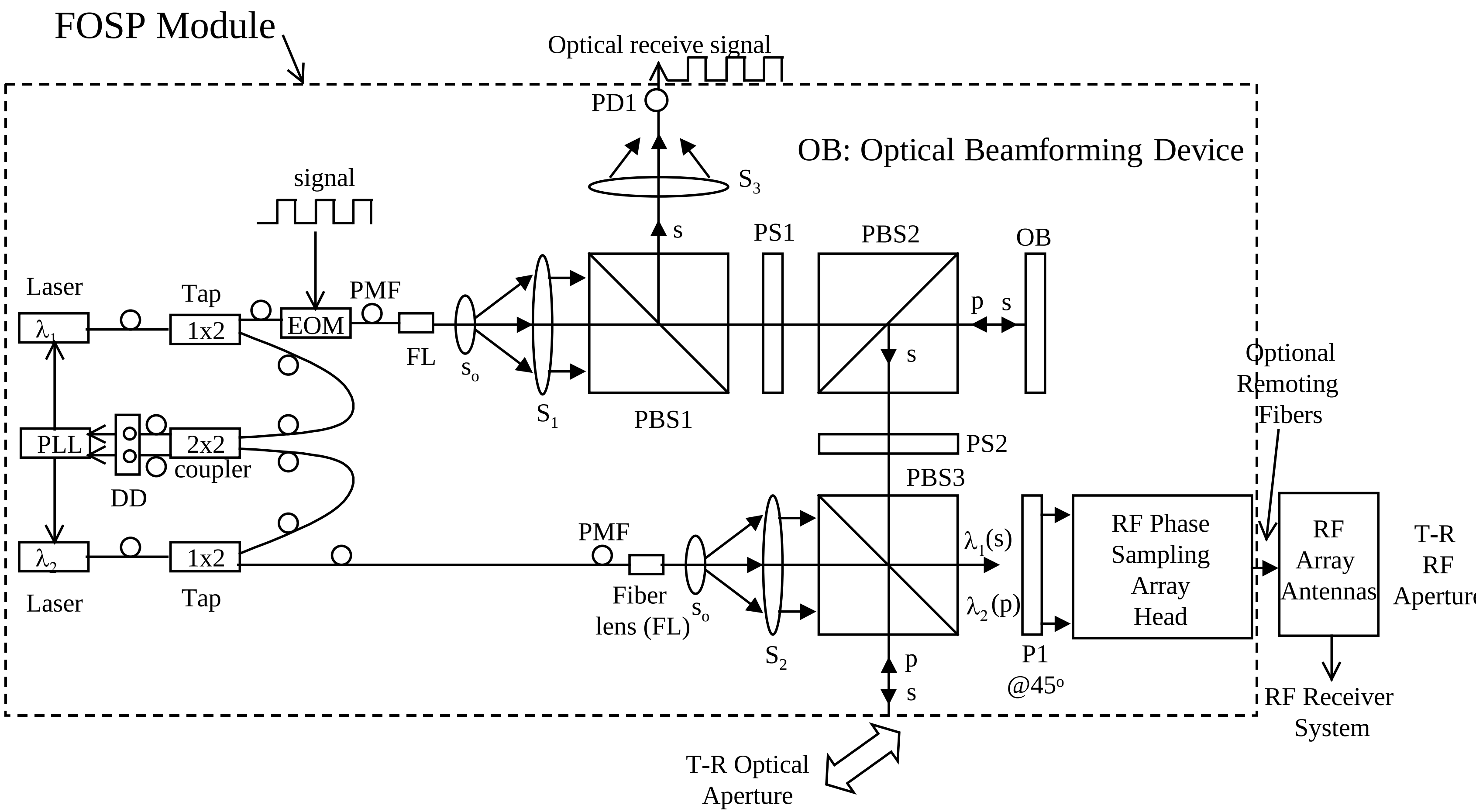
Prevents Beam Blocking and Still Delivers High Data Rate LOS Links by:

- Use of Scanned/Switched LOS Beams from Multiple Transmitters
- Use of 3D Beamforming to Create Multiple Simultaneous LOS Beams – 3-D scan is in 1-D, 2-D, or 3-D spatial directions using a variety of scanning methods

* N. A. Riza technique is Not the Hybrid Classification (Narrow TX & Wide RX) of the Kahn & Barry, IEEE Proc. 1997.

N.A. Riza, "Reconfigurable optical wireless," IEEE *Lasers and Electro- Optics Society 1999 12th Annual Meeting Proc.*, 1999.
N. A. Riza technique called Hybrid Diffused-LOS Method in paper by A. Mahdy and J. S. Deogun, IEEE Wireless Comm. and Networking Conf. 2004.

2001: * A New Flexible Agile Optical-RF Wireless T/R Aperture

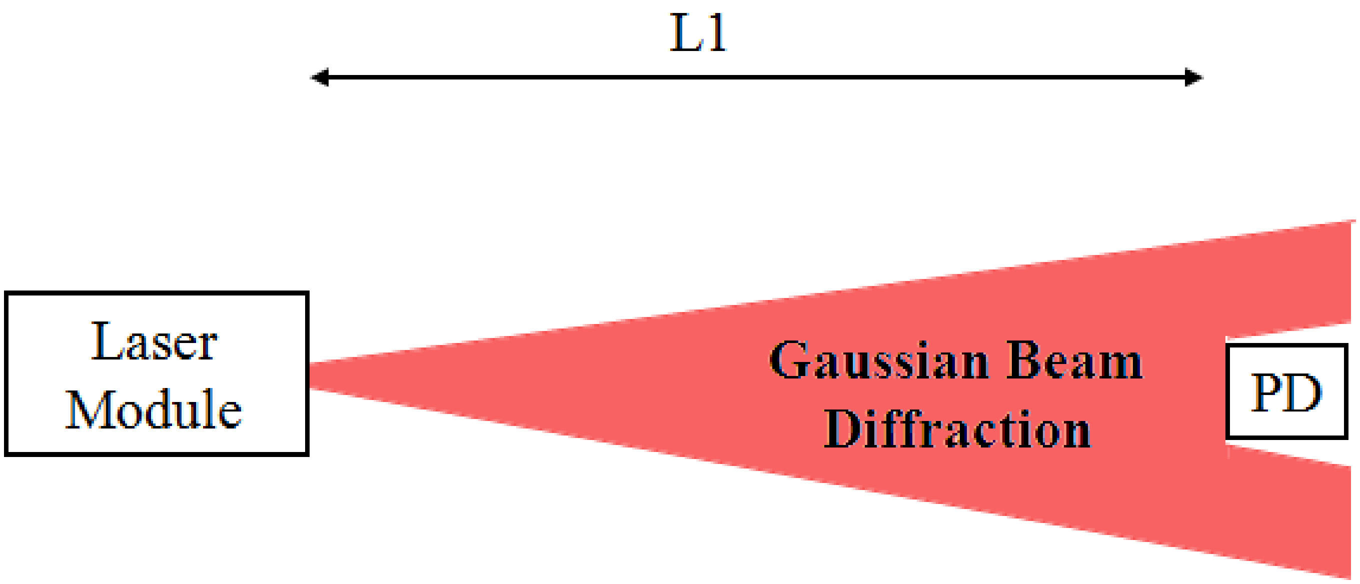


* N.A. Riza, US SBIR Proposal and Award on joint RF-EO Antenna System, 2001.

- N. A. Riza, “ Flexible Agile Hybrid Optical-RF Antenna System for Communications and Radar,” 19th IEEE International Conference on Microwaves, Radar & Wireless Communications, Warsaw, Poland, May 23, 2012.

Non-Smart Laser Optical Wireless Link

Unconditioned Laser Beam

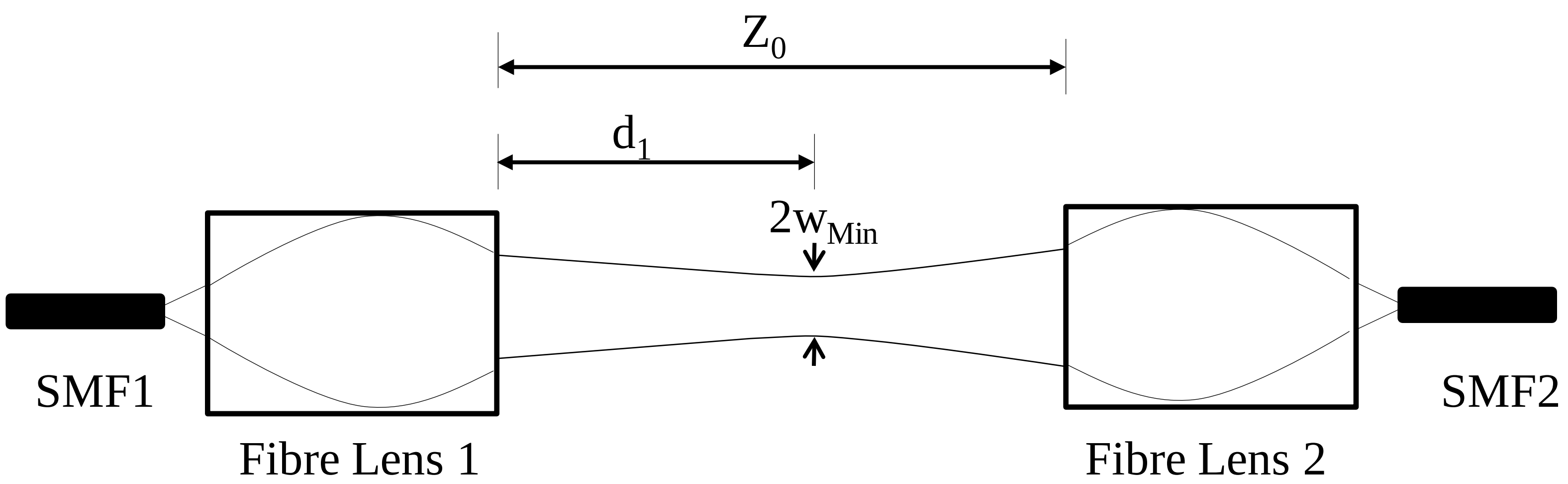


Lots of Optical Power Wasted
& Increasing Loss with Increasing Link Range

2003: The Energy Efficient Short Range (< 13 cm) Optical Wireless Link

Free Space Optical Communications

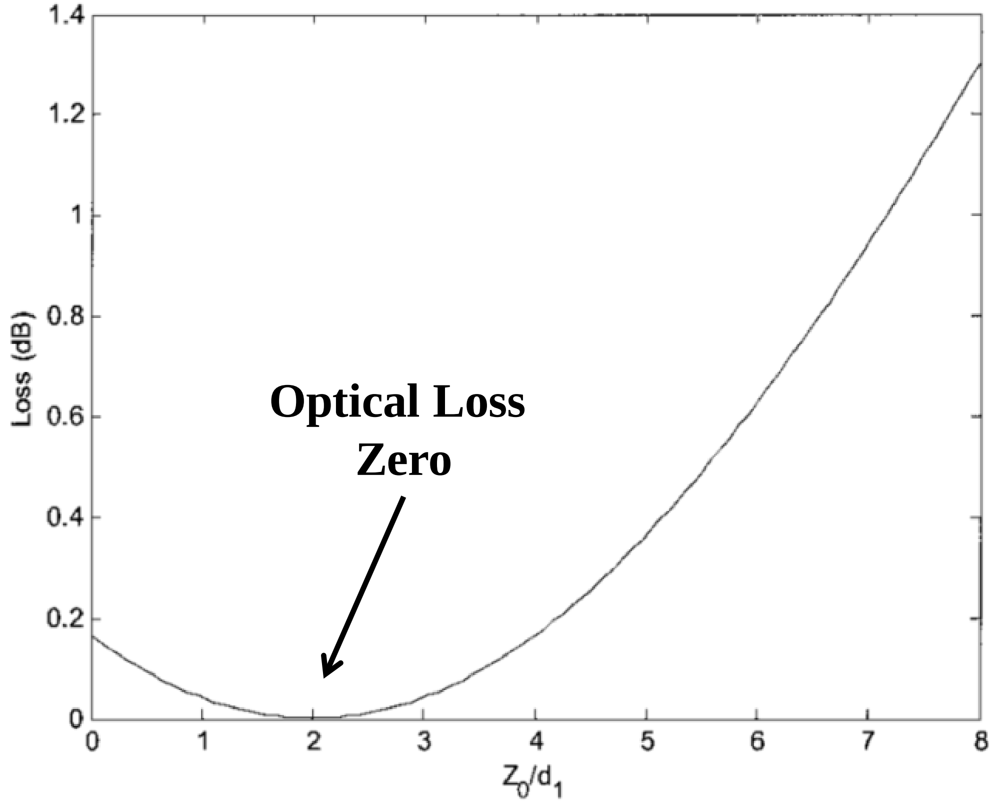
The Problem: Optical Link Loss due to Laser Beam Propagation Increases as Square of Link Distance, Causing Significant Loss – e.g., Reduces Data Rate, Increases Link Cost, Size, Weight.



Demonstrated Zero Link Beam Propagation Loss via Self-Imaging Fiber Lenses For Short Range SMF-Freespace-SMF Link

- M. van Buren and N. A. Riza, " Foundations for low loss fiber gradient-index lens pair coupling with the self-imaging mechanism," Applied Optics, LP, Vo.42, No.3, Jan. 20, 2003.

