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无线光通信中的空时编码研究进展(一)

柯熙政,谌　娟,邓莉君

(西安理工大学 自动化与信息工程学院,陕西 西安 710048)

摘　要：MIMO 技术在射频通信领域已被深入研究,使空间成为一种可以用于提高通信性能的资源。无线光通信与射频通信在调制/解调方法、信道特性诸方面有很大的差异。文中评述了国内外有关无线光 MIMO 技术的研究进展，对无线光 MIMO 的提出背景进行了详细分析，最后通过实验说明了 MIMO 对大气湍流的抑制效应。实验结果表明:无线光 MIMO 不但使空间成为一种资源,提高了无线光通信的信道容量,而且可以抑制大气湍流效应,扩大了无线光通信的应用场合。

关键词：无线光通信；　空时编码；　进展

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Research progress of space-time code in wireless optical communications(Ⅰ)

Ke Xizheng, Chen Juan, Deng Lijun

(School of Automation and Information Engineering, Xi'an University of Technology, Xi'an 710048, China)

Abstract: MIMO technology has been intensively studied in RF communications, enable space as a kind of resources that can be used in improving communication performance. There are lot of differences between wireless optical communication and RF communication, such as modulation/demodulation method and channel characteristics. The research progress of wireless optical MIMO technology at domestic and abroad was reviewed, a detail analysis of the background of the wireless optical MIMO was carried out. The effects of MIMO inhibits atmospheric turbulence was illustrated by the experiment at last. The results show that the wireless optical MIMO not only make the space as a kind of resources that can be improve the capacity of wireless optical communication channel, but also inhibit atmospheric turbulence effect, expanded field of wireless optical communication applications.

Key words: wireless optical communication;　space-time coding;　progress

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作者简介:柯熙政(1962-),男,教授,主要从事无线激光通信方面的研究。Email:xzke@263.net

0 引 言

MIMO(Multiple-Input Multiple-Out-put)在发送端或接收端采用多个天线,可以显著抑制信道的衰落、降低误码率、提高频谱利用率[1-4],使空间成为一种可以用于提高通信性能的资源。在无线激光通信中,空时编码综合了空间分集(Space diversity)和时间分集(Time diversity)的优点,同时提供分集增益和编码增益。空时编码既能提高通信系统的信道容量,又能抑制信道衰落。无线激光通信和射频通信之间的差异主要表现在:(1) 相对于射频通信而言,激光在大气中传播时受到大气环境的影响更为复杂;(2) 影响两种通信方式中的噪声机制不完全相同;(3) 传递信号时所采用的调制方法不同;(4) 所传递的信号的表示方法不同。文中在介绍国内外无线光MIMO技术的同时,也介绍了笔者在无线光MIMO技术方面的研究进展。

1 空时编码研究概况

1.1 无线光 MIMO 的兴起

自1960年以来,人们就对无线激光通信展开了广泛的研究[5-24]。国际上从事无线激光通信研究的机构主要有欧洲的欧洲航天署(ESA)、日本的邮政部通信研究室(CTL)和宇宙开发事业团(NASDA)、美国航空宇宙航行局(NASA)和美国空军等。1980年,林肯实验室采用外差法实现了端到端的高码率的卫星通信演示实验[24]。1985年,美国空军研制了地面站与LITE(Laser inter sate-llitetransmission experiment)系统之间的半双工光链路联结实验[22]。20世纪80年代后期,欧洲航天署在两颗卫星间建立了激光通信链路,进行了卫星间激光通信单元技术的验证[2,23]。

1982年,J.Nakai研究了光信道中的编码和调制技术,为光通信的发展奠定了基础[25]。后来,人们将RS码[26]、网格编码调制技术(Trellis Coded modulation,TCM)码[27]、BCH码[28]、TURBO码[29-30]、LDPC码[31]以及交织技术[32] 、级联码[33-34]等应用于无线激光通信,但还是很难满足大容量、高速率和远距离的通信要求。

1995年,日本成功地在地面站与试验卫星ETSVI之间进行了星-地链路的光通信实验;同年,美国的战略导弹防御组织研制出了全天候跟踪扫瞄试验系统。1996年12月,Thermo Trex公司还进行了地面站与飞机之间的光通信实验。从事大气激光通信相关工作的国外厂家还包括Air Fiber公司、Light Pointe公司、Terabeam公司和Canon公司等。

1997年,加利福尼亚理工学院的James Lesh和Keith Wilson等人首先提出了多光束发射的概念[35],以抑制大气激光传输中的湍流效应,实现大气信道的有效补偿。

