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INTERNATIONAL ROADMAP FOR DEVICES AND SYSTEMS™

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2022 INTENTION DOCUMENT

MASS DATA STORAGE AND NON-VOLATILE MEMORY ROADMAP

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ABSTRACT

Digital storage technology is a key ingredient in all computer systems, from computing in large and small data centers, at the edge of networks and in endpoint processors used in civic infrastructure, factories, agriculture, homes and various wearable and embedded devices. Digital storage is where data lives. The amount of digital data generated is growing exponentially, driven by the increasing use of various sensors, including video cameras, the use of large training sets for various types of artificial intelligence training and once trained, for the use of AI models for inference from the data center to the edge and finally connected endpoint.

Although most of this data is transitory and not kept longer term, its use generates data that is retained for longer or shorter periods of time, driving the demand for more digital storage. As with other computing technologies, in order to enable this greater storage of data, digital storage is often distributed across a hierarchy of technologies that trade off performance (both bandwidth and latency) with the cost of storage. In addition, endurance and the expected life of the storage media are important characteristics that disadvantage or favor mass digital storage technologies, particularly for high use and archival applications.

There are many types of digital storage technology, including new non-volatile solid state storage technologies. These technologies continue to evolve, generally lowering the price to storage the growing volume of digital content. Many of these technologies compete with each other for various applications (e.g HDDs and SSDs). This roadmap will discuss the drivers, enablers and challenges for various digital storage technologies including NAND flash memory and solid state drives (SSDs) as well as other SSDs built on other non-volatile memory technologies, hard disk drives (HDDs), magnetic tape and various types of optical storage and optical disc recording technology. We also intend to include DNA storage for the first time.

The roadmap will also look at the same factors for various non-volatile solid-state memories that are in more limited commercial production and in use as stand-alone memory as well as memory built into embedded devices such as Systems on Chip (SoCs), including magnetic random-access memory (MRAM), resistive random-access memory (RRAM), ferroelectric random-access memory (FRAM) and phase change memory (PCM) and other solid-state non-volatile memory technologies that are not yet in commercial production.

These factors will be used to create a roadmap table for the evolution of these various mass storage and non-volatile memory technologies (built upon expected changes in important specifications for each technology) for the next ten years.

Key words: hard disk drive, HDD, solid state drive, SSD, NAND, magnetic random-access memory, MRAM, resistive random-access memory, RRAM, ferroelectric random-access memory, FRAM, phase change memory, PCM, optical disc, DVD, Blu-ray, Archive Disc, 3D Xpoint, Optane, non-volatile memory, non-volatile memory express, NVMe, connect express link, CXL, universal chiplet interconnect express, UCIe, DNA storage

"MASS STORAGE AND NON-VOLATILE MEMORY ROADMAP" WHITE PAPER

1. INTRODUCTION

1.1. CHARTER

This working group is continuing the activities formerly done with iNEMI on creating a roadmap for non-volatile memory and mass data storage. This group has been creating this roadmap for over 20 years and wishes to continue this effort as part of the IEEE IRDS. The working work will review technical developments, drivers and applications as well as projected roadmaps for NAND-flash based solid state drives (SSDs), hard disk drives (HDDs), magnetic tape, optical disc technology, DNA storage as well as non-volatile solid state memory technologies such as magnetic random-access memory (MRAM), resistive random-access memory (RRAM), ferroelectric random-access memory (FRAM), phase change memory (PCM) and many other emerging non-volatile memory technologies. This roadmap effort intends to continue to provide iNEMI with a high-level version of the report for their continued roadmaps from the more detailed IEEE IRDS Mass Storage and Non-Volatile memory roadmap.This roadmap effort is based off of the framework and prior work done for about 20 years as an iNEMI roadmap. We realize that some of the work on evolving memory technologies and architectures that may include non-volatile memory technologies are also covered in other IRDS roadmapping efforts and we would plan on including and referencing their other IRDS roadmaps into our mass storage and non-volatile memory efforts where that is appropriate.