2003: The Energy Efficient Short Range Optical Wireless Link (<13 cm)



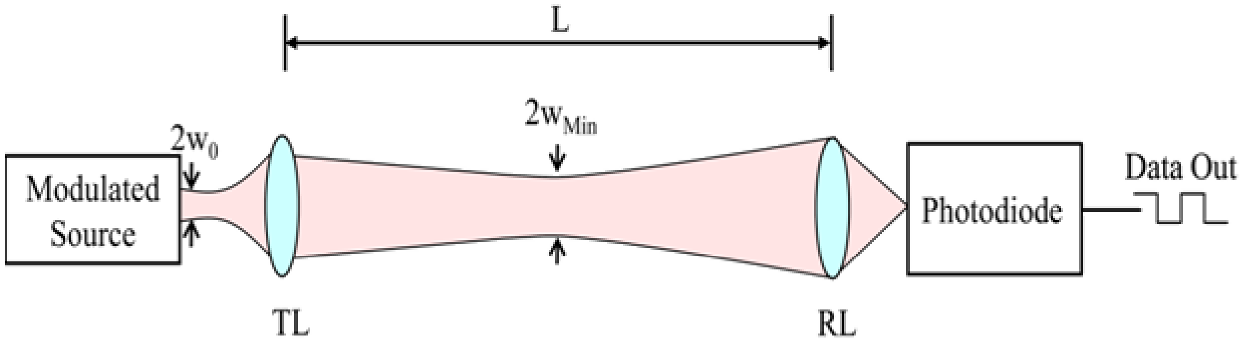
Demonstrated Zero Link Beam Propagation Loss via Self-Imaging Fibre Lenses For Short Range SMF-Freespace-SMF Link

M. van Buren and N. A. Riza, ***Applied Optics*****, vol. 42, pp. 550-565, 2003.**

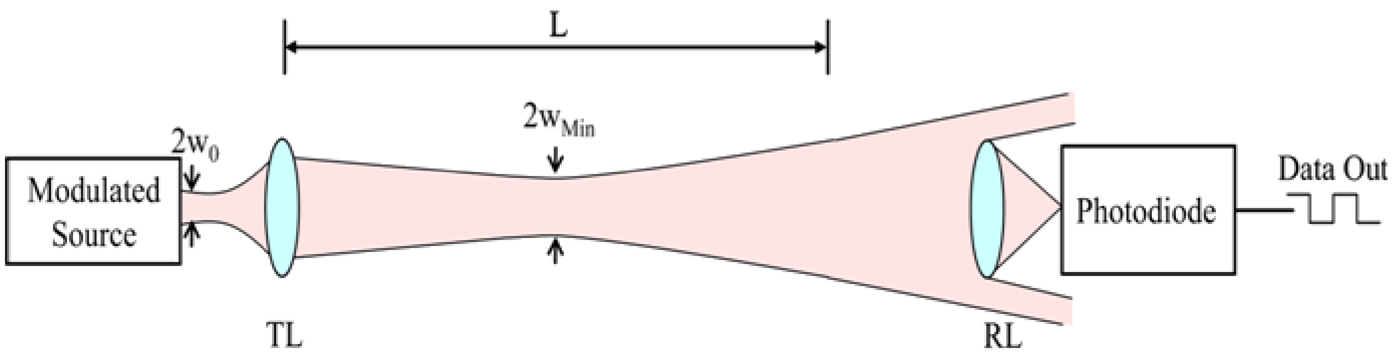
Non-Smart Efficient Link (Fixed Range)

Free Space Optical Communications

In Range
Efficient Link



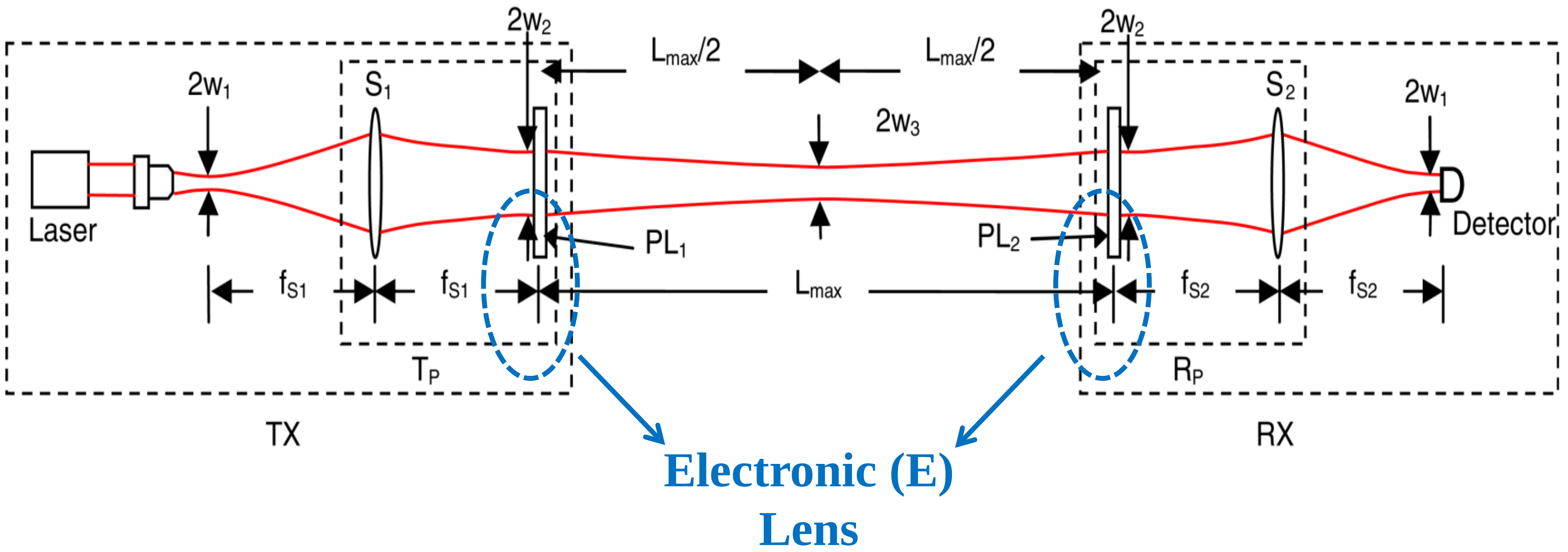
Out of Range
Non-Efficient
Link



Lots of Optical Power Wasted when Not in Range

2006: The Energy Efficient Longer & Variable Range Optical Wireless Link (>13 cm)

Low Loss Laser Communications using E-Lens



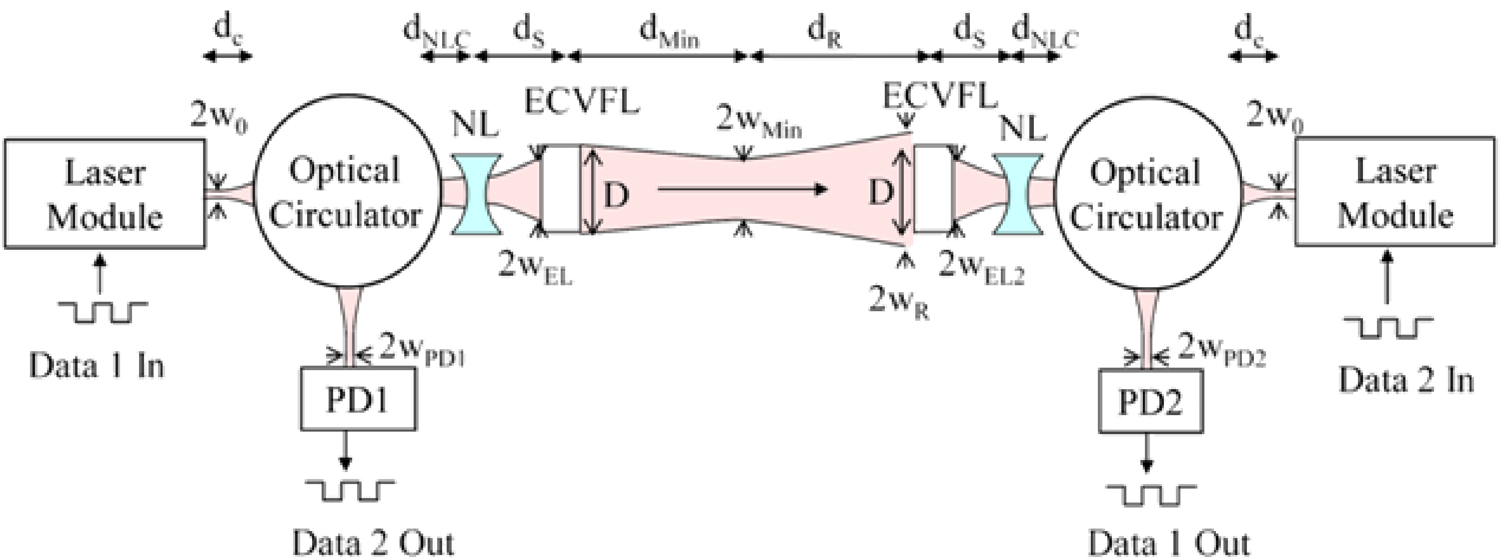
Ability to Adapt for Changing Link Length

Major Reduction in Propagation Loss for Indoor and Space Based Links

N. A. Riza and S. A. Khan, "Ultra-low loss laser communications technique using smart beamforming optics," *Optics Communications*, vol. 257, Issue 2, pp. 225-246, January 2006.

2011: Smart Visible Wireless Laser Link

Common T/R Design
E-Lens Used: Concave to Convex Powers



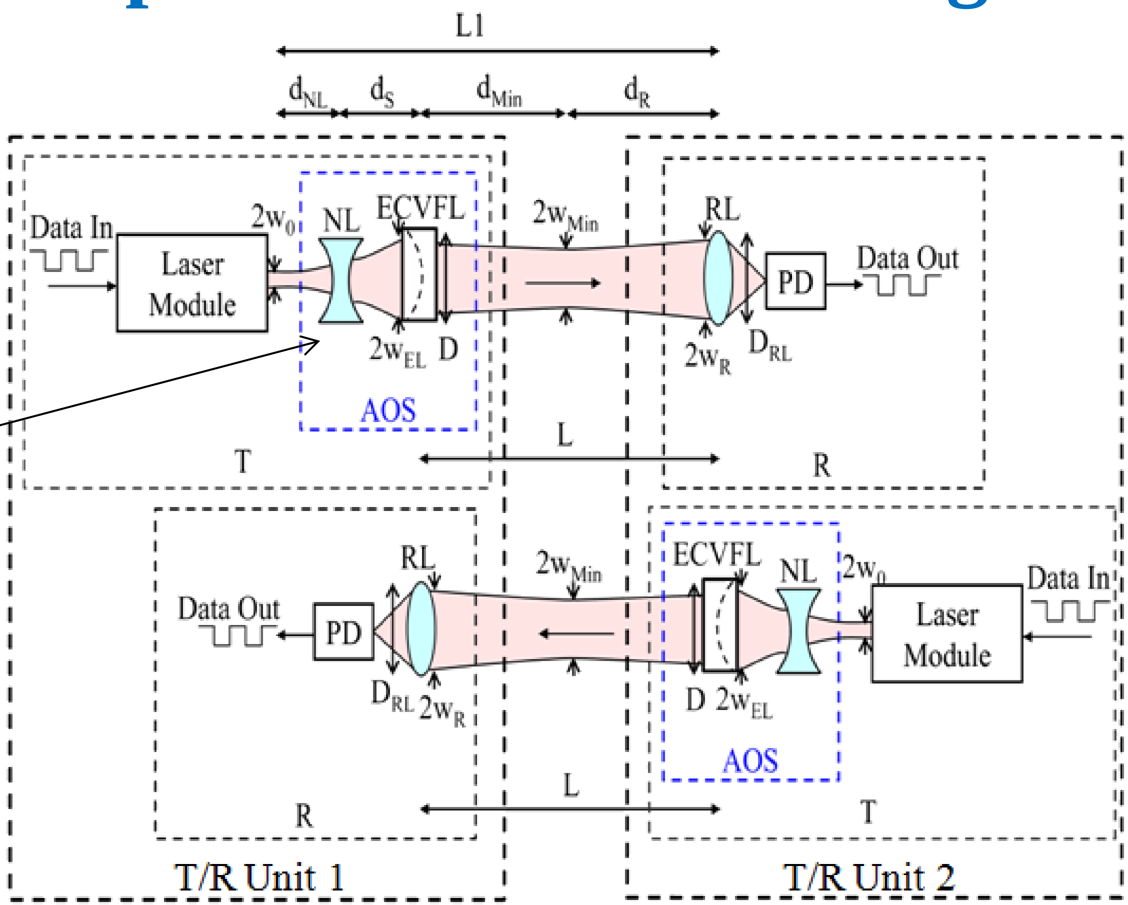
Why Visible: Easier Link Alignment, Low Cost Light Sources.

Smart in Terms of:
Link Alignment, Loss, Data Rate, User Search

P. J. Marraccini and N. A. Riza, "Power Smart In-door Optical Wireless Link Design," *Journal of the European Optical Society: Rapid Publications (JEOS:RP)*, vol. 6, pp. 11054, 2011.