自多光束发射的概念提出以来,美国麻省理工学院的林肯实验室和美国的喷气推进实验室(Jet Propulsion Laboratory,JPL)进行了多光束的大气传输实验,取得了大量的实验结果[36-39]。1995年10月~1996年5月,美日联合成功验证了多光束发射技术抑制大气湍流效应的有效性[40]。I.I.Kim等人进行了大气闪烁测量实验[36],发现随着发射光束数目的增加,大气湍流引起的接收光强起伏依次减小。参考文献[41-42]给出了湍流大气中多光束传输的理论模型。

1996年,基于各小孔径接收器输入信号衰落相互独立的假设,Ibrahim[43]对采用接收分集技术的无线激光通信性能进行了研究。2000年,贝尔实验室采用多光束传输技术成功地研制了大气激光通信的原型系统[44]。2002年,JPL使用多个光束开展了距离为46.8 km的光传输实验[45],对输出信号的合并问题进行了研究,并进行了外场实验[46-48]。

2001年,JPL的通信工程研究室和美国斯坦福大学的激光通信研究组在分集接收和光信号检测方面进行了深入研究[49]。同年,麻省理工学院的Haas和Shapiro等人[50]提出了大气激光通信的空时编码准则并给出了其误码性能限。但该理论仅适合于外差探测方式,外差探测要求接收机本地振荡激光和发射激光的频率必须非常稳定,而且频率稳定度至少要达到10~11的数量级,影响了其实用化进程[51]。参考文献[52]也给出了空时编码准则和误码性能限,但将该方法用于直接检测的大气激光通信系统仍存在困难。

2002年,Zhu等人[53,56]将射频通信中的时域检测技术、似然比检测理论和分集接收技术应用到大气激光通信中,并研究了其抑制湍流效应的有效性。2003年,Simon和Vilnrotter等人对传统的Alamouti码进行了改进[55],给出了采用强度调制/直接检测式的大气激光通信中实现空时编码的方法。同年,

Yazan, A, Alqudah 和 Mohsen Kavehrad 等人针对室内无线光信道提出了一种正交空时编码[56]。

2004年,Pan Feng 等人[57]分析了星-地之间多光束传输链路的光强起伏特性;S, G, Wilson 和 M, Brandt-Pearce 等人分析了采用 QPPM 调制技术的 MIMO 光通信的误码性能[58]。在相同的条件下,Maäté Brandt-Pearce 和 Stephen Wilson[59]等人采用 PPM 调制技术设计了一种汉明权重相等的编码方案，并分析了误码性能限。

2005年,Simon 和 Vilnrotter 等人又提出了一种适合于强度调制/直接检测式的空时编码方案[60],但该方案仅适用于 OOK 调制和 2-PPM 调制。2006年,Angulta 等人[61]针对采用多光束传输的通信系统,分析了空时编码的模式。

2007年,Angulta 等人[62]分析了减小光强起伏的能力与各光束空间相关性、传输距离、湍流条件、发射器间距和接收器孔径等有关。美国 Pennsylvania 州立大学的 Navidpour 等人[63]发现空间分集的性能受各子信道的空间相关性的影响严重。同年,CAO 等人[64]提出了一种适合于 PPM 调制的大气激光通信 MIMO 系统;Antonio García-Zambrana 分析了强湍流信道中 Simon 提出的空时分组码的误码性能[65]。

2008年,Neda 等人[66]对多光束发射-多 APD(雪崩光电二极管)探测接收时的地面光通信链路进行了分析；针对强度调制/直接检测式光通信，参考文献[67]在散弹噪声和发送功率受限的情况下,分析了泊松衰落信道中 MIMO 的中断容量;Nick Letzepis 等人采用 PPM 调制,研究了高斯机制下自由空间光通信中 MIMO 系统的性能[68];Majid Safari 等人[69]采用 OOK 调制研究了重复码和空时块编码的性能;Syed Ali Raza 等人[70]将 MAC 层(媒质访问控制层)和物理层编码(正交空时编码)相结合,提出了一种交叉编码方案,利用训练序列来完成信道参数的估计。

2009年,Georgia Ntogari 等人[71]结合强度调制/直接检测技术研究了在散射丰富的室内环境下空时编码的性能。2010年,Ehsan Bayaki 等人[72]针对强度调制/直接检测方式,推出了采用两个激光器和任意探测器接收时自由空间光通信中空时编码出现成对错误概率的封闭式。同年,Antonio 等人[73]针对强湍流信道提出了一种空时网格码，并分析了其误码性能。因此,需要在 IM/DD 式的大气激光通信中进一步研究空时编码的构造、设计、性能和适用范围等。