1.2. SCOPE OF WORKING GROUP EFFORT

This working group will explore the historical trends and create projections for mass storage and non-volatile memory technologies that include NAND flash SSDs, HDDs, magnetic tape, optical storage, DNA storage as well as MRAM, RRAM, FRAM and PCM and other developing non-volatile memory technologies. Our roadmapping group does not intend to create an independent roadmap for volatile memories such as DRAM and SRAM, although it might refer to other IRDS roadmaps that include these technologies for reference in discussing the use of non-volatile memories. This work will carry out this work with a team of people who are experts in the various digital storage and non-volatile memory technologies which includes people who have been involved in the prior iNEMI roadmaps as well as new participants as needed to cover the various topics.

1.2.1. ROADMAP FRAMEWORK

We will look at each of the mass storage and non-volatile memory technologies both individually and as potential competitors for particular applications. For each technology we will discuss the situational analysis, business and technical issues, provide a roadmap of quantified key attribute needs, critical issues, technology needs including research, development and implementation, gaps and showstoppers and recommendations on priorities and alternative technologies.

1.2.1.1. ARCHITECTURES

NVMe and NVMe-oF, CXL, hierarchical storage architectures, embedded non-volatile memory architectures, block, file and object storage devices and systems, computational storage and memory, in-memory computing, possibly UCIe

1.2.1.2. VERTICALS/APPLICATIONS/SERVICES

Verticals include data centers storage, enterprise storage, storage redundancy (including RAID and erasure codes), edge storage and non-volatile memory in embedded devices.

Applications include various AI applications (both training and inference) and in data centers, at the network edge as well as in endpoint devices, other common data intensive applications, storage hierarchies, backup, cold storage, archiving.

1.3. LINKAGES AND STAKEHOLDERS

Digital storage and non-volatile memory are key elements of all computing and so the development of these technologies will be important for people designing or using computing systems in data centers (large and small), at the network edge (e.g. in cell towers or neighborhoods), in factories and in agriculture and in endpoint devices including in the home, in mobile devices and in various wearable and medically insertable devices.

1.3.1. STAKEHOLDER ORGANIZATIONS

SNIA, NVM Express Organization, The CXL Consortium, UCI Express Consortium, INSIC, DNA Data Storage Alliance, digital storage and non-volatile memory manufacturers (such as Seagate, WDC, Toshiba, Samsung, SK Hynix, Kioxia, Micron, EverSpin, Fujitsu, Sony, Panasonic, Honeywell, TSMC, Intel and others), storage system manufacturers (Dell, Lenovo, HPE, IBM, Hitachi Vantara, Quantum, Fujifilm, Sony, Panasonic, NEC, AWS, Google, Microsoft, Alibaba, Tencent, Pure, VAST Data and many other companies). There are also many research institutions and universities working on various storage and memory technologies including IMEC, CEA Leti, DSI, UCSD, Stanford, UC Berkeley, UCLA, Carnegie Mellon, Univ. of Minnesota, University of Alabama, Tohoku University and many others.

1.3.2. IRDS CROSS-CUT TEAM COORDINATION

We will need to share information with the IRDS roadmap teams focusing on developments in volatile (and non-volatile) memory technologies as well as teams focusing on emerging storage and memory interconnects and architectures including NVMe, NVMe over fabric (NVMe-oF), CXL and UCIe.

1.3.3. STANDARDS ORGANIZATIONS

For some of the storage related work, the Storage Networking Industry Association (SNIA) would seem like a good standards group. It is possible that some of the hard disk drive interface standards groups may be interested as well as the LTO magnetic tape organization. INSIC may also be interested, although they don’t do standards.

1.3.4. OTHER ENABLING TECHNOLOGIES AND ORGANIZATIONAL CAPABILITIES

Because of the value of storage data digital security and privacy of this data is an important factor in the practical use of digital storage and non-volatile memory technologies and this will be guided by regulation and public and private policies.