2011: The Smart Visible Wireless Link

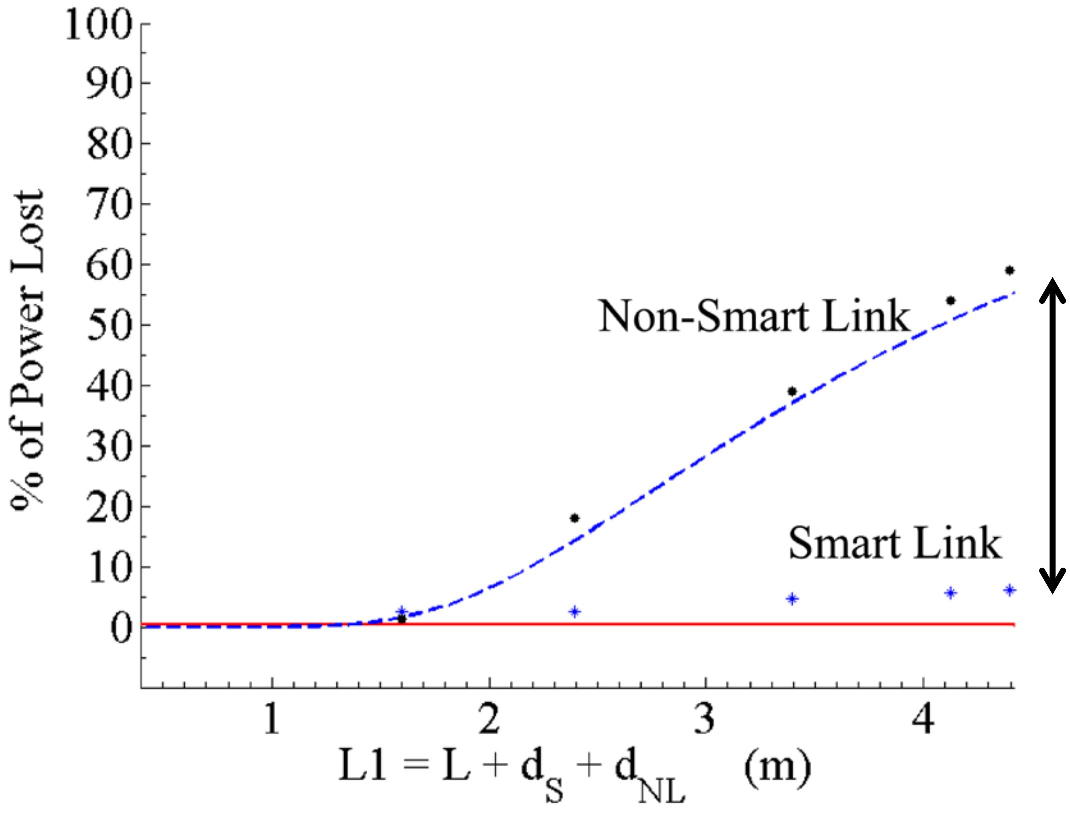
Separated T/R Link Design



Concave Lens (NL) Expands Beam

P. J. Marraccini and N. A. Riza, "Power Smart In-door Optical Wireless Link Design," *Journal of the European Optical Society: Rapid Publications (JEOS:RP)*, vol. 6, pp. 11054, 2011.

2011: Demonstration of Low Loss Visible Smart Link Using a Single Mode Laser



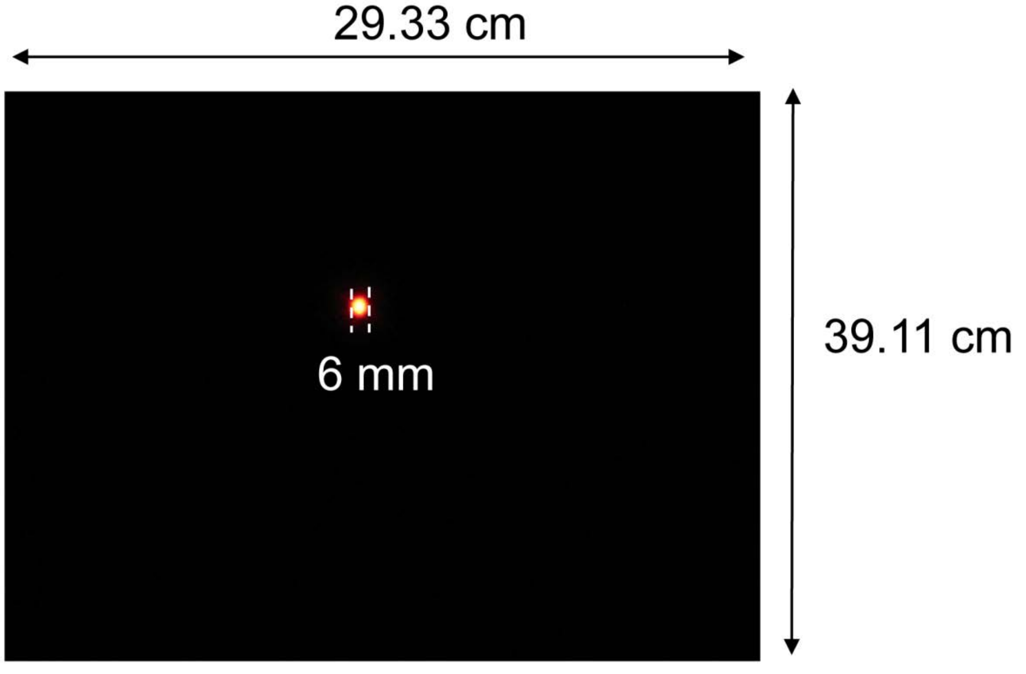
Smart Link
2.3X the Power
<7% Loss Over Entire Range

5.29X SNR Improvement
>1.3×10^6X BER Improvement (Q changes from 3 to 6)

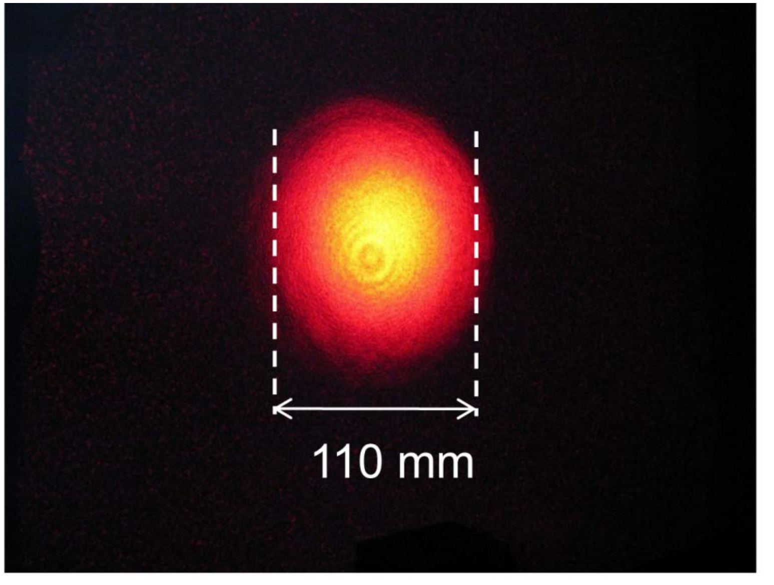
P. J. Marraccini and N. A. Riza, "Power Smart In-door Optical Wireless Link Design," *Journal of the European Optical Society: Rapid Publications (JEOS:RP)*, vol. 6, pp. 11054, 2011.

2011: Visible Single Mode Laser Smart Link in Search Beam Mode

Non-Smart



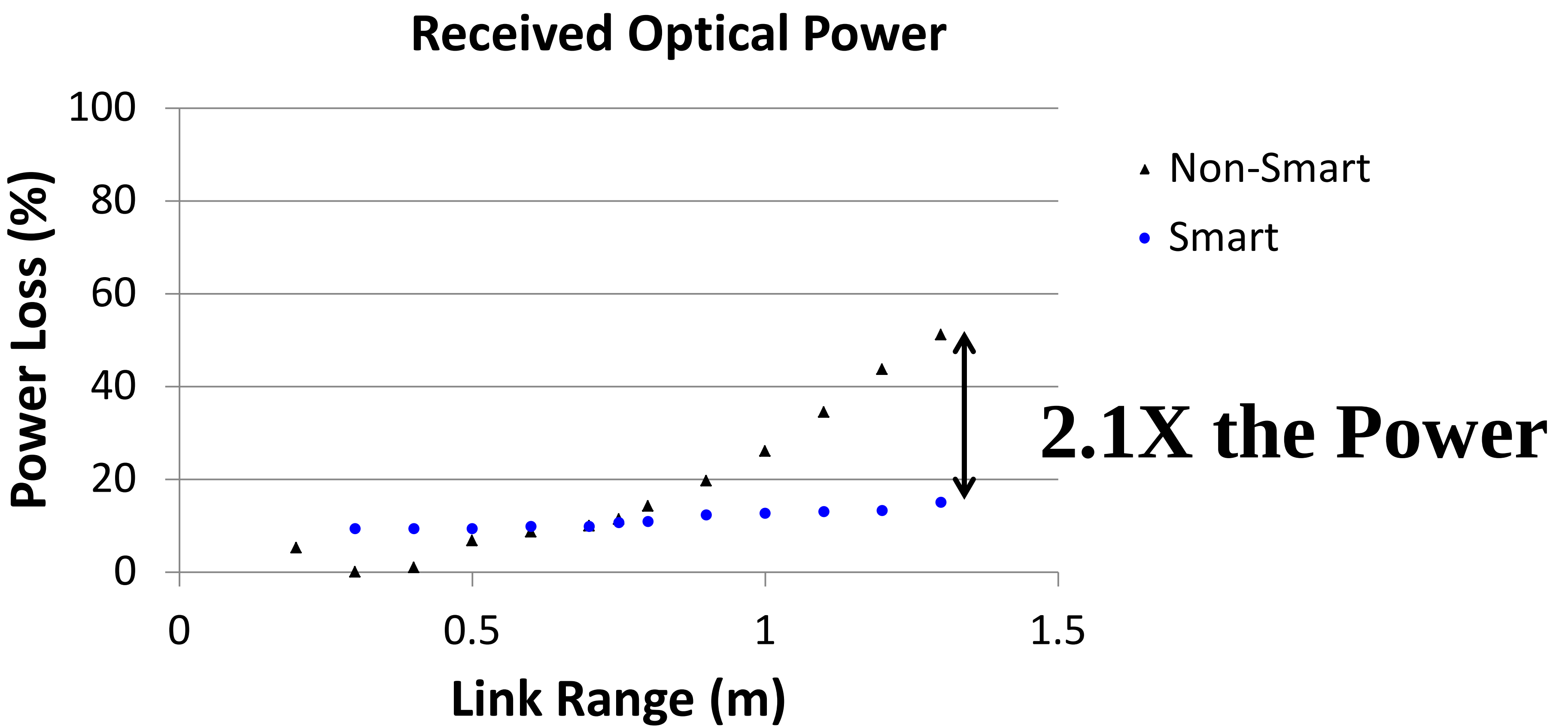
Smart



18 Times Larger!

Visible Multi-Mode Laser Link

50 MHz Laser Link



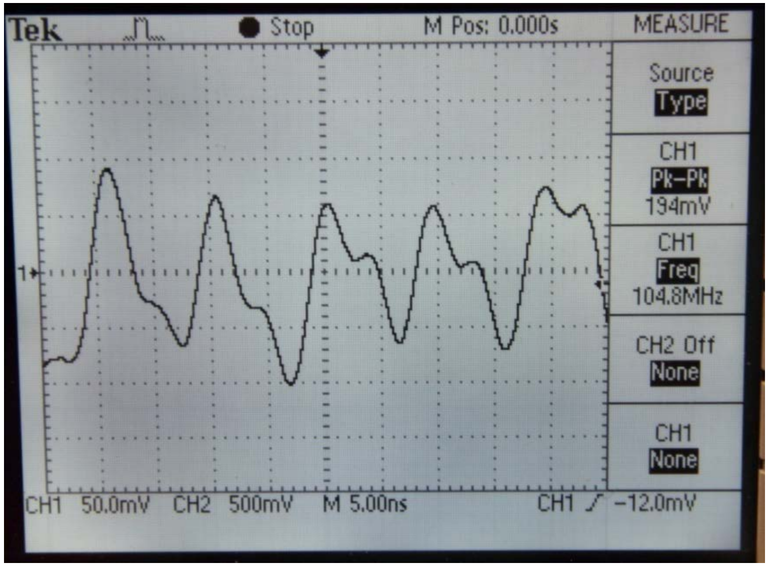
4.41X SNR Improvement

Visible LED Link

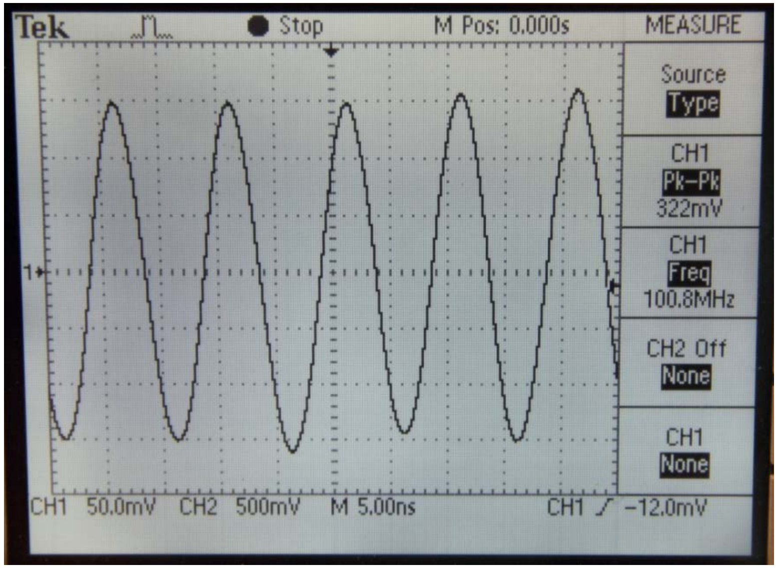
Photo-Detected RF Signals Benefit from Smart Link