1.2　国内无线光 MIMO 的研究

国内对于多光束发射和接收技术的研究已经在逐步展开。1999年,西北核技术研究所对多束激光在大气中的传输进行了研究。结果表明:相对于单光束传输而言,采用多光束传输时的接收光强提高了两倍[74]。2003~2004年,电子科技大学研究了多光束传输的理论,表明多光束能很好地抑制大气湍流效应[75-76]。

2004年,国防科技大学[77-79]研究了多光束传输的信道模型、空时编码以及多光束光源的温度场等。中国科学院上海光学精密机械研究所实现了155/622 Mb/s 多发射器激光通信系统[80]。

2005年,华中光电子技术研究所[81]、燕山大学[82]等对大气激光通信中的分集技术进行了研究，并分析了其系统性能。目前,安徽大学[83]、北京航空航天大学[84]等单位也有相关报道。2006年,武汉大学采用 QAM 调制将射频通信中的空时编码应用于无线光通信,并通过仿真实验验证了空时块编码的性能[85]。自2007年起,西安理工大学展开了大气激光通信中空时编码技术的相关研究，进行了光 MIMO 通信实验。嗣后,华中科技大学[86-87]、长春理工大学[88-89]也纷纷展开了无线光通信中空间分集、时间分集、光 MIMO 技术和空时编码的相关研究。值得一提的是,马晶教授带领的团队,首先在我国实现了星地激光通信。

2　多孔径发射/多孔径接收实验

2.1　多光束发射系统组成及实验

图1是多光束发射的实验系统组成,整个系统包括发射和接收两部分组成,该实验发射端采用两束波长相同的激光发射，激光采用波长为532 nm的绿光,接收端采用单个孔径接收,接收透镜直径为0.1 m,激光器通过卡塞格林望远镜进行发射,发射光束通过大气传输,在接收端通过接收透镜汇聚成一束光,然后用探测器进行探测,探测器与电脑上的数据采集卡相连,通过数据采集卡进行接收端的数据采集，所测得的数据用于光强方差的计算。实验于2011年11月24日晚上9点进行,实验地点为西安理工大学教六楼与教五楼之间,实验期间为晴天,微风[90-91]。

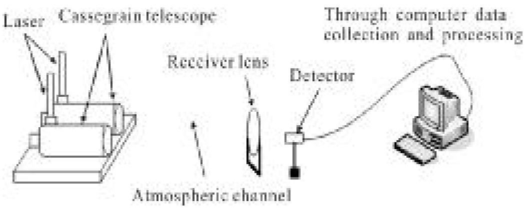

图1 多光束发射实验系统的组成

Fig.1 Experimental system of multi-beam transmitter

该实验分别采集了单束光发射和两束光发射时的光强数据,以便进行单发射和多发射系统的性能比较。

图2是单光束发射、单个孔径接收时测得的采样电压值,采样频率为2 MHz,实验中取用3 000个数据。图中是离散的点,可以看出,大部分数据集中在47 mV附近,有少量的数据点稍微偏离中心位置,这是由于光强闪烁造成的。图3是用两束光发射,在接收端用单个透镜接收时的采样电压值,从图中可以看出,相比较于单光束发射,采用两束光发射的电压波动减小,相对稳定。

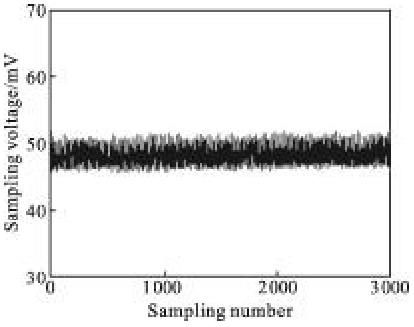

图2 单发射单接收所测量的电压值

Fig.2 Measured voltage of single transmit single receiving system

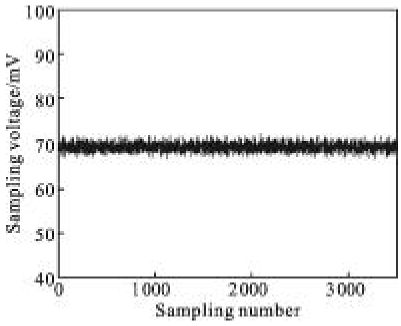

图3 双光束发射单孔径接收所测得的电压值

Fig.3 Measured voltage of dual transmit single receiving system

根据理论计算得到单发射单接收和双发射单接收的光强方差值分别为3.400 1和2.380 0,实验测得的数据通过计算得到的方差分别为1.881 5和0.885 2。理论和实验测量数据表明:双光束发射的光强方差比单光束发射的方差要小,采用多光束发射系统能降低光强起伏发差,提高通信系统性能。