2. CURRENT TECHNOLOGY SITUATION AND PLANS

2.1. TECHNOLOGY TOPIC AREAS

2.1.1. NAND FLASH AND SSDS

NAND flash technology includes planar flash used for some legacy applications as well as 3D NAND that consists of layers of NAND flash cells. The move to 3D NAND was required to continue the density growth of NAND flash since it became very hard to reduce the feature size of NAND memory cells to 15nm or less. Moving to a 3D structure allowed relaxing the feature size, making more manufacturable memory cells. Current 3D products have up to 176-layers but industry players project that 500-layers or more may be possible, although the cost advantages of increasing layer count decline as the layer count increases.

In addition to 3D NAND flash structures, higher capacity is also possible by dividing up the voltage difference between the flash memory cells states to enable more bits per memory cell. Two (MLC) and three (TLC) bits per cell are common as is four bits per cell (QLC, using in consumer storage but starting to show up in enterprise applications. There are even companies that plan five bits per cell (PLC) flash in the next few years. The higher density from more bits per cell comes at the price of lower endurance and lower performance. These issues can be minimized with clever designs that limit cell writing and include more parallel performance to improve effective performance. A key element in making NAND flash useful is various technologies built into the flash controller.

NAND flash memory products, including SSDs have significantly higher performance than HDDs although their read write speed are different due to the need to do an erase write cycle on NAND flash memory cells. Enterprise SSD performance today is over 500MB/s sequential reading and 10-15% lower sequential writing. With 3D NAND layer count and higher bits per memory cell helping to increase NAND flash capacity, the price of NAND flash has been declining. The current cost of enterprise NAND flash SSD storage is about $0.20/GB ($200/TB).

2.1.2. HDDs

The technologies used in mass storage and non-volatile memory include magnetic recording (on rigid and flexible media and including various magneto-resistive reading technologies). 3.5-inch nearline HDDs are currently available with storage capacities of 20 to 22TB, using various types of energy assisted magnetic recording and without or with shingled magnetic recording (SMR). These HDDs have up to 10 disks in a helium sealed enclosure and provide 10’s of MB/s of write and read performance. The current price of nearline HDD storage is about $0.02/GB or $20/TB.

The data rate from nearline HDD will increase to twice that with the introduction of dual stage actuators in the near future and will double again with four stage actuators later. The higher data rates are important for very high HDD capacity rebuilds as well as data access. The HDD companies project that they can introduce 40TB 3.5-inch form factor nearline HDDs by 2026 using more advanced energy assisted magnetic recording.

There are also plans to make these HDDs with 11 or possibly 12 disks (requiring the use of glass substrates to avoid flutter with thinner disks). Higher capacities up to 100TB may be possible with higher disk count and digital storage areal densities approaching 50Tb per square inch.

2.1.3. Magnetic Tape

Half-inch magnetic tape cartridges are available with up to 18TB native (uncompressed) capacity (LTO-9, announced in 2020). The current price of LTO magnetic tape storage is about $0.004/GB or $4/TB (although current supply chain issues result in higher prices). Magnetic tapes have high data rates for writing and reading of 100’s of MB/s once the tape is inserted into a tape drive. This will increase with the linear and track density of future tape formats.

In addition to the LTO format, IBM makes enterprise half-inch cartridge tapes with a different format and native capacities up to 20TB. Both LTO and IBM enterprise tapes currently use barium ferrite particle tapes. This tape technology was introduced with the LTO 8 tapes.

The LTO consortium has a roadmap out to LTO 12 with planned half-inch tape cartridge native capacities of 192TB. Increasing tape areal density depends upon the thickness of the plastic substrates as well as the track and linear recording density. Laboratory demonstrations of magnetic tape technology by IBM Zurich and Fujifilm in 2020 show the feasibility of over 580TB for a half-inch cartridge tape.