Distance of 1.1 m

Non-Smart



Smart



Non-Smart versus Smart
>2X Range Extension for Visible LED Link

Visible LED Link

Camera Beam Profile of Received Beam

Distance of 0.45 m

Non-Smart

Smart

12.6 cm

18.9 cm

18.9 cm

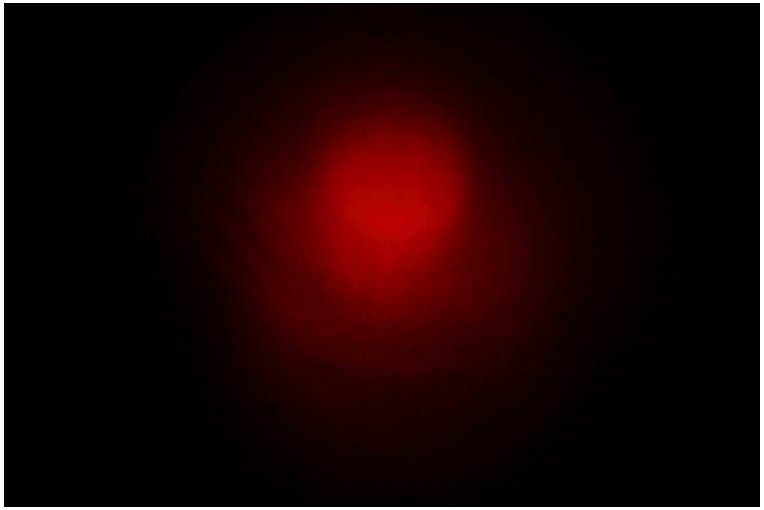
Same Scale and Exposure

Visible LED Link

Camera Beam Profile of Received Beam

Distance of 2.5 m

Non-Smart | **Smart**



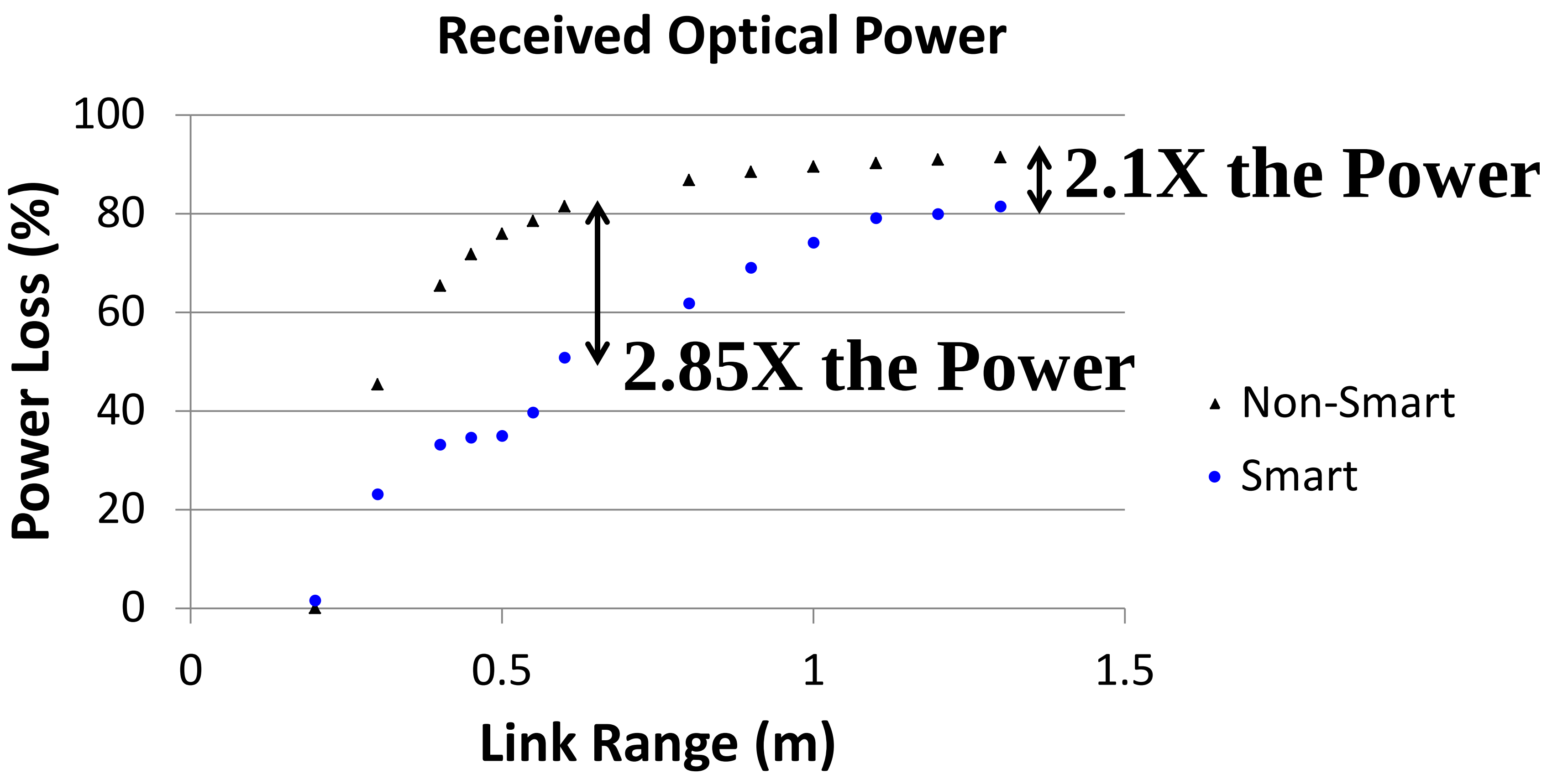
49 cm

73.5 cm | 73.5 cm

Same Scale and Exposure

Visible LED Link

100 MHz LED Link



>4.41X SNR Improvement

2012: Proposed Dual Mode Smart Link

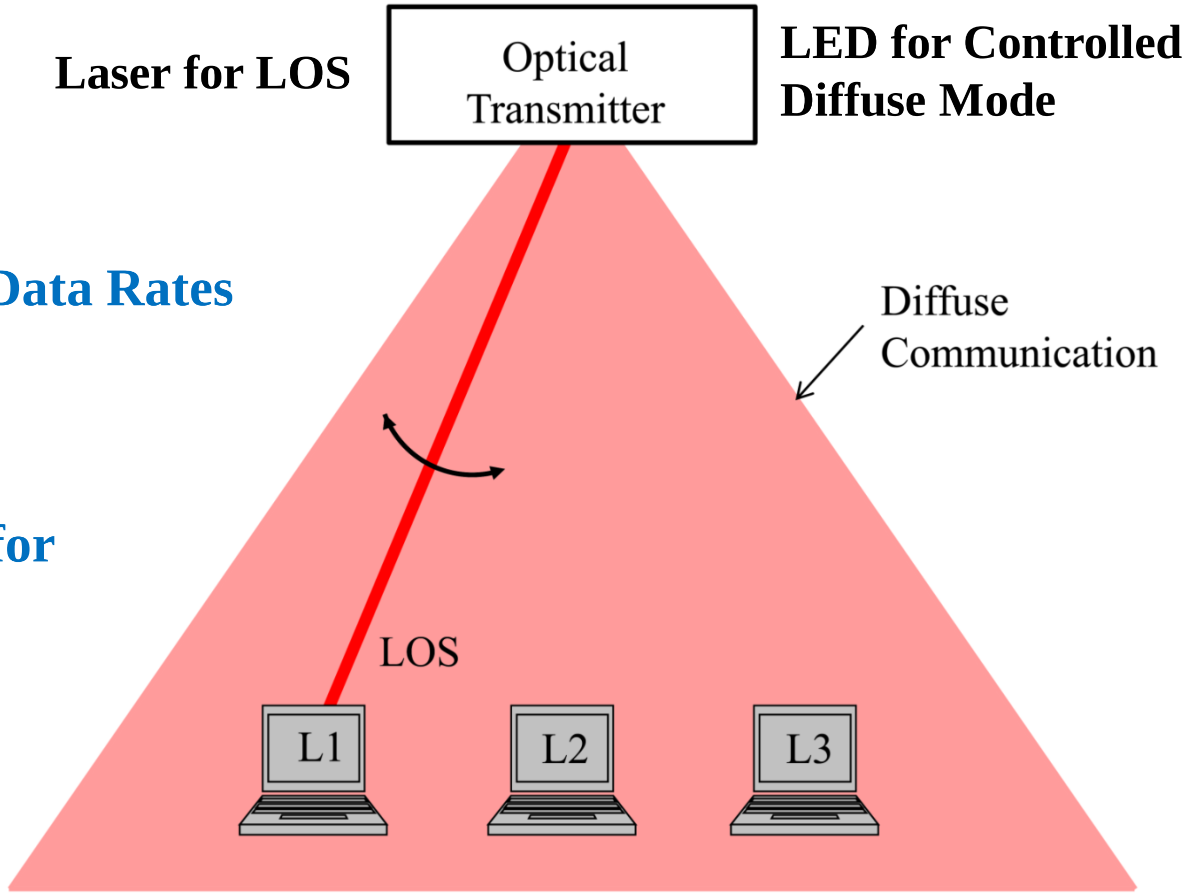
Motivation

LOS	Diffuse
• High Data Rates	•Low Data Rates (Due to Multipath Effects)
• Highly Prone to Physical Blocking	•Robust to Physical Blocking
•Poor Use of Limited Light Energy (Non-Smart)	•Poor Use of Limited Light Energy (Non-Smart)

Want to Achieve Fast Data Rates, Robustness to Physical Blocking, and Energy Efficiency

2012: Proposed Smart Visible Dual Mode Link

Combining Smart LOS and Smart Diffuse Optical Wireless



Laser Smart LOS for High Data Rates

and

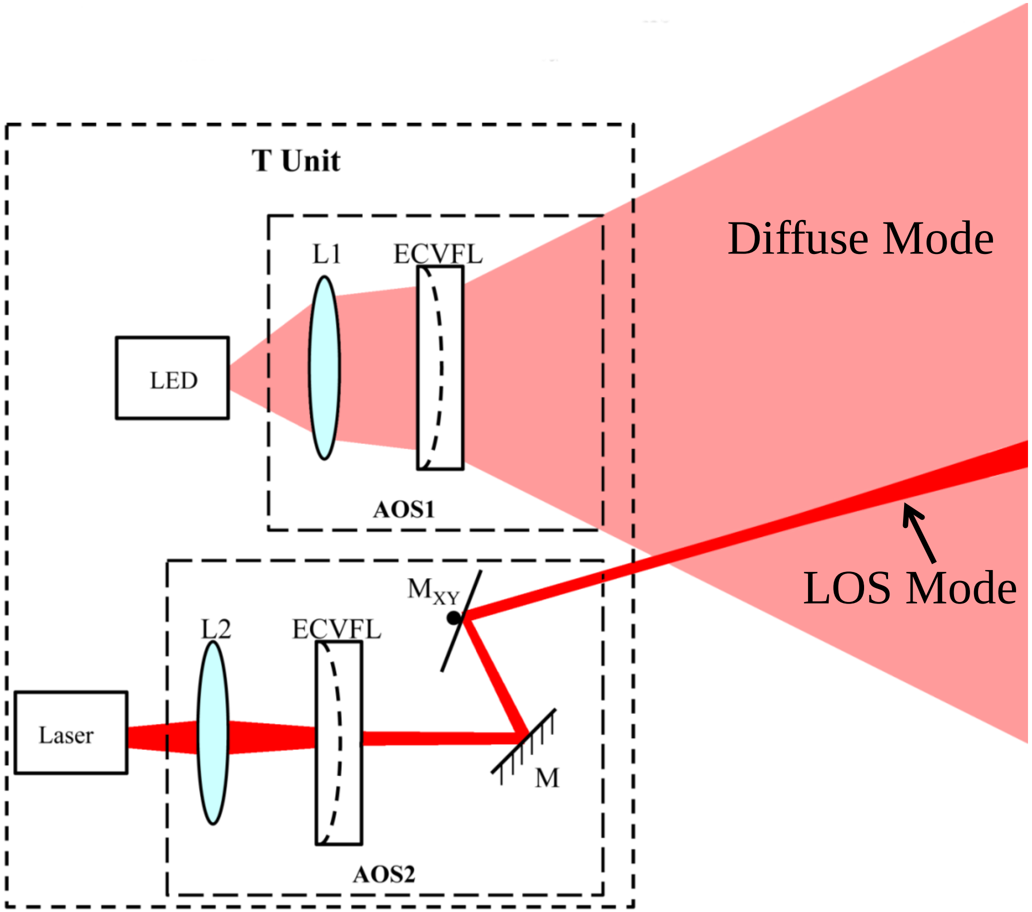
LED Smart Diffused Mode for Robustness to Blocking

Switch between Laser & LED   Or USE Both Sources

N. A. Riza and P. J. Marraccini, " Power Smart In-door Optical Wireless Link Applications," 8th IEEE International Wireless Communications and Mobile Computing Conference (IWCMC), Limassol, Cypress, August 27-31, 2012.

Visible Dual Mode Smart Link

Ùsing 3D Optical Beam Forming



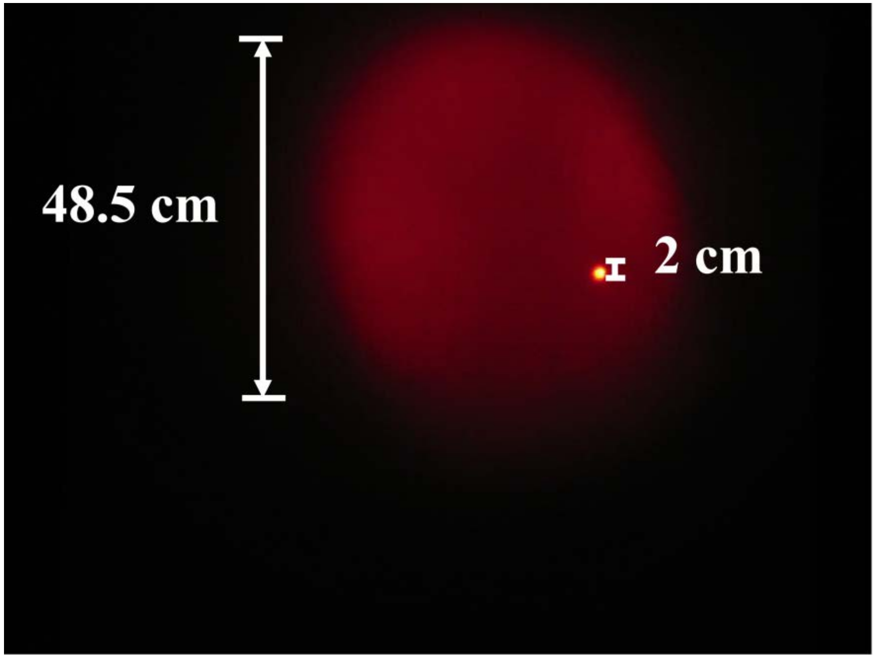
High Data Rates, Robust to Blocking, <u>and Energy Efficient</u>

P. J. Marraccini and N. A. Riza, "Dual Mode Indoor Optical Wireless Data Link Design using Micro-Optics For Robust Energy Efficient Operations," European Optical Society (EOS) Annual Meeting Proc., Aberdeen, 2012.