2.2 多孔径接收系统构成及相关实验

图4是多孔径接收系统的结构示意图,图中发射端主要由卡塞格林望远镜和激光器组成,接收端由包含三个孔径的接收透镜、光束汇聚透镜阵列和探测器及计算机数据采集处理单元组成。其中,三个透镜的间距为0.1 m,透镜的直径为0.1 m。当发射端的激光束到达接收透镜表面并穿过透镜时会出现三束光,需要用汇聚光束的透镜和反射镜阵列将三束光合为一束,光路比较复杂,这其中的关键点是要保持发射光束的稳定,否则光束合并很难实现。

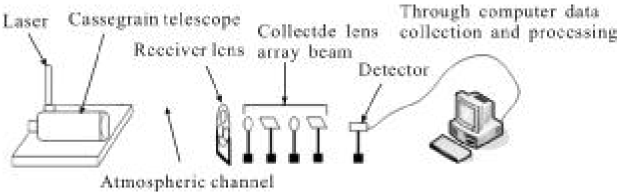

图4 多孔径接收系统结构示意图

Fig.4 Diagram of multi-aperture receiving system

该实验于2011年10月25日晚9点进行,当时天气为阴天,实验中用到的激光器是波长为532 nm的绿光,接收端的数据采集卡采样频率为40 MHz,当光束通过三孔径接收透镜后,通过探测器接收并通过电脑采集数据,实验时单孔径、二孔径和三孔径接收的数据各测量了两组,图5是采用单孔径接收时的采样电压值样本之一,图6是二孔径接收时的采样电压值样本之一。图7是三孔径接收时的采样电压值样本之一。

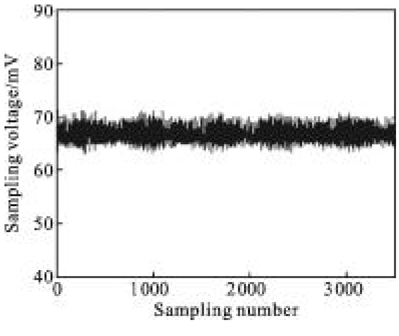

图5 单孔径接收时的采样电压值

Fig.5 Received sampling voltage by sigle aperture

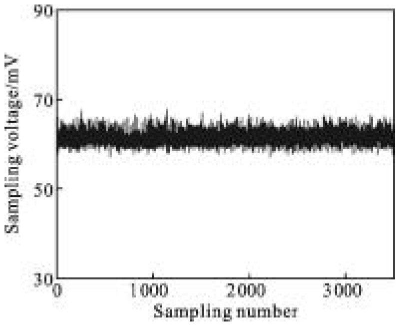

图 6 二孔径接收时的采样电压值

Fig.6 Received sampling voltage by two apertures

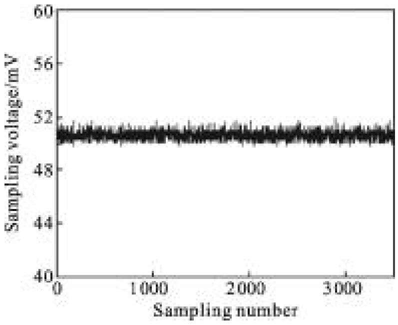

图 7 三孔径接收时的采样电压值

Fig.7 Received sampling voltage by three apertures

对比单孔径接收、二孔径接收和三孔径接收可以看出,随着孔径数目的增多,所测量到的数据抖动减小,整体比较平稳,根据该实验所测得的数据分别对每种情况的两组数据进行了方差的计算,测得单孔径接收的方差分别为 5.9763 和 5.717,理论计算得到的方差为 4.8638;采用二孔径接收时实验数据计算出的方差分别为 2.8183 和 2.8181, 理论计算得到的数据为 2.0372;采用三孔径接收时实验数据计算得到的两组方差分别为 0.1042 和 0.1050, 理论计算得到的方差为 0.5998。总体看来可以得出结论:随着孔径数目的增加光强,方差逐渐减小,说明多孔径接收能更有效地抑制湍流的影响,提高激光传输性能。

通过多光束发射和多孔径接收的相关实验,并计算实验所测得的数据的光强方差,对比不同数目光束发射时的光强起伏方差以及不同数目接收孔径接收时的光强方差,可以得出结论:多光束发射系统和多孔径接收系统要比单光束发射、单孔径接收系统更能有效地抑制湍流效应给激光传输带来的影响。

3 结 论

文中叙述了无线光 MIMO 的提出背景, 使笔者从其中的发展过程中获得启迪。通过实验说明了无线光 MIMO 对大气湍流的抑制作用, 尽管实验中的通信距离短, 但也可以看出增加发射天线和接收天线的数目可以达到抑制大气效应的目的。该系列论文之“二”将详细分析分层空时编码的特性。

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