Magnetic tape can have a shelf life under proper environment conditions of about 30 years, making it a useful archive media compared to magnetic HDDs (maximum life of 5-10 years) and SSDs (maximum life of 3-5 years, depending upon use). Magnetic tape can be in a cold archive where tapes must be accessed from shelves or a warmer or active archive, where the tapes are retrieved by robots from slots in a tape library and moved to tape drives where they can be written or read. If a library is used, the total price of storage must include the library and drives as well as the magnetic tapes, increasing the price of tape storage somewhat.

2.1.4. Optical Storage

The most common optical storage uses various disc formats such as CVD, DVD and Blu-ray discs. The highest capacity discs use the archival disc technology developed by Sony and Panasonic. These are write-once discs available in a 4.7-inch diameter 12-cartridge format with a disc capacity of 100, 300 and 500 GB. The Archival Disc roadmap also projects a 1TB disc sometime in the future that may use holographic recording technology.

The reducing use of optical discs as a content distribution format has significantly reduced the volume of optical discs produced annually. Although optical disc libraries using the Archival Disc format are used in some applications, such as Facebook photo storage, the use of optical storage in archiving seems to be less common than archives using magnetic tape or HDDs. The reduced production of optical discs overall may make optical discs less competitive than these other archive storage technologies.

2.1.5. DNA Storage

This is a technology that, although is likely several years from production, are showing promise for archival storage. Synthetic DNA used for digital storage can have a lifetime than any of the other storage technologies mentioned here—in the case of dehydrated DNA, this shelf live could be hundreds of years. In addition, DNA has the potential of providing very high-density storage, potentially beyond the capabilities of magnetic storage. There are several startup companies working on DNA for data storage and we would plan to include roadmaps on this technology in the 2022 roadmap, with experts from DNA storage added to our roadmap committee.

2.1.6. Non-volatile Memory

This includes many solid-state non-volatile memory technologies such as MRAM, RRAM, FRAM and PCM as well as some emerging memory technologies that aren’t available in commercial products yet. The MRAM technologies include spin tunnel torque (STT) MRAM, Spin orbit torque (SOT) MRAM and other types of magnetoresistive technologies still in the laboratory.

These technologies are available in stand-alone memories and as memory in embedded devices. The latter application uses MRAM (and also RRAM) to replace NOR flash in these embedded devices because MRAM (and RRAM) can be scaled to smaller features than 28nm (the limit to NOR flash). In addition, MRAM is also being used to replace or supplement higher level SRAM because MRAM memory cells are much smaller than SRAM memory cells and also because the MRAM memory is non-volatile, allowing more low energy consumption states that are important for battery and harvested energy powered devices. The move from STT MRAM to faster SOT MRAM could enable even more replacement of SRAM by non-volatile MRAM. It is possible that if MRAM or one of the other non-volatile solid state memory technology achieves enough production volume that its price could approach that of DRAM, but that prospect is many years off.

Resistive RAM (RRAM) is also available in foundries for non-volatile memory in embedded devices. Like MRAM, RRAM scales to smaller nodes than NOR flash and may be able to supplement some SRAM, replacing volatile with non-volatile memory.

RRAM, FRAM products are also available as stand-alone products from various companies. Ferroelectric memory traditionally was made with unusual material for semiconductor fabs such as lead and bismuth. In 2011 a crystalline form of hafnium oxide was discovered that had strong ferroelectric properties. Hafnium oxide is used as a high k dielectric in many CMOS processes and there are companies working on the use of hafnium oxide in memory devices in CMOS devices. Ferroelectric hafnium oxide has also been used in the laboratory to enhance the memory retention of DRAM.

Phase change memory has a long history and is available in stand-alone memory from several companies. Probably the most well-known is Intel's Optane memory, which is a phase change memory developed by Intel and Micron under the name of 3D XPoint. Intel began to offer NVMe SSDs with Optane memory in 2017 and in 2018 announced DIMMs with Optane memory. In 2020 Intel and Micron announced a second-generation 3D XPoint with 4 layers versus 2 layers in the first-generation product. In March 2022 Intel indicated that they would soon announce a third-generation Optane product. Intel sells for a price between that of NAND flash and DRAM and has become the highest volume newer non-volatile solid state memory technology.