Visible Dual Mode Non-Smart Link

LED and Single Mode Laser Operation Experiment

Distance of 3.35 m



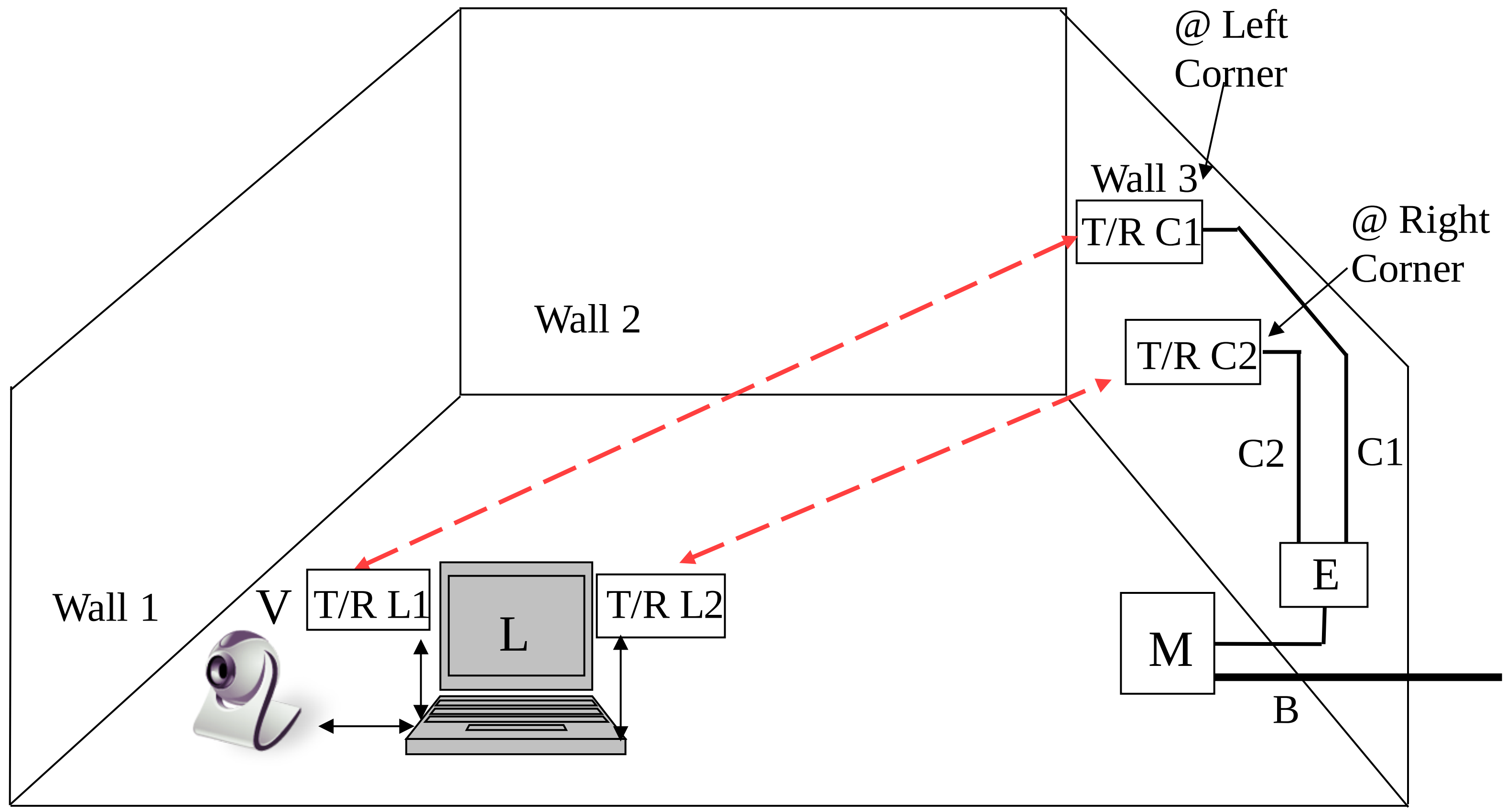
~ Half a Meter Diameter LED Beam at 3.35 m Range
LED Beam Coverage >> Laser LOS Coverage
Received LED Beam Power/Area << Received Laser Beam Power/Area

Solved Coverage versus Received Power Problem.

Applications for the Indoor Smart Optical Wireless Links

N. A. Riza and P. J. Marraccini, " Power Smart In-door Optical Wireless Link Applications," 8th IEEE International Wireless Communications and Mobile Computing Conference (IWCMC), Limassol, Cypress, August 27-31, 2012.

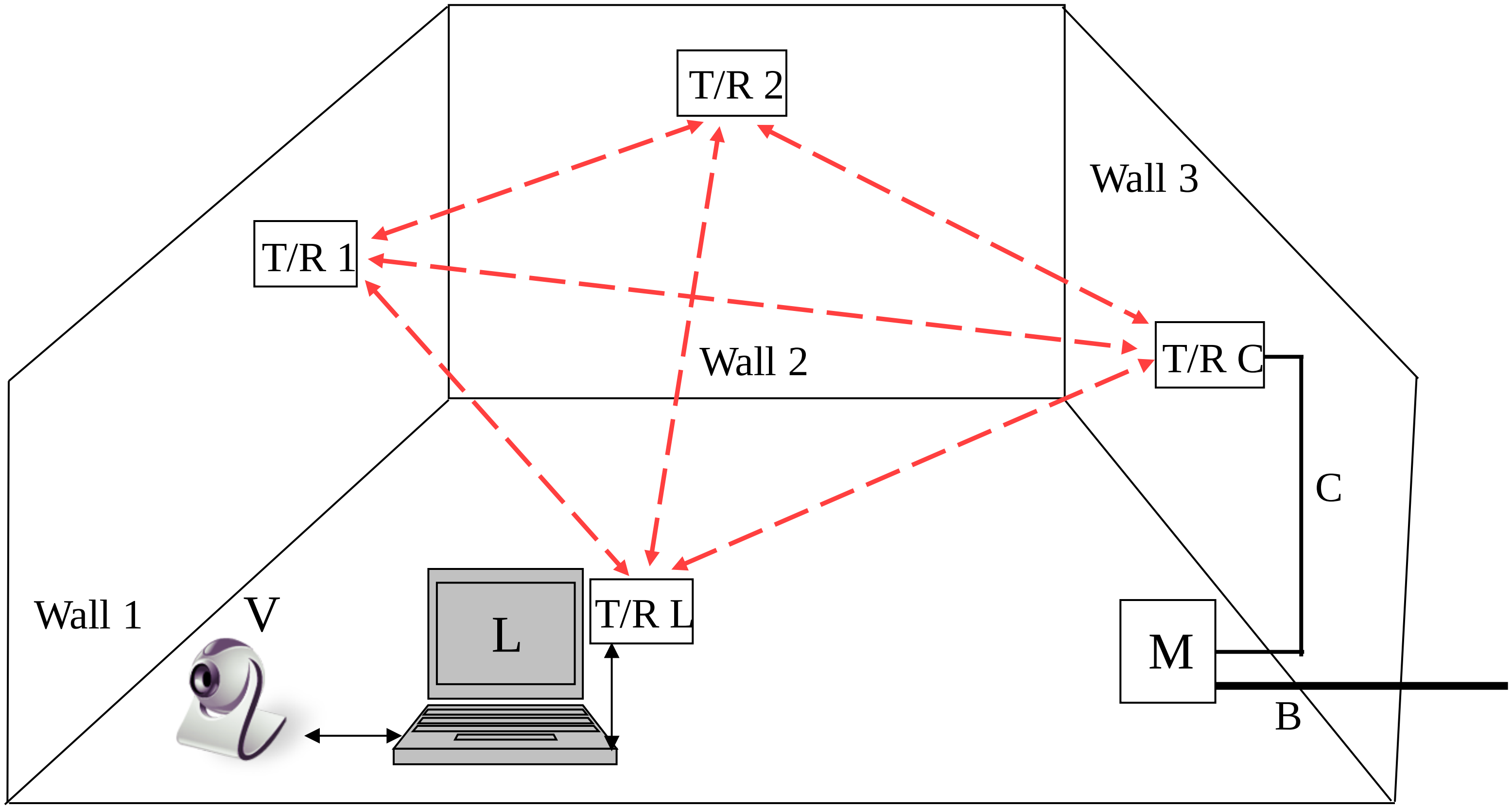
Indoor Non-Blocking Scenario



Simultaneous Beams

N. A. Riza and P. J. Marraccini, " Power Smart In-door Optical Wireless Link Applications," 8th IEEE International Wireless Communications and Mobile Computing Conference (IWCMC), Limassol, Cypress, August 27-31, 2012.

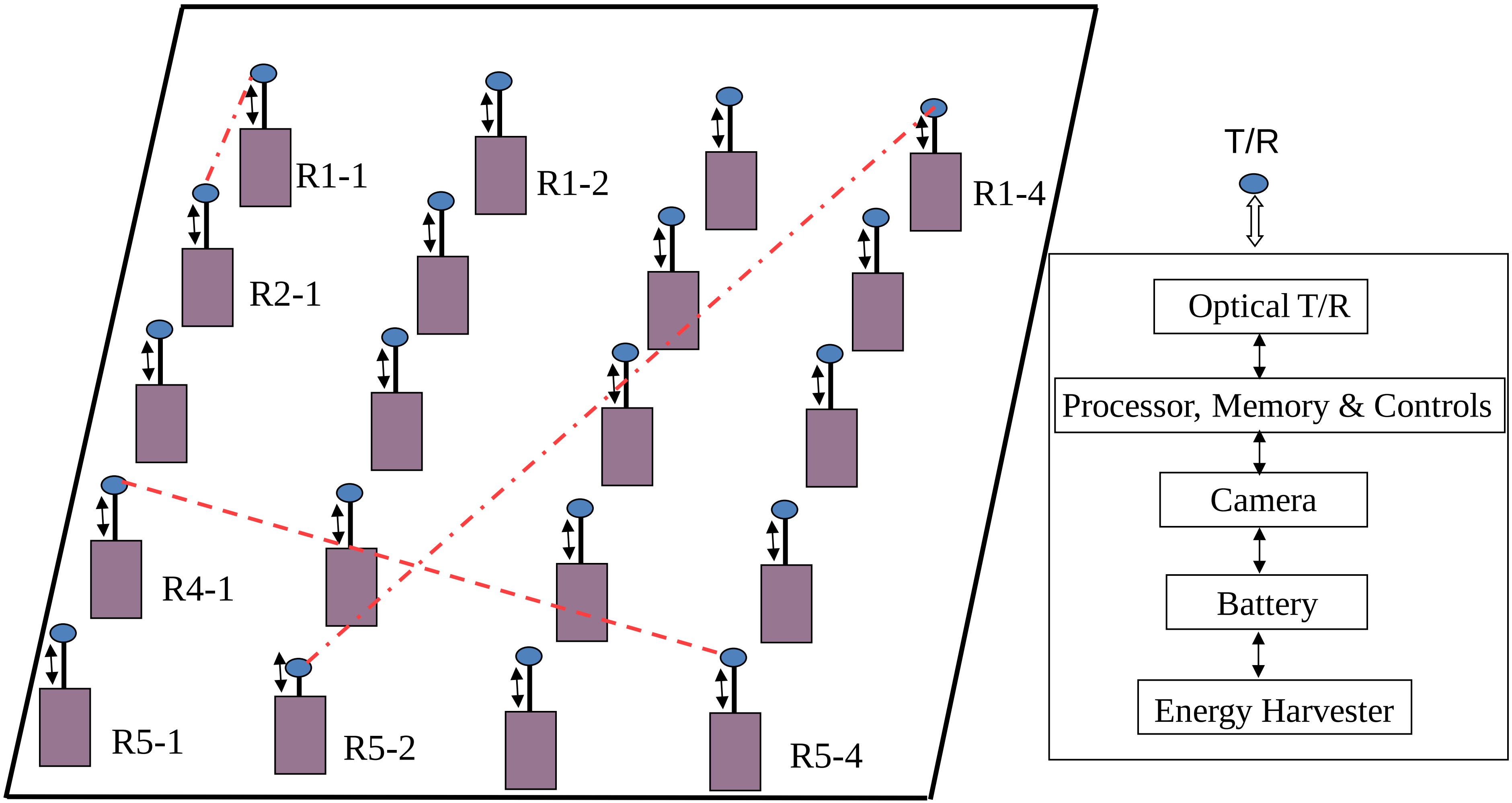
Indoor Non-Blocking Scenario



Relaying via Multiple T/R Units

N. A. Riza and P. J. Marraccini, “ Power Smart In-door Optical Wireless Link Applications,” 8th IEEE International Wireless Communications and Mobile Computing Conference (IWCMC), Limassol, Cypress, August 27-31, 2012.

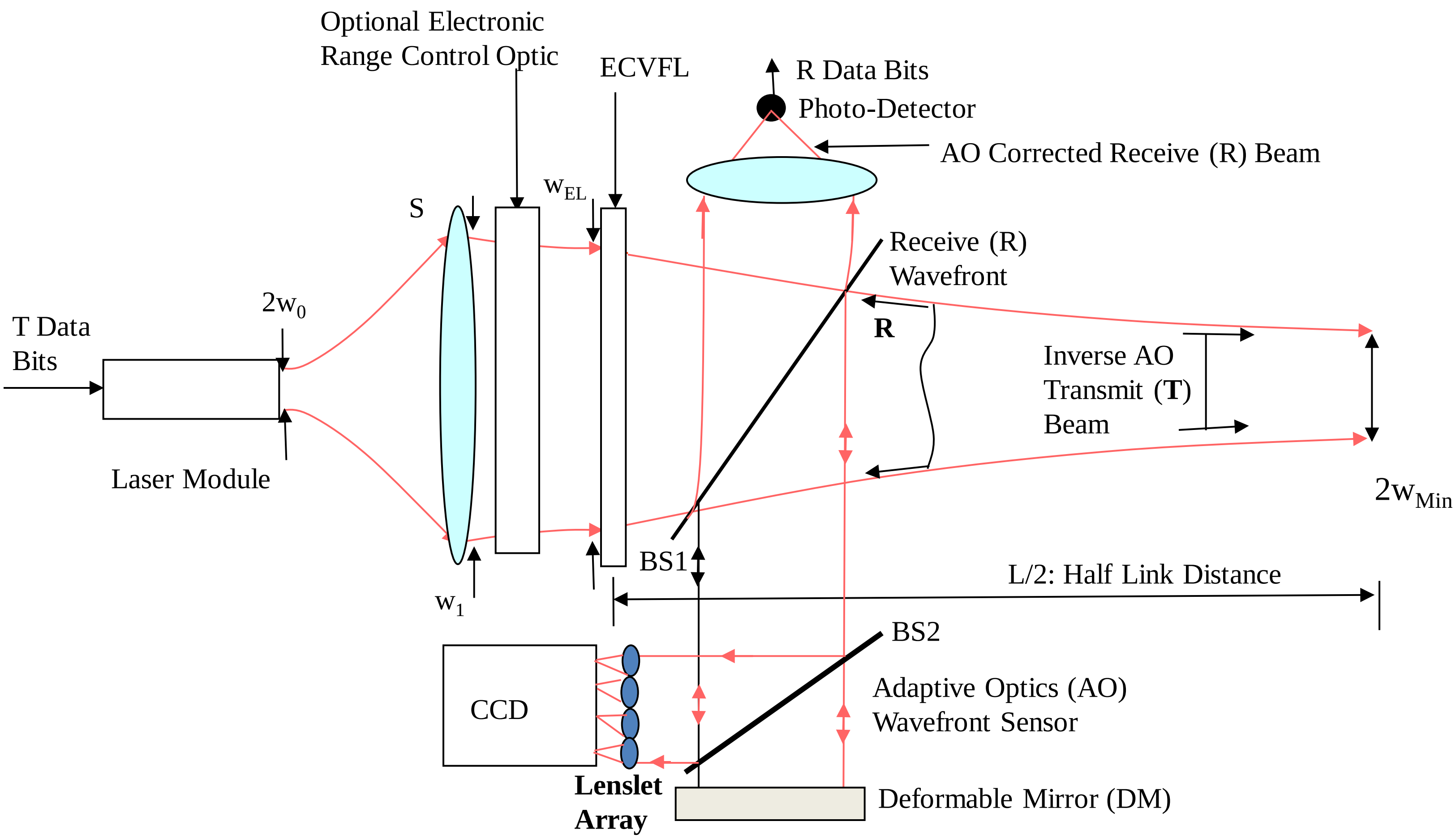
Indoor Applications



Server Room

N. A. Riza and P. J. Marraccini, " Power Smart In-door Optical Wireless Link Applications," 8th IEEE International Wireless Communications and Mobile Computing Conference (IWCMC), Limassol, Cypress, August 27-31, 2012.

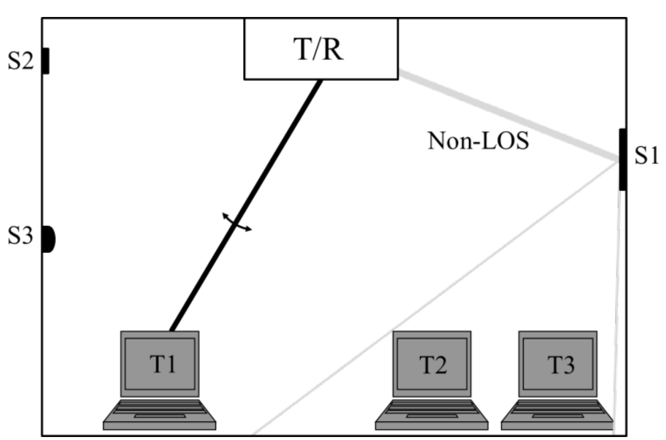
Outdoor Smart Optical Wireless System



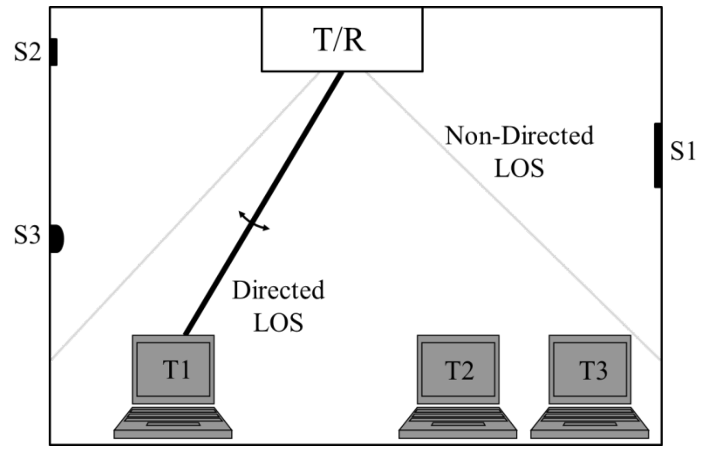
N. A. Riza, "Enabling the Ultimate in Optical Wireless Communications: The Zero Propagation Loss Design," IEEE Communications Society 3rd Int. Symp. on High Capacity Optical Networks and Enabling Technologies (HORNET) 2006 Conference, Charlotte, USA, Sept. 6-8, 2006.

N. A. Riza and P. J. Marraccini, " Power Smart In-door Optical Wireless Link Applications," 8th IEEE International Wireless Communications and Mobile Computing Conference (IWCMC), Limassol, Cypress, August 27-31, 2012.

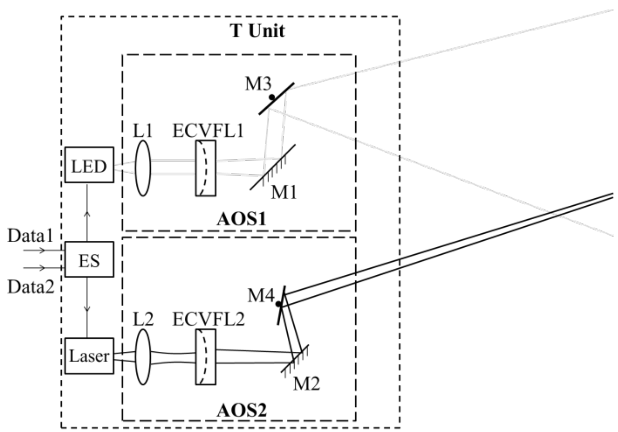
Smart Indoor Optical Wireless System



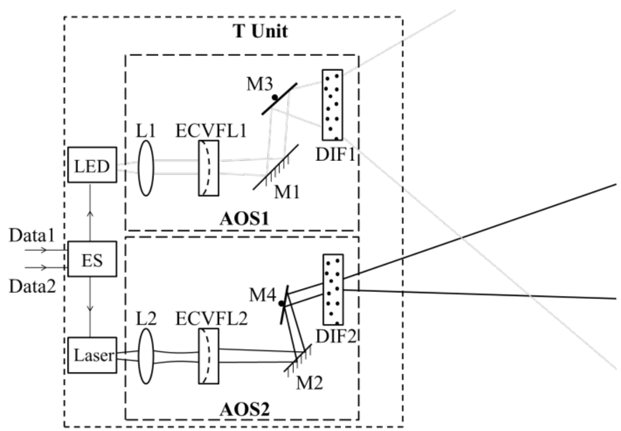
(a)



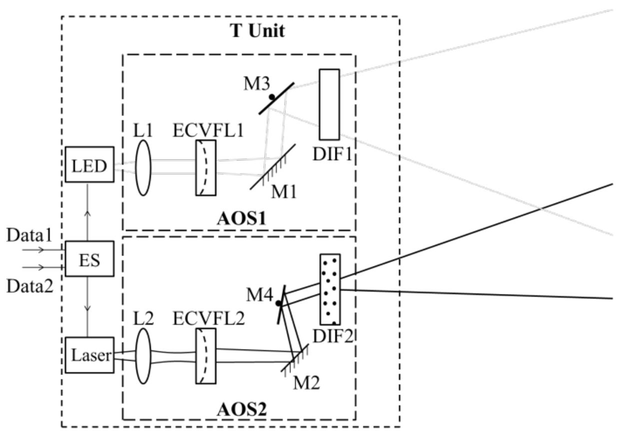
(b)



(c)



(d)

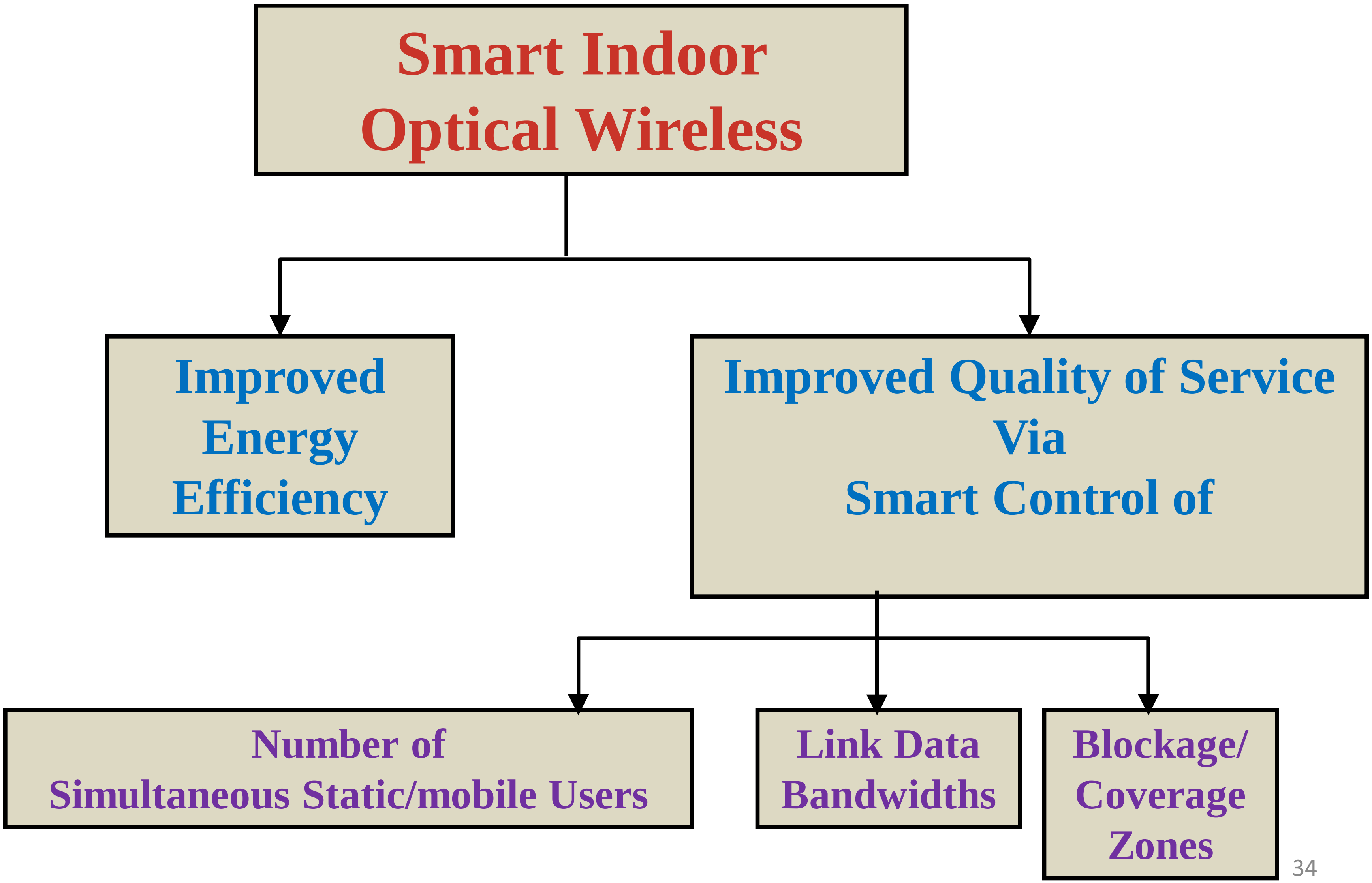


(e)

Shown is the proposed smart multi-mode indoor optical wireless approach. Wireless operations are shown using (a) non-LOS diffuse mode and directed LOS mode and (b) directed LOS mode and non-directed LOS mode. (c) A dual-mode transmitter design is shown using a laser, LED, ECVFLs and scan mirrors. (d) and (e) show advanced dual-mode transmitter designs using electronic diffusers. In (d), both electronic diffusers are on and diffuse the light while in (e) only DIF2 is on and diffusing light.

P. J. Marraccini and N. A. Riza, "Smart multiple-mode indoor optical wireless design and multimode light source smart energy-efficient links," SPIE Optical Engineering Journal, Vol.52, 5, May 2013.