2.2. TODAY'S CHALLENGES

SSDs, HDDs, magnetic tape and to some extent, optical discs compete with each other for mass storage applications. This competition is based upon performance, price and other issues such as endurance (for NAND flash). The emerging non-volatile solid-state memory technologies are generally seeking an increasing number of niche applications to drive production volume in order to decrease the cost of manufacturing these memories and invite additional investment to develop future generations of technologies.

2.3. STANDARDS

There are standards in development, particularly for interconnects that are undergoing continuing development. These include NVMe, CXL and UCIe as well as the various HDD interface standards activities for SATA, SAS and fiber channel.

2.4. ROADMAP ENGAGEMENT NEEDS

This roadmap effort requires expertise in the various digital storage technologies as well as the various ways that these mass storage and non-volatile memories can work together to meet the needs of particular applications—such as storage system designers.

3. REQUIREMENTS AND TECHNOLOGY GAPS

The roadmap will be created by the core roadmap group meeting and working on the updated roadmap document, plus recruiting some expertise in DNA storage to help us with that topic for the roadmap.

The roadmap will discuss the likely developments in the competing mass storage and non-volatile memory technologies and the trends towards and away from the use of these technologies for particular applications. In particular, for HDDs we will discuss the move from using HDDs in various legacy enterprise, PC and consumer storage application and the growing use of nearline HDDs for data center applications. We will also discuss the growing uses for NAND flash in industrial, automotive and consumer applications as well as SSDs for PCs and data center and enterprise applications. We will also explore the potential future of optical storage for enterprise and data center applications.

A similar effort and expertise is needed to create a roadmap on the various emerging non-volatile memory technologies, particularly regarding any developing momentum for implementation of these technologies for standalone as well as embedded memory applications.

4. Roadmap Timeline Chart

See examples of this in prior iNEMI Mass Storage Roadmap document, available at inemi.org.

5. Contributors

We are currently seeing if former roadmap experts are on-board for 2022 and we also plan to recruit new member to cover new areas (such as DNA storage), to provide insights on storage technology and applications or to replace those who didn't respond or said they didn't want to contribute in 2022. The list below is participants from the 2019 roadmap.

Chair: R. F. Hoyt, Consultant

Co-Chair: T. M. Coughlin, Coughlin Associates, Inc.