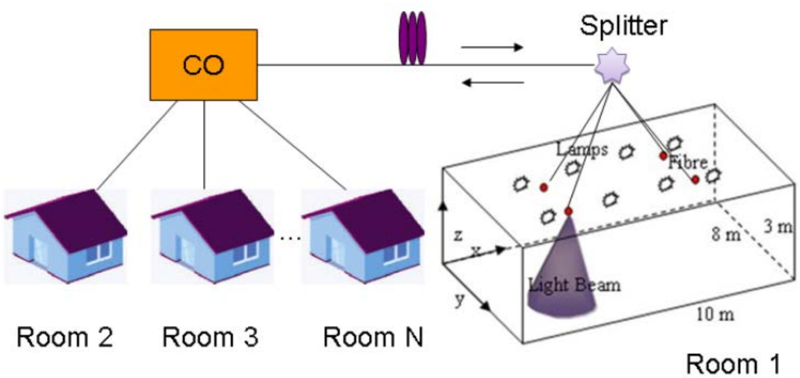
Summary of Smart Indoor Optical Wireless

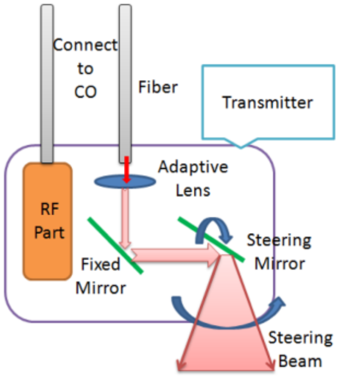


2010: Recent Similar Work in the Context of 1999 Riza Works

Prof. Skafidas Group, Univ. Melbourne, Australia

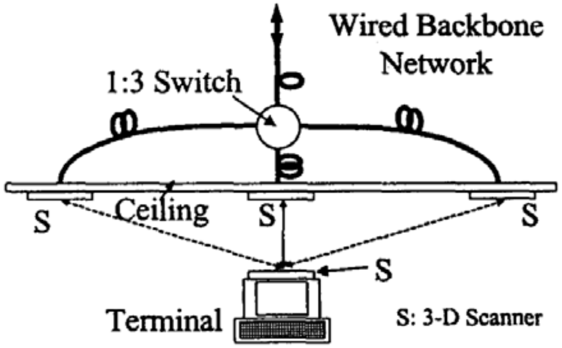
E-Lens for Constant Coverage Area by Using Spatially Agile LOS Beams (2010)[1]

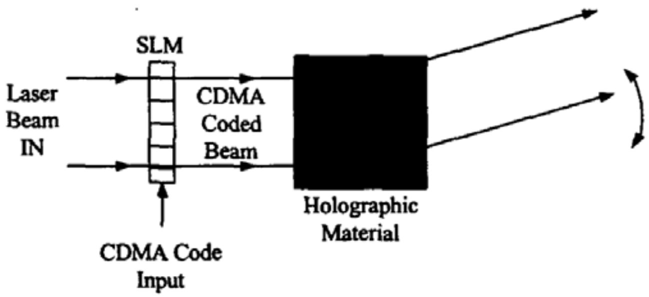




Reconfigurable Optical Wireless[2] Proposed by N. A. Riza (1999)

- **Use of Scanned/Switched LOS Beams from Multiple Transmitters**
- **Use of 3D Beamforming to Create Multiple Simultaneous LOS Beams**





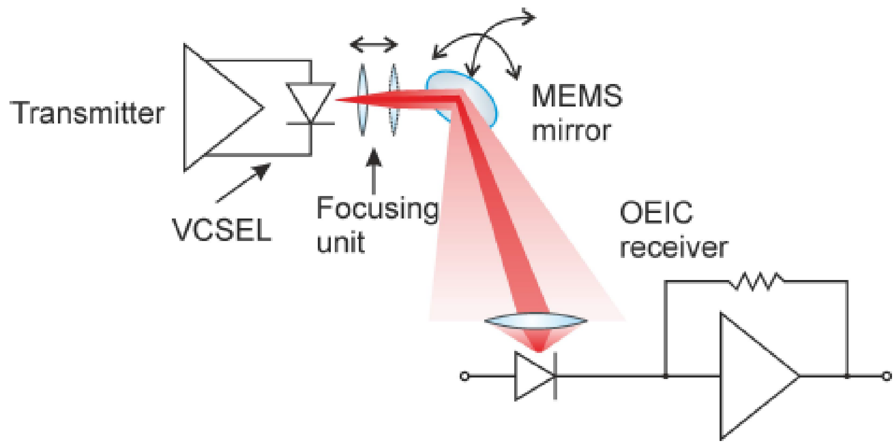
[1]K. Wang, A. Nirmalathas, C. Lim, and E. Skafida, "Indoor Gigabit Optical Wireless Communication System for Personal Area Networks," *23rd Annual Meeting of the IEEE Photonics Society*, Denver, 2010.

[2]N.A. Riza, "Reconfigurable optical wireless," *IEEE Lasers and Electro- Optics Society 12th Annual Meeting Proc.*, 1999.

2013: Recent Similar Work in the Context of 1999 Riza Works

Prof. Zimmermann Group, TU Vienna, Austria

Adaptive-Lens and 2-D scan MEMS mirror for a Spatially Agile LOS Beam (2013)[1]



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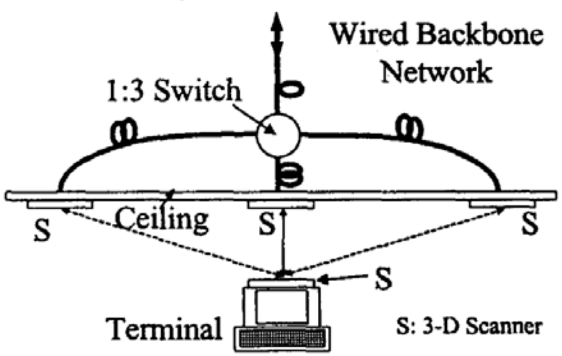
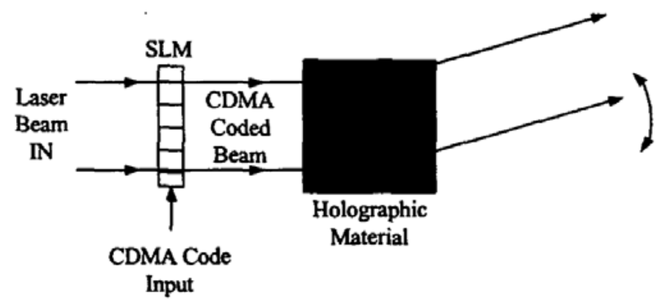
- **Use of Scanned/Switched LOS Beams from Multiple Transmitters**
- **Use of 3D Beamforming to Create Multiple Simultaneous LOS Beams**





[1] P. Brandl, S. Schidl, A. Polzer, W. Gaberl, & H. Zimmermann, "Optical wireless communication with adaptive focus and MEMS-based beam steering," IEEE Photonics Technology Letters, 25(15), 1428-1431, 2013.

[2] N.A. Riza, "Reconfigurable optical wireless," *IEEE Lasers and Electro- Optics Society 12th Annual Meeting Proc.*, 1999.

2014: Recent Similar Work in the Context of 1999 Riza Works

Prof. Koonen Group,
TU Eindhoven, Netherlands

Scanning of LOS Multiple Beams using Wavelength Tuning (2014)[1]

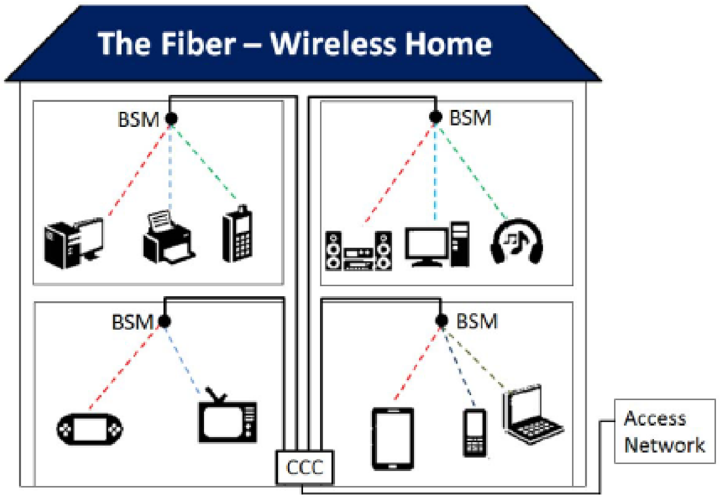
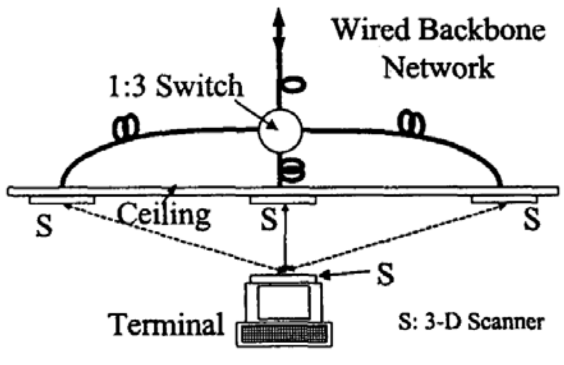
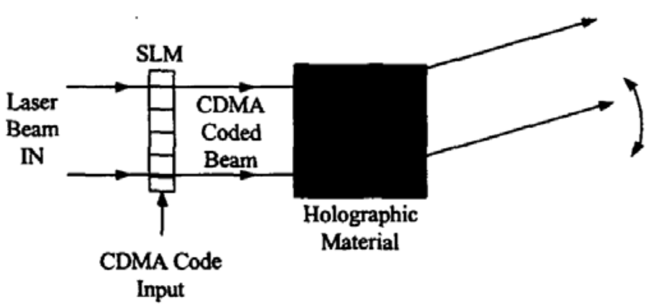


Fig. 1. Fiber-wireless-equipped home with beam-steering modules (BSM) at the access points and a central communication controller (CCC).

Reconfigurable Optical Wireless[2] Proposed by N. A. Riza (1999)

- **Use of Scanned/Switched LOS Beams from Multiple Transmitters**
- **Use of 3D Beamforming to Create Multiple Simultaneous LOS Beams**





S: Can be a W-MOS-Wavelength multiplexed optical scanner with 1-D, 2-D, & 3-D scan capabilities [2] .

[1] C. Oh, E. Tangdiongga, A. Koonen, "Steerable pencil beams for multi-Gbps indoor optical wireless communication," Optics Letters, 2014 and T. Koonen, et.al., "Reconfigurable free-space optical indoor network using multiple pencil beam steering," Proc. 19th OECC/ Proc. 39th ACOFT, 2014.

[2] N.A. Riza, "Reconfigurable optical wireless," *IEEE Lasers and Electro- Optics Society 12th Annual Meeting Proc.*, 1999.

First Works on Optical Wireless for Data Centers Cited in Table*

TABLE III: Summary of Major Wireless DCN Research Directions.

Wireless Technology	Highlights	Reference	Year	Simulation	Physical Topology	Logical Topology	Challenges
RF	First proposal of a wireless DCN in general, and using 60 GHz RF links in particular.	Ramachandran et al. [42]	2008	✗	NA	NA	NA
Hybrid RF	Motivate using Flyways, on-demand additional links (wired or wireless), added to provide additional capacity.	Kandula et al. [7]	2009	✓	Rows	Tree	• Topology-independent model (a module can communicate with any module within its range.) • Non-configurable links with fixed capacity.
Pure RF	A preliminary study to propose the idea of emulation well-known existing topologies, such as Tree and Fat-tree using pure 60 GHz DCNs.	Vardhan et al. [43]	2010	✗	Cellular (hexagonal single cell)	Tree/Fat-tree	Limited scalability as a complete DCN is designed using a single hexagonal cell of racks.
Hybrid RF	Performance measurement and simulations are done using 60 GHz devices prototype to evaluate the viability of flyways [7] concept.	Halperin et al. [44]	2011	✓	Rows	Tree	• Topology-independent model (a module can communicate with any module within its range.) • Non-configurable links with fixed capacity.
Hybrid RF	Addressing the design of a hybrid network architecture and formulating the provisioning of links in a hybrid RF DC into an optimization problem.	Cui et al. [17], [45], [46]	2011	✗	NA	NA	Topology-independent model (a WTU can communicate with any WTU in its range).
Hybrid RF	Guaranteed LOS links between adjacent rows of racks. Data is relayed row by row.	Katayama et al. [47]	2011	✗	Rows	NA	Poor performance with respect to packet delivery latency is expected due to the multihop communication.
FSO	• Propose power smart indoor FSO link using electronically controlled variable focus lens (ECVFL). • Suggest the use of power smart links in DCNs.	Marraccini and Riza [135]	2011	✗	NA	NA	NA
Hybrid RF	Propose and realize 3D beamforming 60 GHz links reflected off the ceil to overcome the LOS problem.	Zhang et al. [48]	2011	✗	Rows	Flexible	• Complexity of establishing a link. • Effect of ceil reflector's imperfection.
Hybrid RF	Extend their work by establishing a small 3D beamforming testbed to evaluate the work in [48].	Zhou et al. [18]	2012	✗	Rows	Flexible	
Pure RF	Pure 60 GHz DCN that features cylindrical racks arranged in semi-regular mesh and connected by a special Cayley Graph.	Shin et al. [32]	2012	✗	Cellular	Cayley	Cellular topology may lead to higher packet delivery latency due to multihop communication.
Hybrid FSO	Extend their work in [135] by discussing applications of power smart links and suggest the use of mechanical pedestals to establish LOS inter-rack links.	Riza and Marraccini [55]	2012	✗	Grid	NA	Mechanical systems present a risk of failure that may impact the availability and durability of the network.
Hybrid FSO	• FSO links are configured using switchable mirrors and ceil mirror. • A configurable link is realized by choosing from a set of preconfigured links.	Hamedazimi et al. [6]	2013	✓	Rows	Flexible	• Imperfection of the ceil mirror. • Manual preconfiguration can be time consuming, require specialized manpower, and impact the DCN availability.

* A. Hamza, Jitender Deogun, and Dennis Alexander, " Wireless Communication in Data Centers: A Survey," IEEE Surveys and Tutorials, PP 99 (1), Jan. 2016.

N. A. Riza References for Smart Optical Wireless & Its Motivation

N. A. Riza, J. E. Hershey, and A. A. Hassan "Novel multi-dimensional coding scheme for multi-access optical communications," Multigigabit Fiber Comm. OE/Fibers Conf. Proc. SPIE, Vol. 1790, pp.110-120, 1992.

N. A. Riza and M. C. DeJule, "A novel programmable liquid crystal lens device for adaptive optical interconnect and beamforming applications," presented at the International Conference on Optical Computing, Edinburgh, Scotland, 22–25 August 1994.

A. Hassan, J. Hershey, and N. Riza, "Spatial optical CDMA," IEEE J. Sel. Areas Commun. 13, 609–613, 1995.

N. A. Riza, "Optical Multiple Beamforming Systems for Wireless Communication Antennas," SPIE Conference Proceeding on Wireless Communications, Vol.2556, pp. 139-150, July 1995.

N. A. Riza and S. Yuan, "Demonstration of a liquid-crystal adaptive alignment tweeker for high-speed infrared band fiber-fed free-space systems," Opt. Eng., vol. 37, no. 6, pp. 1876-1880, 1998.

N. A. Riza, "Switchboard in the sky: freespace optics platform for communications and processing," IEEE LEOS Ann. Mtgs. Digest, Dec., 1998.

N. A. Riza and Y. Huang, "High Speed Optical Scanner for Multi-Dimensional Beam Pointing and Acquisition," IEEE-LEOS Annual Meeting, San Francisco, CA, Nov. 1999.

N.A. Riza, "Reconfigurable optical wireless," IEEE Lasers and Electro-Optics Society 12th Annual Meeting Proc, Vol. 1, pp. 70 –71, 1999.

N. A. Riza, Special Issue Guest Editor of the SPIE Optical Processing Working Group NewsLetter on the Topic of " Freespace Optical Wireless," October 2001.

Z. Yaqoob and N. A. Riza, "Smart Free-Space Optical Interconnects and Communication Links using Agile WDM Transmitters", 2001 Digest of the LEOS Summer Topical Meetings , 30 July-1 Aug. 2001.

N. A. Riza References for Smart Optical Wireless & Its Motivation

N. A. Riza, “Flexible Agile Optical-RF Antenna System,” SBIR Phase 1 Contract Report, 2002.

N. A. Riza, Organizer and Chair, 2002 IEEE LEOS Annual Meeting Special Symp. of Agile Laser Beams and Applications, Glasgow, Scotland, Nov. 2002.

Z. Yaqoob and N. A. Riza, “ 2π sterradian coverage transmit-receive lasercom system using smart multiplexing of multiplexed optical scanners,” Freespace laser communications and Laser Imaging II, 47th Annual SPIE Meeting, 7-11 July, Seattle, Washington, USA, 2002.

M. A. Arain and N. A. Riza, “Free Space Optical Wireless using Code-Multiplexed Optical Scanner,” IEEE INMIC Conf., December 2002.

M. van Buren and N. A. Riza, “ Foundations for low loss fiber gradient-index lens pair coupling with the self-imaging mechanism,” Applied Optics, LP, Vo.42, No.3, Jan. 20, 2003.

Z. Yaqoob and N. A. Riza, “Low loss wavelength-multiplexed optical scanners using volume Bragg gratings for transmit-receive lasercom systems,” Optical Engineering, Vol.43, No.5, pp.1128-1135, May 2004.

N. A. Riza, “Enabling the Ultimate in Optical Wireless Communications: The Zero Propagation Loss Design,” IEEE Communications Society 3rd International Symposium on High Capacity Optical Networks and Enabling Technologies (HORNET) 2006 Conference, Charlotte, USA, Sept. 6-8, 2006.

N. A. Riza and S. A. Khan, “Ultra-low loss laser communications technique using smart beamforming optics,” Optics Communications, Vol. 257, Issue 2, pp. 225-246, 15 January 2006.
N. A. Riza and S. A. Khan, Erratum, Optics Communications, Vol. 259, Issue 2, pp.888-890, 15 March 2006.

P. J. Marraccini and N. A. Riza, “ Power Smart In-door Optical Wireless Link Design,” online Journal of the European Optical Society (JEOS) Rapid Publications, Vol.6, 11054, Dec.02, 2011.

N. A. Riza References for Smart Optical Wireless & Its Motivation

P. J. Marraccini and N. A. Riza, "Reconfigurable Visible Wireless Optical Link for Indoor Applications," Royal Irish Academy (RIA) Communications and Radio Science Conference, Dublin, March 30, 2012.

N. A. Riza, " Flexible Agile Hybrid Optical-RF Antenna System for Communications and Radar," 19th IEEE International Conference on Microwaves, Radar & Wireless Communications, Warsaw, Poland, May 23, 2012.

N. A. Riza and P. J. Marraccini, " Power Smart In-door Optical Wireless Link Applications," 8th IEEE International Wireless Communications and Mobile Computing Conference (IWCMC), Limassol, Cypress, August 27-31, 2012.

P. J. Marraccini and N. A. Riza, "Dual Mode Indoor Optical Wireless Data Link Design using Micro-Optics For Robust Energy Efficient Operations," EOS Ann. Mtg. Proc., Aberdeen, 2012.

P. J. Marraccini and N. A. Riza, "Smart multiple-mode indoor optical wireless design and multimode light source smart energy-efficient links," SPIE Optical Engineering Journal, Vol.52, 5, May 2013.

N.A.Riza and P.J.Marraccini,"Programmable optic-based robust underwater/free-space optical data transfer link designs for applications using high power lasers," Photonics Ireland Conference Proceedings, Sept. Cork, 2015.

Additional References for Optical Wireless/FSOC/Li-Fi

R. S. Lawrence and J. W. Strohbehn, "A survey of clear-air propagation effects relevant to optical communications," Proc. IEEE, vol. 58, pp. 1523–1545, October 1970.

J. R. Pierce, "Optical channels: Practical limits with photon counting," IEEE Trans. Commun., vol. COM-26, pp. 1819–1821, Dec. 1978.

F. R. Gfeller and U. H. Bapst, "Wireless in-house data communication via diffuse infrared radiation," Proc. IEEE, vol. 67, pp. 1474–1486, November 1979.

C.S. Yen and R.D. Crawford, "The Use of Directed Optical Beams in Wireless Computer Communication," Proceeding of Globecom 85, New Orleans, 39.1.1-39.1.5, pp.1181-1184, 1985.

Y. Nakata, J. Kashio, T. Kojima, and T. Noguchi, "In-house wireless communication system using infrared radiation," Proc. of the Seventh International Conference on Computer Communications, pp.333-338, October 30-November 2, 1985, Sydney, Australia.

D. J. T. Heatley, D. R. Wisely, I. Neild and P. Cochrane, "A review of Optical Wireless," British Telecom Engineering Journal, vol. 17, W 4, IEC825, 1993.

Peter P. Smyth, Philip L. Eardley, Kieran T. Dalton, David R. Wisely, Paul McKee, and David Wood, "Optical Wireless a Prognosis," SPIE Proc. on Wireless Data Transmission, vol 2601, pp. 211 – 225, Philadelphia, October 1995.

K. Nishida, "A Proposal of Multi Beam Transmitter for Non-Directed Diffuse Indoor Optical Wireless Communication System," Personal, Indoor and Mobile Radio Communications, Vol. 1, pp. 242 – 246, 1996.

J. M. Kahn and J. R. Barry, "Wireless Infrared Communications," Proceedings of the IEEE, vol. 85, no. 2, February 1997.

D. Wisely and I. Neild, "A 100 Mbit/s Tracked Optical Wireless Telepoint," Personal, Indoor and Mobile Radio Communications, Vol. 3, pp. 964 – 968, 1997.

J. M. Kahn, R. You, P. Djahani, A. G. Weisbin, B. K. Teik, and A. Tang, "Imaging diversity receivers for high-speed infrared wireless communication," IEEE Commun. Mag. 36, 88–94, 1998.

R. Ramirez-Iniguez and R.J. Green, "Indoor optical wireless communications," IEE Colloquium on Optical Wireless Communications, (Ref. no.1999/128), pp.14/1–14/7, 1999.

Additional References for Optical Wireless/FSOC/Li-Fi

S. Miyamoto, Y. Hirayama, N. Morinaga, "Indoor wireless local area network system using infrared and radio communications," Proceedings of APCC/OECC'99 5th Asia Pacific Conference on Communications/Proc. of 4th Optoelectronics and Communications Conference, Beijing, China. 1999, vol. 1, pp. 790-793.

P. Djahani and J. M. Kahn, "Analysis of infrared wireless links employing multibeam transmitters and imaging diversity receivers," IEEE Trans. Commun. 48, 2077–2088 , 2000.

S. T. Jivkova and M. Kavehrad, "Multispot diffusing configuration for wireless infrared access," IEEE Trans. on Commun. 48, 970–978 (2000).

K. Nonaka, Masanori Hamada, and Yoshiyuki Isobe, "High-speed optical wireless access with a smart beam control mechanism," SPIE Asia-Pacific Optical and Wireless Communications. International Society for Optics and Photonics, 2004.

Y. Tanaka, T. Komine, S. Haruyama, and M. Nakagawa, "Indoor visible light data transmission system utilizing white LED lights," IEICE Trans. on Commun. E86-B, 2440–2454, 2003.

H. Izadpanah, T. Elbatt, V. Kukshya, F. Dolezal, and B. K. Ryu, "High-availability free space optical and RF hybrid wireless networks," IEEE Wireless Networks, vol. 10, pp. 45–53, 2003.

Scott Bloom, Eric Korevaar, John Schuster, Heinz Willebrand, "Understanding the performance of free-space optics," OSA Journal of Optical Networking, vol. 2, pp. 178-200, June 2003.

M. Kavehrad and S. Jivkova, "Indoor broadband optical wireless communications: optical subsystems designs and their impact on channel characteristics," IEEE Wireless Commun. 10, 30– 35, 2003.

A. G. Al-Ghamdi and J. M. H. Elmirghani, "Performance Evaluation of a triangular Pyramidal Fly-Eye Diversity Detector for Optical Wireless Communications," IEEE Communications Magazine, pp. 80 – 86, 2003.

K. Liang, H. Shi, S. J. Sheard, and D. C. O'Brien, "Transparent Optical Wireless Hubs Using Wavelength Space Division Multiplexing," in Free space laser communications IV, Proc. SPIE 5550, 80–87 , 2004.

T. Komine and M. Nakagawa, "Fundamental analysis for visible-light communication system using LED lights," IEEE Trans. on Consumer Electron. 50, 100–107, 2004.

M. O. Zaatari, "Wireless optical communications systems in enterprise networks," The Telecommunications Review, pp. 49-57, 2003.
A. Mahdy and J. S. Deogun, "Wireless optical communications: A survey," IEEE Wireless Communications and Networking Conference, vol.4, pp. 2399–2404, 2004.

Additional References for Optical Wireless/FSOC/Li-Fi

T.-H. Ho, S. D. Milner, and C. C. Davis, “Fully optical real-time pointing, acquisition, and tracking system for free space optical link,” SPIE, Free-Space Laser Communication Technologies XVII, G. Stephen Mecherle, Ed., vol. 5712, pp. 81–92, 2005.

D. C. O’Brien and M. Katz, “Optical wireless communications within fourth-generation wireless systems,” OSA Journal of Optical Networking, Vol. 4, No. 6, June 2005

B. Cochenour, L. Mullen, A. Laux, and T. Curran, “Effects of Multiple Scattering on the Implementation of an Underwater Wireless Optical Communications Link, MTS/IEEE Oceans 2006, pp. 1-6, 2006.

Charoen Tangtrongbenchasil, Yoichi Hamada, Toshihiro Kato, and Koji Nonaka, “Optical wireless communications and autonomous beam control moving user terminal,” IEICE Trans. Commun., vol.E 90–b, November 2007.

J. Grubor, O.C. Gaete Jamett, J.W. Walewski, S. Randel, K.-D. Langer, “High-Speed Wireless Indoor Communication via Visible Light,” Wireless 2007.

Dominic C. O'Brien, Lubin Zeng, Hoa Le-Minh, Grahame Faulkner, Joachim W. Walewski, Sebastian Randel, “Visible Light Communications: Challenges and possibilities,” IEEE 19th International Symp.on Personal, Indoor and Mobile Radio Communications (PIMRC), Cannes, 2008.

A. Kashyap, K. Lee, M. Kalantari, M. S Khuller, “Integrated topology control and routing in wireless optical mesh networks,” Elsevier Computer Networks Journal, vol. 51, pp. 4237-4251, October 2007.

Kazuhiko Wakamori, Kamugisha Kazaura, and Ikuo Oka, “Experiment on Regional Broadband Network Using Free-Space-Optical Communication Systems,” IEEE/OSA Journal of Lightwave Technology, vol. 25, pp. 3265-3273, November 2007.

R.J. Green, H. Joshi, M.D. Higgins and M.S. Leeson, “Recent developments in indoor optical wireless Systems,” IET Commun., vol. 2, 2008.

O. Bouchet, M. E. Tabach, M. Wolf, D. C. O’Brien, G. E. Faulkner, J. W. Walewski, S. Randel, M. Franke, S. Nerreter, K. D. Langer, J. Grubor, and T. Kamalakis, “Hybrid wireless optics (HWO): Building the next-generation home network,” in Proc. 6th Int. Symp. Communication Systems, Networks and Digital Signal Processing, (CNSDSP 2008), pp. 283–287, 2008.

R. H. Katz, “Tech Titans Building Boom,” IEEE Spectrum, Feb. 2009.

H. Elgala,, Raed Mesleh, and Harald Haas., "Indoor broadcasting via white LEDs and OFDM,” IEEE Trans. Consumer Electronics, 55.3,1127-1134, 2009.

C. Oh, E. Tangdiongga, and A. M. J. Koonen. "42.8 Gbit/s Indoor Optical Wireless Communication with 2-Dimensional Optical Beam-steering," Optical Fiber Communication Conference. Optical Society of America, 2015.