D. Aune, Univ. of MN and Seagate (HDD)

J. Barber, IBM (Tape)

E. Childers, IBM (Tape)

J. Deak, Multidimensional Technology (MRAM)

R. Dennison, Research Development Consultants (HDD)

J. Handy, Objective Analysis (SSD, NAND)

E. Herzog, IBM (Tape)

M. Hill, IBM (Tape)

M. Johnson, Naval Research Lab. Ret. (MRAM)

M. Kief, Seagate, ASTC (HDD)

M. Lantz, IBM (Tape)

S. Merriman, SpectraLogic (Tape)

R. G. Zech, ADVENT Group (Optical)

J. Zhu, Carnegie Mellon Univ. (MRAM)

H. Zia Shakari, SpectraLogic (TAPE)

6. ACRONYMS/ABBREVIATIONS

TERM	DEFINITION
AFR	Annual Failure Rate
AOD	Advanced Optical Disc (now HD DVD)
ASIC	Application Specific Integrated Circuit
AV	Audio Video
BAR	Bit Aspect Ratio
BD	Blu-ray Disc
BDA	Blu-ray Disc Association
BEOL	Back End of Line. The final processes in semiconductor manufacture.
BL	Blue Laser
BPM	Bit Patterned Media
Byte	1 byte = 8 bits
CAD	Computer Aided Design
CAE	Computer Aided Engineering
CAV	Constant Angular Velocity
CCP	Confined Current Path
CD	Compact Disk
CD-RW	Write-once Compact Disc
CD-RW	Rewritable Compact Disc
Chalcogenides	Certain alloys containing one or more group VI elements that exhibit reversible change between the disordered (amorphous) and ordered (crystalline) atomic structure, the most common being Ge2Sb2Te5
CMOS	Complementary Metal Oxide Semiconductor
CLV	Constant Linear Velocity
CPP	Current Perpendicular to Plane
CW	Continuous Wave
DL	Double Layer
DMD	Digital Multi Disc
DRAM	Dynamic Random-Access Memory. The semiconductor memory most commonly used for program storage in today's computing systems.
DS	Double Sided
DTR	Discrete Track Recording
DVD	Digital Versatile Disk
ECC	Error Correction Code
ECMA	Industry Standards Association for Communication and Consumer Electronics
EPRML	see PRML
E2PRML	see PRML
EVD	Enhanced Versatile Disc (mainland Chinese HD AV standard)

TERM	DEFINITION
EUV	Extreme UltraViolet
FDE	Full Disk Encryption
Flash	Semiconductor memory based upon a technology where charges are trapped in a floating gate of an insulated-gate field-effect transistor.
FMD	Fluorescent Multi Disc
FRAM	Ferroelectric Random Access Memory: A possible successor to Flash memory that uses molecules that exhibit a hysteresis similar to that of magnetics, although no magnetic materials are used.
FVD	Forward Versatile Disc (Taiwanese AV standard)
GaN	Gallium Nitride (basic semiconductor material of most blue lasers diodes)
Gb	gigabit (10^9 bits)
GB	gigabyte (10^9 bytes; 1 byte = 8 bits)
GMR	Giant Magnetoresistive
GPR	Generalized Partial Response
Green	Energy Efficient, using Little Energy
HAMR	Head Assisted Magnetic Recording
HD DVD	High Definition DVD
HDD	Hard Disk Drive
HDS	Holographic Data System
HDTV	High Definition Television
HGA	Head Gimbal Assembly
Hi-MD	Second-generation Mini Disc
HOLOMEM	Holographic Memory
HSM	Hierarchical Storage Management
HVD	Holographic Versatile Disc
IDEMA	International Disk Drive Equipment and Materials Association
IP	Intellectual Property
	Patents, trade secrets, and know-how that companies may license to others to collect royalties or may use to forestall competitors from manufacturing competing products.
INSIC	International Storage Industry Consortium
IOPS	Input/Output Operations per Second
IRDS	International Roadmap for Devices and Systems
ISI	Inter-symbol Interference
ISO	International Standards Organization
ISOM	International Symposium on Optical Memory
ITRS	The International Technology Roadmap for Semiconductors. An industry consortium focused on enabling future generation semiconductor manufacture
L0	The top layer of a dual-layer optical disc

TERM	DEFINITION
L1	The bottom layer of a dual-layer optical disc
LD	Laser Diode
LDPC	Low Density Parity Check Code
LTO	Linear Tape Open format
M/L	Multi-Layer
Magnetoresistance	The mechanism used to read an MRAM. Magnetoresistance produces a high or low resistance in the signal path depending on the magnetization of the cell.
MAMMOS	Magnetically Amplifying MO System
MAMR	Microwave Assisted Magnetic Recording
MARS	Mastering and Replication System
MEMS	Micro-electromechanical Systems
ME	Metal Evaporated Tape Media
MLC	Multi-Level cell
	A technique used to multiply the number of megabytes that can be stored on a given size silicon chip by putting more than one bit of data onto a single memory bit location.
MD	Mini Disc
MF	Multi Function
ML	Multi-Level
MO	Magneto-Optical
MP	Metal Particle Tape Media
MR	Magneto-resistive
MRAM	Magnetic Random Access Memory
MTJ	Magnetic Tunnel Junction. An older type of MRAM technology.
MTTF	Mean Time to Failure
NAND	A basic function of Boolean logic in which an output is false whenever all inputs are true. Although this term is usually spelled in all caps, NAND is not an acronym.
NAND Flash	The less expensive of two types of Flash memory (NAND and NOR) which makes it more suitable for mass storage applications.
NAS	Network Attached Storage
NA	Numerical Aperture
NFR	Near Field Recording
NOR	A basic function of Boolean logic in which an output is false whenever any input is true. Although this term is usually spelled in all caps, NAND is not an acronym.
NOR Flash	The more expensive of two types of Flash memory (NAND and NOR) which makes it less suitable for mass storage applications
NSIC	National Storage Industry Consortium
NFR	Near-Field Recording
ODL	Optical Disc Library

TERM	DEFINITION
ODS	Optical Data Storage
OMA	Opto-Mechanical Assembly
OPU	Optical Pickup Unit
OUM	Ovonic Unified Memory. Another name for PCM. Named for the material's inventor Stanford Ovshinsky
PB	peta-byte (10^{15} bytes)
PC	Personal Computer
PC	Phase Change
PCM	Phase Change Memory
PCRAM	Phase Change Random Access Memory. Another name for PCM
PDD	Professional Disc for Data
Perovskite	Crystals in a class of compounds that share the of crystal structure found in $CaTiO_3$.
Pinned	A layer in an MRAM whose magnetic orientation cannot be changed. Used as a reference.
PRAM	Phase (change) Random Access Memory. Another name for PCM
Probe Storage	Storage method which utilizes a tip or probe to make marks or indentations 10 nanometers in diameter small in a film
Process Node	The measure of the smallest line that can be printed on a silicon wafer, which governs the size and cost of the hip that can be manufactured on that line.
PRML	Partial Response Maximum Likelihood, Signal coding
EPRML	with a controlled amount of inter-symbol interference (ISI)
E^2PRML	decoded with the ML (maximum likelihood) algorithm.
	The E's stand for Extended. The more E's, the greater ISI that can be tolerated.
PTM	Phase Transition Mastering
PZT	Lead Zirconium Titanate ($PbZr_xTi_1$-xO_3). A type of Perovskyte crystal used in certain ferroelectric memories (FRAMs).
PTM	Phase Transition Mastering
RLL	Run Length Limited
R	Recordable (write-once; same as WO or WORM)
RO	Read-Only (same as ROM)
RW	Re-Writable
SAF	Synthetic Anti-Ferromagnetic (magnetic media)
S-AIT	Super-Advanced Intelligent Tape
SDTV	Standard Definition Television
SNR	Signal to Noise Ratio
SSD	Solid-state disk, a replica of the function of an HDD but manufactured using semiconductor memory and no mechanical moving parts.

TERM	DEFINITION
SSFD	Small Form Factor Disc
SIL	Solid Immersion Lens
SL	Single Layer
SLC	Single Level Cell. The original approach to Flash storage, where each NAND cell is used to store a single bit of data.
SMT	Surface Mount Technology
SNIA	Storage Networking Industry Association
SS	Single-sided
STT	Spin Torque Transfer. A means of programming an MRAM
SYSCON	System Controller
Tb	Terabit (10^{12} bits)
TB	Terabyte (10^{12} bytes)
Tiering	The process of maintaining copies of frequently-needed data in faster more costly storage while keeping the less-frequently- needed data in slower, less costly storage.
Tiered Storage	A storage architecture that offers a variety of places to store data that range from slow inexpensive storage to more expensive fast storage.
TMR	Tunneling Magneto-resistive
USB	Universal Serial Bus. An interface available on all PCs that supports high-speed data upload and download through a very small connector.
VHDL	Very High Density Logic
UDO	Ultra-Density Optical
VFL	Variable Frequency Lens
VHDL	Very High Density Logic
VMD	Versatile Multilayer Disc
WO	Write-Once (same as WORM)
WORM	Write Once Read Mostly

7. APPENDIX

7.1. APPENDIX A – 2019 INEMI MASS STORAGE ROADMAP

To access the 2019 iNEMI Mass Data Storage Roadmap, visit www.inemi.org.

ANTI-TRUST STATEMENT

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